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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
08/07/2006	00	New site profile for the Lawrence Berkeley National Laboratory. First approved issue. Training required: As determined by the Task Manager. Initiated by Paul A. Szalinski.
04/02/2007	01	Approved Revision 01 initiated to include Task 5 and PID review comments which were omitted from Rev 00. Constitutes a total rewrite of document. Incorporates internal formal review comments and additional NIOSH formal review comments. Attributions and Annotations added. Incorporates internal formal review comments regarding the Attributions and Annotation section only. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Paul A. Szalinski.

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ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
AMAD	activity median aerodynamic diameter
ANL-E	Argonne National Laboratory-East
Bq	becquerel
Ci	curie
cm	centimeter
cpm	counts per minute
d	day
DOE	U.S. Department of Energy
dpm	disintegrations per minute
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
F	fast (solubility rate)
ft	foot
g	gram
HILAC	heavy-ion linear accelerator
hr	hour
HVL	half-value layer
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis (computer program)
in.	inch
keV	kiloelectron-volt, 1,000 electron-volts
kg	kilogram
kV	kilovolt
kVp	applied kilovoltage; peak kilovoltage
L	liter
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LRL	Lawrence Radiation Laboratory
LRL-B	Lawrence Radiation Laboratory Berkeley
m	meter
M	moderate (solubility rate)
mA	milliampere
MDA	minimum detectable activity
MDL	minimum detection limit
MeV	megaelectron-volt, 1 million electron-volts
MFP	mixed fission products

min	minute
mL	milliliter
mm	millimeter
mo	month
MPC	Maximum Permissible Concentration
mR	milliroentgen
mrem	millirem
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH-Office of Compensation Analysis and Support Claims Tracking System
NTA	nuclear track emulsion, type A
NTLF	National Tritium Labeling Facility
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
pCi	picocurie
PHA	pulse height analysis
POC	probability of causation
S	slow (solubility rate)
s	second
SRDB Ref ID	Site Research Database Reference Identification Number
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
WB	whole-body
WBC	whole-body count
wk	week
yr	year
µg	microgram
µm	micrometer
µCi	microcurie
§	section or sections

1.0 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

1.1 PURPOSE

This site profile provides technical basis information to be used to evaluate the total occupational radiation dose that can reasonably be associated with a worker's radiation exposure at Lawrence Berkeley National Laboratory (LBNL). This dose results from exposure to external and internal radiation sources in LBNL facilities, to X-ray examinations performed for medical screening, and to onsite environmental releases. This site profile includes methods for estimating doses that could have occurred while an employee was not monitored or was inadequately monitored as well as doses that were missed due to analytical detection limits or incomplete or missing monitoring records (i.e., missed dose).

This site profile can be a tool when performing dose reconstructions for LBNL workers. The Integrated Modules for Bioassay Analysis (IMBA) computer program is a tool useful for internal dose calculations. Information on measurement uncertainties is an integral component of the NIOSH approach. This document describes how to evaluate uncertainty associated with LBNL exposure and dosimetry records

1.2 SCOPE

This site profile consists of a site description (Section 2.0) and discussions of occupational medical dose, occupational environmental dose, occupational internal dose, and occupational external dose (Sections 3.0 to 6.0).

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 7.0.

2.0 SITE DESCRIPTION

This section describes major LBNL facilities and operations. LBNL was founded in 1931 on the University of California, Berkeley campus. It was originally known as the University of California Radiation Laboratory. In July 1945, LBNL moved from the Berkeley campus to a 134-acre site in the hills to the east [1]. LBNL began defense work in 1941 when the National Defense Research Committee appointed Ernest O. Lawrence to study the potential military uses of ^{235}U (Maroncelli and Karpin 2002). Assignment of dose should begin in 1942 when the Manhattan Engineer District was founded.

LBNL is alternatively referred to in reference documents as Berkeley Lab, Lawrence Radiation Laboratory (LRL), and Lawrence Radiation Laboratory, Berkeley (LRL-B). This document uses LBNL for consistency.

Table 2-1 provides a general description of LBNL buildings and lists the radionuclides of concern [2]. From the 1950s to the present, the laboratory has maintained its status as a major international center for physics research and has diversified its research program into almost every realm of scientific investigation. Along with its historical specialty of accelerator research and nuclear physics, the laboratory currently maintains divisions that investigate astrophysics, nuclear fusion, earth sciences, genomics, health physics, computer science, materials science, environmental science, and other areas [3]. In addition, the laboratory is the site of a number of National User Facilities, including the Advanced Light Source, the National Center for Electron Microscopy, the National Energy Research Scientific Computing Center, the Energy Sciences Network, and the future Molecular Foundry [4].

Table 2-2 lists the quantities of the radionuclides that workers could have encountered by area [5]. This list is not intended as a complete radiological history, but rather as a discussion to familiarize dose reconstructors with the variety of radionuclides that have been present at LBNL.

Table 2-1. Area information and parameters.[a]

Building(s)	Description	Period	Radionuclides[b]
1 (on campus)	Donner Laboratory	1931	H-3, C-14, P-32, P-33, Sr-90, I-125, Th-232, U-238
2 (on campus)	Advanced Materials Laboratory and Center for X-ray Optics (formerly the Crocker Laboratory)	1931	N-13, O-15
3	Laboratory of Chemical Biodynamics (Calvin Laboratory)		H-3, C-14, P-32, S-35, P-33
4 and 5	Magnetic Fusion Energy		H-3, C-14, P-32, S-35
6, 9, 10, and 80	Advanced Light Source (formerly the 184-in. cyclotron complex)	1940 to present	Be-7, Co-57, Co-58, Co-60, Ni-63, Fe-55, Fe-59, Mn-54, Na-2,2 Zn-65, Am-241, Am-243, Cm-246, Cm-248, Np-237, Pu-238, Pu-239, Pu-240, U-235, Tc-99, Pu-242, Pu-241, N-13, O-15, Na-24, Ar-41, Ni-57, Th-232
8 (on campus)	Hearst Laboratory		Am-241, U
10	Cell & Molecular Biology Research & Photography	1986	H-3, C-14, P-32, S-35, Cr-51
14	Accelerator and Fusion Research and Earth Sciences		H-3
16	Magnetic Fusion Energy Laboratory		U-234, U-235, U-238
19 (on campus)	LeConte Hall		Fe-55, Fe-59, Co-60, Au-198, Au-199, Hg-203, Ga-67, In-112, Ba-127, Cs-127, Ba-131, Cs-131, Cs-137, Sr-90
22 (on campus)	Latimer Hall		C-14
26/76	Medical Services and Bioassay, Radiation and Analytical Measurements Laboratory		I-125, I-129, I-131, U-238, C-11, C-14, Be-7, F-18, P-32, S-35, U-232, Sr-90 Ac-228, Ag-108, Ba-133, Ce-144, Cm-243, Am-241, Am-243, Br-76, Br-77, Cm-244, Bk-249, Cf-249, Cf-250, Cm-245, Cm-246
31 (on campus)	Hesse Court		Depleted U
36 (on campus)	2232 Piedmont		Sr-90, Am-241, Na-24, Cl-36, K-42
38 (on campus)	Lewis Hall		Co-57, Fe-59, Co-60, Sn-119, Gd-153
50B	Physics		Ag-106m, Au-194, Co-56, Co-57, Co-58, Co-60, Mn-52, Mn-54, Na-22, Ni-57, Re-184m, Sc-48, Se-75, Ta-182, V-48, Zn-65m Be-7, Ag-105
51	Contains the Bevatron and Bevalac		Be-7, Co-57, Co-58, Co-60, Fe-55, Fe-59, Mn-54, Na-22, Ni-63, Zn-65, Na-24, Ni-57, Ni-57, Cf-252, U, Am-241, Am-243, Ra-226, Bk-249
52	Magnetic Fusion Energy Laboratory		H-3, C-14, P-32, S-35, Am-241, Cf-250, Cm-243, Cm-248, Np-237, Pu-239, Pu-244, Th-229, Th-230, Th-232, U-232, U-235, U-236, U-238, Pu-242
53	SuperHILAC Development		
55/56	Research Medicine/Radiation Biophysics, Biomedical Isotope Facility	1964	H-3, C-14, F-18, P-32, I-131, Sr-90, Xe-127, Nb-95, Ru-103, Gd-153, Tl-201, I-123, I-125, Sn-113, Tc-99m, Co-57, Cr-51, Nb-95, O-15, Cu-64, Ce-141, N-13, Sr-85, Sc-46, C-11, Co-55,
56	Biomedical Isotope Facility		C-11, Co-55, Co-57, F-18, N-13, O-15, O-14, F-17

Building(s)	Description	Period	Radionuclides[a]
57 (on campus)	Donner Pavilion		P-32, Sr-82, Sr-85, Sr-90, I-125, I-131, In-111
58 and 58A	Accelerator Research and Development		
60	High Bay Laboratory		
62	Materials and Chemical Sciences		U-238
63 and 64	Accelerator and Fusion Research		P-32
70 and 70A	Nuclear, Materials, Chemical, Life, and Earth Sciences		H-3, C-14, P-32, Fe-59, I-125, Sr-90, Th-232, Tc-99, Ce-141, Ce-144, Pa-233, Sm-153, Te-153m, Yb-169, Zn-65, Sc-46, Na-22, Na-24, S-35, Ca-45, Ca-49, Mn-54, Fe-59, Y-90, Rh-101, Ru-106, Sb-124, Ce-141, Tm-170, Cs-134, Eu-152, Am-243, Bi-207, Sc-49, Co-60, Zr-88, Rb-86, Zr-95, Sb-122, Ta-182, Tl-204, Th-229, Yb-175, Ho-166m, Hf-175, Ac-227, Pa-233, Am-241, Cm-244, U-233, U-234, U-235, U-238, Pu-238, Pu-239, Ra-226, Np-237, Cf-249, Cf-252, Tb-161, Cm-248
71	HILAC	1957 to December 23, 1992	Sc-46, Sc-49, Sr-90, Zr-88, Y-90, Zr-95, Tc-99, Sb-124, Tb-161, Tm-170, Yb-175, Ta-182, Tl-204, Th-229, Th-232, U-233, U-234, U-235, U-238
72	Health Physics	1961	P-32, Na-24, Ti-44, Cr-51 Mn-54, Co-58, Fe-59, Co-60, Cu-64, Zn-65, Br-82, Nb-95, Zr-95, Zr-97, Cd-113, Sb-122, Sb-124, Ba-133, Xe-133, Eu-152, Ta-182, Hg-194, Au-198, Bi-207, Ac-227, Th-228, Th-229, Pa-231, Th-232, U-238
73	Atmospheric Aerosol Research		H-3
74	Research Medicine/Radiation Biophysics, Cell and Molecular Biology		H-3, C-11, N-13, C-14, O-15, F-18, P-32, S-35, Sc-46, Fe-59, Cu-64, Sr-85, Nb-95, Tc-99m, Ru-103, I-123, I-125, I-131, Tl-201, Pb-210, Th-232, U-233, U-234/235, U-238, Pu-238, Am-241
75	Radioisotope Service a National Tritium Facility		H-3, Sr-90, Th-232, Act. Products, C-11, C-14, F-18, I-125, I-129, I-131, P-32, S-35, Sr-90, U-232, Kr-81, Kr-85
75A	Compact, Processing and Storage Facility		Th-232, Sr-90
76			C-11, C-14, F-18, I-125, I-129, I-131, P-32, S-35, Sr-90, U-232, Am-241
84			H-3, C-14, P-32, S-35
85	Hazardous Waste Handling Facility		H-3, C-14, Sr-90, I-125, Th-232
88	88-in. Cyclotron		Be-7, C-11, N-13, C-14, O-14, O-15, F-17, F-18, Na-21, Na-22, Na-24, P-32, S-35, Sc-46, Cr-51, Mn-54, Fe-55, Co-56, Co-57, Ni-57, Co-58, Fe-59, Co-60, Cu-60, Zn-62, Zn-63, Ni-63, Zn-65, Ge-71, Se-75, Br-76, Br-77, Kr-76, Kr-77, Kr-79, Y-88, Sr-90, Zr-95, Zr-97, U-238, Sc-93, Ac-227, Am-241, Au-198, Cs-134, Cs-137, Gd-148, Eu-152, Eu-154, Pb-212, Np-237, Np-239, Th-229, Th-232, Pa-233, Pu-238, Pu-239, Sb-124, Pa-231, Cf-249, Cf-252
934	Molecular and Cell Biology		H-3, P-32, S-35, C-14, I-125
977	Life Sciences and Physical Biosciences		H-3, P-32, P-33, S-35, C-14, Cd-109

a. Blank values indicate not applicable or data not available.
b. Particle size assumed as the default value of 5-µm activity median aerodynamic diameter (AMAD) because no site-specific data have been found.

Table 2-2. Magnitude of activities by area.

Building	Radionuclides	Activity (Ci)[a]
1, Room 159	K-42	0.001
	F2-65	0.001
	Zn-65	0.001
	Sr-85	0.001
	I-131	0.001
1, Room 212	Fe-59	0.001
1, Room 213	C-14	Trace
1, Room 216	C-14	0.005
	P-32	0.03
	Cr-51	0.01
	Fe-55	0.01
	Fe-59	0.01
	Sr-90	0.02
	Y-90	0.1
	I-131	0.02
	Hg-203	0.01
1, Room 227	P-32	0.05
	I-131	0.25
1, Room 230	Ca-47	0.001
	Zn-65	0.001
	I-131	0.001
1, Room 261	P-32	0.5
	I-131	0.001
1, Room 264	F-18	0.01
	Fe-52	0.1
	Ge-68	0.001
	As-71	0.1
	I-123	0.001
1, Room 271	Na-24	0.001
	P-32	0.5
1, Room 308	C-14	0.005
1, Room 322	P-32	(b)
1, Room 326	P-32, P-33	(b)
1, Room 330	H-3	Tracers
1, Room 361	P-32	(b)
1, Room 364	F-18	1E-6
	Fe-52	1E-6
	Fe-59	1E-6
	Ga-68	1E-6
	As-71	1E-6
	I-131	1E-6
	Hg-203	1E-6
1, Room 366	P-32, P-33	(b)
1, Room 373	H-3, C-14, P-32, P33, S-35, I-125	(b)
1, Room 471	P-32	0.005
2, Rooms 101 and 101A	Ca-45	Tracers
	Sr-85	Tracers
	Sr-90	Tracers
	Am-241	Tracers
2, Room 102	Na-22	0.005
	Ca-45	0.001
	Sr-85	0.001
	Sr-90	0.002
	Eu-152/Eu-154	0.0015
	Ac-227	0.003
	Am-241	0.00015

Building	Radionuclides	Activity (Ci)[a]
2, Room 103	Ca-45	Tracers
2, Room 104	Sr-85	Tracers
2, Room 108	Sr-90	Tracers
2, Room 116	Am-241	Tracers
3, Room 120	C-14	0.01
3, 2nd floor lab	H-3	5E-6
	C-14	5E-6
	P-32	5E-6
3, Room 214	H-3	30
	C-14	0.05
	Varied	Isotope storage
3, Room 250	C-14, P-32, P-33, S-35	(a)
3, 3rd floor lab	H-3	5E-6
	C-14	5E-6
	P-32	5E-6
3, Room 318	H-3	Varied
	C-14	0.03
	P-32	Varied
3, Room 322	Varied	Calibration standards
3, Room 326	C-14	30
4	Cs-137	0.2 (July 1963)[c]
5	Co-60	3,100 (1955)[c]
6	Am-241, Am-243, Cm-248, Eu-152, Eu-154, Np-237, Pu-239, Sr-90, Th-232, U-233, U(natural), U-235, U-238, Pu-241, Pu-242, Tc-99	(b)
8, Room 360	Am-241	0.0066
	U	1 kg, various compounds
10	Cs-137	1,050 (1968)[c]
16, Room 101	U-234, U-235, U-238	(b)
19 (LeConte Hall)	Co-60	0.02
19, Room 79	Varied	0.01, experiment residues
	Pb-197/Pb-209	1.5 (cyclotron target)
19, Room 81	Varied	0.01, experiment residues
19, Room 86	Fe-55/Fe-59	1 (reactor capsule)
	Ga-67	1.5 (cyclotron target)
	In-112	2 (cyclotron target)
	Ba-127/Cs-127	1.5 (cyclotron target)
	Ba-131/Cs-131	24 (reactor capsule)
	Au-198	1.5 (cyclotron target)
	Au-199	1.5 (cyclotron target)
	Hg-203	0.03
19, Room 405	Sr-90	0.001
	Cs-137	0.001
22, Latimer Hall Room 710	C-14	Tracers
26, Rooms 6, 24, 30, 31, and 32	Alpha, Am-241, beta-gamma, C-11, C-14, F-18, H-3, I-125, I-129, I-131, P-32, S-35, U-232, Sr-90	(b)
31, Hesse Court	Depleted U	7 kg (gaseous conversion of UCl_4 to UCl_6)
36, 2232 Piedmont basement	Sr-90 Am-241	0.001 0.001
36, 2232 Piedmont kitchen	Na-24 Cl-36 K-42	0.001 0.001 0.001
38, Lewis Hall	Co-57/Co-60	0.02
	Fe-59	0.025
	Sn-119	0.0005
	Gd-153	0.001

Building	Radionuclides	Activity (Ci)[a]
50	Ag-106m, Au-194, Co-56, Co-57, Co-58, Co-60, Mn-52, Mn-54, Na-22, Ni-57, Re-184m, Sc-48, Se-75, Ta-182, v-48, Zn-65m Be-7, Ag-105	(b)
50B, Room 6209	Ag-106m, Au-194, Co-56, Co-57, Co-58, Co-60, Mn-52, Mn-54, Na-22, Ni-57, Re-184m, Sc-48, Se-75, Ta-182, V-48, Zn-65, Be-7, Sc-46, Ag-105	(b)
51	Be-7, Co-57, Co-58, Co-60, Fe-55, Fe-59, Mn-54, Na-22, Ni-63, Zn-65, Na-24, Ni-57, Ni-57, Cf-252, U, Am-241, Am-243, Ra-226, Bk-249	(b)
52, Rooms 109 and 111	Act Products, Am-241, Cf-250, Cm-243, Cm-248, Np-237, Pu-239, Pu-244, Th-229, Th-230, Th-232, U-232, U-235, U-236, U-238, Pu-242	(b)
55	Sr-90	30 (spill - 1964)[c]
55, Room 116	H-3, C-14, Co-57, Cr-51, F-18, Gd-153, H-3, I-125, I-131, Nb-95, Ru-103, Sn-113, Tc-99m, Tl-201	(b)
55, Room 118	C-14, Co-57, Cr-51, F-18, Gd-153, H-3, I-125, I-131, Nb-95, Ru-103, Sn-113, Tc-99m, Tl-201	(b)
55, Room 120	H-3, C-11, C-14, Co-55, Co-57, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Gd-153, Tl-201, Sc-46	(b)
55, Room 122	H-3, C-11, C-14, F-18, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
55, Room 126	H-3, C-11, C-14, F-18, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
55, Room 128	H-3, C-11, C-14, F-18, Ce-141, Cu-64, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46, Co-55, Co-57, I-123, I-125, I-131, Tc-99m, I-125, Gd-153, Sn-113	(b)
55, Room 134	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, N-13, O-15, O-14, F-17, Ce-141, Cu-64, Nb-95, Ru-103, Sr-85, Tl-201, Sc-46, Cr-51, Gd-153, H-3, Sn-113, Tl-201	(b)
55, Room 136	C-14, F-18, H-3, I-125	(b)
55, Room 139	C-11, C-14, Cr-51, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, Ce-141, Cu-64, N-13, Nb-95, O-15, Ru-103, Sr-85, Tl-201, Sc-46	(b)
55, Room 139A	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, Ce-141, Cu-64, N-13, Nb-95, O-15, Ru-103, Sr-85, Tl-201, Sc-46	(b)
55, Room 151	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, N-13, O-15, O-14, F-17, Ce-141, Cu-64, Nb-95, Ru-103, Sr-85, Tl-201, Sc-46, Cr-51, Gd-153, H-3, Sn-113, Tl-201	(b)
55, Room 200	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
56, Room 100	C-11, Co-55, Co-57, F-18, N-13, O-15, O-14, F-17	(b)
56, Room 101	C-11, Co-55, Co-57, F-18, N-13, O-15, O-14, F-17	(b)
57, Cowell Hospital, 3rd floor	Y-90	1
57, Cowell Hospital, 4th floor	I-125	0.01
57, Cowell Hospital, 4th floor	I-131	0.001
62, Rooms 114 and 145	U-238	
64, Room 234	P-32	(b)
69, Room 150	Various activation products	(b)
70	Cm-242/Pu-238	
70, Room 103	Ce-141, Ce-144, Fe-59, H-3, P-32, Pa-233, Sm-153, Te-125m, Yb-169, Zn-65, Sc-46	(b)
70, Room 108C	Ce-141, Ce-144, Fe-59, H-3, P-32, Pa-233, Sm-153, Te-125m, Yb-169, Zn-65, Sc-46	(b)
70, Room 114	U-238	(b)
70, Room 114A	U-238	(b)
70, Room 133	Ce-141, Ce-144, Fe-59, H-3, P-32, Pa-233, Sm-153, Te-125m, Yb-169, Zn-65, Sc-46	(b)

Building	Radionuclides	Activity (Ci)[a]
70, Room 147	Am-241, Cf-250, Cm-243, Cm-248, Np-237, Pu-239, Pu-244, Th-229, Th-230, Th-232, U-232, U-235, U-236, U-238, Pu-242	(b)
70, Room 147A	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, U-236, Bk-249, Cf-250, U-234, Es-254, P-32, Na-21, Na-22, Co-57, Cu-60, Na-22, Ni-57, Sc-93, Zn-62, Zn-63, Ac-227, Au-198, C-11, Cf-249, Cf-252, Co-56, Co-57, Co-58, Cr-51, Cs-134, Cs-137, Fe-55, Fe-59, Mn-54, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
70, Room 203	Am-241, Am-243, Bi-207, Cf-249, Cf-252, Cm-248, Er-165, Er-169, Er-171, Es-253, Eu-152, Fm-257, Hf-172, Hf-175, Hf-181, Ho-166, Ho-166m, Na-22, Nb-95, Np-237, Pu-238, Pu-239, Ra-226, Rh-101, Rh-102, Ta-182, Tb-160, Th-229, Tm-170, U-233, U-235, U-238, Y-90, Zr-88, Zr-95, Cm-244, Mn-54, Sr-90, Tl-204, Bk-249, Es-254	(b)
70, Room 209	Am-241, Am-243, Bi-207, Cf-249, Cf-252, Cm-248, Er-165, Er-169, Er-171, Es-253, Eu-152, Fm-257, Hf-172, Hf-175, Hf-181, Ho-166, Ho-166m, Na-22, Nb-95, Np-237, Pu-238, Pu-239, Ra-226, Rh-101, Rh-102, Ta-182, Tb-160, Th-229, Tm-170, U-233, U-235, U-238, Y-90, Zr-88, Zr-95, Cm-244, Mn-54, Sr-90, Tl-204, Bk-249, Es-254	(b)
70, Room 210	Am-241, Am-243, Bi-207, Cf-249, Cf-252, Cm-248, Er-165, Er-169, Er-171, Es-253, Eu-152, Fm-257, Hf-172, Hf-175, Hf-181, Ho-166, Ho-166m, Na-22, Nb-95, Np-237, Pu-238, Pu-239, Ra-226, Rh-101, Rh-102, Ta-182, Tb-160, Th-229, Tm-170, U-233, U-235, U-238, Y-90, Zr-88, Zr-95, Cm-244, Mn-54, Sr-90, Tl-204, Bk-249, Es-254	(b)
70A	Co-60	9,800 (July 1965)[c]
70A, Room 1103	C-11, C-14, H-3, P-32	(b)
70A, Room 1115	C-11, C-14, P-32, P-33	(b)
70A, Room 117A	C-11, H-3	(b)
70A, Room 1121A	C-11, H-3	(b)
70A, Room 1121B	C-11, H-3	(b)
70A, Room 1129	Co-60, Ni-63, Ni-65, Sr-90, Tc-99, Cs-137, Eu-152, Eu-154, Eu-155, Am-241, Am-243, Bk-249, Cf-249, Cm-243, Cm-244, Cm-245, Cm-246, Cm-248, Cf-249, Cf-250, f-252, Es-254, Np-237, Np-239, Pa-231, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-235, U-236, U-238	(b)
70A, Room 1145	Co-60, Ni-63, Ni-65, Sr-90, Tc-99, Cs-137, Eu-152, Eu-154, Eu-155, Am-241, Am-243, Bk-249, Cf-249, Cf-250, Cf-252, Cm-243, Cm-244, Cm-245, Cm-246, Cm-248, Cf-249, Es-254, Np-237, Np-239, Pa-231, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-235, U-236, U-238, U(natural)	(b)
70A, Room 1145A	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1145B	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)

Building	Radionuclides	Activity (Ci)[a]
70A, Room 1149	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1151	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1159A	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1159B	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1165	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 1165A	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 2211	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 2215	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 2217	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)

Building	Radionuclides	Activity (Ci)[a]
70A, Room 2217B	Am-241, Am-243, Cf-249, Cm-243, Cm-245, Cm-246, Cm-248, Co-60, Eu-152, Eu-154, Eu-155, Ni-65, Np-237, Np-239, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-244, Ra-226, Ru-106, Th-229, Th-230, Th-232, U-232, U-232, U-233, U-235, U-236, U-238, Tc-99, Pa-231, Pu-242, Cm-244, Cs-137, Ni-63, Pu-241, Sr-90, Bk-249, Cf-250, U-234, Es-254	(b)
70A, Room 2229A	Am-241, C-14, Fe-59, Np-237, Pb-210, Pu-238, Th-232, U-233, U-238, U-234/235	(b)
70A, Room 2229B	Am-241, C-14, Fe-59, Np-237, Pb-210, Pu-238, Th-232, U-233, U-238, U-234/235	(b)
70A, Room 4419	Kr-81, Kr-85	(b)
70A, Room 4429	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4429A	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4429C	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4459	Th-228, Th-230, U(natural), U-234, U-235, U-238, Tc-99	(b)
70A, Room 4463	Th-228, Th-230, U(natural), U-234, U-235, U-238, Tc-99	(b)
71, Cave B	(b)	(b)
71, Cave N	(b)	(b)
72, Room 102	U-238	(b)
72, Room 112A	U-238	(b)
72, Room 128	P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, 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-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
72, Room 137	P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, 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-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
72C, Rooms 155, 163, 169, 171, and 173	U-238	(b)
73, Room 109	H-3	(b)
74	Co-60/P-32/Cs-137	1,500 (1962 and 1968)[c]
74, Room 144A	Th-232, U(natural), U-238, Tc-99	(b)
74, Room 2011	Am-241, C-14, Fe-59, Np-237, Pb-210, Pu-238, Th-232, U-233, U-238, U-234/235	(b)
74, Room 238C	H-3, O-32, P35	(b)
74, Rooms 265 and 265A	P-32	(b)
74, Room 285	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
74, Room 312	C-11, C-14, H-3, P-32	(b)
74, Room 330	C-11, C-14, H-3, P-32	(b)
74, Room 330A	C-11, C-14, H-3, P-32	(b)
74, Room 344	C-11, C-14, H-3, P-32	(b)
74, Room 350	C-11, C-14, H-3, P-32	(b)
74D, Room 1	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
75	Cs-137	30 (March 1967)[c]
75, Room 103, 107 and Storage Locker	H-3	(b)
75, Room 109	H-3, activation products	(b)
75, Room 113	H-3, activation products	(b)
75, Room 127	Alpha, Am-241, beta-gamma, C-11, C-14, F-18, H-3, I-125, I-129, I-131, P-32, S-35, U-232, Sr-90	(b)

Building	Radionuclides	Activity (Ci)[a]
75D, Room 101B	Activation Products, Various, Kr-81, Kr-85	(b)
76, Room 135 and Storage Locker	Am-241, C-11, C-14, F-18, H-3, I-125, I-129, I-131, P-32, S-35, U-232, Sr-90	(b)
84, Room 101	P-32	(b)
84, Room 153	C-14, H-3, P-32	(b)
84, Room 155	H-3, P-32, S-35	(b)
84, Room 157	H-3, P-32, S-35	(b)
84, Room 161	H-3, P-32, S-35	(b)
84, Room 175	H-3, P-32, S-35	(b)
84, Room 201	P-32	(b)
84, Room 220	P-32	(b)
84, Room 263	P-32, C-14, H-3	(b)
85, Room MW1	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW2	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW3	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW4	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW5	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW6	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW7	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW8	Alpha, beta-gamma, C-14, H-3	(b)
85, Room RW1	Alpha, beta-gamma, C-14, H-3	(b)
85, Room RW2	Alpha, beta-gamma, C-14, H-3	(b)
85, Room Scintillation Vial Room	Alpha, beta-gamma, C-14, H-3	(b)
85, Room Staging Area	Alpha, beta-gamma, C-14, H-3	(b)
88, Room 134	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Room 135	H-3, C-11, N-13, Na-22, Be-7, O-14, Ne-19, Ne-18, Br-76, Br-77, Kr-76, Kr-77, Kr-79, P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, 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-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
88, Cave 0	Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15, Br-76, Br-77, Kr-76, Kr-77, Kr-79, Ne-19, Ne-18	(b)
88, Cave 1	C-11, N-13, Na-22, Be-7, O-14, Ne-19, Ne-18, Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave 2	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave 3	H-3, C-11, C-14, P-32, P-33	(b)
88, Cave 4	H-3, C-11, C-14, P-32, P-33	(b)
88, Cave 4C	Activation products, Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15	(b)
88, Cave 4C roof	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave Roofs	Act Products, Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15, Ne-19, Ne-18	(b)
88, East Alley	Br-76, Br-77, Kr-76, Kr-77, Kr-79	(b)
88, East alley mezzanine	Br-76, Br-77, Kr-76, Kr-77, Kr-79, Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)

Building	Radionuclides	Activity (Ci)[a]
88, East alley niche	C-11, N-13, Na-22, Be-7, O-14, Ne-19, Ne-18, Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Entire Vault roof	Activation products, Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15, Br-76, Br-77, Kr-76, Kr-77, Kr-79	(b)
977, Room 205	H-3, P-32, P-33, S-35	(b)
977, Room 240	H-3, P-32, S-35	(b)
977, Room 285	C-14, Cd-109, H-3, P-32, S-35	(b)

a. Maximum quantity present in the building in curies unless otherwise noted.
b. No quantity and/or isotope information available.
c. Date used where indicated in the historical documents.

3.0 OCCUPATIONAL MEDICAL DOSE

Table 3-1 lists the entrance skin exposure (ESE) and organ doses for posterior-anterior (PA) chest radiography at different times at LBNL. Beginning in the early years and continuing through March 1975, the assigned doses are the default values given by ORAUT (2005a). Calculated doses for the later times are based on measurements of the ESE and other factors with the LBNL equipment. The earliest document found (de Castro and Thomas 1975) reports results from a survey of the Picker radiographic X-ray unit conducted on March 19, 1975. The report states, "At a typical chest technique of 86 kV, 200 mA, large spot, 1/30 sec, 72 inches [= 183 cm], the direct beam exposure was 7 mR." Collimation is described as "satisfactory," and the filtration is "assumed sufficient [6]." For the PA view, if one assumes a chest thickness of 26 cm and allows 5 cm for the thickness of the cassette, the implied source-to-skin distance is 183 cm – 31 cm = 152 cm [7]. It follows from the measurement that the ESE is $(7\ mR)(183/152)^2 = 10\ mR$. These data are consistent with subsequent survey results reported through 1986 for this X-ray machine (de Castro 1977; Vaughan 1982; de Castro 1983; de Castro and Hill 1984; de Castro 1986). This unit was in use until its replacement by a new machine about September 28, 1987 (Bradfield 1987). The change was made to a Picker model BGX 625R stationary, general-purpose system, manufactured in 1987 (Thomas 1991; Bradfield-Montoya 1994). Based on available documents, the two Picker machines apparently served in succession for making medical X-rays at LBNL dating back to at least 1975. Chest X-rays were discontinued at LBNL, and the second Picker machine was removed by about the end of 1993 [8]. No policy statements with records of frequency were found. In the absence of other information, a pre-employment PA chest radiograph and subsequent annual frequency should be assumed [9].

Under an interagency agreement, the second Picker system was given a thorough inspection by the Food and Drug Administration on February 23, 1989 (Goldstein 1989). All components were found to operate within applicable Federal or manufacturer's specifications. The measured exposure for a routine chest X-ray was 11.2 mR with the technique of 300 mA at 84 kVp in the automatic exposure control mode. No significant problems were incurred in the operations. Regular control procedures were conducted to monitor performance over the years. Over time, the ESE measured in subsequent surveys remained close to 10 mR. Allowing a conservative factor of approximately 2, the value ESE = 20 mR is used to estimate organ doses for all times after March 1975.

In Table 3-2, the data from Table 3-1 are presented as the maximum organ doses in any calendar year. Following ORAUT (2005a), an uncertainty of ±30% at 1 sigma is estimated for an individual ESE or organ dose.

Table 3-1. Parameters and organ doses for 14- by 17-in. PA chest radiography.[a,b,c]

Period	Frequency	Applicability	PA chest ESE (mR)	Organ doses (rem) from 14- by 17-in. PA chest radiography						
				Thyroid	Ovaries	Testes	Lungs	Breast	Uterus	Bone marrow
Pre-1970	Unknown	Unknown	200	3.48E-02	2.50E-02	5.00E-03	9.02E-02	9.80E-03	2.50E-02	1.84E-02
1970–3/75	Unknown	Unknown	100	3.20E-03	1.00E-04	1.00E-06	4.51E-02	4.90E-03	1.30E-04	9.20E-03
4/75–1979	Unknown	Unknown	20	6.40E-04	2.00E-05	2.00E-07	9.02E-03	9.80E-04	2.60E-05	1.84E-03
1980–1993	Unknown	Unknown	20	1.56E-03	1.04E-04	2.00E-07	1.35E-02	2.32E-03	1.04E-04	3.56E-03

Period	Organ doses (rem) from 14- by 17-in. PA chest radiography									
	Eye/brain	Liver/gall bladder/spleen	Urinary bladder	Colon/ rectum	Thymus	Esophagus	Stomach	Bone surface	Remainder	Skin
Pre-1970	6.40E-03	9.02E-02	2.50E-02	2.50E-02	9.02E-02	9.02E-02	9.02E-02	9.02E-02	9.02E-02	2.70E-01
1970–3/75	3.20E-03	4.51E-02	1.00E-04	1.00E-04	4.51E-02	4.51E-02	4.51E-02	4.51E-02	4.51E-02	1.35E-01
4/75–1979	6.40E-04	9.02E-03	2.00E-05	2.00E-05	9.02E-03	9.02E-03	9.02E-03	9.02E-03	9.02E-03	2.70E-02
1980–1993	1.56E-03	1.35E-02	1.04E-04	1.04E-04	1.35E-02	1.35E-02	1.35E-02	1.35E-02	1.35E-02	2.80E-02

a. Values for the pre-1970 and the 1970 to 3/1975 periods are taken from Table 6-5 of ORAUT (2005a).
b. The default values (ORAUT 2005a) for beam quality of 2.5 mm Al HVL prior to 1980 and 4.0 mm Al HVL for subsequent years are assumed.
c. No policy statement on LBNL frequency was found. In the absence of other information, the assumption of an annual frequency is reasonable.

Table 3-2. Maximum organ doses by year for 14- by 17-in. PA chest radiography.

Year	Organ doses (rem) from 14- by 17-in. PA chest radiography							
	Maximum thyroid	Maximum ovaries	Maximum testes	Maximum lungs	Maximum breast	Maximum uterus	Maximum bone marrow	Maximum eye/brain
Pre-1970	3.48E-02	2.50E-02	5.00E-03	9.02E-02	9.80E-03	2.50E-02	1.84E-02	6.40E-03
1971–1975	3.20E-03	1.00E-04	1.00E-06	4.51E-02	4.90E-03	1.30E-04	9.20E-03	3.20E-03
1976–1979	6.40E-04	2.00E-05	2.00E-07	9.02E-03	9.80E-04	2.60E-05	1.84E-03	6.40E-04
1980–1993	1.56E-03	1.04E-04	2.00E-07	1.35E-02	2.32E-03	1.04E-04	3.56E-03	1.56E-03

Year	Organ doses (rem) from 14- by 17-in. PA chest radiography								
	Maximum liver/gall bladder/spleen	Maximum urinary bladder	Maximum colon/rectum	Maximum thymus	Maximum esophagus	Maximum stomach	Maximum bone surface	Maximum remainder	Maximum skin
Pre-1970	9.02E-02	2.50E-02	2.50E-02	9.02E-02	9.02E-02	9.02E-02	9.02E-02	9.02E-02	2.70E-01
1970–1975	4.51E-02	1.00E-04	1.00E-04	4.51E-02	4.51E-02	4.51E-02	4.51E-02	4.51E-02	1.35E-01
1976–1979	9.02E-03	2.00E-05	2.00E-05	9.02E-03	9.02E-03	9.02E-03	9.02E-03	9.02E-03	2.70E-02
1980–1993	1.35E-02	1.04E-04	1.04E-04	1.35E-02	1.35E-02	1.35E-02	1.35E-02	1.35E-02	2.80E-02

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

Occupational environmental dose results from releases or direct radiation due to facility operations. Inhalation of environmental radionuclides results in internal dose to the whole body or body organs. The site profile analysis determined the internal dose for workers outside the facilities from air concentrations from releases from stacks and individual buildings.

The site profile preparers reviewed site environmental reports for data that would be useful in reconstructing ambient radiation levels. Ambient radiation dose rates include natural background radiation and sources at the facility.

The laboratory used and created small amounts of radioactive material, created localized radiation areas with machines (X-ray machines and accelerators), and produced tritiated materials for wide distribution to other research facilities. Nuclear reactions were studied in the accelerators, which started on the site in the early 1930s as small devices (bench top) and progressed to specially built large buildings with controls and shielding. Workers and technicians who had access to the accelerators and experimental rooms had the highest risk and were, therefore, monitored for radiation exposure.

LBNL was involved in much of the discovery of the radiological properties of materials, and awareness of the hazards grew with each step in size and power of accelerator. Those working with the machines were monitored by state-of-the-art methods for internal and external dose [10]. The LBNL hillside site is small. The distance from the accelerators to the maximum exposed member of the public was less than 1,500 m. Documentation of the site boundary impact began in 1959 and continues today.

Tritium was used in large quantities in the National Tritium Labeling Facility (NTLF), which began operation in the early 1980s. Releases and doses to the personnel and public were well documented over the course of operations, and those practices continue today after shutdown. Potable water has always been supplied from off the site by the local utility.

Methods of measuring deposition and air concentrations have varied over the years in terms of technique and locations. A cursory review shows long-term interest in fallout. Fallout and naturally occurring radioactive materials dominate any deposition from onsite releases and resuspension.

Radionuclides were either created on the site or purchased, and the large variety created an extensively diverse source term. However, except for tritium and accelerator-induced byproducts, these nuclides were present only in small quantities needed for research. Laboratories at LBNL were some of the first to use hoods and airflow to control exposure to hazardous material [11] (Thaxter 1950a).

Interviews with the dosimetry staff indicated that every monitored worker has a dosimetry file that is accessible today. Those who were not monitored would have been exposed to external radiation from outside the well-designed shield walls and from releases through ventilation systems. In addition, these facilities were always being improved and were operated on an intermittent schedule. Concepts of long-term steady-state exposure are not consistent with the nature of this facility.

Table 4-1 lists the maximum external gamma and neutron radiation measurements in millirem per year. There is not sufficient data available to provide measured uncertainty. The values listed in the table are those documented in the annual LBNL environmental reports. Early interest was the maximum possible dose from surveys (usually during accelerator runs) and analysis. In later years

with better monitoring, improved shielding, and the development of as-low-as-reasonably-achievable (ALARA) policy, the reported doses fell dramatically [12]. The annual average measurements, as opposed to the maximum values, were at 50% of maximum or less [13]. It is reasonable to use 75% of the maximum as the likely value, and 25% of the maximum as the likely uncertainty as an estimate of unmonitored dose [14].

Table 4-1. External gamma and neutron radiation.[a,b,c]

Year	Dose (mrem/yr)	Reference
1942	140	--
1943	150	--
1944	170	--
1945	190	--
1946	210	--
1947	230	--
1948	250	--
1949	280	--
1950	310	--
1951	350	--
1952	390	--
1953	430	--
1954	480	--
1955	530	--
1956	590	--
1957	660	--
1958	730	--
1959	810	Patterson (1962)
1960	650	Patterson (1962)
1961	450	Patterson (1962)
1962	312	LRL (1963)
1963	173	Lichliter (1964)
1964	113	Patterson (1965)
1965	74.6	Patterson (1966)
1966	124	LRL (1967)
1967	76	LRL (1968)
1968	132	LRL (1969)
1969	291	Kelly (1970)
1970	173	LRL (1971)
1971	283	Kelly (1972)
1972	57	Cantelow (1973)
1973	28	Thomas (1974)
1974	28.3	Stephens and Cantelow (1975)
1975	95.87	Cantelow (1976)
1976	5.35	Stephens (1977)
1977	5.3	Stephens (1978)
1978	7.29	Schleimer (1979)
1979	10.1	Schleimer (1980)
1980	4	Schleimer (1981)
1981	15.1	Schleimer (1982)
1982	24.5	Schleimer (1983)
1983	5.8	Schleimer (1984)
1984	5.4	Schleimer (1985)
1985	1.8	Schleimer (1986)
1986	3.5	Schleimer (1987)
1987	3.5	Schleimer (1988)
1988	1.9	Schleimer (1989)
1989	2.6	Schleimer and Pauer (1990)
1990	7	Schleimer and Pauer (1991)
1991	2	Pauer, Schleimer, and Javendal (1992)
1992	2.3	Balgobin et al. (1993)
1993	2.96	University of California (1994)
1994	1.53	LBNL (1995a)
1995	2.1	LBNL (1996)
1996	3.3	LBNL (1997)
1997	2	LBNL (1998)
1998	5	LBNL (1999)
1999	4	LBNL (2000)
2000	4	LBNL (2001)
2001	0.65	LBNL (2002)
2002	3.2	LBNL (2003)
2003	0.2	LBNL (2004)
2004	0.28	LBNL (2005a)

a. No values were reported from 1942 to 1958; the values provided are projections.
b. Highest of perimeter or onsite data was used. In general, due to the terrain of the facility, the perimeter readings are higher than the local onsite readings. This is due to the small size of the site, elevation differences, and skyshine with more shielding in the walls than roofs of the accelerator buildings. The dose values reflect a 365-d 24-hr measurement less background [15].
c. Energies are 30 to 250 keV for photons and 0.1 to 2 MeV for neutrons. Neutron component of dose is typically ≥70% of total [16].

The following is a description of how the estimates of external exposure were generated for the period before 1959 and for two recent years (2002 and 2004) for which measurements of "not detected" were reported.

The 2002 and 2004 estimates were based on averages of the 5 preceding years rounded to two significant digits.

As the number and power of accelerators grew on the site, exposures to unmonitored workers and the environment grew (Goldhaber 1981). Many of the earlier reports would not meet the expectations of

today and often included values based on crude measurements and calculations with only enough precision to demonstrate that limits were not exceeded. The use of the first reported doses beginning in 1959 probably produces projected doses much greater than actual doses. These reported values form a basis for the dose estimates for the preceding years as described in the next three paragraphs [17].

An assumption of linear growth from 1942 to 1959 would indicate under-reported doses in the late 1950s, which would be expected to be closer to the doses in the 1960s [18]. An assumption of the average dose reported from 1959 to 2004 would overestimate the doses in the 1940s [19]. This analysis estimated the doses based on a compromise using a parabolic curve that begins near background in 1942 and peaks with the reported value in 1959 [20].

The parabolic curve estimates provide sufficient dose for the workers in the 1950s and more reasonable doses in the first years. The average value in these estimates (0.348 rem/yr) is four times the average reported (0.087 rem/yr) from 1959 to 2003. This provides an ample margin to ensure that the dose is not underestimated [21].

In Thomas et. al. (2000) it was determined that 1959 had the highest annual dose of any year at LBNL. In this report doses were revised based on modern knowledge of both the energy spectrum of accelerator produced neutrons and the appropriate coefficient functions for different irradiation geometries. For the years 1959 through 1975 the revised values were approximately one-half the values shown in Table 4-1. Values were also estimated back through calculation to 1954 when the Bevatron became operational. These estimated values are consistently lower than those shown in Table 4-1. Using the higher values shown in Table 4-1 is favorable to claimants without being excessively conservative, i.e. a factor of about two times.

Table 4-2 lists the maximum site-wide annual median intakes in becquerels per year via inhalation. The data were derived from the LBNL annual environmental reports; the maximum reported values were used. Water supplies are from East Bay Municipal Utility District off the site, and no indication of soil contamination exceeding a background level has been found, so there would have been no doses from intakes from soil and drinking water. LBNL attributes gross alpha results to ^{232}Th and gross beta results to ^{90}Sr for the purposes of dose calculation; these assumptions should be made. Thorium is representative of naturally occurring alpha emitters, and strontium is representative of the beta component of fallout. By using these nuclides in the calculations, the resulting doses would not underestimate the actual doses [22].

Missing data are filled in with the estimates as explained below and are based on the available maximum observed values in the annual environmental reports.

- Alpha: Reported alpha concentrations appear to be independent of operational effects of the Laboratory and relatively constant over time. Therefore, a good representation of the alpha concentrations and intake is the average of all the measurements, which results in an intake of 0.43 Bq/yr [23].

- Beta: The principal contributor to gross beta concentrations is fallout from atmospheric nuclear weapons testing. The later years of missing data were assigned a value of 10 Bq/yr for gross beta intake [24]. This represents a modest overestimate of the intake. The intakes in the early years before 1961 were estimated to be reduced at a rate that would bring the intake in 1942 to values close to the most recent observations. This would account for the gradual rise in beta concentrations due to weapons testing and the effects (if any) of increased nuclide inventory on the site and increased power levels of the accelerators [25].

- Tritium: Tritium releases, concentrations, and subsequent intakes are related to accelerator and NTLF operations. Annual data are available from 1974 to 2003. The value for 2004

Table 4-2. Maximum site-wide annual median intakes (Bq/yr) via inhalation.[a,b,c,d]

	Respiration rate: 2,400 m^3/yr (2,000 hrs/yr)			
Year	Gross alpha	Gross beta	Tritium	C-14
1942	*0.43*	*12*	*4,900*	*760*
1943	*0.43*	*15*	*5,800*	*890*
1944	*0.43*	*17*	*6,800*	*1100*
1945	*0.43*	*20*	*8,000*	*1200*
1946	*0.43*	*24*	*9,400*	*1500*
1947	*0.43*	*28*	*11,000*	*1700*
1948	*0.43*	*33*	*13,000*	*2000*
1949	*0.43*	*39*	*15,000*	*2400*
1950	*0.43*	*46*	*18,000*	*2800*
1951	*0.43*	*54*	*21,000*	*3300*
1952	*0.43*	*63*	*25,000*	*3900*
1953	*0.43*	*75*	*29,000*	*4,500*
1954	*0.43*	*88*	*34,000*	*5,300*
1955	*0.43*	*100*	*40,000*	*6,300*
1956	*0.43*	*120*	*48,000*	*7,400*
1957	*0.43*	*140*	*56,000*	*8,700*
1958	*0.43*	*170*	*66,000*	*10,000*
1959	*0.43*	*200*	*78,000*	*12,000*
1960	*0.43*	*230*	*91,000*	*14,000*
1961	0.3432	273.6	*110,000*	*17,000*
1962	0.0888	511.2	*130,000*	*20,000*
1963	0.0888	849.6	*150,000*	*23,000*
1964	0.0888	198.96	*170,000*	*27,000*
1965	0.0888	35.52	*210,000*	*32,000*
1966	0.0888	12.432	*240,000*	*38,000*
1967	0.0888	29.28	*280,000*	*44,000*
1968	0.0888	28.32	*330,000*	*52,000*
1969	0.0888	17.76	*390,000*	*61,000*
1970	0.444	44.4	*460,000*	*72,000*
1971	0.444	23.088	*550,000*	*85,000*
1972	0.0888	7.104	*640,000*	*100,000*
1973	0.07104	1.8648	*750,000*	*120,000*
1974	0.444	32.856	888,000	17,760
1975	0.6216	26.4	213,120	30,240
1976	0.5328	71.04	328,800	239,760
1977	0.3552	46.08	710,400	79,920
1978	0.444	24.96	2,222,400	40,080
1979	0.6216	20.424	1,687,200	32,856
1980	0.5328	21.312	62,160	31,080
1981	0.444	41.76	97,680	17,760
1982	0.3552	12.432	266,400	26,640
1983	0.1776	9.768	355,200	26,640
1984	0.2664	12.432	8,880,000	2,664,000
1985	0.3552	12.432	3,720,000	97,680
1986	0.07104	4.44	1,065,600	35,520
1987	0.444	17.76	444,000	35,520
1988	0.444	14.208	266,400	17,760
1989	0.7992	11.544	976,800	26,640
1990	0.5328	12.432	266,400	35,520
1991	0.444	1.5984	444,000	17,760
1992	0.5328	15.096	631,200	17,760
1993	0.444	14.208	427,200	31,200

Year	Respiration rate: 2,400 m^3/yr (2,000 hrs/yr)			
	Gross alpha	Gross beta	Tritium	C-14
1994	3.6408	6.216	213,120	142,080
1995	*0.43*	*10*	184,800	8,160
1996	*0.43*	*10*	13,200	*2100*
1997	*0.43*	*10*	26,640	*4100*
1998	*0.43*	*10*	21,384	*3300*
1999	0.552	3.12	2,592	2,592
2000	*0.43*	*10*	12,168	*1900*
2001	*0.43*	*10*	11,208	*1700*
2002	*0.43*	*10*	2,952	*500*
2003	*0.43*	*10*	528	*100*
2004	0.48	3.6	0	384

a. The site is so small that the environmental samples are representative of the site as a whole.
b. Highest of perimeter or onsite data was used. In general, due to the terrain of the facility, the perimeter readings are higher than the local onsite readings due to the small size of the site, elevation differences, and the height of the stack release points. Since 1964, the maximum reported value for the year was used except for 1986 because of the inordinate contribution from Chernobyl. Earlier years showed significant fluctuation due to fallout; because of its location on the west coast, LBNL routinely transmitted data on fallout to the U.S. Atomic Energy Commission.
c. Estimated values in italics
d. Data from environmental reports listed in Table 4-2 for the appropriate year. The references are included in the References section of this document and are available from the Site Research Database or at www.lbl.gov.

(2,500 Bq/yr) was chosen to conform with the trend in previous years and average ratio to ^{14}C (see ^{14}C discussion below) [26]. The years before 1974 were trended downward back to 1942 to values consistent with recent measurements, which are the lowest values observed. The assumption is that the site tritium concentration before operations began was no higher than the lowest observed concentrations. This is consistent with the trend of accelerator development and the operation of the NTLF [27].

- Carbon-14: Carbon-14 releases, concentrations, and intakes are related to accelerator operations. The average ratio of ^{14}C to tritium in the years during which both were reported is 0.155 [28]. When one data point is missing, this value is used to estimate missing data in later years. For the years before 1974, a trend identical to the tritium estimates was employed.

All estimates were limited to no more than two significant digits.

5.0 OCCUPATIONAL INTERNAL DOSE

The LBNL bioassay records show that the selection of personnel for bioassay and the radionuclides for analysis have been based on the work performed by the individual. Selection of employees to be included in the bioassay program was typically made by the Laboratory's Safety Services Department through its staff of monitors. The monitors were directly aware of the radionuclides used throughout the Laboratory and were therefore best qualified to select employees at risk for potential internal exposure. Unmonitored workers should be assessed using coworker data and the tolerance levels discussed below if there is evidence that they worked with uncontained radioactive materials; otherwise, environmental data should be used.

Bioassay measurement results were noted in the files as early as 1946. The earliest bioassay results are *in vitro* measurements. *In vitro* samples were primarily routine urine samples but even the earliest records showed measurement results for feces and sputum. Methods used to analyze the samples varied but relied primarily on standard methods (McClelland 1958) in use at other laboratories such as Los Alamos National Laboratory (LANL). Bioassay monitoring programs were in place beginning in 1947. However, in the early years monitoring was performed on an as-needed basis and was not covered by a formal documented program (LRL undated). Routine bioassay monitoring of employees was initiated about 1961 (Howe 1961a). Beginning in 1996, the bioassay program changed such that personnel were selected for operational bioassay based on the radionuclide authorization program and reviews of work performed. The program currently uses these operational bioassays to evaluate worker exposure or, most often, to verify the absence of internal exposures. This program was started because so few worker groups were expected to exceed the 100 mrem/yr of internal exposure required to put them into a routine monitoring program [29].

Table 5-1 lists the *in vitro* types of bioassay, the periods, and the frequencies of monitoring. Table 5-2 lists the *in vitro* sample types and the analysis codes found in the records.

From 1960 to 1996, both *in vitro* and *in vivo* monitoring records and associated interpretations exist and are available in the spreadsheet discussed below. *In vivo* monitoring consisted primarily of whole-body counts (WBCs) performed at LBNL from 1960 to 1996. The WB counter used throughout this period was at the Donner laboratory. It was designed, built, and operated by Dr. Thornton Sargent, III, who modeled it after the counter at Argonne National Laboratory–East (ANL-E). The WBC was in an 8- by 9- by 6-ft room, shielded by walls of 6-in. “pre-atomic age” steel lined with 0.125 in. of lead. The main detector was a 9.375- by 4-in. NaI(Tl) crystal positionable in any geometry over a 1-m arc bed or an Argonne chair. The large crystal was used for counting energies above 50 keV. The WBC was equipped with a probe that could be mounted with 2-in. diameter crystals either 0.125 or 0.25 in. thick for counting low-energy gamma-emitting isotopes such as ^{125}I. The 1960 calibration of the counter was performed by “performing studies in which patients were injected with known amounts of various radioactive isotopes, and then immediately counted…” (Vargha 1996a).

After 1996, LBNL no longer performed WBCs but rather relied on Lawrence Livermore National Laboratory (LLNL) for occasional monitoring. Table 5-3 lists the *in vivo* monitoring and data storage from 1960 to the present.

Table 5-4 summarizes the detection limits found in available documents for *in vitro* bioassays. The minimum detectable activities (MDAs) in Table 5-4 were taken from the analysis results. In some cases, the analysis method was not available and the detection limit was not specified. Some of the records reviewed showed results for any positive net measurement, some simply noted "neg." LBNL appears to have reported only measurements above the detection limit. Table 5-6 lists the method codes used to identify analysis methods for bioassay samples. These codes were obtained from a computer listing of the analysis results [30].

Table 5-5 summarizes the detection limits found for *in vivo* bioassays. Because the WB counter was the same system for most of the history for LBNL, there is not much variation. Count times were typically 15 min but individual counts might have been increased to obtain lower detection limits [31]. The count time is noted in the individual records.

Copies of results from all individual bioassays were distributed to the employee, the medical files (Medical Services) and Safety Services. Vargha (1996b) contains information on the records for the WBCs between 1960 and 1996 and notes that the electronic files from 1960 to 1996 were available.

Table 5-1. Internal dose control program (*in vitro*).

Monitoring type	Routine/special	Period	Frequency
Urine, feces, and sputum from 1 employee assayed for alpha counts[a]	Special	1946	(b)
Urine, feces, and blood from a few employees were sent to ANL-E for analysis[a]	Unknown, probably special	1947	(b)
All employees included in medical program that included chest X-ray, hematology, and urinalysis[a]	Routine	1947	Periodic
Began developing a bioassay program through LANL[a]	Unknown	1950	(b)
Samples were sent to LLNL for analysis[a]	Unknown	1956–1959	(b)
Bioassay laboratory was started and presumably routine urine samples were analyzed[a]	Routine	1960	(b)
Nasal smears appeared to be obtained as a matter of routine following spills or after hood filter changes[c]	Special	1957–1960	(b)
Urine 24-hr, employees working with transuranic elements, Sr-90, and radium[d]	Routine	1961	Quarterly
Urine 24-hr, employees working with activity but not defined by the quarterly frequency[d]	Routine	1961	Annual
Urine 24-hr, employees with less potential for exposure[d]	Routine	1961	Every 5 yr
Urine 24-hr, radiochemists and Health Chemistry personnel more highly exposed to alpha emitters[e]	Routine	1962	Semiannual
Urine 24-hr, radiochemists and Health Chemistry personnel, selected members of building trades frequently assigned work in active areas, and selected administrative personnel whose exposure is essentially zero and who should be considered controls[e]	Routine	1962	Annual
Urine 24-hr, Sr-90[f]	Special	1962	Weekly Semiweekly
Feces [32]	Special	1962	Special
Blood [33]	Special	1962	Special
Urine 24-hr[g]	Routine	1974	Annual[c]
Urine, feces, sputum[g]	Special	1974	Special[c]
Urine[h]	Routine	1975	Annual
Feces[h]	Special	1975	Special
Breath, radioactive carbon[h]		1975	Special
Urine spot, H-3 [34]		1983	(b)
Urine spot, C-14		1993	(b)
Urine, 24-hr [35]	Routine[i]	1995–present	(b)
Feces [36]	Special[i]	1995–present	(b)
Urine, spot [37]		1995–present	(b)

a. LRL (undated).
b. Frequency not applicable or not available.
c. Nasal smear alpha and beta counts were documented following numerous spills in Building 70 between 1957 and 1961. The radionuclides involved in the spill were sometimes documented: Pu, Am, Pu-240, Pu-239, Am-241, Cm-244, Ru-106, Ac-227, and Tb-161 (Kaufman 1957; Alloway 1957; LRL 1958a,b,c,d, 1959a,b, 1960, 1961).
d. Howe (1961a) identifies that LBNL should establish a "full-fledged bioassay program." An attachment to the memorandum, "Bioassay Program Features," identified routine scheduling. It is not clear if the quarterly frequency was implemented. Review of an electronic file of historical samples shows a number of employees provided routine urine samples more frequently than annually but it might have been at the discretion of the laboratory staff based on type of work rather than a scheduled frequency.
e. Soule (1962).
f. Selected individuals performing Sr-90 work were followed at weekly or semiweekly intervals from March 1962 through the end of 1962 (Low-Beer 1963). It is not clear that this was the practice throughout the history of the Laboratory.
g. Hartsough (1974) indicates that the frequency for bioassay can be increased for employees who show a consistent history of positive bioassay results. Special monitoring was performed at the request of the employee or Safety Services of Health Physics. Examples of cause for special bioassay included fire involving radioactive materials, rupture of containment devices, air sample results at or above the maximum permissible concentration (MPC), high surface-swipe activity, and skin cuts or punctures while working with radioactive material.
h. Pickler (1975).
i. Routine measurements are required only when the relative hazard of an operation shows a likelihood of incurring an intake that would result in a dose greater than 100 mrem. LBNL uses routine monitoring but relies mainly on "supplementary" bioassay programs. Routine programs are implemented when the dose equivalent is expected to be above 100 mrem. LBNL uses the quantity thresholds published in NUREG-1400 for relatively heavy elements (Hickey et al. 1993), and the quantity thresholds in the U.S. Nuclear Regulatory Commission Regulatory Guide Series for H-3 and radioiodines, to establish the need for routine bioassays. Supplementary bioassays are implemented at thresholds below the 100-mrem guideline. Threshold values used at LBNL are provided in AlMahamid (2005).

Table 5-2. Sample type (*in vitro*).[a]

Routine monitoring type	Sample type	Period	Frequency
Urine 24-hr	RU = Routine urine	1960–1997	Annual
Urine	SU = Special urine	1960–1997	(b)
Blood	SB =Special blood	1965–1988	(b)
Fecal	SF = Special fecal	1960–1980	(b)
Nasal	SN = Special nasal	1957–1960 1969–1989	(b)
Sputum	SS = Special sputum	1967–1974	(b)
Urine	TU = Tritium urine	1968–1995	(b)

a. SB, SN, SS, and TU sample types should be verified. These codes are seen throughout the history of the records. In some cases the code is a best guess based on Szalinski (2006) and review of sample analysis. Two other codes (SH and SL) were noted in the files only once each and are therefore not in the table. The periods are generally taken from the historical database of records.
b. Frequency not applicable or not available.

Table 5-3. Internal dose control program (*in vivo*).

Monitoring type and storage		Period	Frequency
WBC–[a] Records storage media:[b] 1. Alphabetically by individual, spectrum printouts are on paper tape 2. Electronic magnetic tape cassettes	Routine	1960–1983	Annual
	Accident	1960–1983	(c)
	Outside referral	1960–1983	(c)
	Health chemistry	1960–1983	Annual
WBC–[a] Records storage media:[b] 1. Alphabetically by individual 2. Electronic 8-in. diskettes	Routine	1983–1996	Annual
	Accident	1983–1996	(c)
	Outside referral	1983–1996	(c)
	Special studies	1983–1996	(c)
WBC at LLNL[d]	Special	1996–present	(c)

a. WBCs were performed at LBNL from 1960 to 1996.
b. Vargha (1996b).
c. Frequency not applicable or not available.
d. AlMahamid (2005, Appendix 2). LBNL employee Jim Floyd indicated that after 1996 WBCs were no longer performed at LBNL and that LBNL relied on LLNL (Szalinski 2006). The Laboratory also moved away from routine annual monitoring around 1996 and relied on the authorization process for use of radionuclides and knowledge of the work to specify bioassay requirements and follow-up or periodic bioassays to verify the absence of internal exposures (Szalinski 2006).

Since 1946 air sampling was performed routinely using the “filter queen approach” (Thaxter 1950b), gloveboxes to contain contamination were in routine use (Browne 1950; Thaxter 1950b, 1953, 1958), and air samples showed activity levels that were low compared to the permissible levels (Thaxter 1958). This 1958 document noted that between 1948 and 1958 breathing zone air samplers were assessed daily in all operating laboratories and only an average of 3/mo of approximately 2,000 monthly air samples showed air concentrations near the maximum permissible concentration (MPC) for occupational exposure found in NCRP Handbook 52 (NCRP, 1953). Also noted was that between 1948 and 1958 no air samples had significant airborne concentrations of long-lived alpha emitters approaching ten percent of the amount indicated as contributing a 1-wk dose to man (300 mrem/wk).

Table 5-4. *In vitro* detection limits.[a]

Radionuclide	Period	Sample type[a]	Method/description	MDA
Gross alpha	1957–1961	N	Wet ashed (HNO_3 + H_2SO_4) 60-min count time.[b] Method use of 3N HCl is also noted in 1957 records (Alloway 1957).	1 dpm
Gross alpha Isotopes of thorium, plutonium, curium, actinium, and neptunium	1960–1969	U	Livermore method without modification.[c,d] Coprecipitation of the activity with $BiPO_4$. Sometime later the method was changed to lanthanum fluoride coprecipitation and the MDA improved to 0.2 dpm/24-hr urine.[e] Method descriptions note that uranium, radium, and polonium are not detected by this method (Author unknown, no date). (Method Code 10)	0.3 dpm/24-hr urine (0.15 pCi/24-hr urine)
Gamma emitters Gross alpha (assumed to include isotopes of thorium, plutonium, curium, actinium, and neptunium) Gross beta (assumed to include Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products)	1969–present	U or F	Analysis of 24-hr urine sample.[f] Preparation of the sample by alkaline phosphate precipitation to eliminate monovalent cations. The ash from the alkaline phosphate precipitation is suspended in 10 mL of 2N HNO_3. The whole sample is counted by gamma spectroscopy using a 4-in. NaI crystal and a 400-channel PHA (gamma: Method Code 04). One-fifth of the sample is then plated on aluminum for counting gross beta activity in a Nuclear-Chicago gas-flow proportional counter (gross beta: method code 50). The remaining four-fifths of the sample is processed by bismuth phosphate and lanthanum fluoride coprecipitation and counted for gross activity in the Nuclear-Chicago gas-flow proportional counter (gross alpha: Method Code 10).	Gamma 10 nCi Alpha 0.1 pCi Beta 1 pCi
Gross beta	1957–1961	N	Wet ashed (HNO_3 + H_2SO_4) 60-min count time.[b] Method use of 3N HCl is also noted in 1957 records (Alloway 1957).	30 dpm
Gross beta, Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products	1960–1969	U	LANL method without modification. Phosphate precipitation. The method in McClelland (1958) describes that radionuclides include Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products. Another reference (Author unknown, no date) notes that protactinium is not detected by this method. (Method Code 50)[c,d]	5.1 dpm/24 hr urine (1968) 2 dpm/24 hr urine (1969)
Am-241, Pu-239	1962		Column chromatography, electroprecipitation, and PHA[g] 1962 was the only reference to this method.	Not specified
Am-241, Am-243	1995–present	U	Alpha spectrometry	0.02 pCi
	1995–present	F	Alpha spectrometry	0.02 pCi
Bk-249	1995–present	U	Gross beta or alpha spectrometry	0.02 pCi
C-14	1968–1993	U	Sample is decolorized using activated charcoal and counted on a liquid scintillation counter. (Method Code 02)	5.0 nCi/L (1974)
	1993–present	U	C-14 was listed in LBNL (1995b) but the method was not specified.	2.0 nCi/L (1993)
Cm-243, Cm-244, Cm-246, Cm-248,	2005–present	U or F	Method not specified.	0.02 pCi/sample
Cf-252	1965–1995	U or F	Gross alpha using LLNL method: Coprecipitation of the activity with $BiPO_4$.	0.3 dpm/24-hr urine
Cf-252, Cm-244	1968		Alpha PHA was used to indicate the relative ratio of Cf-252:Cm-244.	Not specified

Radionuclide	Period	Sample type[a]	Method/description	MDA
Cf-249, Cf-252	1995–present	U or F	Method not specified.	0.02 pCi
Fe-55, Fe-59	1995–present		Method not specified.	Not specified
H-3	1968–1982	U	Liquid scintillation counting (Method Code 03)	0.02 µCi/L
	1982–1995	U		0.01 µCi/L
	1995–present	U		4.5 pCi/sample
I-125	1980–1984	U	Gamma spectroscopy (Method Code 05)	0.02 nCi/L
Na-22, Na-24	1995–present		Method not specified.	Not specified
Np-237, NP-239	1995–2005	U	Method not specified.	0.05 pCi of Np-237
	2005–present	U or F	Method not specified.	0.02 pCi/sample
P-32, P-33	1963–1995	U	Ammonium phosphomolybdate precipitation (Method Code 71)	20 pCi/L
	1995–present	U or F	Method not specified.	1.5 pCi
Protactinium	1960		Method not specified (1960 only year noted for protactinium).	Not specified
	2005–present (Pa-231)	U or F	Method not specified.	0.02 pCi/sample
Pu-238, Pu-239	1995–present	U or F	Method not specified.	0.02 pCi
Pu-241	2005–present	U or F	Method not specified.	0.02 pCi/sample
Rare earths (primarily Pm-147)	1961	U	Method not specified (1961 only year noted).	3 dpm/24-hr urine
Ra-226	1995–present	U	Method not specified.	0.1 pCi/L not listed in LBNL 1995b but assumed[h]
Sulfur S-35	1962–1992	U or F	Urine analysis and fecal analysis (Method Code 52)	0.2 nCi/L (1982)
	1992–present	U	Barium sulfate precipitation	0.1 nCi/L (1992)
Strontium Sr-90, Sr-89	1961–1995		Oak Ridge method of ion exchange chromatography (Sunderman and Townley 1960) (Method Code 51)	Not specified
Thorium	1995–2005	U	Method not specified.	Not listed in LBNL 1995b assume 0.1 pCi/L[h]
	2005–present	U or F	Method not specified.	0.02 pCi/sample

Radionuclide	Period	Sample type[a]	Method/description	MDA
Uranium	1961–1988	U	LANL method of solvent extraction with dibutyl phosphate (McClelland 1958) (Method Code 11)	0.15 dpm/24-hr urine
	1988–1995	U	Anion exchange chromatography	0.15 dpm/24 hr urine
	1995–2005	U	Method not specified.	Not listed in LBNL (1995b); use previous MDA 0.15 dpm/24-hr urine.
	1995–2005	F	Method not specified.	Not listed; use 1 pCi/sample[h]
	2005–present	U or F	Method not specified.	0.02 pCi/sample

a. Blanks in this table indicate not applicable or no data available. Sample types: N= nasal smears, U=urine, F=Fecal.
b. LRL (1958b).
c. Low-Beer (1962) and McClelland (1958).
d. Howe (1961b).
e. Author unknown (no date).
f. Patterson, Low-Beer, and Sargent (1969). Although this 1969 reference specifies a 10-nCi detection limit for gamma emitters, numerous bioassay records on the NIOSH-Office of Compensation Analysis and Support Claims Tracking System (NOCTS) showed a gamma detection limit of 30 dpm/specimen (13 pCi/specimen). Personnel performing dose reconstruction should use the MDA specified with the results.
g. Low-Beer (1963).
h. When an MDA was not specified for the radionuclides listed in the LBNL TBD for internal dosimetry (LBNL 1995b), the value from ANSI HPS N13.30, Table C.4 was used and assumed to be conservative.

Table 5-5. *In vivo* detection limits.[a]

Radionuclide	Method/description	Period	MDA
Gamma-emitting radionuclides 50 keV–2 MeV (including thyroid counts for I-131, I-123) Be-7, Na-22,24, Mn-54, Ni-57,63, Fe-55,59, Co-57,58,60, Zn-65	WBC.[b] The Donner WB counter was an ANL-E type, with a 6-in. steel shield. The individual sits in an inclined chair and is counted by a 9- by-4- in. by 9.375-in. NaI(Tl) crystal. The gamma pulses were analyzed by a 400-channel PHA, calibrated at 5 keV/PHA, for a 0–2.0 MeV spectrum range. Between 1960 and 1983, data were recorded on printed paper tape, which was then keypunched for computer analysis. Calibration of the area under the photopeaks to yield microcuries of body burden was obtained from the spectra of medical patients injected with known quantities of short-lived radionuclides with various gamma-ray energies. Count time was routinely 15 min, but later references showed longer count times when lower MDAs or better counting statistics were needed and tolerated by the subject.	1960–1996	1–10 nCi for the nuclides listed Assume 1 nCi for I-123 and I-125. Assume 10 nCi for other listed nuclides.
Gamma-emitting radionuclides <50 keV (e.g., I-125)	WBC when count was performed using smaller (2-in.-diameter by 0.25-in.-thick)[b] detector. WBCs were also noted to identify the presence of high-energy beta emitters such as P-32 and Y-90, presumably through increases in the Compton continuum due to bremsstrahlung.[c]	1960–1996	10 nCi for I-125[d]
Am-241, Am-243	Lung count for Np-239 [38]	1995–1996	50 pCi
F-18	WBC [39]	1995–1996	640 pCi
P-32	WBC (only one count for P-32 found in NOCTS) [40]	1971–1996	1E5 pCi

a. Blanks in this table indicate not applicable or no data available.
b. Patterson, Low-Beer, and Sargent (1969).
c. Vargha (1996a).
d. A specific MDA for I-125 was not found. Vargha (1996b) specifies that the recommended count times produced MDAs for most isotopes in the range of 1 nCi. Based on the energy and photon yield for I-125, 10 nCi was assumed here.

Table 5-6. Unit codes and description of units [41].

Computer code (Method Code)	Description of units	Radionuclides reported with results
1	dpm/sample	None listed
2	nCi/L dpm/g C (only one sample result observed was reported in dpm/g C)	C-14
3	µCi/L nCi/L (only a few samples were reported in nCi/L	H-3
4	nCi/L	I-125 (gamma emitters)
5	nCi/L	I-125, Sr-85, Cr-51
	pCi/L	Cs-137
6	nCi/L	I-125
10	dpm/d	Gross alpha
	dpm/L (one sample)	Gross alpha
	µCi/L (one sample)	H-3
11	dpm/d	U-238
14	Dpm	None listed
15	dpm/d	None listed
16	(a)	
17	(a)	
18	(a)	
19	(a)	
50	dpm/d, dpm/L	Gross beta
51	dpm/d	Sr-90
52	nCi/L	S-35
54	(a)	
55	nCi/L	Ca-45
71	nCi/L	P-32

a. Codes 16, 17, 18, 19, and 54 were observed in a computer listing of assays but there were no results or radionuclides reported with these codes. Note: only positive results are shown in the computer listing, copies of original records are marked "neg" when the result is below the detection level.

Additional table notes:
1. The available computer listing of results shows only measurement units for positive results and only radionuclides for some of the positive results.
2. These Method Codes are seen throughout the bioassay records from 1960 to 1996.

The Laboratory's work was devoted to fundamental research on new elements, new isotopes, or properties of already known isotopes (Thaxter 1958). An important consideration at LBNL was that contamination could invalidate weeks of expensive research work and nuisance contamination was several orders of magnitude lower than the MPCs (Thaxter 1953). Air sample filter paper analysis results were compared to published tolerance levels for the radionuclide of concern (Thaxter 1950b). Tolerance levels were the 1949 Chalk River Tolerances (MPCs for radionuclides in air) (Saunders 1950). A table of the 1949 MPCs from the Chalk River Canada conference (Warren 1949) is provided in Table 5-7.

Similar documentation of the low airborne concentration levels can be found in a 1953 document that refers to the previous 6 yr of air sample data (back to 1947) (Thaxter 1953). This document noted that daily breathing zone air samples outside the gloveboxes between 1947 and 1953 showed all samples to be below 5×10^{-11} µCi/cm^3 beta/gamma. This document also noted the vigorous attempts to achieve no detectable airborne contamination (~2 dpm/ft^3) for long-lived transuranic alpha emitters.

Using the above information for long-lived radionuclides and noting that no air samples between 1948 and 1958 had activity greater than 0.1, times the amount indicated as contributing a 1-wk dose (Thaxter 1958). Where the weekly dose was 0.3 rem, and, based on MPCs at the time, the intake of

Table 5-7. 1949 Chalk River tolerances, maximum permissible concentrations in inspired air.[a]

Radionuclide	Maximum permissible concentrations in air	
	µg/cc	µCi/ml
Ra-226	4.0E-12	4.0E-12
U-nat	25 µg/m^3 [b]	1.7E-11
U-233 soluble salts	6.0E-9	6.0E-11
U-233 insoluble salts	2.5E-11	2.5E-13
Pu-239	5.0E-12	3.0E-13
Sr-90/Y-90	-	1.0E-10
H-3	-	1.0E-6
C-14	-	1.0E-6
Na-24	-	1.0E-6
P-32	-	2.0E-6
S-35	-	1.0E-6
Ar-41	-	1.0E-6
I-131	-	1.0E-9
Co-60	-	2.0E-9
Xe-133	-	1.0E-5
Xe-135	-	3.0E-5

a. Table values were obtained from Warren (1949), "Minutes of the Permissible Doses Conference held at Chalk River, Canada, September 29-30, 1949." In some cases the tolerance value was provided in µg/cm^3 and was converted for this table to µCi/mL.
b. U-nat was the one concentration reported in units of µg/m^3.

^{227}Ac and its progeny that will result in less than 0.3 rem/wk is 1.4 × 10^{-2} µCi. The maximum air concentration for long-lived radionuclides is calculated to be:

$$\frac{0.1*1.4E-2uCi/wk}{40hr/wk*60m/hr*2E4ml/m}=3E-11uCi/ml$$ [1]

Using the information in Thaxter (1953), an upper limit on the beta/gamma airborne concentration could be assumed to be less than 5 × 10^{-11} µCi/cm^3.

Air sample analysis detection limits for alpha particles were documented to be 1 cpm above background (Thaxter 1952). The counter efficiency is assumed to be 38% and the filter paper efficiency is assumed to be 75% (Thaxter 1950b).

Table 5-8 lists radionuclides used in each facility. Information on the compounds was very limited and therefore not included in the table. A few WBC records contained some information about the compound, but most were noted with “unknown” under the compound heading. The solubility type (type F, fast absorption, type M, moderate absorption, or type S, slow absorption) for some of the radionuclides can be found in International Commission on Radiological Protection (ICRP) Publication 78, *Individual Monitoring for Internal Exposure of Workers* (ICRP 1998). Publication 78 also provides information on the class assigned for gases and vapors (Class SR-1 soluble or reactive, Class SR-2 highly soluble or reactive, and Class SR-0 insoluble and nonreactive). The particle size for all

[1] The use of ^{227}Ac and its progeny in this calculation as representing long lived isotopes comes directly from Thaxter (1958). Thaxter (1958) described a review of approximately 2000 air samples from the period 1948 - 1958 and that no air samples had approached 1/10 of the value representing 0.3 rem/week. It was described that 1.4 uCi of Ac-227 + daughters inhaled in a week results in a dose of 0.3 rem. This was then converted to an air concentration in this equation.

particulate radionuclides should be assumed to be 5-μm AMAD in accordance with the ICRP recommendations for occupational exposure.

Table 5-8. Radionuclides[a,b] and fraction activity[a] by facility.

Current building no.	Building activity and compounds	Radionuclide	Fraction
1	Donner Laboratory (1961–present)	C-14	4.28E-01
		H-3	2.29E-01
		I-125	2.31E-01
		P-32	2.57E-02
		S-35	8.55E-02
		Alpha	1.41E-04
		Beta	8.44E-04
3	Calvin Laboratory	C-14	4.40E-03
		H-3	5.37E-02
		P-32	8.59E-02
		P-33	1.77E-01
		S-35	6.79E-01
4	(Nuclides obtained from 1977, 1979 worker bioassay lists)	C-14	
		H-3	
		P-32	
		S-35	
6, 16, 52	**6**: 184-in. Cyclotron (1957) Advanced Light Source (present) **16**: Sherwood Laboratory (1961) Accelerator and Fusion Research (present) **52**: General research (1961) Accelerator and Fusion Research (present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators (Building 6) identified in Patterson, Low-Beer, and Sargent (1969)[c]	U-238	2.90E-04
		N-13	9.93E-01
		O-15	5.19E-03
		Ar-41	1.38E-03
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Fe-55	
		Fe-59	
		Mn-54	
		Na-22	
		Na-24	
		Ni-57	
		Ni-63	
		Zn-65	
10	Biomedical research (1986) (nuclides obtained from 1977, 1979, 1982, 1983, 1986 worker bioassay lists)	C-14	
		Cr-51	
		H-3	
		P-32	
		S-35	
		Beta-gamma	
15	(Nuclides obtained from 1977 worker bioassay lists)	H-3	
25	Mechanical Technology (nuclides obtained from 1977, 1979, 1982, 1983, 1986 worker bioassay lists)	Th	
		U-238	
		U	
26, 76	Radioanalytical Laboratories (present)	Ac-228	1.51E-08
		Ag-108	2.65E-11
		Am-241	4.15E-03
		Am-243	2.56E-06
		Ba-133	2.27E-04
		Be-7	5.07E-10
		Bk-249	9.91E-04
		Br-76	6.94E-09
		Br-77	3.78E-10
		C-14	1.54E-02
		Ce-144	5.72E-07
		Cf-249	4.30E-04
		Cf-250	7.57E-08
		Cm-243	2.59E-07
		Cm-244	2.12E-08
		Cm-245	1.44E-10
		Cm-246	1.13E-09

Current building no.	Building activity and compounds	Radionuclide	Fraction
26, 76 (Cont'd.)		Cm-248	4.54E-10
		Co-56	9.83E-10
		Co-57	7.00E-06
		Co-58	5.29E-10
		Co-60	1.64E-04
		Cr-51	1.25E-10
		Cs-134	9.63E-06
		Cs-137	2.17E-03
		Eu-152	3.93E-11
		Fe-55	1.95E-05
		H-3	1.77E-01
		Hg-194	9.08E-09
		I-125	3.80E-01
		I-129	4.20E-05
		I-131	3.81E-01
		K-40	1.89E-09
		Kr-76	1.51E-10
		Mn-54	7.69E-06
		Na-22	1.63E-08
		Nb-95	1.63E-09
		Ni-63	1.01E-05
		Np-237	3.69E-06
		Np-239	5.33E-08
		Os-185	1.44E-09
		P-32	3.78E-03
		Pa-231	9.72E-08
		Po-210	1.51E-08
		Pu-238	5.46E-04
		Pu-239	1.59E-03
		Pu-241	3.40E-03
		Pu-242	1.66E-08
		Ra-226	2.27E-06
		Ra-228	1.69E-04
		Ru-106	2.27E-11
		S-35	2.42E-02
		Sb-125	8.81E-10
		Sr-89	6.65E-07
		Sr-90	1.38E-04
		Tc-99	1.10E-06
		Th-229	9.08E-08
		Th-230	5.19E-06
		Th-232	1.76E-05
		U-232	3.79E-05
		U-233	3.78E-03
		U-235	4.17E-05
		U-238	5.06E-04
		Zn-65	1.20E-05
29 51	(Nuclides obtained from 1979 worker bioassay lists) Bevatron [Uranium and beta-gamma nuclides obtained from 1982, 1983, 1986 worker bioassay lists; Am-241, Am-243, Bk-249, Cf-252, and Ra-226 obtained from LBNL (1995b); the remainder of the radionuclides were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969).[c]] Building is currently undergoing decontamination and decommissioning.	Alpha	
		U	
		Beta gamma	
		Am-241	
		Am-243	
		Bk-249	
		Cf-252	
		Ra-226	
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Fe-55	
		Fe-59	
		Mn-54	
		Na-22	

Current building no.	Building activity and compounds	Radionuclide	Fraction
51 (Cont'd.)		Na-24	
		Ni-57	
		Ni-63	
		Zn-65	
55, 56, 64	**55**: Animal house (1961) Center for functional imaging and life sciences research (present) **56**: Biomedical isotope facility (present) **64**: Accelerator design (1961) Life sciences research (present)	C-14	2.67E-08
		Co-57	7.63E-08
		Gd-153	2.29E-08
		H-3	1.12E-05
		I-123	4.40E-05
		I-125	1.09E-04
		I-131	6.02E-06
		Nb-95	1.14E-07
		P-32	4.58E-07
		Ru-103	1.53E-07
		Sn-113	7.63E-08
		Tc-99m	3.16E-05
		Tl-201	9.91E-07
		F-18	1.00E+00
		Alpha	3.71E-09
		Beta	5.92E-08
57	(Nuclides obtained from 1982 worker bioassay lists)	I-125	
		I-131	
		In-111	
		P-32	
		Sr-82	
		Sr-85	
		Sr-90	
62	Materials and Molecular Research (nuclides obtained from 1982, 1983, 1986 worker bioassay lists)	Th-228	
70, 70A	**70/70A**: Nuclear Chemistry (1961) **70**: Environmental energy technology, nuclear science, and earth sciences research (present) **70A**: Nuclear, chemical, and life sciences research (present)	Ac-227[d]	
		Am-241	7.60E-06
		Am-243	1.52E-04
		Bi-207	7.60E-06
		C-14	5.51E-01
		Ca-45	1.20E-05
		Ca-49	2.38E-08
		Ce-141	2.59E-06
		Cf-249	7.60E-07
		Cf-252	7.60E-09
		Cm-244	2.13E-08
		Cm-248	1.08E-07
		Co-60	3.61E-06
		Cs-134	1.46E-06
		Eu-152	1.07E-05
		Fe-59	6.88E-03
		H-3	2.76E-01
		Hf-175	8.58E-06
		Ho-166m	6.08E-06
		I-125	2.25E-04
		Mn-54	1.52E-07
		Na-22	1.52E-06
		Na-24	2.65E-05
		Np-237	1.70E-03
		P-32	4.13E-02
		Pa-233	3.60E-06
		Pu-238	4.35E-05
		Pu-239	6.99E-06
		Ra-226	1.52E-06
		Rb-86	1.93E-04
		Rh-101	7.60E-08
		Ru-106[c]	
		S-35	1.06E-02
		Sb-122	1.90E-07

Current building no.	Building activity and compounds	Radionuclide	Fraction
70, 70A (Cont'd.)		Sb-124	1.10E-06
		Sc-46	1.34E-03
		Sc-49	1.19E-08
		Sr-90	6.08E-06
		Ta-182	1.52E-06
		Tb-161[c]	
		Tc-99	8.04E-02
		Th-229	2.17E-05
		Th-232	9.44E-04
		Tl-204	1.52E-06
		Tm-170	1.52E-05
		U-233	2.61E-04
		U-234	1.08E-04
		U-235	1.08E-04
		U-238	3.81E-04
		Y-90	1.22E-05
		Yb-175	1.96E-06
		Zr-88	4.56E-07
		Zr-95	7.60E-04
		Alpha	4.04E-03
		Beta	2.38E-02
71	HILAC (1961) Accelerator and fusion research (present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969)[c]	F-18	1.20E-08
		H-3	1.00E+00
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Fe-55	
		Fe-59	
		Mn-54	
		Na-22	
		Na-24	
		Ni-57	
		Ni-63	
		Zn-65	
72	Health Physics (1961) Low-background facility (present)	Ac-227	8.33E-08
		Au-198	2.83E-06
		Ba-133	2.99E-09
		Bi-207	3.01E-08
		Br-82	2.48E-07
		Cd-113	6.40E-09
		Co-58	9.23E-01
		Co-60	1.20E-03
		Cr-51	1.51E-06
		Cu-64	4.96E-04
		Eu-152	4.96E-04
		Fe-59	2.95E-02
		Hg-194	4.68E-08
		Mn-54	2.68E-06
		Na-24	9.92E-04
		Nb-95	1.34E-09
		P-32	9.50E-06
		Pa-231	4.94E-08
		Sb-122	2.97E-11
		Sb-124	9.92E-04
		Ta-182	5.28E-08
		Th-228	5.23E-12
		Th-229	2.62E-05
		Th-232	4.96E-08
		Ti-44	1.35E-07
		Xe-133	3.97E-10
		Zn-65	3.47E-11

Current building no.	Building activity and compounds	Radionuclide	Fraction
72 (Cont'd.)		Zr-95	4.10E-02
		Zr-97	1.82E-03
74, 83, 84	**74**: Animal bioradiological laboratory (1961) **74, 83, 84**: Life sciences research (present)	C-14	4.92E-03
		H-3	5.05E-01
		P-32	3.46E-02
		S-35	4.56E-01
75	Radioisotope services (1961) Former waste handling facility, operations ceased in 1997 Former National Tritium Labeling Facility operations ceased in 2001	H-3	1.00E+00
		Alpha (Th-232)	1.69E-09
		Beta (Sr-90)	5.72E-09
85	Hazardous waste handling facility (present)	C-14	1.44E-01
		H-3	8.56E-01
		I-125	9.97E-06
		Alpha (Th-232)	1.17E-06
		Beta (Sr-90)	2.79E-06
88	88-in cyclotron (1961 – present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969)[c]	U-238	1.40E-10
		C-11	9.94E-01
		Cr-51	1.95E-12
		Fe-55	8.19E-13
		Fe-59	2.03E-12
		Ge-71	6.37E-03
		Zr-95	1.56E-12
		Zr-97	2.34E-12
		Y-88	3.12E-12
		Alpha	4.72E-07
		Beta	1.63E-06
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Mn-54	
		Na-22	
		Na-24	
		Ni-57	
		Ni-63	
		Zn-65	
934	Previously Leased Building use of biomedical radionuclides for DNA Labeling (nuclides obtained from 1982, 1983, 1986 worker bioassay lists)	C-14	
		H-3	
		I-125	
		P-32	
		S-35	
977[e]		H-3	
		P-32	
		P-33	
		S-35	
		C-14	
		Cd-109	

a. Blank values in this table indicate not applicable or data not available. Unless otherwise noted, this table was derived from data reported for calendar years 2001 to 2004 as part of the National Emission Standards for Hazardous Air Pollutants (DOE 2002, 2003, 2004, 2005). Where stack emissions were not measured, LBNL derived a "receipts releasable" inventory of radionuclides available for release. While the emissions identified during this limited period are probably not fully representative of the source term in each building, they do provide an estimate of the types of radionuclides to which employees might have been exposed. Activity fractions were obtained by dividing the activity total by the total activity for all radionuclides in a specific building/buildings over the 4 yr.

b. Buildings and radionuclides were added based on historical lists (e.g. bioassay lists, LBNL 2005a,b; Patterson, Low-Beer, and Sargent 1969). Radionuclide fractions were not determined for these.

c. Although Patterson, Low-Beer, and Sargent (1969) identified these radionuclides as potential exposure sources, the article concluded that "normal habits of cleanliness and occasionally the use of protective clothing … are adequate to insure that the ordinary accelerator worker at LRL-Berkeley will not receive radiation exposure of any consequence from internal sources."

d. Ac-227, Ru-106, and Tb-161 were added to the list of radionuclides for Building 70 because there were documented spills in Building 70 between 1957 and 1960 where these radionuclides were listed; no attempt to determine a radionuclide fraction has been made.

Additional table notes:

1. Radionuclides obtained from LBNL (2005a).
2. The information on the compounds was very limited and, therefore, this column has not been completed. A few of the WBCs reviewed contained some information about the compound, but most noted "unknown."

6.0 OCCUPATIONAL EXTERNAL DOSE

This section describes the program for measuring skin and WB doses to workers from sources that were external to the body. Workers at LBNL were exposed to radiation from a variety of radioactive materials and radiation-producing machines. Personnel dosimeter records are generally available for all periods at LBNL for workers who had any potential for occupational radiation exposure. The operations and radiation safety staffs routinely reviewed dosimeter results for compliance with radiation control limits and investigated doses that approached annual or quarterly limits. LBNL used personnel dosimeters to measure and record doses from external radiation to designated workers throughout the history of its operations. These dosimeters included one or more of the following:

- Personnel WB beta/photon dosimeters
- Pocket ionization chamber dosimeters (electrometers/electroscopes, etc.)
- Personnel extremity dosimeters
- Personnel neutron dosimeters

LBNL began operations using dosimeter and processing technical support provided by the Metallurgical Laboratory at the University of Chicago. After 1952, LBNL operated its own fully functional personnel dosimetry program with in-house processing. Exposure data were recorded by film badges and thermoluminescent dosimeters (TLDs). Early exposure records also provided *electroscope* (or at times, *electrometer* or *E* was used) results, which supplemented the results measured by film. Dose reconstructors should use the electroscope results in a qualitative manner because no data were found on the calibration or energy response of these devices; they should use the film or TLD results to estimate the actual exposure or the electroscope reading if no corresponding dosimeter reading exists. The electroscope results include daily readings in tables captioned "dosimeter," "slow neutron," and "electroscope." The three readings, which occurred on the same dates, were evidently used to measure exposure at the end of work shifts [42]. There are data in worker records that show a comparison of the film dosimeter to electroscope records for the same interval; the data are similar and correlate, but they are not identical. This is probably due to a combination of differences in energy dependence, calibration techniques, where the dosimeters were worn in relation to each other, exposure geometry, etc.

Where the records bear the heading, "All readings are recorded in daily doses," the daily dose is 100 mrem. The units are in fractions of 100 mrem (e.g., 0.08 = 8 mrem; Heinzelman 2003).

There are no records of reporting beta exposure using film from before 1979. This is presumed to be because the radiation protection staff at the time felt that deep dose was controlling to meet regulatory limits (i.e., that the shallow dose could not exceed the deep dose by a high enough amount to come close to the higher regulatory limit). The radiation protection staff was aware of the need to monitor for nonpenetrating radiation and used a film badge containing filters (LRL 1958e). Inasmuch as the limit for WB (deep) dose was 5 rem/yr and for skin (shallow) dose was 15 rem/yr, it is reasonable to assume that the shallow dose could not exceed the deep dose by more than a factor of 3 [43]. For cases where the shallow dose is important to reconstruction and is not reported, dose reconstructors should apply a factor of 3 to the WB dose to estimate the shallow dose.

Table 6-1 lists dosimeter types, periods of use, exchange frequencies, minimum detection limits (MDLs), and potential annual missed doses for LBNL. Tables 6-2 and 6-3 list the energies and percentages for neutron and beta/photon radiation, respectively. If more than one energy range and percentage combination is provided, dose reconstructors should use the combination that is most favorable to claimants. Table 6-4 summarizes recorded dose practices, and Table 6-5 summarizes the interpretation of the reported data. Table 6-6 lists adjustments to recorded dose, and Table 6-7

lists the bias and uncertainty of each specific dosimeter system. The adjustment to neutron dose by a factor of 2 provided in Table 6-6 should be used unless claimant records provide sufficient information to use the more specific ICRP Publication 60 correction factor provided in Table 6-3 (ICRP 1991). There is limited information about the use of extremity dosimeters before 1982. It appears that X-ray film was used as finger rings; there is no reference to wrist dosimeters (as were used at LANL or Oak Ridge National Laboratory) [44]. When extremity dose data is reported for a worker it should be assumed that the dosimeter characteristics were the same as for the general use dosimeters as described in Table 6-1. Estimates of missing dose can use dose results for coworkers or the recorded dose before and after the period of the missing dose. Unmonitored workers should be assigned environmental doses as discussed in Section 4 or coworker data, as appropriate. Assignment of dose to unmonitored workers is addressed in NIOSH (2002).

Table 6-1. LBNL dosimeter type, period of use, exchange frequency, MDL, and potential annual missed dose.

Period of use	Dosimeter	MDL[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
1941–1981[d] [45]	Photon/electron - DuPont 558 and 519 film[e]	0.015	Weekly (n = 50)	0.375
		0.020	Biweekly (n = 25)	0.25
		0.030	Monthly (n = 12)	0.18
	Neutron - Kodak NTA film[f]	0.050	Weekly (n = 50)	1.25[g]
		0.050	Biweekly (n = 25)	0.625[g]
		0.050	Monthly (n = 12)	0.30[g]
1982–1985 [46]	Photon/electron/neutron - Harshaw TLD (TLD-100, TLD-200, TLD-600, and TLD-700)	0.010	Monthly (n = 12)	0.06
		0.020	Quarterly (n = 4)	0.04
1985–present [47]	Photon/electron - Panasonic 810AS and 802AS TLD	0.010	Monthly (n = 12)	0.06
		0.015	Quarterly (n = 4)	0.03
		0.025	Semiannual (n = 2)	0.025
	Neutron - CR-39	0.010	Monthly (n = 12)	0.06
		0.010	Quarterly (n = 4)	0.02

a. Estimated MDLs for each dosimeter technology. Dose values were recorded at levels less than the MDL.
b. Exchange frequencies were dependent on work assignment. If the exchange frequency is not evident based on trends in an individual's personnel records, assume a monthly exchange frequency. If there is a possibility of more frequent monitoring than monthly that is not evident from review of worker data, the dose reconstructor should contact LBNL to request additional information.
c. Annual missed dose calculated using the MDL/2 method from NIOSH (2002).
d. From 1941 to 1952, ANL-E processed film dosimeters for LBNL. The procedure to process the dosimeter was described by Pardue, Goldstein, and Wollan (1944). From 1952 to 1955, LBNL processed film dosimeters using an equivalent method.
e. No record of the type of beta/gamma film used initially is available, but DuPont films were in use by ANL-E by the late 1950s (ORAUT 2006).
f. The beginning of neutron monitoring is uncertain, but it appears to have been in use as early as 1951. Records indicate that films were developed but not routinely read before 1960. Films were apparently not evaluated unless there was a gamma dose measured for the same period (ORAUT 2006; CER 1981).
g. Neutron energies below 500 keV should be considered as unmonitored due to the insensitivity to neutrons with energies less than 500 keV (NIOSH 2002). Doses should be assigned in accordance with the guidelines in NIOSH (2002) and Table 6-6 below.

Table 6-2. Selection of beta and photon radiation energies and percentages [48].

Buildings	Functional category	Radiation type	Energy selection (MeV)	Percentage
1, 2, 3, 4, 5, 5A, 7, 8, 9, 10, 11, 14, 16, 18, 19, 20, 22, 24, 25, 29, 38, 39, 55, 71	**Chemistry:** radioactive materials including Co-60, S-90, fission products, enriched uranium, depleted uranium, natural uranium, and others	Beta	>15	100
		Photon	30–250	25
			> 250	75
6, 26, 70, 70A, 88	**Chemistry Heavy Elements Facility:** Cf-252, Cm-244, Am-241, U-233, Pu-239, and others	Beta	>15	100
		Photon	<30	25
			30–250	50
			> 250	25
75	**Waste Storage Yard:** fission products, enriched uranium, natural uranium and others	Beta	>15	100
		Photon	30–250	25
			> 250	75
72, 74, 75	**Irradiators:** Co-60, Cs-137	Beta	>15	100
		Photon	30–250	25
			> 250	75
51, 71	**Cyclotrons and Accelerators**	Beta	>15	100
		Photon	<30	0
			30-250	10
			>250	90

Table 6-3. Selection of neutron radiation energies and percentages [49].

Buildings	Description	Radiation type	Energy selection (MeV)	Percentage	ICRP 60 Correction Factor
1, 2, 3, 4, 5, 5A, 7, 8, 9, 10, 11, 14, 16, 18, 19, 20, 22, 24, 25, 29, 38, 39, 55, 71	**Chemistry:** radioactive materials including Co-60, S-90, fission products, enriched uranium, depleted uranium, natural uranium, and others	Neutron	0.1–2.0	100	1.91
6, 26, 70, 70A, 88	**Chemistry Heavy Elements Facility**: Cf-252 Cm-244, Am-241, U-233, Pu-239, and others	Neutron	0.1–2.0	90	1.71
			2.0-20	10	0.13
75	**Waste Storage Yard:** fission products, enriched uranium, natural uranium, and others	Neutron	0.1–2.0	90	1.71
			2.0-20	10	0.13
72, 74, 75	**Irradiators:** Co-60, Cs-137	Neutron	0.1–2.0	100	1.91
51, 71	**Cyclotrons and Accelerators**	Neutron	0.1–2.0	50	0.95
			2.0-20	50	0.65

Table 6-4. Recorded dose practices [50].

Period	Dosimeter measured quantities	Compliance dose quantities
Photon/electron film dosimeter + NTA neutron dosimeter		
1941–1981	Gamma (G) Neutron (N)	WB = gamma + neutron
Photon/electron/neutron–Harshaw TLD		
1982–1985	Gamma (G) Neutron (N)	Total = photon + neutron (γ + η) Skin = shallow = photon + neutron Hand = finger extremity dose
Photon/electron/neutron–Panasonic TLD + CR-39 neutron dosimeter		
1985–present	Skin Photon Neutron	Skin = photon + neutron (P/N) WB = Photon + neutron

Table 6-5. Interpretation of reported data [51].

Period	Reported quantity	Description	Interpretation of zeroes	Interpretation of blanks (no data)	Rollup of individual and annual data	Monitored/ unmonitored
1941–1981	rem	Reported WB doses include gamma. Neutron doses were designated with "N." Claimant records indicate that some recorded results are expressed as a fraction of the daily dose limit of 100 mrem.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Total deep WB dose	From review of LBNL documents, it is not clear if all employees were continuously monitored. However, the monitoring records appear to be complete. It can be assumed if no monitoring records are included in an employee's file that the individual was not monitored.
1982–1985	rem	Reported WB doses qualified as either photon or neutron.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	
1985–present	rem	Photon deep, neutron deep, and skin dose reported.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	

Table 6-6. Adjustments to recorded dose.

Period	Dosimeter	Facility	Adjustment to reported dose
1941–1985[a]	Photon dosimeters[b]	All facilities	Use roentgen-to-organ dose conversion factors.
1985–present	Photon dosimeters	All facilities	Use *Hp(10)*-to-organ dose conversion factors.
All years	Neutron dosimeters[c]	All facilities	Multiply reported doses by factor of 2 to account for ICRP (1991) weighting factors.

a. Beta and nonpenetrating dose was not reported before 1982. In general, nonpenetrating radiation doses should be assigned as <30-keV photons if the employee worked with or around plutonium; otherwise, >15-keV electrons should be assigned (ORAUT 2005b). The guidance from Oak Ridge Associated Universities (ORAU) is:

> *If the nature of the nonpenetrating dose is unknown, consider the following guidance:*
> 1. *For a likely noncompensable case, it is acceptable to assume the nonpenetrating dose is associated with <30-keV photons, as this maximizes POC.*
> 2. *For a likely compensable case, it is acceptable to assume the nonpenetrating dose is associated with >15-keV electrons, as this minimizes POC.*
> 3. *If the compensability decision may hinge on this issue, and if the partitioning of the nonpenetrating dose cannot be decided based on the available information, additional research might be required.*

b. The doses from low-energy photons (<30 keV) were underestimated for 1982 to 1985 as a result of the design of the dosimeter holder (ORAUT 2005c). The dose from <30-keV photons should be calculated by the following formula:

$$Photon < 30kev = (shallow - WB) \times 2$$

c. The NTA dosimeter (1941 to 1969) exhibited a lower energy threshold of approximately 500 keV (NIOSH 2002). The photon dose was measured adequately and all LBNL neutron dose was accompanied by a significant photon dose. For neutron dose received before 1969, the dose should be adjusted by using a neutron-to-photon ratio. The neutron exposure was determined with a neutron-to-photon ratio of 0.73 ±2.1 [52]. The geometric mean was 0.73, and the geometric standard deviation was 2.1[53]. The assumed upper 95th percentile was assumed to be 2.47 [54].

Table 6-7. Bias and uncertainty [55].

Site-specific dosimetry system	Bias magnitude and range		Uncertainty factors	
	Overall bias[a]	Range in bias[b]	Systematic[c]	Random[d]
Photon/electron film (1941–1981) nonplutonium facility (as listed in Tables 2-1 and 2-2)	1.27	1.23–1.60	1.2	1.8
Neutron NTA film (1941–1981) nonplutonium facility (as listed in Tables 2-1 and 2-2)	1.0	0.5–2.0	1.05	2.0
Photon/electron film (1941–1981) plutonium facility (as listed in Tables 2-1 and 2-2)	1.0	0.25–2.0	1.05	1.3
Neutron NTA film (1941–1981) plutonium facility (as listed in Tables 2-1 and 2-2)	1.0	0.5–2.0	1.05	2.0
Harshaw photon/electron/neutron TLD (1982–1985)	1.12	1.04–1.2	1.05	1.2
Panasonic photon/electron TLD (1985–present)	1.0	0.8–1.2	1.05	1.2
CR-39 neutron (1985–present)	1.0	0.6–1.5	1.05	1.5

a. Based on the distribution of energy levels and geometry judged most likely. Divide recorded dose by the table's bias value to calculate deep dose.
b. Range of overall bias factors based on alternative distributions of energy levels and geometry.
c. Systematic uncertainty resulting from lack of knowledge about actual distributions of energy levels and geometry.
d. Random uncertainty resulting from variation among workers in energy levels and geometry.

7.0 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database.

[1] Turpin, Baynard. ORAU Team, Task 3. May, 2006. "About Berkeley Lab" on the Lawrence Berkeley National Laboratory home page found at: http://www.lbl.gov/LBL-PID/LBL-Overview.html.

[2] Turpin, Baynard. ORAU Team, Task 3. May, 2006. Table 2-1 information was obtained from a document titled: RadMap, Legacy and Current Radioactive Material Locations, by Michael R. Dupray of LBNL.

[3] Turpin, Baynard. ORAU Team, Task 3. May, 2006. 1995 LBNL Site Environmental Report, Introduction and Purpose, found at: http://www.lbl.gov/ehs/esg/95ser/95serchap1.htm#Introduction%20and%20Purpose

[4] Turpin, Baynard. ORAU Team, Task 3. May, 2006. "About Berkeley Lab" on the Lawrence Berkeley National Laboratory home page found at: http://www.lbl.gov/LBL-PID/LBL-Overview.html

[5] Turpin, Baynard. ORAU Team, Task 3. May, 2006, Table 2-2 information was obtained from the same source as item 2-2 and Project Document number 030007011, "Radioisotope Inventory, LRL-Berkeley "Appendix B Spaces," March 17, 1964. [SRDB Ref ID: 20693]

[6] De Castro, T. M., and S. B. Thomas, LBNL, Health Physics Department, 1975.

That the collimation and filtration were checked in the survey of March 19, 1975 and found to be acceptable is a relevant indication that the equipment was operating properly.

[7] ORAUT-OTIB-0006, Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures.
Distances selected for computations are consistent with this document.

[8] Bradfield, N. E., LBNL, X-Ray System Supervisor, 1987.
This document has numerous handwritten notes, ending on last page with “Changes made 9/28/87 Installation of New Picker”, signed by Nancy E. Bradfield, RN. Document establishes date of replacement for X-ray equipment.

[9] Turner, James E. ORAU Team, Task 3. May, 2006.
The assumption of an annual X-ray screening frequency is consistent with common practice at other laboratories. Cases with reconstructed doses in the NOCTS files for LBNL have used an assumed annual frequency.

[10] East, James. ORAU Team, Task 3. May, 2006. Summary statement to provide general background on the quality and effectiveness of the monitoring program. Based on Subject Expert’s perception of referenced documents.

[11] East, James. ORAU Team, Task 3. May, 2006. Various papers and memoranda in the early 50’s were presented on the subject regarding the design and effectiveness. Cited 1950 memorandum on hood design for radiochemistry specifying many features still in use today. Background information.

[12] East, James. ORAU Team, Task 3. May, 2006. Summary of the environmental monitoring data, from the beginning of observations in 1959 show a significant drop in ambient dose rates. This is perceived as a result of a combination of factors, reduction in the weapons testing fallout, improved instrumentation and monitoring program, and implementation of the ALARA concept. Programs evolved from portable instrument spot checks to use of continuous monitoring with film badges and later TLDs.

[13] East, James. ORAU Team, Task 3. May, 2006. Many years only reported maximum observed values. Later, average values were also reported. For consistency, and to be favorable to claimants, the maximum value was chosen for all years.

[14] East, James. ORAU Team, Task 3. May, 2006. No one worker received the maximum value every year, and the requirements of the computer code for inputs of average and maximum uncertainty lead to the estimates provided and remain favorable to claimants.

[15] East, James. ORAU Team, Task 3. May, 2006. Summary statement based on facts reported in the Environmental Reports over the years. The portable instrument readings were converted from hourly rates to annual for consistency.

[16] East, James. ORAU Team, Task 3. May, 2006. This statement is drawn from notations in many of the Environmental Reports and represents the capabilities of the monitoring at the time observations were made.

[17] East, James. ORAU Team, Task 3. May, 2006. Based on data presented in available environmental reports listed in the Reference section. Background information to support the estimates provided in the next paragraph.

[18] East, James. ORAU Team, Task 3. May, 2006. The growth in the power of the accelerators is viewed to be almost exponential. The back side of the curve (1959 on) shows a sharp drop in reported doses. A linear estimate of these years would overestimate observed doses. These two observations provide logical basis for the statement.

[19] East, James. ORAU Team, Task 3. May, 2006. Statement of the obvious effects of applying average dose observed over the early years, overestimating earliest years, and underestimating the later.

[20] East, James. ORAU Team, Task 3. May, 2006. The parabolic curve best parallels the growth in accelerator power, and mirrors the decline in observed doses in the following years.

[21] East, James. ORAU Team, Task 3. May, 2006. The previous paragraphs provide the reason for selecting the parabolic curve, and this paragraph summarizes the effects of doing so.

[22] East, James. ORAU Team, Task 3. May, 2006. The internal dose calculated in the record by LBNL are from releases and based on Th for alpha and Sr for beta because these were predominate and/or have the highest dose per activity factors and are favorable to the claimant.

[23] East, James. ORAU Team, Task 3. May, 2006. As stated, the average value for the observed years provides a good estimate of the other years. There appears to be little or no impact from LBNL operations, nor should there be from accelerator operations.

[24] East, James. ORAU Team, Task 3. May, 2006. Some of the recent environmental reports did not include beta activity in air, necessitating the estimates for the missing years. These estimates were based on recent years that were reported, and a round number above this trend was selected to be favorable to the claimant.

[25] East, James. ORAU Team, Task 3. May, 2006. Justification for the estimates is provided in the text for the years where observations are not available. Multiple effects are being addressed, the rise in airborne concentrations from atmospheric weapons testing and the increasing accelerator power and resulting generation of beta airborne concentrations, most of which are short lived and/or have low dose to activity conversion factors.

[26] East, James. ORAU Team, Task 3. May, 2006. The measurement for H-3 in 2004 was not reported. An estimate of H-3 was based on a H-3 to C-14 ratio. The ratio chosen is representative (average) of the data and favorable to claimant. Further discussion of similar technique is provided in the paragraph on C-14.

[27] East, James. ORAU Team, Task 3. May, 2006. Measurements were not available prior to 1974. It is well established that H-3 and C-14 are common byproducts of accelerator operation. It is reasonable to assume that the rise in airborne concentrations is proportional to accelerator power and operation time. The linear estimate from the peak downwards towards initial operations provides for concentrations favorable to the claimant. This upward rise was controlled in the later years with aggressive shielding design with steps in power level, see

environmental reports for summaries of the shielding efforts for the new and modified accelerator projects.

[28] East, James. ORAU Team, Task 3. May, 2006. The ratio of C-14 to H-3 was calculated for each of the years where both values were reported (1974-1995). The average of the twenty-two observations was 0.155, the maximum was 0.73 and minimum of 0.02. This factor was applied to C-14 from 1996 to 2003 (except for 1999 when a value of 2592 was reported. As discussed above, the only year this was applied to H-3 in reverse was 2004, the only year that C-14 was reported and H-3 was not reported.

[29] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. Information on the decision to eliminate routine bioassays and use operational bioassays (based on scheduled work) was obtained during a telephone conversation between Elizabeth Langille and James Floyd (LBL Group Leader EH&S), May 6,2006 [SRDB Ref. ID 23402].
Documentation for the approach is also found in:
AIMahamid, I., 2005, Technical Basis Document for Internal Dosimetry, EH&S Procedure 301, Rev.4, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May 12. [SRDB Ref. ID: 21162]

[30] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. "LBNL Electronic Record of Results 1960 – 1996," ORAU Team 2006. [SRDB Ref. ID: 23841]
The electronic record of results was obtained from J. Floyd, LBNL Group Leader EH&S and includes a listing of method codes for the bioassay sample analysis results table. Where specific analyses were found in NOCTS records or in other SRDB records and could be compared to the electronic records, the method codes were verified to match those in the electronic records.

[31] Sargent, Thornton III, 1991, LBNL, Whole Body Counter Facility Operations Manual, January 22. [SRDB Ref. ID: 20900]
The operator aid specifies that a 15 minute count time is used but then provides a step to "assess the need for other counts in other geometries, as per detailed instructions." These instructions implied that special instructions might include an increased count time to achieve a desired detection limit.

[32] Low-Beer, A. DeG., 1963, "Report of Bioassay Program for 1962," memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 31. [SRDB Ref. ID: 21252]
The analysis of special fecal samples was noted in this document for 1962. Earlier special fecal samples are also noted in the electronic record of results found in SRDB Ref. ID 23481.

[33] Low-Beer, A. DeG., 1963, "Report of Bioassay Program for 1962," memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 31. [SRDB Ref. ID: 21252]
The analysis of special blood samples was noted in this document for 1962. Earlier special blood (SB) samples are also noted in the electronic record of results found in SRDB Ref. ID 23481.

[34] LBNL, 1983, Radiochemical Assay Report, July 12. [SRDB Ref. ID: 20880]
The record showed that spot urine collection was used for H-3 analysis during this time period. Spot urine collection may also have been used for H-3 earlier than 1983 at LBNL but of the records reviewed, this was the earliest date noted.

[35] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
This internal dosimetry program document provides information that routine 24 hour urine bioassay samples were obtained and analyzed for certain workers.

[36] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
This internal dosimetry program document provides information that fecal bioassay samples were obtained and analyzed as special bioassays when determined necessary.

[37] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
This internal dosimetry program document provides information that spot urine bioassay samples were obtained and analyzed as determined necessary by EH&S.

[38] LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[39] LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[40] Langille, Elizabeth A. ORAU Team, Task 3. May 31, 2006. A review of the bioassay records in approximately 100 claims on NOCTS showed a file in 1971 (Claim 16237) where the individual was counted on a WBC and an analysis for P-32 was performed. This file was used to establish the beginning time for this method as 1971. Using WBC to analyze for P-32 was also noted in 1995 LBNL Technical Basis document for internal dosimetry and so the method was assumed to be available until LBNL stopped performing WBC in 1996.
LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]
The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[41] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. "LBNL Electronic Record of Results 1960 – 1996," ORAU Team 2006. [SRDB Ref. ID: 23841]
The electronic record of results was obtained from J. Floyd, LBNL Group Leader EH&S and includes a listing of method codes for the bioassay sample analysis results table. Where specific analyses were found in NOCTS records or in other SRDB records and could be compared to the electronic records, the method codes were verified to match those in the electronic records.

[42] Guido, Joseph, ORAU Team, Task 5. June 5, 2006. Mr. Guido reviewed the original data from multiple claims and made the observation that the readings represented the end of work shifts.

[43] Thomas, Bill R. ORAU Team, Task 3. June 5, 2006. Mr. Thomas reviewed the manual for radiation safety practices published in 1958 (LRL, 1958e). It appeared that the RADCON staff implemented a procedure that limited the deep dose and adequately limited the shallow dose. In the absence of other data, a ratio was established for shallow exposure to deep exposure of 3:1.

[44] Guido, Joseph. ORAU Team, Task 5. June 5, 2006. Mr. Guido and Mr. Thomas discussed the lack of results for extremity dose prior to 1982. Mr. Guido summarized the records from several claimants. Wrist dosimeters were used at LANL and ORNL for the same time period; it appeared that the technology was available.

[45] Smith, Matthew H. ORAU Team. May 22, 2006. Mr. Smith and Mr. Thomas discussed the limited response of NTA film to neutrons with an energy below 800 keV. There were no documented studies of the poor response provided by LBNL. Mr. Smith suggested a response similar to that selected in the Hanford TBD (ORAUT, 2004) and information derived for the Rocky Flats Plant in OTIB-0027 (ORAUT, 2005c). It was necessary to establish a neutron to photon ratio in order to modify the NTA dosimeter results. For operations handling transuranics including plutonium, the neutron to photon ratio was judged to be similar to Hanford plutonium operations with a geometric mean of 0.73, GSD 2.1, and upper 95% 2.47 (ORAUT, 2004).

[46] Smith, Matthew H. ORAU Team. May 22, 2006. Mr. Smith and Mr. Thomas discussed the limited response of NTA film to neutrons with an energy below 800 kev. There were no documented studies of the poor response provided by LBNL. Mr. Smith suggested a response similar to that selected in the Hanford TBD (ORAUT, 2004) and information derived for the Rocky Flats Plant in OTIB-0027 (ORAUT, 2005c). It was necessary to establish a neutron to photon ratio in order to modify the NTA dosimeter results. For operations handling transuranics including plutonium, the neutron to photon ratio was judged to be similar to Hanford plutonium operations with a geometric mean of 0.73, GSD 2.1, and upper 95% 2.47 (ORAUT, 2004).

[47] Smith, Matthew H. ORAU Team. May 22, 2006. Mr. Smith and Mr. Thomas discussed the limited response of NTA film to neutrons with an energy below 800 kev. There were no documented studies of the poor response provided by LBNL. Mr. Smith suggested a response similar to that selected in the Hanford TBD (ORAUT, 2004) and information derived for the Rocky Flats Plant in OTIB-0027 (ORAUT, 2005c). It was necessary to establish a neutron to photon ratio in order to modify the NTA dosimeter results. For operations handling transuranics including plutonium, the neutron to photon ratio was judged to be similar to Hanford plutonium operations with a geometric mean of 0.73, GSD 2.1, and upper 95% 2.47 (ORAUT, 2004).

[48] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr Thomas reviewed the types of activities described in Chapter 2 of the LBNL TBD. Given the type of operations, the energy fractions were selected in a manner similar to the LLNL and LANL facilities.

[49] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr Thomas reviewed the types of activities described in Chapter 2 of the LBNL TBD. Given the type of operations, the energy fractions were selected in a manner similar to the LLNL and LANL facilities.

[50] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr. Thomas reviewed the original data from multiple claims in the NOCTS database and made the observation that codes assigned to external dosimetry were updated overtime. The types of dosimeters were described in the documentation provided with the exposure data.

[51] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr. Thomas reviewed the original data from multiple claims in the NOCTS database and made the observation that codes assigned to external dosimetry were updated over time. The types of dosimeters were described in the documentation provided with the exposure data.

[52] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr. Thomas reviewed the results provided in the NOCTS database to identify the frequency that dosimeters were exchanged. Design and type of film was described in the Argonne East TBD (ORAUT, 2006). Mr. Joe Guido, ORAU Task 5, June 5, 2006 confirmed that film badges were used through 1981 by reviewing claims in the NOCTS database.

[53] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr. Thomas reviewed the results provided in the NOCTS database to identify the frequency that dosimeters were exchanged. The MDL was equivalent to that of the LLNL and LANL programs for similar dosimeters and processing procedures.

[54] Thomas, Bill R. ORAU Team, Task 3. May 1, 2006. Mr. Thomas reviewed the results provided in the NOCTS database to identify the frequency that dosimeters were exchanged. The MDL was equivalent to that of the LLNL and LANL programs.

[55] Smith, Matthew H. ORAU Team. May 22, 2006. Mr Smith reviewed that bias and uncertainty described for the types of dosimeters and LBNL facilities. He recommended that the table be revised to be consistent with the Hanford TBD (ORAUT, 2004) and information derived for the Rocky Flats Plant in OTIB-0027 (ORAUT, 2005C).

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GLOSSARY

absorbed dose
Amount of energy in rads or grays deposited in a substance by ionizing radiation per unit mass of the substance. See *dose*.

absorption type
Categories for materials according to their speed of absorption in the body, which replaced the earlier inhalation clearance classes. Defined by the International Commission on Radiological Protection, the absorption types are F for fast absorption (formerly inhalation class D), M for moderate absorption (formerly inhalation class W), and S for slow absorption (formerly inhalation class Y). Also called *solubility type*.

activity median aerodynamic diameter (AMAD)
Diameter of a unit density sphere with the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol. In relation to health physics, normally assumed to be 5 micrometers. Also called *aerodynamic equivalent diameter*.

acute exposure
Radiation exposure to the body delivered in a short period. See *chronic exposure*.

alpha radiation
Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2. Alpha particles have low penetrating power and a short range (a few centimeters in air). Outside the body, the most energetic alpha particle generally fails to penetrate the dead layers of cells covering the skin or a sheet of paper. Alpha particles emitted by radionuclides inside the body are a more significant health risk.

background radiation
Radiation from cosmic sources, naturally occurring radioactive materials including naturally occurring radon, and global fallout from the testing of nuclear explosives. Background radiation does not include radiation from source, byproduct, or Special Nuclear Materials regulated by the U.S. Nuclear Regulatory Commission. The average individual exposure from background radiation is about 360 millirem per year.

becquerel (Bq)
International System unit of radioactivity equal to 1 disintegration per second; 1 curie equals 37 billion (3.7×10^{10}) becquerels.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron. Most of the direct fission products are (negative) beta emitters. Exposure to large amounts of beta radiation from external sources can cause skin burns (erythema), and beta emitters can be harmful inside the body. Thin sheets of metal or plastic can stop beta particles.

bioassay

Determination of kinds, quantities, or concentrations, and in some cases locations of radioactive material in a living body, whether by direct measurement (*in vivo* measurement) or by analysis and evaluation of materials excreted or removed from the body (*in vitro* measurement). Also called *radiobioassay*.

body burden

Amount of radioactive material in an individual's body at a particular point in time.

chronic exposure

Radiation dose to the body delivered in small amounts over a long period (e.g., days or years). For the purposes of input to the Interactive RadioEpidemiological Program, chronic exposure is selected under exposure rate for beta and neutron dose. See *acute exposure*.

curie (Ci)

Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

depleted uranium (DU)

Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium. As examples, spent (used) fuel elements, byproduct tails, residues from uranium isotope separation, and some weapons materials contain DU. DU can be blended with highly enriched uranium to make reactor fuel or used as a raw material to produce plutonium.

dose

In general, the effects of ionizing radiation in terms of the specific amount of energy absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays. Various terms narrow the type of dose, and some are additive:

- Absorbed dose is the amount of energy deposited in a substance by ionizing radiation.
- Collective dose is the sum of the doses to a specific population.
- Committed dose is the dose over time (usually 50 years for workers) to a specific organ or tissue from an intake of radioactive material.
- Cumulative dose is the sum of all doses to the same portion of the body or to the whole body over time.
- Deep dose is the dose at a 1-centimeter depth in tissue (1,000 milligrams per square centimeter).
- Effective dose is the sum of the equivalent doses in the principal tissues and organs of the body, each weighted by a tissue weighting factor that accounts for the probabilities of fatal and nonfatal cancers according to severity and the average length of life lost due to an induced cancer. It indicates the biological effect of the radiation exposure in that tissue.
- Equivalent dose or dose equivalent is the absorbed dose in a tissue or organ multiplied by a weighting factor for the particular type of radiation.

- Organ dose is the dose to a specific organ.
- Penetrating dose is that from higher energy photon (gamma and X-ray) radiation and neutron radiation that penetrates the outer layers of the skin. Nonpenetrating dose is that from beta and lower energy photon radiation.
- Personal dose equivalent is the dose equivalent in soft tissue below a specified point on the body at a specified depth.
- Shallow dose is the dose at a 0.07-millimeter depth in tissue (7 milligrams per square centimeter).
- Skin dose is the dose to the skin.
- Whole-body dose is the dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder.

deep dose equivalent (DDE, $H_{d,}$ $H_p(10)$)
Dose equivalent in units of rem or sievert for a 1-centimeter depth in tissue (1,000 milligrams per square centimeter). See *dose*.

depleted uranium (DU)
Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium. As examples, spent (used) fuel elements, byproduct tails, residues from uranium isotope separation, and some weapons materials contain DU. DU can be blended with highly enriched uranium to make reactor fuel or used as a raw material to produce plutonium.

dose equivalent (*H*, DE)
Product of absorbed dose in units of rem or sievert in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose. See *dose*.

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual. See *film dosimeter*, *neutron film dosimeter*, *and thermoluminescent dosimeter*.

dosimetry
Measurement and calculation of internal and external radiation doses.

dosimetry system
System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

enriched uranium (EU)
Uranium in which processing has increased the proportion of ^{235}U to ^{238}U to above the natural level of 0.7%. Reactor-grade uranium is usually about 3.5% ^{235}U; weapons-grade uranium contains greater than 90% ^{235}U.

exposure

In general, the act of being exposed to ionizing radiation. See *acute exposure* and *chronic exposure*. In this document, exposure does not refer to the radiological physics concept of charge liberated per unit mass of air.

film

Radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*.

film dosimeter

Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called *film badge*.

fission products

(1) Radionuclides produced by fission or by the subsequent radioactive decay of radionuclides. (2) Fragments other than neutrons that result from the splitting of an atomic nucleus.

gamma radiation

Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma rays are very penetrating, but dense materials such as lead or uranium or thick structures can stop them. Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

gray (Gy)

International System unit of absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium; 1 Gy equals 1 joule per kilogram or 100 rads.

ionizing radiation

Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage. Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons, positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons.

intake

Radioactive material taken into the body by inhalation, absorption through the skin, injection, ingestion, or through wounds. Depending on the radionuclide involved, intakes are in units of mass, activity, or potential alpha energy.

internal dose or exposure

Dose received from radioactive material in the body.

internal dose assessment

Estimation of an intake of radioactive material and the consequent internal radiation dose based on measurements in the work environment and/or bioassay.

in vitro

Of or relating to a process that takes place under artificial conditions or outside a living organism (e.g., in the laboratory). From Latin meaning *in glass*.

in vivo

Of or relating to a process that takes place in a living organism. From Latin meaning *in life*.

lung solubility type

See *absorption type*.

minimum detectable activity or amount (MDA)

Lowest amount of radioactive activity or substance amount detectable by a specific instrument or process. Smallest amount or activity of a radionuclide in a sample or organ that yields a result above the detection level with a specific probability of a Type II (false negative) error while accepting an specific probability of a Type I (false positive) error.

minimum detection level (MDL)

Lowest amount (mass or activity) of a substance detectable by a specific instrument or process. Often assumed to be the level at which a dose is detected at the 2-sigma level (i.e., 95% of the time). Also called *minimum detectable limit* and *minimum detection limit* or *level*.

missed dose

Dose to monitored workers that was not measured or recorded due to such factors as a missing or damaged dosimeter or a result below the detection limits of the dosimeter. Missed dose is especially important in the early years of radiation monitoring, when relatively high detection limits were combined with short exchange periods.

monitoring

Periodic or continuous determination of the presence or amount of ionizing radiation or radioactive contamination in air, surface water, ground water, soil, sediment, equipment surfaces, or personnel (for example, bioassay or alpha scans). In relation to personnel, monitoring includes internal and external dosimetry including interpretation of the measurements.

natural uranium (U, U-nat, NU)

Uranium as found in nature, approximately 99.27% ^{238}U, 0.72% ^{235}U, and 0.0054% ^{234}U by weight. The specific activity of this mixture is 2.6×10^7 becquerels per kilogram (0.7 picocuries per gram). See *uranium*.

neutron

Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen.

neutron film dosimeter

Film dosimeter with a nuclear track emulsion, type A, film packet.

nuclear track emulsion, Type A (NTA)

Film sensitive to fast neutrons made by Eastman Kodak. The developed image has tracks caused by neutrons that visible under oil immersion with about 1,000-power magnification.

occupational dose

Internal and external ionizing radiation dose from exposure during employment. Occupational dose does not include that from background radiation or medical diagnostics, research, or treatment.

occupational exposure

Exposure to radiation and/or to radioactive material from sources of radiation, whether in the possession of the DOE site contractor or other person, in a restricted area or in the course of employment in which the individual's assigned duties. Occupational exposure does not include exposure to background radiation, as a patient from medical practices, from voluntary participation in medical research programs, or as a member of the public.

occupational medical exposure

Exposure to radiation or radioactive materials from medical diagnostic procedures during physical examinations that are required as a condition of employment. For dose reconstruction, occupational medical exposure is a component of occupational exposure.

personal dose equivalent [$H_p(d)$]

Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square centimeter), respectively, for the skin (shallow) and whole-body (deep) doses. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively. The International Commission on Radiological Measurement and Units recommended $H_p(d)$ in 1993 as dose quantity for radiological protection.

photon

Basic unit of electromagnetic radiation. Photons are massless “packages” of light energy that range from low-energy microwave photons to high-energy gamma rays. Photons have energies between 10 and 100 kiloelectron-volts. See *photon radiation*.

photon radiation

Electromagnetic radiation of light energy (photons) from microwaves to gamma rays. Gamma rays and X-rays are examples of ionizing photon radiation, which have enough energy to penetrate matter, including the body, and deposit energy in that matter.

probability of causation (POC)

For dose reconstruction under the Energy Employees Occupational Illness Compensation Act, the percent likelihood that a worker incurred a particular cancer from occupational exposure to radiation.

rad

Traditional unit for expressing absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium. A dose of 1 rad is equivalent to the absorption of 100 ergs per gram (0.01 joule per kilogram) of absorbing tissue. The rad has been replaced by the gray in the International System of Units (100 rads = 1 gray). The word derives from radiation absorbed dose.

radiation

Subatomic particles and electromagnetic rays (photons) that travel from one point to another, some of which can pass through or partly through solid materials including the human body. See *ionizing radiation*.

radioactivity

Disintegration of certain elements (e.g., radium, actinium, uranium, and thorium) accompanied by the emission of alpha, beta, gamma, and/or neutron radiation from unstable nuclei.

radiograph

Photographic image produced on film by gamma rays or X-rays. Some of the rays (photons) can pass through parts of an item, while more opaque parts partially or completely absorb them and thus cast a shadow on the film.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The average American receives 360 millirem a year from background radiation. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

roentgen (R)

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulomb per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0°C and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

routine monitoring

Monitoring carried out at regular intervals during normal operations. See *special monitoring*.

shallow absorbed dose (D_s)

Absorbed dose at a depth of 0.07 centimeters (7 milligrams per square centimeter) in a material of specified geometry and composition.

shallow dose equivalent [SDE, H_s, $H_p(0.07)$]

Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

sievert (Sv)

International System unit for dose equivalent, which indicates the biological damage caused by radiation. The unit is the radiation value in gray (equal to 1 joule per kilogram) multiplied by a weighting factor for the type of radiation and a weighting factor for the tissue; 1 Sv equals 100 rem.

special monitoring

Monitoring in addition to the routine monitoring program carried out for special purposes such as estimating the amount of radionuclide deposited in a person after a known or suspected accidental intake or after a known or suspected environmental release. See *routine monitoring*.

spot sample
In relation to bioassay, usually a single void of urine.

thermoluminescent dosimeter (TLD)
Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated by radiation, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose.

transuranic (TRU) elements
Elements with atomic numbers above 92 (uranium). Examples include plutonium and americium. All isotopes of the transuranic elements are radioactive, they are naturally either rare or nonexistent on Earth, and most are known only as a result of research using nuclear reactors and particle accelerators because of extremely short half-lives.

unmonitored dose
Potential unrecorded dose that could have resulted because a worker was not monitored. See *missed dose*.

uranium (U)
Heavy, metallic, and radioactive element with atomic number 92. Most natural uranium as found in ores is ^{238}U with trace levels of other isotopes. Uranium-235 (0.7% of natural uranium) is fissile by itself and used in nuclear weapons as well as reactors. Uranium-238 (99.3% of natural uranium) is fissionable by fast neutrons and used in nuclear reactors. Natural uranium contains a minute amount of ^{234}U. See *depleted uranium*, *enriched uranium*, and *natural uranium*.

whole-body (WB) dose
Dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder and commonly defined as the absorbed dose at a tissue depth of 10 millimeters (1,000 milligrams per square centimeter). Also called *penetrating dose*. See *dose*.

X-ray
(1) See *X-ray radiation*. (2) See *radiograph*.

X-ray radiation
Penetrating electromagnetic radiation (photons) of short wavelength (0.001 to 10 nanometers) and energy less than 250 kiloelectron-volts. X-rays usually come from excitation of the electron field around certain nuclei. Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.