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Subject Experts: Paul A. Szalinski, Baynard Turpin, James E. Turner, James East, Elizabeth A. Langille, and Bill R. Thomas

Document Owner

Approval:	Signature on File Paul A. Szalinski, TBD Team Leader	Approval Date:	07/19/2006
Approval:	Signature on File John M. Byrne, Task 3 Manager	Approval Date:	07/19/2006
Concurrence:	Signature on File Edward F. Maher, Task 5 Manager	Concurrence Date:	07/19/2006
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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AMAD	activity median aerodynamic diameter
ANL-E	Argonne National Laboratory-East
Bq	becquerel
Ci	curie
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
HILAC	heavy-ion linear accelerator
hr	hour
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
keV	kiloelectron-volt, 1,000 electron-volts
KPA	kinetic phosphorescence analysis
L	liter
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley 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)
MDA	minimum detectable amount
MDL	minimum detection limit
MeV	megaelectron-volt, 1 million electron-volts
MFP	mixed fission products
min	minute
mR	milliroentgen
mrem	millirem
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health

pCi	picocurie
PHA	pulse height analysis
POC	probability of causation
S	slow (solubility rate)
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
WB	whole-body
WBC	whole-body count
yr	year
µm	micrometer
§	section, 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 code 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).

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. 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 December 1941 when initial work enriching uranium with a cyclotron began.

LBNL is alternately 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. 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. 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.

Table 2-2 lists the quantities of the radionuclides that workers could have encountered by area. 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 used at LBNL.

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

Building(s)	Description	Period	Radionuclides used[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 & 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 & 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 & Fusion Research & 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 Lab		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 & 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 (heavy-ion linear accelerator) 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

Table 2-1 (Continued). Area information and parameters.

Building(s)	Description	Period	Radionuclides used[a]
57 (on campus)	Donner Pavilion		P-32, Sr-82, Sr-85, Sr-90, I-125, I-131, In-111
58 & 58A	Accelerator Research & Development		
60	High Bay laboratory		
62	Materials and Chemical Sciences		U-238
63 & 64	Accelerator & 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 & 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 & 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 & 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 has 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, P33	(b)
1, Room 330	H-3	Tracers
1, Room 361	P-32	(b)
1, Room 364	F-18	1×10^{-6}
	Fe-52	1×10^{-6}
	F2-59	1×10^{-6}
	Ga-68	1×10^{-6}
	As-71	1×10^{-6}
	I-131	1×10^{-6}
	Hg-203	1×10^{-6}
1, Room 366	P-32, P33	(b)
1, Room 373	H-3, C-14, P-32, P33, S-35, I-125	(b)
1, Room 471	P-32	0.005
2, Room 101 & 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

Table 2-2 (Continued). Magnitude of activities by area.

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	5×10^{-6}
	C-14	5×10^{-6}
	P-32	5×10^{-6}
3, Room 214	H-3	30
	C-14	.05
	varied	Isotope storage
3, Room 250	C-14, P-32, P33, S-35	(a)
3, 3rd floor lab	H-3	5×10^{-6}
	C-14	5×10^{-6}
	P-32	5×10^{-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

Table 2-2 (Continued). Magnitude of activities by area.

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)
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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)

Table 2-2 (Continued). Magnitude of activities by area.

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)

Table 2-2 (Continued). Magnitude of activities by area.

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)

Table 2-2 (Continued). Magnitude of activities by area.

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 & 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)

Table 2-2 (Continued). Magnitude of activities by area.

Building	Radionuclides	Activity (Ci)[a]
75D, Room 101B	Act 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, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), mixed fission products (MFP), 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, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFP, Various, Actinide Tracers, Gamma Tracers	(b)
88, Cave 2	Ac-227, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFP, 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	Act 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, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFP, 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, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFP, Various, Actinide Tracers, Gamma Tracers	(b)

Table 2-2 (Continued). Magnitude of activities by area.

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, Act Products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFP, Various, Actinide Tracers, Gamma Tracers	(b)
88, Entire Vault roof	Act 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.
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 gives the entrance skin exposure (ESE) and organ doses for PA chest radiography at different times at LBNL. For the early times through March 1975, the assigned doses are the default values given by (ORAUT 2005). 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". For the PA view, if one assumes a chest thickness of 26 cm and allows 5 cm for the thickness of the cassette, then the implied source-to-skin distance (SSD) is 183 cm – 31 cm = 152 cm. It follows from the measurement that the skin-entrance exposure 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 1977a, de Castro 1977b, 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, these 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. No policy statements providing records of frequency were found. In the absence of other information, an annual frequency should be assumed.

Under an interagency agreement, the second Picker system was given a thorough inspection by the Food and Drug Administration (FDA) 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 skin-entrance exposure measured in subsequent surveys remained close to 10 mR. Allowing a conservative factor of approximately two, 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 (ORAU 2005a), an uncertainty of ±30% at one sigma is estimated for an individual ESE or organ dose.

Table 3-1. Summary of 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 1970-3/1975 periods are taken from Table 6-5 of (ORAU 2005a).
b. The default values (ORAUT 2005) 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 as a result of 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. Unmonitored workers could have been exposed to occupational doses internally from onsite releases to the air.

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 large specially built 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. 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 the mid-1950s and continues today.

Tritium was used in large quantities in the National Tritium Labeling Facility, which began operation in the early 1980s. Releases and doses to the personnel and public were well documented over the course of operations and 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.

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 reported 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 ALARA policy, the reported doses fell dramatically. The annual average measurements, as opposed to the maximum values, were at 50% of max or less. In order to generate the likely value and uncertainty, it would be reasonable to use 75% of the maximum value, and 25% of the maximum as the uncertainty as an estimate of unmonitored dose. Table 4-2 lists the maximum site-wide annual median intakes in Becquerel's per year via inhalation. Water supplies are offsite from East Bay Municipal Utility District, 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 Th-232 and gross beta results to Sr-90 for the purposes of dose calculation; these assumptions should be made here. Thorium as representative of naturally occurring alpha emitters. Strontium as representative of the beta component of fall out. By using these nuclides in the calculations, the resulting doses would not under estimate the actual doses.

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

Alpha -- Reported alpha concentrations appear to be independent of operational effects of the lab 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 intake of 0.43 Bq per year.

Beta -- Principle contributor to the gross beta concentrations is fallout from atmospheric nuclear weapons testing. The later years of missing data were assigned a value of 10 Bq/y for gross beta intake. This represents a modest overestimate of the intake. The early years prior to 1961 were estimated to be reduced at a rate that would bring the intake in 1939 to values close to most recent observations. This would account for the gradual rise in beta due to weapons testing, and the effects (if any) of increased nuclide inventory on site, and increasing power of accelerators.

Tritium – Tritium releases, concentrations, and subsequent intake are related to accelerator and National Tritium Labeling Facility (NTLF) operations. Annual data are available from 1974 through 2003. The value for 2004 (2500 Bq/y) was chosen to conform with the trend in the proceeding years and average ratio to C-14 (see C-14 discussion). The early years, prior to 1974, were trended down back to 1939 to values consistent with recent measurements which are the lowest values observed. The assumption that the site Tritium concentration before operations began, was no better than the lowest observed concentrations. This is consistent with the trend of accelerator development and to the operation of the NTLF.

Carbon-14 – C-14 releases, concentrations, and intakes are related to accelerator operations. The average ratio of C-14 to Tritium in the years both were reported is 0.155. When one data point is missing, this value is used to estimate the missing data in the later years. In years before 1974, a trend identical to the Tritium estimates was employed.

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

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

Year	Dose (mrem/yr)	Reference
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	Kelley (1972)
1972	57	LRL (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	Stephens (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	LBL (1988)
1988	1.9	LBL (1989)
1989	2.6	LBL (1990)
1990	7	LBL (1991)
1991	2	LBL (1992)
1992	2.3	LBL (1993)
1993	2.96	LBL (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	ND	LBNL (2003)
2003	0.2	LBNL (2004)
2004	ND	LBNL (2005b)

a. No values were reported from 1939 to 1958.
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.
c. Energies are 30-250 keV for photons and 0.1-2 MeV for neutrons. Neutron component of dose is typically≥70% of total.

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

	Respiration rate: 2,400 m^3/yr (2000 hrs/yr)			
Year	Gross alpha	Gross beta	Tritium	C-14
1939	*0.43*	*8*	*3000*	*470*
1940	*0.43*	*9*	*3500*	*550*
1941	*0.43*	*11*	*4200*	*650*
1942	*0.43*	*12*	*4900*	*760*
1943	*0.43*	*15*	*5800*	*890*
1944	*0.43*	*17*	*6800*	*1100*
1945	*0.43*	*20*	*8000*	*1200*
1946	*0.43*	*24*	*9400*	*1500*
1947	*0.43*	*28*	*11000*	*1700*
1948	*0.43*	*33*	*13000*	*2000*
1949	*0.43*	*39*	*15000*	*2400*
1950	*0.43*	*46*	*18000*	*2800*
1951	*0.43*	*54*	*21000*	*3300*
1952	*0.43*	*63*	*25000*	*3900*
1953	*0.43*	*75*	*29000*	*4500*
1954	*0.43*	*88*	*34000*	*5300*
1955	*0.43*	*100*	*40000*	*6300*
1956	*0.43*	*120*	*48000*	*7400*
1957	*0.43*	*140*	*56000*	*8700*
1958	*0.43*	*170*	*66000*	*10000*
1959	*0.43*	*200*	*78000*	*12000*
1960	*0.43*	*230*	*91000*	*14000*
1961	0.3432	273.6	*110000*	*17000*

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

	Respiration rate: 2,400 m^3/yr (2000 hrs/yr)			
Year	Gross alpha	Gross beta	Tritium	C-14
1962	0.0888	511.2	*130000*	*20000*
1963	0.0888	849.6	*150000*	*23000*
1964	0.0888	198.96	*170000*	*27000*
1965	0.0888	35.52	*210000*	*32000*
1966	0.0888	12.432	*240000*	*38000*
1967	0.0888	29.28	*280000*	*44000*
1968	0.0888	28.32	*330000*	*52000*
1969	0.0888	17.76	*390000*	*61000*
1970	0.444	44.4	*460000*	*72000*
1971	0.444	23.088	*550000*	*85000*
1972	0.0888	7.104	*640000*	*100000*
1973	0.07104	1.8648	*750000*	*120000*
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
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 (AEC).
c. Estimated values in italics
d. Data from environmental reports listed in Table 4.1 for the appropriate year.

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 their monitor staff. 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.

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 from 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 monitoring of employees was initiated in 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.

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.

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 Argonne National Laboratory-East (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 Lawrence Livermore National Laboratory (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	Semi-annual
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 Semi-weekly
Feces	Special	1962	Special
Blood	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		1983	(b)
Urine spot, C-14		1993	(b)
Urine, 24-hr	Routine[i]	1995–present	(b)
Feces	Special[i]	1995–present	(b)
Urine, spot		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 radionuclide(s) 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 (RU) samples more frequently than annually but it may have been at the discretion of the laboratory staff based on type of work rather than as scheduled frequency.
e. Soule (1962).
f. Selected individuals performing Sr-90 work were followed at weekly or semi-weekly 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 may be increased for employees that 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, high surface swipe activity, and skin cuts or punctures while working with radioactive material.

h. Pickler (1975).

i. Routine measurements are only required when the relative hazard of an operation shows a likelihood of incurring an intake resulting 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 requiring bioassay 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 discussions with LBNL employee James Floyd 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.

From 1960 to 1996 both *in vitro* and *in vivo* monitoring records and associated interpretations exist and are available in the Excel 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 located at the Donner laboratory. It was designed, built, and operated by Dr. Thornton Sargent, III, who modeled it after the counter at ANL-E. The WBC was located 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 shows 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." A specific reporting level was not observed in the records and they appear to have reported only measurements above the detection limit. Table 5-6 shows the method codes used to identify analysis methods for bioassay samples. These codes were obtained from a computer listing of the analysis results.

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 employeeJim Floyd indicated that after 1996 WBC were no longer performed at LBNL and they relied on LLNL. 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).

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 isn't much variation. Count times were typically 15 minutes but individual counts may have been increased to obtain lower detection limits. 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 to 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. The historical database showed approximately 10,000 samples were collected between 1960 and 1997. It is noted that some of the original records calculate the activity concentration but where the result is below the detection level it is noted "neg." The electronic database appears to include only those results that are above the detection level; sample results below the detection level are entered as 0. It may be useful for personnel performing dose reconstruction to review a copy of the electronic records which is contained in an Excel spreadsheet and can be accessed using SRDB Ref. ID 23481. This electronic record is noted to contain a table of samples with sequential assay numbers from 1 to 9999. Unfortunately the table of results does not have results for each assay number. The data gaps have been identified to LBNL personnel.

Table 5-7 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 particulate radionuclides should be assumed to be 5-µm AMAD in accordance with the ICRP recommendations for occupational exposure.

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.[e] Method uses 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.[b,c] 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 [g] Method descriptions note that uranium, radium, and polonium are not detected by this method [SRDB Ref ID 21251] (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-60, 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 pulse-height analyzer (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.[e] Method uses 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	Los Alamos 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 LRL(1962) [SRDB Ref ID: 21251] notes that protactinium is not detected by this method. (Method Code 50)[b,c]	5.1 dpm/24 hr urine (1968) 2 dpm/24 hr urine (1969)
Am-241, Pu-239	1962		Column chromatography, electroprecipitation, and pulse height analysis (PHA)[d] 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 the 1995 TBD 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 Livermore 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

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[h]
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	Amonium phosphomolybdate precipitation (Method code 71)	20 pCi/L
	1995 – present	U or F	Not specified	1.5 pCi
Protactinium	1960		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	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 TBD but assumed (Note q)
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 et al. 1960) (Method Code 51)	Not specified
Thorium	1995 - 2005	U	Method not specified	Not listed in TBD assume 0.1 pCi/L (note q)
	2005 – present	U or F	Method not specified	0.02 pCi/sample
Uranium	1961–1988	U	Los Alamos 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 TBD use previous MDA 0.15 dpm/ 24 hr urine
	1995 - 2005	F	Method not specified	Not listed use 1 pCi/sample (note q)
	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. Low-Beer (1962) and McClelland (1958).
c. Howe (1961b).
d. Low-Beer (1963).
e. LRL (1958b).
f. Patterson, Low-Beer, and Sargent (1969). Although this 1969 reference specifies a 10 nCi detection limit for gamma emitters, numerous bioassay records on 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. LRL (1962) Bioassay Process – Circa 1962 [SRDB Ref ID 21251]
h. LBNL (1995b)

Additional Table notes:

1. The detection limits noted in results for "Bioassays beginning with A" (LRL 1965–1990). Periods identified are sometimes based on the record of available results (the historical database of records).
2. Also used in Table 5-4: Internal Dosimetry Evaluations (LBL 1980–1993).
3. Method Code refers to the code in the historical database of bioassays.
4. Where the period has a starting date of 1995 thee information was obtained from the Technical Basis Document for Internal Dosimetry, LBNL (1995b)
5. The majority of the bioassay records in NOCTS were observed to be gross alpha, gross beta, and gamma spec with the detection limits noted with the results.
6. Periods of time generally cover the period from when the first analysis was observed in the records to the year that a new method was noted; methods may have been used before or after the specified times. The time periods were obtained from bioassay records in the data capture files as well as bioassay records in the NOCTS claim files.
7. The bioassay records within the files in NOCTS are noted to usually show the method used and the detection limit.
8. In some cases a radionuclide was noted in the LBNL internal dosimetry TBD but the method and MDA were not specified
9. The year beside the MDA indicates the year that this MDA was first noted in the analysis records.
10. 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.
11. Methods other than the ones listed may have been used. The assumption is made that other methods would have resulted in improved MDAs and those listed in this table are conservative resulting in claimant favorable dose reconstruction.

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

Monitoring method	Radionuclide	Method/description	Period	MDA
In vivo	Gamma-emitting radionuclides 50 keV – 2 MeV (including thyroid counts for I-131, I-123) B-7, N-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 pulse-height analyzer, calibrated at 5keV/PHU, 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 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
In vivo	Gamma-emitting radionuclides <50 keV (e.g., I-125)	WBC when count was performed using smaller (2 inch diameter by ¼ inch 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 (note d)
In vivo	Am-241, Am-243	Lung count for Np-239	1995 – 1996	50 pCi
In vivo	F-18	WBC	1995 - 1996	640 pCi
In vivo	I-125, I-131	Thyroid count	1995 – 1996	
In vivo	P-32	WBC (only one count for P-32 found in NOCTS)	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.

Additional Table notes:

1. Pickler (1975) refers to use of the Helgeson WB counter. This is the only reference found to this counter.
2. The detection limits noted in results for "Bioassays beginning with A" (LRL 1965–1990). Periods identified are sometimes based on the record of available results (the historical database of records).
3. Also used in Table 5-5: Internal Dosimetry Evaluations (LBL 1980–1993) and WBC records in NOCTS claims.
4. Most WBC records reviewed showed only the note "normal activity." In a few cases a detection limit for the radionuclide of concern was listed in the notes section of the WBC record. Quantified activity in WBC was frequently noted to be in the range of 1 – 10 nCi.
5. WBC after 1996 were performed at LLNL, and there have been very few performed since that time. If the detection limits are not noted on the LLNL results, the table above can be used as an estimate for dose reconstruction.
6. 10 nCi can be used as a conservative estimate for the MDA.

Table 5-6. Unit codes and description of units.

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[c]	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.

b. The available computer listing of results only shows measurement units for positive results and only shows radionuclides for some of the positive results.

c. These method codes are seen throughout the bioassay records from 1960-1996.

Table 5-7. 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" Cyclotron (1957) Advanced Light Source (present) **16**: Sherwood Laboratory (1961) Accelerator and Fusion Research (present) **52**: General research (1961) Accelerator and Fusion Research (present) The radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators (Bldg 6) identified in Patterson, Low-Beer, and Sargent (1969)[d]	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

Table 5-7 (Continued). Radionuclides[a,b] and fraction activity[a] by facility.

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 [U, 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 1995 Internal Dose TBD (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)[d]] 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	

Table 5-7 (Continued). Radionuclides[a,b] and fraction activity[a] by facility.

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[c]	
		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

Table 5-7 (Continued). Radionuclides[a,b] and fraction activity[a] by facility.

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) The 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)[d]	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

Table 5-7 (Continued). Radionuclides[a,b] and fraction activity[a] by facility.

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 bio-radiological 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" cyclotron (1961 – present) The 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)[d]	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 appliicable 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 of time is likely 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. Ac-227, Ru-106, and Tb-161 were added to the list of radionuclides listed 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.

d. 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."

e. Radionuclides obtained from (LBNL 2005a).

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 (i.e. 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. For purposes of dose reconstruction, the electroscope results should be used in a qualitative manner because no data was found on the calibration or energy response of these devices; the film or TLD results should be used to estimate the actual exposure. The electroscope results include daily readings in tables captioned "dosimeter," "slow neutron," and "electroscope." The three readings occurred on the same dates and were evidently used to measure exposure at the end of work shifts. There are data in claimant records which shows a comparison of the film dosimeter to electroscope records for the same interval; the data are similar and correlate, but are not identical. This is likely due to a combination of energy dependence, calibration, where worn in relation to each other, geometry, etc.

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

There are no records of monitoring for beta exposure using film.

Table 6-1 lists dosimeter types, periods of use, exchange frequency, 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. Where more than one energy range and percentage combination is provided use the combination which is 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 of X2 provided in Table 6-6 should be used unless claimant records provide sufficient information to use the more specific ICRP 60 correction factor provided in Table 6-3. There is limited information about the use of extremity dosimeters prior to 1982. It appears that xray film were used as finger rings; there is no reference to wrist dosimeters as used at LANL or ORNL. Estimates of missed dose can use dose results for coworkers or the recorded dose before and after the period of missed dose.

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 - 1969[d]	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
		0.050	Biweekly (n=25)	0.625
		0.050	Monthly (n=12)	0.30
1969 - 1985	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	Photon/electron - Panasonic 810AS and 802AS TLD	0.010	Monthly (n=12)	0.06
		0.015	Quarterly (n=4)	0.03
		0.025	Semi-annual (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, Argonne East processed film dosimeters for LBNL. The procedure to process the dosimeter was described by Pardue in a 1944 report (Pardue, et al, 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 had been a gamma dose measured for the same period (ORAU, 2006) (Dolecek, 1981).

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

Buildings	Description	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, Cs137	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.

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 2.0-20	90 10	1.71 0.13
75	**Waste Storage Yard** fission products, enriched uranium, natural uranium and others	Neutron	0.1–2.0 2.0-20	90 10	1.71 0.13
72, 74, 75	**Irradiators** Co-60, Cs137	Neutron	0.1–2.0	100	1.91
51, 71	**Cyclotrons and Accelerators**	Neutron	0.1–2.0 2.0-20	50 50	0.95 0.65

Table 6-4. Recorded dose practices.

Year	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		
1986–present	Skin Photon Neutron	Skin = photon + neutron (P/N) WB = Photon + neutron

Table 6-5. Interpretation of reported data.

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.	Zeroes were generally not reported. Reported zero should be interpreted 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	All employees with significant exposure potential were monitored (more than 95% of employees were monitored before 1958). After 1958, all employees were monitored continuously.
1982–1985	rem	Reported WB doses qualified as either photon or neutron	Zeroes were generally not reported before 1980. Reported zero should be interpreted 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	All employees were monitored continuously.
1985–present	rem	Photon deep, neutron deep, and skin dose reported.	Zeroes were typically reported. Reported zero should be interpreted 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	All employees were monitored continuously.

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.
1986–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 Publication 60 weighting factors (ICRP 1991).

a. Beta and non penetrating dose was not reported prior to 1982. In general, non-penetrating radiation doses should be assigned as <30 keV photons if the employee worked with or around Plutonium, otherwise, > 15 keV electrons should be assigned (ORAU, 2005d). The guidance from ORAU is as follows,

If the nature of the non-penetrating dose is unknown, consider the following guidance:
1. For a likely non-compensable case, it is acceptable to assume the non-penetrating dose is associated with <30 keV photons, as this maximizes POC.
2. For a likely compensable case, it is acceptable to assume the non-penetrating 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 may be required.

b. The dose from low energy photons (<30 kev) were underestimated from 1941 through 1985 as a result of the design of the dosimeter holder (ORAU, 2005). The dose from <30 kev photons should be calculated by the following formula:

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

c. The NTA dosimeter (1941-1969) exhibited a lower energy threshold of approximately 700 kev (ORAU, 2004). The photon dose was measured adequately and all LBNL neutron dose was accompanied by a significant photon dose. For neutron dose received prior to 1969, the dose should be adjusted by using a neutron to photon ratio. The ratio varied by operation and task. For Buildings 6, 26, 70, 70A, 75 and 88, the neutron exposure was determined with a neutron to photon ratio of 0.73±2.10. The geometric mean was 0.73 and the geometric standard deviation was 2.10. The upper 95th percentile was assumed to be 2.47.

Table 6-7. Bias and uncertainty.

Site-specific dosimetry system	Bias magnitude and range		Uncertainty factors	
	Overall bias[a]	Range in bias[b]	Systematic[c]	Random[d]
Photon/electron film (1941–1969) non Pu facility	1.27	1.23-1.60	1.2	1.8
Neutron NTA film (1941–1969) non Pu facility	1.0	0.5–2.0	1.05	2.0
Photon/electron film (1941–1969) Pu facility	1.0	0.25–2.0	1.05	1.3
Neutron NTA film (1941–1969) Pu facility	1.0	0.5–2.0	1.05	2.0
Harshaw photon/electron/neutron TLD (1969–1985)	1.12	1.04–1.2	1.05	1.2
Panasonic photon/electron TLD (1986–present)	1.0	0.8–1.2	1.05	1.2
CR-39 neutron (1986–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 regarding actual distributions of energy levels and geometry.
d. Random uncertainty resulting from variation among workers in energy levels and geometry.

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GLOSSARY

absorbed dose
Energy absorbed per unit mass; units are rad and gray.

activity median aerodynamic diameter (AMAD)
The 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.

acute
Pertaining to intakes received "acutely," i.e., within a short period.

alpha radiation
Radiation consisting of charged particles identical with the isotope helium-4.

background radiation
Radiation received that is not associated with a worker's occupation. This includes cosmic and terrestrial sources.

backscatter
Radiation that is scattered backwards, enhancing skin dose in areas where X-ray beam enters the body.

becquerel (Bq)
The derived International System unit of radioactivity equal to one disintegration per second.

beta radiation
Radiation consisting of electrons emitted spontaneously from the nuclei of certain radioactive elements.

bioassay
Measurement of amount or concentration of radioactive material either in the body or in biological material excreted or removed from the body. Another word for *radiobioassay*.

bioassay procedure
A procedure used to determine the kind, quantity, location, and retention of radionuclides in the body by direct (*in vivo*) measurements or by *in vitro* analysis of material excreted or removed from the body.

body burden
The quantity of radioactive material contained in the individual's body at a particular point in time.

chronic
Pertaining to low-level intakes received on a prolonged basis.

curie
A special unit of activity. One curie exactly equals 3.7×10^{10} nuclear transitions per second.

dose

A general term for absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent.

deep dose equivalent

Dose equivalent at a depth of 1.0 cm in soft tissue.

depleted uranium

The uranium remaining after removing ^{235}U from natural uranium. The remaining isotopic content is typically on the order of 99.8% ^{238}U, 0.2% ^{235}U, and a trace amount (0.001%) of ^{234}U.

dose equivalent (H)

The product of absorbed dose (*D*) in rad (or gray) in tissue, a quality factor (*Q*), and other modifying factors (*N*). Dose equivalent is expressed in units of rem (or sievert) (1 rem = 0.01 sievert).

dosimeter

A device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual. (See *film dosimeter*, *neutron film dosimeter*, *thermoluminescent dosimeter*.)

dose equivalent

Product of absorbed dose and a quality factor or radiation weighting factor. With absorbed dose in rad, unit is rem.

dosimetry

The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external and internal sources of radiation.

dosimetry system

A system used to assess dose equivalent from external radiation to the whole body, skin, or extremities. This includes the fabrication, assignment, and processing of dosimeters as well as interpretation and documentation of the results.

exposure

The general condition of being subjected to ionizing radiation, such as by exposure to ionizing radiation from external sources or to ionizing radiation sources inside the body. In this document, exposure does not refer to the radiological physics concept of charge liberated per unit mass of air.

film

In the context of this document, a packet that contains one or more pieces of film in a light-tight wrapping. The film when developed has an image caused by radiation that can be measured using an optical densitometer. (See *nuclear emulsion*.)

film dosimeter

A small packet of film within a holder that attaches to a wearer.

fission products
Isotopes formed during fission of uranium or plutonium.

gamma rays
Electromagnetic radiation (photons) originating in atomic nuclei and accompanying many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Physically, gamma rays are identical to X-rays of high energy, the only essential difference being that X-rays do not originate in the nucleus.

gray
Unit of absorbed dose, defined as 1 joule per kilogram. It is equal to 100 rad.

intake
The amount of radionuclide taken into the body by inhalation, absorption through intact skin, injection, ingestion, or through wounds. Depending on the radionuclide involved, intakes can be reported in units of mass, activity, or potential alpha energy.

internal dose or exposure
The dose equivalent received from radioactive material taken into the body (i.e., internal sources).

internal dose assessment
An assessment of the intake and associated internal radiation dose to workers based on measurements taken in the work environment or from individual bioassay measurements.

***in vitro* measurement**
Measurements to determine the presence of or to estimate the amount of radioactive material in the excreta or in other biological materials removed from the body.

***in vivo* measurement**
The measurement of radioactive material in the human body utilizing instrumentation that detects radiation emitted from the radioactive material in the body.

lung solubility type (F, M, or S)
A classification scheme for inhaled material according to its rate of clearance from the pulmonary region of the lung.

minimum detectable amount (MDA)
The smallest amount (activity or mass) of an analyte in a sample that will be detected with a probability of nondetection (Type II error) while accepting a probability of erroneously deciding that a positive (non-zero) quantity of analyte is present in an appropriate blank sample (Type I error).

minimum detection level (MDL)
The minimum quantifiable dose equivalent that a given dosimetry system can reliably measure.

missed dose
The potential dose equivalent that might not have been measured due to the limitation of the dosimeter, even though a worker was monitored.

monitoring (personnel)
The measurement of radioactivity in the whole body, in a region of the body, in material eliminated from the body or in the air for reasons related to the estimation of intake of radioactive material. The term *monitoring* includes interpretation of the measurements.

natural uranium
Uranium is a naturally occurring radioactive element consisting of three isotopes: ^{238}U (99.276%), ^{235}U (0.719%), and a trace amount of ^{234}U (0.0057%).

neutron
A basic particle that is electrically neutral and has nearly the same mass as the hydrogen atom.

neutron film dosimeter
A film dosimeter that contains a nuclear track emulsion, type A, film packet.

nuclear track emulsion, Type A (NTA)
A film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using an appropriate imaging capability such as oil immersion and 1,000-power microscope or a projection capability.

occupational dose
An individual's ionizing radiation dose (external and internal) resulting from that individual's work assignment. Occupational dose does not include doses received as a medical patient or doses resulting from background radiation or participation as a subject in medical research programs.

occupational exposure
Individuals' 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 general public.

occupational medical exposure
Individuals' exposure to radiation or radioactive materials from medical diagnostic procedures during physical examinations which are required as a condition of employment. For the purpose of dose reconstruction, occupational medical exposure is considered a component of occupational exposure.

personal dose equivalent, $H_p(d)$
Represents the dose equivalent in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personnel dosimetry are 0.07 millimeter and 10 millimeters for the skin and body, respectively. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively.

photon
A unit or particle of electromagnetic radiation consisting of X- and/or gamma rays.

primary X-rays
X-rays that constitute the useful beam that emerges from an X-ray machine tube.

rad
Unit of absorbed dose, defined as 100 ergs per gram. It is equal to is 0.01 gray.

radiation
Ionizing radiation: alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions. Radiation, as used in this document, does not include nonionizing radiation, such as radio- or microwaves, or visible, infrared, or ultraviolet light.

radioactivity
The spontaneous emission of radiation, generally alpha or beta particles, gamma rays, and neutrons from unstable nuclei.

rem
Unit of dose equivalent.

roentgen (R)
Unit of exposure.

routine monitoring
Monitoring carried out at regular intervals during normal operations.

secondary X-rays
As distinct from primary X-rays, secondary X-rays are those that are scattered from objects or leak from the source assembly.

shallow absorbed dose (D_s)
The absorbed dose at a depth of 0.07 millimeter in a material of specified geometry and composition.

shallow dose equivalent (H_s)
Dose equivalent at a depth of 0.07 millimeter in tissue.

sievert
The special name for the International System unit of dose equivalent. One sievert equals 1 joule per kilogram, which equals 100 rem.

special monitoring
Monitoring carried out in actual or suspected abnormal conditions (i.e., measurements performed to estimate the amount of radionuclide deposited in a person when an intake is known or is suspected to have occurred).

spot sample
A single void of urine.

thermoluminescence
Property of a material that causes it to emit light as a result of being excited by heat.

thermoluminescent dosimeter (TLD)

A device used to measure radiation dose. It consists of a holder containing solid chips of material that when heated will release the stored energy as light. The measurement of this light provides a measurement of absorbed dose.

transuranic elements

Elements with an atomic number greater than uranium (92).

unmonitored dose

The potential unrecorded dose equivalent that could have resulted because an exposed worker was not monitored.

whole-body dose

Commonly defined as the absorbed dose at a tissue depth of 1.0 centimeter (1,000 milligrams per square centimeter); however, this term is also used to refer to the recorded dose.

X-ray

(1) Electromagnetic radiation emitted by fast electrons slowing down in matter or in certain electronic transitions in atoms. (2) A radiograph produced by X-rays.