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Subject Expert(s):	Stephen Spanos, John J. Fix, Elyse M. Thomas, Paul A. Szalinski, Baynard Turpin, James E. Turner, James East, Elizabeth A. Langille, and Bill R. Thomas		
Site Expert(s):	N/A		

Approval:	Signature on File Ralph W. Kenning, Document Owner	Approval Date:	05/06/2010
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	05/06/2010
Concurrence:	Keith A. McCartney Signature on File for Edward F. Maher, Objective 3 Manager	Concurrence Date:	05/06/2010
Concurrence:	Signature on File Kate Kimpan, Project Director	Concurrence Date:	05/06/2010
Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	05/10/2010

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
08/07/2006	00	New site profile for the Lawrence Berkeley National Laboratory. First approved issue. Training required: As determined by the Task Manager. Initiated by Paul A. Szalinski.
04/02/2007	01	Approved Revision 01 initiated to include Task 5 and PID review comments which were omitted from Rev 00. Constitutes a total rewrite of document. Incorporates internal formal review comments and additional NIOSH formal review comments. Attributions and Annotations added. Incorporates internal formal review comments regarding the Attributions and Annotation section only. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Paul A. Szalinski.
05/10/2010	02	Revision initiated to incorporate SEC-00160 into Section 1.2. Updated boilerplate language. Incorporates guidance on the assignment of recycled uranium contaminants for intakes based on uranium bioassay results. Incorporates guidance on the assignment of plutonium mixtures for intakes based on plutonium bioassay results. Incorporates additional tritium guidance on the assignment of internal dose from stable metal tritides, and organically bound tritium. Incorporated information from historical documents captured since the last revision about X-ray equipment and exams before 1975, the addition of the LAT chest projection to the X-ray exam protocol in the 1970s, and the addition of the oblique(s) chest projection(s) to the X-ray exam protocol in the 1980s. Added Table 3-1, “Frequency of occupational chest X-ray screening”. Added all the organs to Table 3-2, the table of organ doses for all time periods, and added the organ doses from the LAT and OBL chest projections. Organ doses after 1975 are based on X-ray equipment measurements at LBNL, and decreased slightly from the previous revision as a result of using site specific entrance air kerma in air measurements. Added Table 3-3, “Skin dose guidance for various chest projections and periods”, and Table 3-4, “Skin dose (rem) from various chest projections, 1942 to present”. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Ralph W. Kenning.

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ACRONYMS AND ABBREVIATIONS

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

MeV	megaelectron-volt, 1 million electron-volts
MFP	mixed fission products
min	minute
mL	milliliter
mm	millimeter
mo	month
MPC	Maximum Permissible Concentration
mR	milliroentgen
mrad	millirad
mrem	millirem
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH-Office of Compensation Analysis and Support Claims Tracking System
NTA	nuclear track emulsion, type A
NTLF	National Tritium Labeling Facility
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
pCi	picocurie
PHA	pulse height analysis
POC	probability of causation
RPO	right posterior oblique
S	slow (solubility rate)
s	second
SRDB Ref ID	Site Research Database Reference Identification Number
SSD	source-to-skin distance
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
WB	whole-body
WBC	whole-body count
wk	week
yr	year
µg	microgram
µm	micrometer
µCi	microcurie
§	section or sections

1.0 INTRODUCTION

Technical basis documents (TBDs) 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, 42 C.F.R. Pt. 82) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work (NIOSH 2007a).

The statute also 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 excludes Naval Nuclear Propulsion Facilities from being covered under the Act, 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 occupational radiation exposures are considered valid for inclusion in a 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 (NIOSH 2007a):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

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

1.1 PURPOSE

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

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

1.2 SPECIAL EXPOSURE COHORT PETITION INFORMATION FOR LBNL

Prior to 1948 for LBNL, external dosimetry data are unavailable to NIOSH. Consequently, NIOSH finds that it is not likely feasible to estimate with sufficient accuracy, or to bound, the total external doses to members of the proposed class prior to 1948. Beginning in 1948, external dosimetry data are available for some workers. Prior to 1962, internal dose monitoring data available to NIOSH are insufficient for purposes of dose reconstruction or for bounding internal doses. Consequently, NIOSH finds that it is not feasible to estimate with sufficient accuracy or to bound, internal doses to members of the proposed class before 1962. By 1962, the internal dosimetry program at LBNL was fully operational and has remained so through the present day. Beginning in 1962, internal dosimetry data are available and sufficient to bound intakes.

For this reason, the following class of LBNL employees has been recommended by NIOSH for inclusion in the Special Exposure Cohort (SEC) (NIOSH 2010).

Class Recommended by NIOSH for addition to the SEC

- All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Lawrence Berkeley National Laboratory in Berkeley, California, from August 13, 1942 through December 31, 1961, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees included in the Special Exposure Cohort (NIOSH 2010).

Dose reconstruction guidance in this document for periods prior to January 1, 1962 is presented to provide a technical basis for partial dose reconstructions for claims not qualifying for inclusion in the SEC class through December 31, 1961. Although NIOSH finds that it is not possible to completely reconstruct radiation doses for the proposed class, NIOSH intends to use any internal and external monitoring data that may become available (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures) for an individual claim. Therefore, dose reconstructions for individuals employed at LBNL during the period from August 13, 1942 through December 31, 1961, but who do not qualify for inclusion in the SEC, may be performed using these data as appropriate.

1.3 SCOPE

NIOSH has recommended a class of LBNL employees for inclusion in the SEC as described in the section above. The NIOSH recommendation limits the scope of potential external and internal dose reconstructions at LBNL to the following.

- External dose from 1948 to the present. Beginning in 1948, external dosimetry data are available for some workers;
- Internal dose from 1962 to the present. Beginning in 1962, internal dosimetry data are available and sufficient to bound intakes;

The internal dose can be extended for employment prior to the years listed above based on a worker's later years bioassay results and work history.

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

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

2.0 SITE DESCRIPTION

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

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

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

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

Building(s)	Description	Period	Radionuclides[b]
1 (on campus)	Donner Laboratory	1931	H-3, C-14, P-32, P-33, Sr-90, I-125, Th-232, U-238
2 (on campus)	Advanced Materials Laboratory and Center for X-ray Optics (formerly the Crocker Laboratory)	1931	N-13, O-15
3	Laboratory of Chemical Biodynamics (Calvin Laboratory)		H-3, C-14, P-32, S-35, P-33
4 and 5	Magnetic Fusion Energy		H-3, C-14, P-32, S-35
6, 9, 10, and 80	Advanced Light Source (formerly the 184-in. cyclotron complex)	1940 to present	Be-7, Co-57, Co-58, Co-60, Ni-63, Fe-55, Fe-59, Mn-54, Na-2,2 Zn-65, Am-241, Am-243, Cm-246, Cm-248, Np-237, Pu-238, Pu-239, Pu-240, U-235, Tc-99, Pu-242, Pu-241, N-13, O-15, Na-24, Ar-41, Ni-57, Th-232
8 (on campus)	Hearst Laboratory		Am-241, U
10	Cell & Molecular Biology Research & Photography	1986	H-3, C-14, P-32, S-35, Cr-51
14	Accelerator and Fusion Research and Earth Sciences		H-3
16	Magnetic Fusion Energy Laboratory		U-234, U-235, U-238
On Campus	Gilman Hall		Cs-137, enriched uranium, U-233, Pu-239, Am-241
19 (on campus)	LeConte Hall		Fe-55, Fe-59, Co-60, Au-198, Au-199, Hg-203, Ga-67, In-112, Ba-127, Cs-127, Ba-131, Cs-131, Cs-137, Sr-90
22 (on campus)	Latimer Hall		C-14
26/76	Medical Services and Bioassay, Radiation and Analytical Measurements Laboratory		I-125, I-129, I-131, U-238, C-11, C-14, Be-7, F-18, P-32, S-35, U-232, Sr-90 Ac-228, Ag-108, Ba-133, Ce-144, Cm-243, Am-241, Am-243, Br-76, Br-77, Cm-244, Bk-249, Cf-249, Cf-250, Cm-245, Cm-246
31 (on campus)	Hesse Court		Depleted U
36 (on campus)	2232 Piedmont		Sr-90, Am-241, Na-24, Cl-36, K-42
38 (on campus)	Lewis Hall		Co-57, Fe-59, Co-60, Sn-119, Gd-153
50B	Physics		Ag-106m, Au-194, Co-56, Co-57, Co-58, Co-60, Mn-52, Mn-54, Na-22, Ni-57, Re-184m, Sc-48, Se-75, Ta-182, V-48, Zn-65m Be-7, Ag-105
51	Contains the Bevatron and Bevalac		Be-7, Co-57, Co-58, Co-60, Fe-55, Fe-59, Mn-54, Na-22, Ni-63, Zn-65, Na-24, Ni-57, Ni-57, Cf-252, U, Am-241, Am-243, Ra-226, Bk-249
52	Magnetic Fusion Energy Laboratory		H-3, C-14, P-32, S-35, Am-241, Cf-250, Cm-243, Cm-248, Np-237, Pu-239, Pu-244, Th-229, Th-230, Th-232, U-232, U-235, U-236, U-238, Pu-242
53	SuperHILAC Development		

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

Building(s)	Description	Period	Radionuclides[b]
88	88-in. Cyclotron		Be-7, C-11, N-13, C-14, O-14, O-15, F-17, F-18, Na-21, Na-22, Na-24, P-32, S-35, Sc-46, Cr-51, Mn-54, Fe-55, Co-56, Co-57, Ni-57, Co-58, Fe-59, Co-60, Cu-60, Zn-62, Zn-63, Ni-63, Zn-65, Ge-71, Se-75, Br-76, Br-77, Kr-76, Kr-77, Kr-79, Y-88, Sr-90, Zr-95, Zr-97, U-238, Sc-93, Ac-227, Am-241, Au-198, Cs-134, Cs-137, Gd-148, Eu-152, Eu-154, Pb-212, Np-237, Np-239, Th-229, Th-232, Pa-233, Pu-238, Pu-239, Sb-124, Pa-231, Cf-249, Cf-252
934	Molecular and Cell Biology		H-3, P-32, S-35, C-14, I-125
977	Life Sciences and Physical Biosciences		H-3, P-32, P-33, S-35, C-14, Cd-109

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

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

Table 2-2. 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)

Building	Radionuclides	Activity (Ci)[a]
1, Room 326	P-32, P-33	(b)
1, Room 330	H-3	Tracers
1, Room 361	P-32	(b)
1, Room 364	F-18	1E-6
	Fe-52	1E-6
	Fe-59	1E-6
	Ga-68	1E-6
	As-71	1E-6
	I-131	1E-6
	Hg-203	1E-6
1, Room 366	P-32, P-33	(b)
1, Room 373	H-3, C-14, P-32, P33, S-35, I-125	(b)
1, Room 471	P-32	0.005
2, Rooms 101 and 101A	Ca-45	Tracers
	Sr-85	Tracers
	Sr-90	Tracers
	Am-241	Tracers
2, Room 102	Na-22	0.005
	Ca-45	0.001
	Sr-85	0.001
	Sr-90	0.002
	Eu-152/Eu-154	0.0015
	Ac-227	0.003
	Am-241	0.00015
2, Room 103	Ca-45	Tracers
2, Room 104	Sr-85	Tracers
2, Room 108	Sr-90	Tracers
2, Room 116	Am-241	Tracers
3, Room 120	C-14	0.01
3, 2nd floor lab	H-3	5E-6
	C-14	5E-6
	P-32	5E-6
3, Room 214	H-3	30
	C-14	0.05
	Varied	Isotope storage
3, Room 250	C-14, P-32, P-33, S-35	(a)
3, 3rd floor lab	H-3	5E-6
	C-14	5E-6
	P-32	5E-6
3, Room 318	H-3	Varied
	C-14	0.03
	P-32	Varied
3, Room 322	Varied	Calibration standards
3, Room 326	C-14	30
4	Cs-137	0.2 (July 1963)[c]
5	Co-60	3,100 (1955)[c]
6	Am-241, Am-243, Cm-248, Eu-152, Eu-154, Np-237, Pu-239, Sr-90, Th-232, U-233, U(natural), U-235, U-238, Pu-241, Pu-242, Tc-99	(b)
8, Room 360	Am-241	0.0066
	U	1 kg, various compounds
10	Cs-137	1,050 (1968)[c]
16, Room 101	U-234, U-235, U-238	(b)
19 (LeConte Hall)	Co-60	0.02

Building	Radionuclides	Activity (Ci)[a]
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)
Gilman Hall	Cs-137, enriched uranium, U-233, Pu-239, Am-241	(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
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)

Building	Radionuclides	Activity (Ci)[a]
55, Room 126	H-3, C-11, C-14, F-18, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
55, Room 128	H-3, C-11, C-14, F-18, Ce-141, Cu-64, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46, Co-55, Co-57, I-123, I-125, I-131, Tc-99m, I-125, Gd-153, Sn-113	(b)
55, Room 134	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, N-13, O-15, O-14, F-17, Ce-141, Cu-64, Nb-95, Ru-103, Sr-85, Tl-201, Sc-46, Cr-51, Gd-153, H-3, Sn-113, Tl-201	(b)
55, Room 136	C-14, F-18, H-3, I-125	(b)
55, Room 139	C-11, C-14, Cr-51, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, Ce-141, Cu-64, N-13, Nb-95, O-15, Ru-103, Sr-85, Tl-201, Sc-46	(b)
55, Room 139A	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, Ce-141, Cu-64, N-13, Nb-95, O-15, Ru-103, Sr-85, Tl-201, Sc-46	(b)
55, Room 151	C-11, C-14, Co-55, Co-57, F-18, H-3, I-123, I-125, I-131, Tc-99m, N-13, O-15, O-14, F-17, Ce-141, Cu-64, Nb-95, Ru-103, Sr-85, Tl-201, Sc-46, Cr-51, Gd-153, H-3, Sn-113, Tl-201	(b)
55, Room 200	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
56, Room 100	C-11, Co-55, Co-57, F-18, N-13, O-15, O-14, F-17	(b)
56, Room 101	C-11, Co-55, Co-57, F-18, N-13, O-15, O-14, F-17	(b)
57, Cowell Hospital, 3rd floor	Y-90	1
57, Cowell Hospital, 4th floor	I-125	0.01
57, Cowell Hospital, 4th floor	I-131	0.001
62, Rooms 114 and 145	U-238	(b)
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)
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)

Building	Radionuclides	Activity (Ci)[a]
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)
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)

Building	Radionuclides	Activity (Ci)[a]
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)
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)

Building	Radionuclides	Activity (Ci)[a]
70A, Room 2229B	Am-241, C-14, Fe-59, Np-237, Pb-210, Pu-238, Th-232, U-233, U-238, U-234/235	(b)
70A, Room 4419	Kr-81, Kr-85	(b)
70A, Room 4429	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4429A	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4429C	Pb-205, Th-229, Th-232, U-233, U-238	(b)
70A, Room 4459	Th-228, Th-230, U(natural), U-234, U-235, U-238, Tc-99	(b)
70A, Room 4463	Th-228, Th-230, U(natural), U-234, U-235, U-238, Tc-99	(b)
71, Cave B	(b)	(b)
71, Cave N	(b)	(b)
72, Room 102	U-238	(b)
72, Room 112A	U-238	(b)
72, Room 128	P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, C-11, Cf-249, Cf-252, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Eu-152, Eu-154, Fe-55, Fe-59, Mn-54, Na-22, Np-237, Np-239, P-32, Pa-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
72, Room 137	P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, C-11, Cf-249, Cf-252, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Eu-152, Eu-154, Fe-55, Fe-59, Mn-54, Na-22, Np-237, Np-239, P-32, Pa-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
72C, Rooms 155, 163, 169, 171, and 173	U-238	(b)
73, Room 109	H-3	(b)
74	Co-60/P-32/Cs-137	1,500 (1962 and 1968)[c]
74, Room 144A	Th-232, U(natural), U-238, Tc-99	(b)
74, Room 2011	Am-241, C-14, Fe-59, Np-237, Pb-210, Pu-238, Th-232, U-233, U-238, U-234/235	(b)
74, Room 238C	H-3, O-32, P35	(b)
74, Rooms 265 and 265A	P-32	(b)
74, Room 285	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
74, Room 312	C-11, C-14, H-3, P-32	(b)
74, Room 330	C-11, C-14, H-3, P-32	(b)
74, Room 330A	C-11, C-14, H-3, P-32	(b)
74, Room 344	C-11, C-14, H-3, P-32	(b)
74, Room 350	C-11, C-14, H-3, P-32	(b)
74D, Room 1	C-11, Ce-141, Cu-64, F-18, I-123, I-125, I-131, N-13, Nb-95, O-15, Ru-103, Sr-85, Tc-99m, Tl-201, Sc-46	(b)
75	Cs-137	30 (March 1967)[c]
75, Room 103, 107 and Storage Locker	H-3	(b)
75, Room 109	H-3, activation products	(b)
75, Room 113	H-3, activation products	(b)
75, Room 127	Alpha, Am-241, beta-gamma, C-11, C-14, F-18, H-3, I-125, I-129, I-131, P-32, S-35, U-232, Sr-90	(b)
75D, Room 101B	Activation Products, Various, Kr-81, Kr-85	(b)

Building	Radionuclides	Activity (Ci)[a]
76, Room 135 and Storage Locker	Am-241, C-11, C-14, F-18, H-3, I-125, I-129, I-131, P-32, S-35, U-232, Sr-90	(b)
84, Room 101	P-32	(b)
84, Room 153	C-14, H-3, P-32	(b)
84, Room 155	H-3, P-32, S-35	(b)
84, Room 157	H-3, P-32, S-35	(b)
84, Room 161	H-3, P-32, S-35	(b)
84, Room 175	H-3, P-32, S-35	(b)
84, Room 201	P-32	(b)
84, Room 220	P-32	(b)
84, Room 263	P-32, C-14, H-3	(b)
85, Room MW1	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW2	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW3	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW4	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW5	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW6	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW7	Alpha, beta-gamma, C-14, H-3	(b)
85, Room MW8	Alpha, beta-gamma, C-14, H-3	(b)
85, Room RW1	Alpha, beta-gamma, C-14, H-3	(b)
85, Room RW2	Alpha, beta-gamma, C-14, H-3	(b)
85, Room Scintillation Vial Room	Alpha, beta-gamma, C-14, H-3	(b)
85, Room Staging Area	Alpha, beta-gamma, C-14, H-3	(b)
88, Room 134	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Room 135	H-3, C-11, N-13, Na-22, Be-7, O-14, Ne-19, Ne-18, Br-76, Br-77, Kr-76, Kr-77, Kr-79, P-32, Na-21, Na-22, P-32, Co-57, Cu-60, Na-22, Ni-57, P-32, Sc-93, Zn-62, Zn-63, Ac-227, Am-241, Au-198, C-11, Cf-249, Cf-252, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Eu-152, Eu-154, Fe-55, Fe-59, Mn-54, Na-22, Np-237, Np-239, P-32, Pa-233, Pu-238, Pu-239, Sb-124, Se-75, Zn-65, Be-7, Sc-46, Pa-231	(b)
88, Cave 0	Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15, Br-76, Br-77, Kr-76, Kr-77, Kr-79, Ne-19, Ne-18	(b)
88, Cave 1	C-11, N-13, Na-22, Be-7, O-14, Ne-19, Ne-18, Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave 2	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave 3	H-3, C-11, C-14, P-32, P-33	(b)
88, Cave 4	H-3, C-11, C-14, P-32, P-33	(b)
88, Cave 4C	Activation products, Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15	(b)
88, Cave 4C roof	Ac-227, activation products, Am-241, Cf-249, Cf-252, Gd-148, Pb-212, Th-228, Th-229, Th-232, U(natural), MFPs, various, actinide tracers, gamma tracers	(b)
88, Cave Roofs	Act Products, Be-7, C-11, C-14, F-17, F-18, N-13, Na-22, O-14, O-15, Ne-19, Ne-18	(b)

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

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

3.0 OCCUPATIONAL MEDICAL DOSE

In the early years before about 1964, workers had their physical exams (including X-rays) in their private physicians' offices (Parker 1963). Little is known about the specific X-ray equipment used to radiograph workers before 1975. The earliest document found dates from 1963, and contains results from surveys made on a Picker machine that was in the first aid area (Stephens 1963, pp. 294-295). The measurements of the radiation output indicate that the exposure at 72 in. (implying use for chest X-rays) was about 4 mR. For the posterior-anterior (PA) chest projection, if one assumes a chest thickness of 26 cm and allows 5 cm for the thickness of the cassette, the implied source-to-skin distance (SSD) is 183 cm – 31 cm = 152 cm [7]. It follows from the measurement that the entrance air kerma in air is $(4\ mR)(183/152)^2 = 6$ mrad. However, because of the sparse information before 1975, the assigned doses during this early period are the default values in ORAUT (2005a). There is a statement from the site that only PA chests were used in these early years (Author unknown 2007), and no evidence of photofluorography at LBNL has been found to date.

Calculated doses for 1975 and later are based on measurements on the LBNL X-ray equipment. A document from this period (de Castro and Thomas 1975) reports results from a survey of the Picker radiographic X-ray unit 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". A survey in 1977 for the same Picker unit (de Castro 1977b) provides the measured half-value layer (HVL) as 2.8 mm Al eq. at 70 kVp. This equates to an HVL of 3.0 mm Al eq. at 86 kVp, the technique used for PA chests, and is used for the determination of organ doses for this machine. For the PA projection, the entrance air kerma in air at the SSD is $(7\ mR)(183/152)^2 = 10$ mrad. These data are consistent with subsequent survey results for this X-ray machine (de Castro 1977a). It appears that lateral (LAT) chest projections were added to the PA projection in the 1970s (author unknown 2007). This same document provides technique factors for several common procedures, and these are assumed to be the PA chest projection and the LAT chest projection [6]. LAT chest doses are based on this reported technique. In the 1980s, oblique chest radiographs were performed on asbestos workers (Author unknown 2007). This X-ray unit was in use until its replacement by a new machine about September 28, 1987 (Bradfield 1987) [8].

The change was made to a Picker model BGX 625R stationary, general-purpose system, manufactured in 1987 (Thomas 1991; Bradfield-Montoya 1994). Under an interagency agreement, this 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 PA chest X-ray of a 23-cm chest

phantom was 11.2 mR with the technique of 300 mA at 84 kVp in the automatic exposure control mode. No significant problems were found by FDA in the operations. While no specific HVL measurement results are provided, the HVL was in compliance with the FDA standards. For the purpose of dose reconstruction, an HVL of 3.0 will be assumed for this period.

In 1991, FDA again inspected the Picker machine. This time the measured exposure at the skin entrance was 33 mR (Thomas 1991). Again, no HVL information is provided by the FDA inspector, but the machine (including the minimum HVL) was in compliance with existing standards. For the purpose of dose reconstruction, an HVL of 3.0 will be assumed for this period. This machine was still in use in 1994 (Bradfield-Montoya 1994), but was retired in 1995 (Grondona 2010). In the 1990s, LBNL began taking X-rays only on workers who were subject to inhalation hazards like asbestos (Author unknown 2007). Doses for 1991 to 1995 are for the Picker machine, and for 1996 to the present are from ORAUT-OTIB-0006 (ORAUT 2005a), since employees have been sent off-site for X-rays since that time (Grondona 2010).

Table 3-1 summarizes the frequency information for chest X-rays at LBNL. Dose reconstructors should use this information and any information in the individual X-ray records in the claim file when assessing the dose from occupational medical X-rays.

Table 3-2 lists the organ doses for PA, LAT, and both right and left anterior oblique (RAO and LAO, respectively) chest projections at different times at LBNL. Organ doses (except for skin) for the oblique chest are the same as those for the LAT chest, and should be included in dose reconstruction for asbestos workers in the 1980s. If only one oblique projection is recorded in the records, dose reconstructors should assign dose from the RAO. If the records do not specify this degree of detail, dose from both the RAO and LAO should be assigned for the asbestos workers. Table 3-3 contains the skin dose guidance for all projections over all periods, and Table 3-4 contains skin doses for all areas of skin.

ORAUT-OTIB-0006 (ORAUT 2005a) lists the major sources of uncertainty in X-ray output intensity and subsequent dose to the worker. The five sources of uncertainty are (1) X-ray beam measurement error (±2%); (2) variation in peak kilovoltage (±9%); (3) variation in X-ray beam current (±5%); (4) variation in exposure time (±25%); and (5) variation in SSD as a result of worker size (±10%). The 10% uncertainty in output intensity as a result of worker size was based on an inverse square correction of output intensity changes resulting from differences of standard chest thickness of ±7.5 cm.

Information on worker thickness is rarely available, even in the medical literature. However, at the Savannah River Site entrance skin dose measurements were made on nine workers of varying chest thicknesses (builds) (Cooley 1967). While Cooley did not report the measured chest thicknesses for these nine workers, the entrance skin doses were reported and reflect the increases in exposure needed to radiograph thicker body parts, in this case chests. Cooley reports the mean of the measured entrance skin doses as 27 mrem. The standard uncertainty of the range of measurements is 5.6, resulting in an uncertainty of 21% from this source.

Substituting this value into the calculation for combined uncertainty described in ORAUT-OTIB-0006 (ORAUT 2005a) rather than the 10% value used in that document, the resultant standard uncertainty is 34% from these five sources. Rounding this up to 35% would seem to provide an adequate and suitably conservative indication of uncertainty.

Table 3-1. Frequency of occupational chest X-ray screening[a].

Period	Frequency	Comment	Chest projections
1942 to 1969	Preemployment	All employees	PA
	Termination	All employees	PA
	Annually	Employees > 45 years old	PA
	Biennially	Employees < 45 years old	PA
1970–1979	Preemployment	All employees	PA and LAT
	Termination	All employees	PA and LAT
	Annually	Employees > 45 years old	PA and LAT
	Biennially	Employees < 45 years old	PA and LAT
1980–1990	Preemployment	All employees	PA and LAT
	Termination	All employees	PA and LAT
	Annually	Employees > 45 years old Asbestos workers	PA and LAT PA ,LAT, and one or both obliques (RAO or LAO)
	Biennially	Employees < 45 years old Asbestos workers	PA and LAT PA ,LAT and one or both obliques (RAO or LAO)
1991 to present	Physician's discretion	All employees subject to inhalation exposure	PA and LAT

a. Author unknown (2007).

Table 3-2. Organ doses (rem) for chest projections for all periods.a,b

Organ	Projection	1942–1969	1970–1974	1975–1987	1988–1990	1991–1995	1996-present[c]
Thyroid	PA	3.48E-02	3.20E-03	4.60E-04	5.06E-04	1.52E-03	3.90E-03
	LAT/oblique	--	2.88E-02	3.19E-03	3.66E-03	1.10E-02	2.13E-02
Eye/brain	PA	6.40E-03	3.20E-03	4.60E-04	5.06E-04	1.52E-03	3.90E-03
	LAT/oblique	--	2.88E-02	3.19E-03	3.66E-03	1.10E-02	2.13E-02
Ovaries	PA	2.50E-02	1.00E-04	1.80E-05	1.98E-05	5.94E-05	2.60E-04
	LAT/oblique	--	1.50E-04	2.16E-05	2.48E-05	7.43E-05	3.25E-04
Urinary/bladder	PA	2.50E-02	1.00E-04	1.80E-05	1.98E-05	5.94E-05	2.60E-04
	LAT/oblique	--	1.50E-04	2.16E-05	2.48E-05	7.43E-05	3.25E-04
Colon/rectum	PA	2.50E-02	1.00E-04	1.80E-05	1.98E-05	5.94E-05	2.60E-04
	LAT/oblique	--	1.50E-04	2.16E-05	2.48E-05	7.43E-05	3.25E-04
Testes	PA	5.00E-03	1.00E-06	1.00E-07	1.10E-07	3.30E-07	5.00E-07
	LAT/oblique	--	2.50E-05	2.40E-06	2.75E-06	8.25E-06	1.30E-05
Lungs (male)	PA	8.38E-02	4.19E-02	4.96E-03	5.46E-03	1.64E-02	3.14E-02
	LAT/oblique	--	4.83E-02	5.66E-03	6.49E-03	1.95E-02	4.07E-02
Lungs (female)	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Thymus	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Esophagus	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Stomach	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Bone surface	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Liver/gall bladder/spleen	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Remainder organs	PA	9.02E-02	4.51E-02	5.35E-03	5.89E-03	1.77E-02	3.37E-02
	LAT/oblique	--	5.50E-02	6.41E-03	7.34E-03	2.20E-02	4.56E-02
Breast	PA	9.80E-03	4.90E-03	6.90E-04	7.59E-04	2.28E-03	5.80E-03
	LAT/oblique	--	6.38E-02	6.89E-03	7.89E-03	2.37E-02	4.46E-02
Uterus[a]	PA	2.50E-02	1.30E-04	2.30E-05	2.53E-05	7.59E-05	2.60E-04
	LAT/oblique	--	1.50E-04	2.16E-05	2.48E-05	7.43E-05	2.73E-04
Bone marrow (male)	PA	1.84E-02	9.20E-03	1.17E-03	1.29E-03	3.86E-03	8.90E-03
	LAT/oblique		9.25E-03	1.15E-03	1.32E-03	3.96E-03	9.88E-03
Bone marrow (female)	PA	1.72E-02	8.60E-03	1.12E-03	1.23E-03	3.70E-03	8.60E-03
	LAT/oblique	--	7.25E-03	9.12E-04	1.05E-03	3.14E-03	7.67E-03
Entrance skin[d]	PA	2.70E-01	1.35E-01	1.40E-02	1.54E-02	4.62E-02	7.00E-02
	LAT/oblique	--	3.38E-01	3.36E-02	3.85E-02	1.16E-01	1.82E-01

a. Doses before 1975 are based on values in ORAUT-OTIB-0006 (2005a).
b. The LAT doses from this table can be used to determine the dose from oblique projections when claim file records show obliques were performed on asbestos workers.
c. Doses from 1996 to present are from ORAUT-OTIB-0006 (ORAUT 2005a), since X-rays are taken off-site for this time period.
d. Entrance skin dose is determined by multiplying the entrance air kerma in air by the backscatter factors of 1.35 and 1.40 for HVL of 2.5 mm Al and 3.0 mm Al, respectively, from NCRP Report 102 (NRCP 1989, Table B-8). Skin doses for all areas of skin are provided in Tables 3-3 and 3-4.

Table 3-3. Skin dose guidance for various chest projections and periods.

Area of skin	PA before 1970	LAT before 1970	PA after 1970	LAT after 1970	RAO after 1970	LAO after 1970
Right front shoulder	EXSD	ENSD	EXSD	ENSD	EXSD	EXSD
Right back shoulder	ENSD	ENSD	ENSD	ENSD	ENSD	ENSD
Left front shoulder	EXSD	EXSD	EXSD	EXSD	EXSD	EXSD
Left back shoulder	ENSD	EXSD	ENSD	EXSD	ENSD	ENSD
Right upper arm to elbow	ENSD	ENSD	10% ENSD	ENSD	10% ENSD	10% ENSD
Left upper arm to elbow	ENSD	EXSD	10% ENSD	EXSD	10% ENSD	10% ENSD
Left hand	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right hand	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left elbow, forearm, wrist	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right elbow, forearm, wrist	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right side of head (including ear and temple)	10% ENSD	Eye/brain	10% ENSD	10% ENSD	10% EXSD	10% ENSD
Left side of head (including ear and temple)	10% ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% EXSD
Front left thigh	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)
Back left thigh	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)
Front right thigh	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)
Back right thigh	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)	RSD (0.52 M)
Left knee and below	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)
Right knee and below	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)	RSD (0.86 M)
Left side of face	Eye/brain	Eye/brain	Eye/brain	10% ENSD	10% ENSD	10% EXSD
Right side of face	Eye/brain	Eye/brain	Eye/brain	10% ENSD	10% EXSD	10% ENSD
Left side of neck	ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% EXSD
Right side of neck	ENSD	Eye/brain	10% ENSD	10% ENSD	10% EXSD	10% ENSD
Back of head	10% ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front of neck	Eye/brain	Eye/brain	Thyroid	10% ENSD	Thyroid	Thyroid
Back of neck	ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front torso: base of neck to end of sternum	EXSD	Lung	EXSD	Lung	EXSD	EXSD
Front torso: end of sternum to lowest rib	EXSD	Lung	EXSD	Lung	EXSD	EXSD
Front torso: lowest rib to iliac crest	EXSD	Lung	10% EXSD	10% Lung	10% EXSD	10% EXSD
Front torso: iliac crest to pubis	10% EXSD	10% Lung	10% EXSD	10% Lung	10% EXSD	10% EXSD
Back torso: base of neck to mid-back	ENSD	Lung	ENSD	Lung	ENSD	ENSD
Back torso: mid-back to lowest rib	ENSD	Lung	ENSD	Lung	ENSD	ENSD
Back torso: lowest rib to iliac crest	ENSD	Lung	10% ENSD	10% Lung	10% ENSD	10% ENSD
Back torso: buttocks (Iliac crest and below)	10% ENSD	10% Lung	10% ENSD	10% Lung	10% ENSD	10% ENSD
Right torso: base of neck to end of	ENSD	ENSD	ENSD	ENSD	EXSD	ENSD

Area of skin	PA before 1970	LAT before 1970	PA after 1970	LAT after 1970	RAO after 1970	LAO after 1970
sternum						
Right torso: end of sternum to lowest rib	ENSD	ENSD	ENSD	ENSD	EXSD	ENSD
Right torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% ENSD	10% EXSD	10% ENSD
Right torso: iliac crest to pubis (right hip)	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% EXSD	10% ENSD
Left torso: base of neck to end of sternum	ENSD	EXSD	ENSD	EXSD	ENSD	EXSD
Left torso: end of sternum to lowest rib	ENSD	EXSD	ENSD	EXSD	ENSD	EXSD
Left torso: lowest rib to iliac crest	ENSD	EXSD	10% ENSD	10% EXSD	10% ENSD	10% EXSD
Left torso: iliac crest to pubis (left hip)	10% ENSD	10% EXSD	10% ENSD	10% EXSD	10% ENSD	10% EXSD

Table 3-4. Skin dose (rem) from various chest projections, 1942 to present.[a]

Area of skin	PA 1942–1969	PA 1970–1974	LAT 1970–1974	PA 1975–1987	LAT 1975–1987	RAO[b] 1975–1987	LAO[b] 1975–1987	PA 1988–1990	LAT 1988–1990	RAO[b] 1988–1990	LAO[b] 1988–1990	PA 1991–1995	LAT 1991–1995	RAO[b] 1991–1995	LAO[b] 1991–1995
Right front shoulder	5.9E-03	2.9E-03	3.38E-01	4.E-04	3.36E-02	2.E-04	2.E-04	4.E-04	3.85E-02	2.E-04	2.E-04	1.2E-03	1.16E-01	6.E-04	6.E-04
Right back shoulder	2.70E-01	1.35E-01	3.38E-01	1.40E-02	3.36E-02	3.36E-02	3.36E-02	1.54E-02	3.85E-02	3.85E-02	3.85E-02	4.62E-02	1.16E-01	1.16E-01	1.16E-01
Left front shoulder	5.9E-03	2.9E-03	1.5E-03	4.E-04	2.E-04	2.E-04	2.E-04	4.E-04	2.E-04	2.E-04	2.E-04	1.2E-03	6.E-04	6.E-04	6.E-04
Left back shoulder	2.70E-01	1.35E-01	1.5E-03	1.40E-02	2.E-04	3.36E-02	3.36E-02	1.54E-02	2.E-04	3.85E-02	3.85E-02	4.62E-02	6.E-04	1.16E-01	1.16E-01
Right upper arm to elbow	2.70E-01	1.35E-02	3.38E-01	1.40E-03	3.36E-02	3.4E-03	3.4E-03	1.5E-03	3.85E-02	3.9E-03	3.9E-03	4.6E-03	1.16E-01	1.16E-02	1.16E-02
Left upper arm to elbow	2.70E-01	1.35E-02	1.5E-03	1.40E-03	2.E-04	3.4E-03	3.4E-03	1.5E-03	2.E-04	3.9E-03	3.9E-03	4.6E-03	6.E-04	1.16E-02	1.16E-02
Left hand	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Right hand	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Left elbow, forearm, wrist	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Right elbow, forearm, wrist	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Right side of head including ear and temple	2.70E-02	1.35E-02	3.38E-02	1.40E-03	3.4E-03	2.E-05	3.4E-03	1.5E-03	3.9E-03	2.E-05	3.9E-03	4.6E-03	1.16E-02	6.E-05	1.16E-02
Left side of head including ear and temple	2.70E-02	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	2.E-05	1.5E-03	3.9E-03	3.9E-03	2.E-05	4.6E-03	1.16E-02	1.16E-02	6.E-05
Front left thigh	8.E-05	4.E-05	5.E-05	5.E-06	6.E-06	6.E-06	6.E-06	5.E-06	7.E-06	7.E-06	7.E-06	2.E-05	2.E-05	2.E-05	2.E-05
Back left thigh	8.E-05	4.E-05	5.E-05	5.E-06	6.E-06	6.E-06	6.E-06	5.E-06	7.E-06	7.E-06	7.E-06	2.E-05	2.E-05	2.E-05	2.E-05
Front right thigh	8.E-05	4.E-05	5.E-05	5.E-06	6.E-06	6.E-06	6.E-06	5.E-06	7.E-06	7.E-06	7.E-06	2.E-05	2.E-05	2.E-05	2.E-05
Back right thigh	8.E-05	4.E-05	5.E-05	5.E-06	6.E-06	6.E-06	6.E-06	5.E-06	7.E-06	7.E-06	7.E-06	2.E-05	2.E-05	2.E-05	2.E-05
Left knee and below	3.E-05	1.E-05	2.E-05	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	5.E-06	7.E-06	7.E-06	7.E-06
Right knee and below	3.E-05	1.E-05	2.E-05	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	2.E-06	5.E-06	7.E-06	7.E-06	7.E-06
Left side of face	6.4E-03	3.2E-03	3.38E-02	5.E-04	3.4E-03	3.4E-03	2.E-05	5.E-04	3.9E-03	3.9E-03	2.E-05	1.5E-03	1.16E-02	1.16E-02	6.E-05
Right side of face	6.4E-03	3.2E-03	3.38E-02	5.E-04	3.4E-03	2.E-05	3.4E-03	5.E-04	3.9E-03	2.E-05	3.9E-03	1.5E-03	1.16E-02	6.E-05	1.16E-02

Area of skin	PA 1942–1969	PA 1970–1974	LAT 1970–1974	PA 1975–1987	LAT 1975–1987	RAO[b] 1975–1987	LAO[b] 1975–1987	PA 1988–1990	LAT 1988–1990	RAO[b] 1988–1990	LAO[b] 1988–1990	PA 1991–1995	LAT 1991–1995	RAO[b] 1991–1995	LAO[b] 1991–1995
Left side of neck	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	2.E-05	1.5E-03	3.9E-03	3.9E-03	2.E-05	4.6E-03	1.16E-02	1.16E-02	6.E-05
Right side of neck	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	2.E-05	3.4E-03	1.5E-03	3.9E-03	2.E-05	3.9E-03	4.6E-03	1.16E-02	6.E-05	1.16E-02
Back of head	2.70E-02	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Front of neck	6.4E-03	3.2E-03	3.38E-02	5.E-04	3.4E-03	3.2E-03	3.2E-03	5.E-04	3.9E-03	3.7E-03	3.7E-03	1.5E-03	1.16E-02	1.10E-02	1.10E-02
Back of neck	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	3.4E-03	3.4E-03	1.5E-03	3.9E-03	3.9E-03	3.9E-03	4.6E-03	1.16E-02	1.16E-02	1.16E-02
Front torso: base of neck to end of sternum	5.9E-03	2.9E-03	5.50E-02	4.E-04	6.4E-03	2.E-04	2.E-04	4.E-04	7.3E-03	2.E-04	2.E-04	1.2E-03	2.20E-02	6.E-04	6.E-04
Front torso: end of sternum to lowest rib	5.9E-03	2.9E-03	5.50E-02	4.E-04	6.4E-03	2.E-04	2.E-04	4.E-04	7.3E-03	2.E-04	2.E-04	1.2E-03	2.20E-02	6.E-04	6.E-04
Front torso: lowest rib to iliac crest	5.9E-03	3.E-04	5.5E-03	4.E-05	6.E-04	2.E-05	2.E-05	4.E-05	7.E-04	2.E-05	2.E-05	1.2E-04	2.2E-03	6.E-05	6.E-05
Front torso: iliac crest to pubis	6.E-04	3.E-04	5.5E-03	4.E-05	6.E-04	2.E-05	2.E-05	4.E-05	7.E-04	2.E-05	2.E-05	1.2E-04	2.2E-03	6.E-05	6.E-05
Back torso: base of neck to mid-back	2.70E-01	1.35E-01	5.50E-02	1.40E-02	6.4E-03	3.36E-02	3.36E-02	1.54E-02	7.3E-03	3.85E-02	3.85E-02	4.62E-02	2.20E-02	1.16E-01	1.16E-01
Back torso: mid-back to lowest rib	2.70E-01	1.35E-01	5.50E-02	1.40E-02	6.4E-03	3.36E-02	3.36E-02	1.54E-02	7.3E-03	3.85E-02	3.85E-02	4.62E-02	2.20E-02	1.16E-01	1.16E-01
Back torso: lowest rib to iliac crest	2.70E-01	1.35E-02	5.5E-03	1.40E-03	6.E-04	3.4E-03	3.4E-03	1.5E-03	7.E-04	3.9E-03	3.9E-03	4.6E-03	2.2E-03	1.16E-02	1.16E-02
Back torso: buttocks (Iliac crest and below)	2.70E-02	1.35E-02	5.5E-03	1.40E-03	6.E-04	3.4E-03	3.4E-03	1.5E-03	7.E-04	3.9E-03	3.9E-03	4.6E-03	2.2E-03	1.16E-02	1.16E-02
Right torso: base of neck to end of sternum	2.70E-01	1.35E-01	3.38E-01	1.40E-02	3.36E-02	2.E-04	3.36E-02	1.54E-02	3.85E-02	2.E-04	3.85E-02	4.62E-02	1.16E-01	6.E-04	1.16E-01
Right torso: end of sternum to lowest rib	2.70E-01	1.35E-01	3.38E-01	1.40E-02	3.36E-02	2.E-04	3.36E-02	1.54E-02	3.85E-02	2.E-04	3.85E-02	4.62E-02	1.16E-01	6.E-04	1.16E-01
Right torso: lowest rib to iliac crest	2.70E-01	1.35E-02	3.38E-02	1.40E-03	3.4E-03	2.E-05	3.4E-03	1.5E-03	3.9E-03	2.E-05	3.9E-03	4.6E-03	1.16E-02	6.E-05	1.16E-02
Right torso: iliac crest to pubis (right hip)	2.70E-02	1.35E-02	3.38E-02	1.40E-03	3.4E-03	2.E-05	3.4E-03	1.5E-03	3.9E-03	2.E-05	3.9E-03	4.6E-03	1.16E-02	6.E-05	1.16E-02

Area of skin	PA 1942–1969	PA 1970–1974	LAT 1970–1974	PA 1975–1987	LAT 1975–1987	RAO[b] 1975–1987	LAO[b] 1975–1987	PA 1988–1990	LAT 1988–1990	RAO[b] 1988–1990	LAO[b] 1988–1990	PA 1991–1995	LAT 1991–1995	RAO[b] 1991–1995	LAO[b] 1991–1995
Left torso: base of neck to end of sternum	2.70E-01	1.35E-01	1.5E-03	1.40E-02	2.E-04	3.36E-02	2.E-04	1.54E-02	2.E-04	3.85E-02	2.E-04	4.62E-02	6.E-04	1.16E-01	6.E-04
Left torso: end of sternum to lowest rib	2.70E-01	1.35E-01	1.5E-03	1.40E-02	2.E-04	3.36E-02	2.E-04	1.54E-02	2.E-04	3.85E-02	2.E-04	4.62E-02	6.E-04	1.16E-01	6.E-04
Left torso: lowest rib to iliac crest	2.70E-01	1.35E-02	1.E-04	1.40E-03	2.E-05	3.4E-03	2.E-05	1.5E-03	2.E-05	3.9E-03	2.E-05	4.6E-03	6.E-05	1.16E-02	6.E-05
Left torso: iliac crest to pubis (Left hip)	2.70E-02	1.35E-02	1.E-04	1.40E-03	2.E-05	3.4E-03	2.E-05	1.5E-03	2.E-05	3.9E-03	2.E-05	4.6E-03	6.E-05	1.16E-02	6.E-05

Table 3-4. Skin dose (rem) from various chest projections, 1942 to present.[a] (cont'd)

Area of skin	PA 1996–present	LAT 1996–present	RAO[b] 1996–present	LAO[b] 1996–present
Right front shoulder	2.4E-03	1.82E-01	1.4E-03	1.4E-03
Right back shoulder	7.00E-02	1.82E-01	1.82E-01	1.82E-01
Left front shoulder	2.4E-03	1.4E-03	1.4E-03	1.4E-03
Left back shoulder	7.00E-02	1.4E-03	1.82E-01	1.82E-01
Right upper arm to elbow	7.0E-03	1.82E-01	1.82E-02	1.82E-02
Left upper arm to elbow	7.0E-03	1.4E-03	1.82E-02	1.82E-02
Left hand	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Right hand	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Left elbow, forearm, wrist	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Right elbow, forearm, wrist	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Right side of head including ear and temple	7.0E-03	1.82E-02	1.E-04	1.82E-02
Left side of head including ear and temple	7.0E-03	1.82E-02	1.82E-02	1.E-04
Front left thigh	3.E-05	4.E-05	4.E-05	4.E-05
Back left thigh	3.E-05	4.E-05	4.E-05	4.E-05
Front right thigh	3.E-05	4.E-05	4.E-05	4.E-05
Back right thigh	3.E-05	4.E-05	4.E-05	4.E-05
Left knee and below	1.E-05	1.E-05	1.E-05	1.E-05
Right knee and below	1.E-05	1.E-05	1.E-05	1.E-05
Left side of face	3.9E-03	1.82E-02	1.82E-02	1.E-04
Right side of face	3.9E-03	1.82E-02	1.E-04	1.82E-02
Left side of neck	7.0E-03	1.82E-02	1.82E-02	1.E-04
Right side of neck	7.0E-03	1.82E-02	1.E-04	1.82E-02
Back of head	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Front of neck	3.9E-03	1.82E-02	2.13E-02	2.13E-02
Back of neck	7.0E-03	1.82E-02	1.82E-02	1.82E-02
Front torso: base of neck to end of sternum	2.4E-03	4.56E-02	1.4E-03	1.4E-03
Front torso: end of sternum to lowest rib	2.4E-03	4.56E-02	1.4E-03	1.4E-03
Front torso: lowest rib to iliac crest	2.E-04	4.6E-03	1.E-04	1.E-04
Front torso: iliac crest to pubis	2.E-04	4.6E-03	1.E-04	1.E-04
Back torso: base of neck to mid-back	7.00E-02	4.56E-02	1.82E-01	1.82E-01
Back torso: mid-back to lowest rib	7.00E-02	4.56E-02	1.82E-01	1.82E-01
Back torso: lowest rib to iliac crest	7.0E-03	4.6E-03	1.82E-02	1.82E-02

Area of skin	PA 1996 –present	LAT 1996– present	RAO[b] 1996– present	LAO[b] 1996– present
Back torso: buttocks (Iliac crest and below)	7.0E-03	4.6E-03	1.82E-02	1.82E-02
Right torso: base of neck to end of sternum	7.00E-02	1.82E-01	1.4E-03	1.82E-01
Right torso: end of sternum to lowest rib	7.00E-02	1.82E-01	1.4E-03	1.82E-01
Right torso: lowest rib to iliac crest	7.0E-03	1.82E-02	1.E-04	1.82E-02
Right torso: iliac crest to pubis (right hip)	7.0E-03	1.82E-02	1.E-04	1.82E-02
Left torso: base of neck to end of sternum	7.00E-02	1.4E-03	1.82E-01	1.4E-03
Left torso: end of sternum to lowest rib	7.00E-02	1.4E-03	1.82E-01	1.4E-03
Left torso: lowest rib to iliac crest	7.0E-03	1.E-04	1.82E-02	1.E-04
Left torso: iliac crest to pubis (Left hip)	7.0E-03	1.E-04	1.82E-02	1.E-04

a. Values less than 1 mrem shown to one significant digit.
If only one oblique chest X-ray is recorded, dose from the right anterior oblique (RAO) should be used, otherwise, dose reconstructors should assign dose from both.

b. Note that dose from the oblique chest(s) should only be included for asbestos workers.

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

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

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

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

LBNL was involved in much of the discovery of the radiological properties of materials, and awareness of the hazards grew with each step in size and power of accelerator. The LBNL hillside site is small. The distance from the accelerators to the maximum exposed member of the public was less than 1,500 m. Documentation of the site boundary impact began in 1959 and continues today (Stephens 1974).

Tritium was used in large quantities in the National Tritium Labeling Facility (NTLF), which began operation in the early 1980s. The NTLF ceased labeling operations in December 2001. The first phase of closure activities for the NTLF was completed in April 2002, and the second phase was completed in October 2002. Releases and doses to the personnel and public were well documented over the course of operations, and those practices continue today after shutdown. By the end of 2002, emissions from the former NTLF were due primarily to low-level contamination in the building exhaust components that had yet not been removed. Potable water has always been supplied from off the site by the local utility.

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

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

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

Table 4-1 lists the maximum external gamma and neutron radiation measurements in millirem per year. There is not sufficient data available to provide measured uncertainty. The values listed in the table are those documented in the annual LBNL environmental reports. Early interest was the

maximum possible dose from surveys (usually during accelerator runs) and analysis. In later years with better monitoring, improved shielding, and the development of as-low-as-reasonably-achievable (ALARA) policy, the reported doses fell dramatically [12]. The annual average measurements, as opposed to the maximum values, were at 50% of maximum or less [13]. It is reasonable to use 75% of the maximum as the likely value, and 25% of the maximum as the likely uncertainty as an estimate of unmonitored dose [14]. The on-site ambient external radiation doses should be assigned as a normal distribution with a standard deviation of 30 percent.

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

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

As the number and power of accelerators grew on the site, exposures to unmonitored workers and the environment grew (Goldhaber 1981). Many of the earlier reports would not meet the expectations of today and often included values based on crude measurements and calculations with only enough precision to demonstrate that limits were not exceeded. The use of the first reported doses beginning in 1959 probably produces projected doses much greater than actual doses. These reported values form a basis for the dose estimates for the preceding years as described in the next three paragraphs [17].

An assumption of linear growth from 1942 to 1959 would indicate under-reported doses in the late 1950s, which would be expected to be closer to the doses in the 1960s [18]. An assumption of the average dose reported from 1959 to 2004 would overestimate the doses in the 1940s [19]. This

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

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

Year	Dose (mrem/yr)	Reference
1969	291	Kelly (1970)
1970	173	LRL (1971)
1971	283	Kelly (1972)
1972	57	Cantelow (1973)
1973	28	Thomas (1974)

Year	Dose (mrem/yr)	Reference
2001	0.65	LBNL (2002)
2002	3.2	LBNL (2003)
2003	0.2	LBNL (2004)
2004	0.28	LBNL (2005a)

a. No values were reported from 1942 to 1958; the values provided are projections.
b. Highest of perimeter or onsite data was used. In general, due to the terrain of the facility, the perimeter readings are higher than the local onsite readings. This is due to the small size of the site, elevation differences, and skyshine with more shielding in the walls than roofs of the accelerator buildings. The dose values reflect a 365-d 24-hr measurement less background [15].
c. Energies are 30 to 250 keV for photons and 0.1 to 2 MeV for neutrons. Neutron component of dose is typically ≥70% of total [16].
d. The on-site ambient external radiation doses for 2004 can be extended out to later years.

analysis estimated the doses based on a compromise using a parabolic curve that begins near background in 1942 and peaks with the reported value in 1959 [20].

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

In Thomas et al. (2000) it was determined that 1959 had the highest annual dose of any year at LBNL. In this report doses were revised based on modern knowledge of both the energy spectrum of accelerator produced neutrons and the appropriate coefficient functions for different irradiation geometries. For the years 1959 through 1975 the revised values were approximately one-half the values shown in Table 4-1. Values were also estimated back through calculation to 1954 when the Bevatron became operational. These estimated values are consistently lower than those shown in Table 4-1. Using the higher values shown in Table 4-1 is favorable to claimants without being excessively conservative, i.e. a factor of about two times. The on-site ambient external radiation doses for 2004 can be extended out to later years.

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

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

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

- Tritium: Tritium releases, concentrations, and subsequent intakes are related to accelerator and NTLF operations. Annual data are available from 1974 to 2003. The value for 2004 (2,500 Bq/yr) was chosen to conform with the trend in previous years and average ratio to ^{14}C (see ^{14}C discussion below) [26]. The years before 1974 were trended downward back to 1942 to values consistent with recent measurements, which are the lowest values observed. The assumption is that the site tritium concentration before operations began was no higher than the lowest observed concentrations. This is consistent with the trend of accelerator development and the operation of the NTLF [27].

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

The doses from maximum site-wide annual median intakes should be assigned as a constant distribution. Due to their close proximity, the LBNL maximum site-wide annual median intakes can also be assigned for the buildings listed as being on the Berkeley campus. The maximum site-wide annual median intakes for 2004 can be extended out to later years.

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

	Respiration rate: 2,400 m^3/yr (2,000 hrs/yr)					Respiration rate: 2,400 m^3/yr (2,000 hrs/yr)			
Year	Gross alpha	Gross beta	Tritium	C-14	Year	Gross alpha	Gross beta	Tritium	C-14
1942	*0.43*	*12*	*4,900*	*760*	1974	0.444	32.856	888,000	17,760
1943	*0.43*	*15*	*5,800*	*890*	1975	0.6216	26.4	213,120	30,240
1944	*0.43*	*17*	*6,800*	*1,100*	1976	0.5328	71.04	328,800	239,760
1945	*0.43*	*20*	*8,000*	*1,200*	1977	0.3552	46.08	710,400	79,920
1946	*0.43*	*24*	*9,400*	*1,500*	1978	0.444	24.96	2,222,400	40,080
1947	*0.43*	*28*	*11,000*	*1,700*	1979	0.6216	20.424	1,687,200	32,856
1948	*0.43*	*33*	*13,000*	*2,000*	1980	0.5328	21.312	62,160	31,080
1949	*0.43*	*39*	*15,000*	*2,400*	1981	0.444	41.76	97,680	17,760
1950	*0.43*	*46*	*18,000*	*2,800*	1982	0.3552	12.432	266,400	26,640
1951	*0.43*	*54*	*21,000*	*3,300*	1983	0.1776	9.768	355,200	26,640
1952	*0.43*	*63*	*25,000*	*3,900*	1984	0.2664	12.432	8,880,000	2,664,000
1953	*0.43*	*75*	*29,000*	*4,500*	1985	0.3552	12.432	3,720,000	97,680
1954	*0.43*	*88*	*34,000*	*5,300*	1986	0.07104	4.44	1,065,600	35,520
1955	*0.43*	*100*	*40,000*	*6,300*	1987	0.444	17.76	444,000	35,520
1956	*0.43*	*120*	*48,000*	*7,400*	1988	0.444	14.208	266,400	17,760
1957	*0.43*	*140*	*56,000*	*8,700*	1989	0.7992	11.544	976,800	26,640
1958	*0.43*	*170*	*66,000*	*10,000*	1990	0.5328	12.432	266,400	35,520
1959	*0.43*	*200*	*78,000*	*12,000*	1991	0.444	1.5984	444,000	17,760
1960	*0.43*	*230*	*91,000*	*14,000*	1992	0.5328	15.096	631,200	17,760
1961	0.3432	273.6	*110,000*	*17,000*	1993	0.444	14.208	427,200	31,200
1962	0.0888	511.2	*130,000*	*20,000*	1994	3.6408	6.216	213,120	142,080
1963	0.0888	849.6	*150,000*	*23,000*	1995	*0.43*	*10*	184,800	8,160
1964	0.0888	198.96	*170,000*	*27,000*	1996	*0.43*	*10*	13,200	*2100*
1965	0.0888	35.52	*210,000*	*32,000*	1997	*0.43*	*10*	26,640	*4100*
1966	0.0888	12.432	*240,000*	*38,000*	1998	*0.43*	*10*	21,384	*3300*
1967	0.0888	29.28	*280,000*	*44,000*	1999	0.552	3.12	2,592	2,592
1968	0.0888	28.32	*330,000*	*52,000*	2000	*0.43*	*10*	12,168	*1900*
1969	0.0888	17.76	*390,000*	*61,000*	2001	*0.43*	*10*	11,208	*1700*
1970	0.444	44.4	*460,000*	*72,000*	2002	*0.43*	*10*	2,952	*500*
1971	0.444	23.088	*550,000*	*85,000*	2003	*0.43*	*10*	528	*100*
1972	0.0888	7.104	*640,000*	*100,000*	2004	0.48	3.6	2500	384
1973	0.07104	1.8648	*750,000*	*120,000*					

a. The site is so small that the environmental samples are representative of the site as a whole.

b. Highest of perimeter or onsite data was used. In general, due to the terrain of the facility, the perimeter readings are higher than the local onsite readings due to the small size of the site, elevation differences, and the height of the stack release points. Since 1964, the maximum reported value for the year was used except for 1986 because of the inordinate contribution from Chernobyl. Earlier years showed significant fluctuation due to fallout; because of its location on the west coast, LBNL routinely transmitted data on fallout to the U.S. Atomic Energy Commission.
c. Estimated values in italics
d. Data from environmental reports listed in Table 4-2 for the appropriate year. The references are included in the References section of this document and are available from the Site Research Database or at www.lbl.gov.
e. The maximum site-wide annual median intakes for 2004 can be extended out to later years.

5.0 OCCUPATIONAL INTERNAL DOSE

The LBNL bioassay records show that the selection of personnel for bioassay and the radionuclides for analysis have been based on the work performed by the individual. Selection of employees to be included in the bioassay program was typically made by the Laboratory's Safety Services Department through its staff of monitors. The monitors were directly aware of the radionuclides used throughout the Laboratory and were therefore best qualified to select employees at risk for potential internal exposure. In the absence of specific information in the claim records, unmonitored workers who did not work with uncontained radioactive materials should be assigned environmental data. Job categories for which it is more likely that justification exists for assigning environmental internal doses because of the absence of a likelihood of exposure to airborne radionuclides from sources in the workplace can be found in ORAUT-OTIB-0014, Assignment of Environmental Internal Doses for Employees Not Exposed to Airborne Radionuclides in the Workplace (ORAUT 2004a). For the SEC period, environmental intakes should be assigned if the worker was not monitored. The environmental internal dose assigned during the SEC is considered to be a partial dose estimate.

Bioassay measurement results were noted in data captured site records as early as 1946. The earliest bioassay results are *in vitro* measurements. *In vitro* samples were primarily routine urine samples but even the earliest records showed measurement results for feces and sputum. Methods used to analyze the samples varied but relied primarily on standard methods (McClelland 1958) in use at other laboratories such as Los Alamos National Laboratory (LANL). Bioassay monitoring programs were in place beginning in 1947. However, in the early years monitoring was performed on an as-needed basis and was not covered by a formal documented program (LRL undated). From 1952 through 1956 bioassay analyses were performed by Los Alamos Scientific Laboratory for LBNL. In 1956, arrangements were made for LBNL bioassay to be done at the Lawrence Livermore National Laboratory. This arrangement continued until 1959 (LRL undated). LBNL started its own bioassay program in 1960. The extent of the program at the outset is unclear. Routine bioassay monitoring of employees was initiated about 1961 (Howe 1961a). By 1962, the internal dosimetry program at LBNL was fully operational and has remained so through the present day. LBNL began sequentially numbering all of their bioassay results in 1960 and continued this practice through at least 1991. Hard copies of apparently all bioassay results were captured, beginning with sample number 1, which was collected in January 1960. This data has been computerized, and along with any bioassay information provided in the claimant records, is available to the dose reconstructor for dose reconstruction. Beginning in 1996, the bioassay program changed such that personnel were selected for operational bioassay based on the radionuclide authorization program and reviews of work performed. The program currently uses these operational bioassays to evaluate worker exposure or, most often, to verify the absence of internal exposures. This program was started because so few worker groups were expected to exceed the 100 mrem/yr of internal exposure required to put them into a routine monitoring program [29].

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

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

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

a. LRL (undated).
b. Frequency not applicable or not available.
c. Nasal smear alpha and beta counts were documented following numerous spills in Building 70 between 1957 and 1961. The radionuclides involved in the spill were sometimes documented: Pu, Am, Pu-240, Pu-239, Am-241, Cm-244, Ru-106, Ac-227, and Tb-161 (Kaufman 1957; Alloway 1957; LRL 1958a,b,c,d, 1959a,b, 1960, 1961).
d. Howe (1961a) identifies that LBNL should establish a "full-fledged bioassay program." An attachment to the memorandum, "Bioassay Program Features," identified routine scheduling. It is not clear if the quarterly frequency was implemented. Review of an electronic file of historical samples shows a number of employees provided routine urine samples more frequently than annually but it might have been at the discretion of the laboratory staff based on type of work rather than a scheduled frequency.
e. Soule (1962).
f. Selected individuals performing Sr-90 work were followed at weekly or semiweekly intervals from March 1962 through the end of 1962 (Low-Beer 1963). It is not clear that this was the practice throughout the history of the Laboratory.
g. Hartsough (1974) indicates that the frequency for bioassay can be increased for employees who show a consistent history of positive bioassay results. Special monitoring was performed at the request of the employee or Safety Services of Health Physics. Examples of cause for special bioassay included fire involving radioactive materials, rupture of containment devices, air sample results at or above the maximum permissible concentration (MPC), high surface-swipe activity, and skin cuts or punctures while working with radioactive material.
h. Pickler (1975).

i. Routine measurements are required only when the relative hazard of an operation shows a likelihood of incurring an intake that would result in a committed effective dose equivalent greater than 100 mrem. LBNL uses routine monitoring but relies mainly on "supplementary" bioassay programs. Routine programs are implemented when the committed effective dose equivalent is expected to be above 100 mrem. LBNL uses the quantity thresholds published in NUREG-1400 for relatively heavy elements (Hickey et al. 1993), and the quantity thresholds in the U.S. Nuclear Regulatory Commission Regulatory Guide Series for H-3 and radioiodines, to establish the need for routine bioassays. Supplementary bioassays are implemented at thresholds below the 100-mrem guideline. Threshold values used at LBNL are provided in AlMahamid (2005).

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

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

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

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

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

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

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

a. WBCs were performed at LBNL from 1960 to 1996.

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

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 measurement, some simply noted "neg." The original bioassay cards do include values for negative results in many, though not all, instances. Table 5-6 lists the method codes used to identify analysis methods for bioassay samples. These codes were obtained from a computer listing of the analysis results [30].

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

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

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

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

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

Radionuclide	Period	Sample type[a]	Method/description	MDA
Gross alpha	1957–1961	N	Wet ashed (HNO_3 + H_2SO_4) 60-min count time.[b] Method use of 3N HCl is also noted in 1957 records (Alloway 1957).	1 dpm
Gross alpha Isotopes of thorium, plutonium, curium, actinium, and neptunium	1960–1969	U	Livermore method without modification.[c,d] Coprecipitation of the activity with $BiPO_4$. Sometime later the method was changed to lanthanum fluoride coprecipitation and the MDA improved to 0.2 dpm/24-hr urine.[e] Method descriptions note that uranium, radium, and polonium are not detected by this method (Author unknown, no date). (Method Code 10)	0.3 dpm/24-hr urine (0.15 pCi/24-hr urine)
Gamma emitters Gross alpha (assumed to include isotopes of thorium, plutonium, curium, actinium, and neptunium) Gross beta (assumed to include Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products)	1969–present	U or F	Analysis of 24-hr urine sample.[f] Preparation of the sample by alkaline phosphate precipitation to eliminate monovalent cations. The ash from the alkaline phosphate precipitation is suspended in 10 mL of 2N HNO_3. The whole sample is counted by gamma spectroscopy using a 4-in. NaI crystal and a 400-channel PHA (gamma: Method Code 04). One-fifth of the sample is then plated on aluminum for counting gross beta activity in a Nuclear-Chicago gas-flow proportional counter (gross beta: method code 50). The remaining four-fifths of the sample is processed by bismuth phosphate and lanthanum fluoride coprecipitation and counted for gross activity in the Nuclear-Chicago gas-flow proportional counter (gross alpha: Method Code 10).	Gamma 10 nCi Alpha 0.1 pCi Beta 1 pCi
Gross beta	1957–1961	N	Wet ashed (HNO_3 + H_2SO_4) 60-min count time.[b] Method use of 3N HCl is also noted in 1957 records (Alloway 1957).	30 dpm
Gross beta, Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products	1960–1969	U	LANL method without modification. Phosphate precipitation. The method in McClelland (1958) describes that radionuclides include Sr/Y-90, Sr-89, Ba/La-140, Ce/Pr-144, and fission products. Another reference (Author unknown, no date) notes that protactinium is not detected by this method. (Method Code 50)[c,d]	5.1 dpm/24 hr urine (1968) 2 dpm/24 hr urine (1969)
Am-241, Pu-239	1962		Column chromatography, electroprecipitation, and PHA[g] 1962 was the only reference to this method.	Not specified
Am-241, Am-243	1995–present	U	Alpha spectrometry	0.02 pCi
	1995–present	F	Alpha spectrometry	0.02 pCi
Bk-249	1995–present	U	Gross beta or alpha spectrometry	0.02 pCi
C-14	1968–1993	U	Sample is decolorized using activated charcoal and counted on a liquid scintillation counter. (Method Code 02)	5.0 nCi/L (1974)
	1993–present	U	C-14 was listed in LBNL (1995b) but the method was not specified.	2.0 nCi/L (1993)
Cm-243, Cm-244, Cm-246, Cm-248,	2005–present	U or F	Method not specified.	0.02 pCi/sample
Cf-252	1965–1995	U or F	Gross alpha using LLNL method: Coprecipitation of the activity with $BiPO_4$.	0.3 dpm/24-hr urine
Cf-252, Cm-244	1968		Alpha PHA was used to indicate the relative ratio of Cf-252:Cm-244.	Not specified
Cf-249, Cf-252	1995–present	U or F	Method not specified.	0.02 pCi
Fe-55, Fe-59	1995–present		Method not specified.	Not specified
H-3	1968–1982	U	Liquid scintillation counting (Method Code 03)	0.02 µCi/L
	1982–1995	U		0.01 µCi/L
	1995–present	U		4.5 pCi/sample
I-125	1980–1984	U	Gamma spectroscopy (Method Code 05)	0.02 nCi/L
Na-22, Na-24	1995–present		Method not specified.	Not specified
Np-237, NP-239	1995–2005	U	Method not specified.	0.05 pCi of Np-237

Radionuclide	Period	Sample type[a]	Method/description	MDA
	2005–present	U or F	Method not specified.	0.02 pCi/sample
P-32, P-33	1963–1995	U	Ammonium phosphomolybdate precipitation (Method Code 71)	20 pCi/L
	1995–present	U or F	Method not specified.	1.5 pCi
Protactinium	1960		Method not specified (1960 only year noted for protactinium).	Not specified
	2005–present (Pa-231)	U or F	Method not specified.	0.02 pCi/sample
Pu-238, Pu-239	1995–present	U or F	Method not specified.	0.02 pCi
Pu-241	2005–present	U or F	Method not specified.	0.02 pCi/sample
Rare earths (primarily Pm-147)	1961	U	Method not specified (1961 only year noted).	3 dpm/24-hr urine
Ra-226	1995–present	U	Method not specified.	0.1 pCi/L not listed in LBNL 1995b but assumed[h]
Sulfur S-35	1962–1992	U or F	Urine analysis and fecal analysis. (Method Code 52)	0.2 nCi/L (1982)
	1992–present	U	Barium sulfate precipitation	0.1 nCi/L (1992)
Strontium Sr-90, Sr-89	1961–1995		Oak Ridge method of ion exchange chromatography (Sunderman and Townley 1960). (Method Code 51)	Not specified
Thorium	1995–2005	U	Method not specified.	Not listed in LBNL 1995b assume 0.1 pCi/L[h]
	2005–present	U or F	Method not specified.	0.02 pCi/sample
Uranium	1961–1988	U	LANL method of solvent extraction with dibutyl phosphate (McClelland 1958). (Method Code 11)	0.15 dpm/24-hr urine
	1988–1995	U	Anion exchange chromatography	0.15 dpm/24 hr urine
	1995–2005	U	Method not specified.	Not listed in LBNL (1995b); use previous MDA 0.15 dpm/24-hr urine.
	1995–2005	F	Method not specified.	Not listed; use 1 pCi/sample[h]
	2005–present	U or F	Method not specified.	0.02 pCi/sample

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

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

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

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

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

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

Method code	Description of units	Radionuclides reported with results
52	nCi/L	S-35
54	(a)	
55	nCi/L	Ca-45
71	nCi/L	P-32

a. Codes 16, 17, 18, 19, and 54 were observed in a computer listing of assays but there were no results or radionuclides reported with these codes.

Additional table notes:
1. These Method Codes are seen throughout the bioassay records from 1960 to 1996, LRL (1965-1990).

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

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.

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-in. Cyclotron (1957) Advanced Light Source (present) **16**: Sherwood Laboratory (1961) Accelerator and Fusion Research (present) **52**: General research (1961) Accelerator and Fusion Research (present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators (Building 6) identified in Patterson, Low-Beer, and Sargent (1969)[c]	U-238	2.90E-04
		N-13	9.93E-01
		O-15	5.19E-03
		Ar-41	1.38E-03
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Fe-55	
		Fe-59	
		Mn-54	
		Na-22	
		Na-24	
		Ni-57	
		Ni-63	

Current building no.	Building activity and compounds	Radionuclide	Fraction
		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
		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

Current building no.	Building activity and compounds	Radionuclide	Fraction
		Po-210	1.51E-08
		Pu-238	5.46E-04
		Pu-239	1.59E-03
		Pu-241	3.40E-03
		Pu-242	1.66E-08
		Ra-226	2.27E-06
		Ra-228	1.69E-04
		Ru-106	2.27E-11
		S-35	2.42E-02
		Sb-125	8.81E-10
		Sr-89	6.65E-07
		Sr-90	1.38E-04
		Tc-99	1.10E-06
		Th-229	9.08E-08
		Th-230	5.19E-06
		Th-232	1.76E-05
		U-232	3.79E-05
		U-233	3.78E-03
		U-235	4.17E-05
		U-238	5.06E-04
		Zn-65	1.20E-05
29 51	(Nuclides obtained from 1979 worker bioassay lists) Bevatron [Uranium and beta-gamma nuclides obtained from 1982, 1983, 1986 worker bioassay lists; Am-241, Am-243, Bk-249, Cf-252, and Ra-226 obtained from LBNL (1995b); the remainder of the radionuclides were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969).[c]] Building is currently undergoing decontamination and decommissioning.	Alpha	
		U	
		Beta gamma	
		Am-241	
		Am-243	
		Bk-249	
		Cf-252	
		Ra-226	
		Be-7	
		Co-57	
		Co-58	
		Co-60	
		Fe-55	
		Fe-59	
		Mn-54	
		Na-22	
		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

Current building no.	Building activity and compounds	Radionuclide	Fraction
		F-18	1.00E+00
		Alpha	3.71E-09
		Beta	5.92E-08
57	(Nuclides obtained from 1982 worker bioassay lists)	I-125	
		I-131	
		In-111	
		P-32	
		Sr-82	
		Sr-85	
		Sr-90	
62	Materials and Molecular Research (nuclides obtained from 1982, 1983, 1986 worker bioassay lists)	Th-228	
70, 70A	**70/70A**: Nuclear Chemistry (1961) **70**: Environmental energy technology, nuclear science, and earth sciences research (present) **70A**: Nuclear, chemical, and life sciences research (present)	Ac-227[d]	
		Am-241	7.60E-06
		Am-243	1.52E-04
		Bi-207	7.60E-06
		C-14	5.51E-01
		Ca-45	1.20E-05
		Ca-49	2.38E-08
		Ce-141	2.59E-06
		Cf-249	7.60E-07
		Cf-252	7.60E-09
		Cm-244	2.13E-08
		Cm-248	1.08E-07
		Co-60	3.61E-06
		Cs-134	1.46E-06
		Eu-152	1.07E-05
		Fe-59	6.88E-03
		H-3	2.76E-01
		Hf-175	8.58E-06
		Ho-166m	6.08E-06
		I-125	2.25E-04
		Mn-54	1.52E-07
		Na-22	1.52E-06
		Na-24	2.65E-05
		Np-237	1.70E-03
		P-32	4.13E-02
		Pa-233	3.60E-06
		Pu-238	4.35E-05
		Pu-239	6.99E-06
		Ra-226	1.52E-06
		Rb-86	1.93E-04
		Rh-101	7.60E-08
		Ru-106[c]	
		S-35	1.06E-02
		Sb-122	1.90E-07
		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

Current building no.	Building activity and compounds	Radionuclide	Fraction
		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
		F-18	1.20E-08
71	HILAC (1961) Accelerator and fusion research (present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969)[c]	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	
		Ac-227	8.33E-08
72	Health Physics (1961) Low-background facility (present)	Au-198	2.83E-06
		Ba-133	2.99E-09
		Bi-207	3.01E-08
		Br-82	2.48E-07
		Cd-113	6.40E-09
		Co-58	9.23E-01
		Co-60	1.20E-03
		Cr-51	1.51E-06
		Cu-64	4.96E-04
		Eu-152	4.96E-04
		Fe-59	2.95E-02
		Hg-194	4.68E-08
		Mn-54	2.68E-06
		Na-24	9.92E-04
		Nb-95	1.34E-09
		P-32	9.50E-06
		Pa-231	4.94E-08
		Sb-122	2.97E-11
		Sb-124	9.92E-04
		Ta-182	5.28E-08
		Th-228	5.23E-12
		Th-229	2.62E-05
		Th-232	4.96E-08
		Ti-44	1.35E-07
		Xe-133	3.97E-10
		Zn-65	3.47E-11

Current building no.	Building activity and compounds	Radionuclide	Fraction
		Zr-95	4.10E-02
		Zr-97	1.82E-03
		C-14	4.92E-03
74, 83, 84	**74**: Animal bioradiological laboratory (1961) **74, 83, 84**: Life sciences research (present)	H-3	5.05E-01
		P-32	3.46E-02
		S-35	4.56E-01
		H-3	1.00E+00
75	Radioisotope services (1961) Former waste handling facility, operations ceased in 1997 Former National Tritium Labeling Facility operations ceased in 2001	Alpha (Th-232)	1.69E-09
		Beta (Sr-90)	5.72E-09
		C-14	1.44E-01
85	Hazardous waste handling facility (present)	H-3	8.56E-01
		I-125	9.97E-06
		Alpha (Th-232)	1.17E-06
		Beta (Sr-90)	2.79E-06
		U-238	1.40E-10
88	88-in cyclotron (1961 – present) Radionuclides listed without a radionuclide fraction specified were obtained from a list of potential sources produced by accelerators that were identified in Patterson, Low-Beer, and Sargent (1969)[c]	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	
		C-14	
934	Previously Leased Building use of biomedical radionuclides for DNA Labeling (nuclides obtained from 1982, 1983, 1986 worker bioassay lists)	H-3	
		I-125	
		P-32	
		S-35	
		H-3	
Gilman Hall	Research and teaching facilities for faculty and students specializing in physical, inorganic, and nuclear chemistry	Cs-137	
		Enriched uranium	
		U-233	
		Pu-239	
		Am-241	
977		P-32	
		P-33	
		S-35	
		C-14	
		Cd-109	

a. Blank values in this table indicate not applicable or data not available. Unless otherwise noted, this table was derived from data reported for calendar years 2001 to 2004 as part of the National Emission Standards for Hazardous Air Pollutants (DOE 2002, 2003, 2004, 2005). Where stack emissions were not measured, LBNL derived a "receipts releasable" inventory of radionuclides available for release. While the emissions identified during this limited period are probably not fully representative of the source term in each building, they do provide an estimate of the types of radionuclides to which employees might have been exposed. Activity fractions were obtained by dividing the activity total by the total activity for all radionuclides in a specific building/buildings over the 4 yr.
b. Buildings and radionuclides were added based on historical lists (e.g. bioassay lists, LBNL 2005a,b; Patterson, Low-Beer, and Sargent 1969). Radionuclide fractions were not determined for these.
c. Although Patterson, Low-Beer, and Sargent (1969) identified these radionuclides as potential exposure sources, the article concluded that "normal habits of cleanliness and occasionally the use of protective clothing … are adequate to insure that the ordinary accelerator worker at LRL-Berkeley will not receive radiation exposure of any consequence from internal sources."
d. Ac-227, Ru-106, and Tb-161 were added to the list of radionuclides for Building 70 because there were documented spills in Building 70 between 1957 and 1960 where these radionuclides were listed; no attempt to determine a radionuclide fraction has been made.

5.1 PLUTONIUM

If a monitoring result refers to plutonium, dose reconstructors can use the isotopic mix listed in Table 5-8 for material aging times. These values are based on those used for Lawrence Livermore National Laboratory (LLNL) for weapons grade plutonium (Mansfield 2000). These LLNL values are likely representative of any weapons grade plutonium used at LBNL, since there is ongoing collaboration between these two laboratories. For assessing Super S solubility, refer to *Estimating Doses for Plutonium Strongly Retained in the Lung* (ORAUT 2008).

Table 5-8. Isotopic information for aging of weapons-grade plutonium (Mansfield 2000).

Mixture designation	**Fresh**	**5-yr**	**10-yr**	**20-yr**
Years of aging	**0**	**5**	**10**	**20**
Specific activity in mixture (Ci/g)				
Pu-238	6.85E-03	6.59E-03	6.33E-03	5.85E-03
Pu-239	5.81E-02	5.81E-02	5.80E-02	5.80E-02
Pu-240	1.37E-02	1.37E-02	1.37E-02	1.37E-02
Pu-241	5.98E-01	4.70E-01	3.69E-01	2.28E-01
Pu-242	1.57E-06	1.57E-06	1.57E-06	1.57E-06
Am-241	0.00E+00	4.24E-03	7.54E-03	1.21E-02
Pu-239+240	7.18E-02	7.18E-02	7.17E-02	7.17E-02
Pu-alpha	7.87E-02	7.84E-02	7.80E-02	7.76E-02
Activity ratios				
Pu-239+240:Am-241	N/A	1.69E+01	9.51E+00	5.93E+00
Pu-239+240:Pu-238	1.05E+01	1.09E+01	1.13E+01	1.23E+01
Pu alpha:Pu-239+240	1.10E+00	1.09E+00	1.09E+00	1.08E+00
Pu alpha:Pu-238	1.15E+01	1.19E+01	1.23E+01	1.33E+01
Pu-241:Pu alpha	7.60E+00	6.00E+00	4.73E+00	2.94E+00

5.2 URANIUM

LBNL received its uranium from other DOE sites. Starting in 1952, recycled uranium produced by DOE sites contained transuranic, fission and activation contaminants in trace quantities. If a monitoring result refers to uranium, dose reconstructors can use Table 5-9 which provides the list of recycled uranium ratios to be applied for uranium. These values are from Fernald (ORAUT 2004), and reflect upper bound values based on a review of other DOE sites. The recycled uranium ratios are listed in Table 5-9.

Table 5-9. Recycled uranium contaminant ratios for uranium (ORAUT 2004).

	Default value
Contaminant	**Activity per Activity total U**
Plutonium	0.00921
Np-237	0.00366
Tc-99	0.22599

5.3 TRITIUM

Tritium was encountered in several forms: tritium oxide as water or gas (HTO), elemental tritium or tritiated gas (HT), organically bound tritium (OBT), and metal tritides (MTs). Each form has unique characteristics. Tritium handling at LBNL was performed in the Tritium Labeling Facility (Building 75). Stable MTs were handled in Building 75 (LRL 1979), Building 5, and the accelerators in Buildings 6, 51, 71, and 88. Outside these buildings, in cases where exposure to OBT or MTs are not implied by case-specific information, assume HTO. Tritium gas work was done in processing hoods. Compounds of tritium, namely MTs, were usually worked in gloveboxes. Guidance for estimating doses for OBT and MTs is available in ORAUT-OTIB-0066, Calculation of Dose from Intakes of Special Tritium Compounds (ORAUT 2007a).

Site locations for potential exposure to tritium are in listed in Tables 2-1 and 2-2. Bioassay results for tritium are usually available in the dosimetry records. It was LBNL policy that all persons who work in areas where tritium is used must submit urine samples for bioassay (LRL 1970).

5.3.1 Metal Tritides

Tritium exposures in the form of MT aerosols were primarily titanium tritide targets for the accelerator beams. The personnel who would have had the potential of exposure to the MT targets would be chemists, researchers, health physics technicians, and accelerator operators and mechanical technicians who performed work on the accelerators. Titanium tritides were also handled in Building 5 where electrical leads were spot welded to a small rod containing a coating of titanium tritide. The rod was placed in an assembly in a vacuum system, where the system was later evacuated (Garden 1956).

Solubility type M should be assumed for assigning internal dose from titanium tritides. Based on available information, there is no indication that MT solubility type S was a possibility at LBNL. ORAUT-OTIB-0066 (ORAUT 2007a) provides guidance on the evaluation of MT intakes. MTs are referred to as tritium particulates. In addition to potential exposure in the facilities listed above, the claimant telephone interview can provide indications that a person was exposed to MTs.

5.3.2 Organically Bound Tritium

Tritium exposures in the form of OBT are primarily found in pump oils associated with fume hoods. Exposure to OBT would occur during maintenance if contact with the skin was made. If claimant information indicates the need for assigning tritium dose based on OBT, guidance on the calculation of doses from OBT is given in ORAUT-OTIB-0066 (ORAUT 2007a).

6.0 OCCUPATIONAL EXTERNAL DOSE

This section describes the program for measuring Whole Body (WB) penetrating and skin, and hand extremity doses to workers from sources of radiation external to the body. Workers at LBNL were exposed to radiation from a variety of radioactive materials and radiation-producing machines (Patterson and Thomas, 1973, 1994; Coulson et al 1989; Casey et al 1988).

6.1 DOSE RECONSTRUCTION PARAMETERS

Examinations of the beta, photon (X-ray and gamma ray), and neutron radiation type, energy, and geometry of exposure in the workplace, and the characteristics of the LBNL dosimeter responses are important to the assessment of the original recorded dose in relation to the radiation dose equivalent quantity *Hp(d),* where d = 10 mm or d = 0.07 mm for WB deep and shallow dose, respectively. Dose reconstructors can compare earlier dosimetry systems to current systems to evaluate their performance based on the premise that current systems have more stringent criteria, as indicated in DOELAP dosimeter performance testing.

Accuracy and precision of the recorded individual worker doses depend on (Fix et al. 1997):

- Administrative practices that facilities adopted to calculate and record personnel dose based on technical, administrative, and statutory compliance considerations.
- Dosimetry technology, which includes the physical capabilities of the dosimetry system, such as the response to different types and energies of radiation, in particular in mixed radiation fields.
- Calibration and dosimeter response characteristics of the respective monitoring systems and similarity of the methods of calibration to sources of exposure in the workplace.
- Workplace radiation fields, which can include mixed types of radiation, variations in exposure geometries, and environmental conditions.

An evaluation of the original recorded doses, as available, combined with detailed examinations of workplace radiation fields and dosimeter responses to those fields is the recommended option to provide the best estimate of *Hp(d)* for individual workers.

6.1.1 Historical Administrative Practices

As noted in Attachment A, which contains selected references of historical LBNL radiation associated events, LBNL used radiation detection instruments (Norton 1947; UCRL 1948; 1949; 1951; 1952a,b; 1955a,b; 1956) to routinely evaluate workplace radiation fields and personnel dosimeters to measure and record doses from external radiation to workers throughout the history of its operations (Garden 1950, Patterson and Thomas 1994). Certainly measurements using fixed and portable radiation instrumentation were of primary importance to minimizing exposures. Personnel dosimeter records are generally available for all periods at LBNL for workers who had any potential for occupational radiation exposure. The earliest observed film badge results are for 1946 (UCRL 1946). While some site external dosimetry records are available prior to 1948 from site data capture efforts, they are not complete. External dose records prior to 1948 are unavailable in individual claimant files. The operations and radiation safety staffs routinely reviewed dosimeter results for compliance with radiation control limits and investigated doses that exceeded administrative limits (Patterson 1965, Patterson and Thomas 1994). LBNL used portable radiation instrumentation (Norton 1947) and personnel dosimeters to measure, control and record doses from external radiation to designated

workers throughout the history of its operations. These dosimeters included one or more of the following:

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

Early exposure records include pocket ionization or *electroscope* (or at times, *electrometer* or *E* was used) results. Dose reconstructors should use the electroscope results cautiously to assign exposure because no data were found on the calibration or energy response of these devices; they should use preferentially the film or TLD results to estimate the actual exposure. The electroscope results include daily readings in tables captioned "dosimeter," "slow neutron," and "electroscope." The three readings, which occurred on the same dates, were evidently used to measure exposure at the end of work shifts [42]. There are data in worker records that show a comparison of the film dosimeter to electroscope records for the same interval; the data are similar and correlate, but they are not identical. This is probably due to a combination of differences in energy dependence, calibration techniques, where the dosimeters were worn in relation to each other, exposure geometry, etc.

In the earliest years LBL recorded doses in units of “daily doses," which corresponds to a percentage of 100 mrem (Heinzelman 2003). However, it is understood (Patterson and Thomas, 1994) that all recorded doses were converted to units of roentgen in the early 1950s.

Explicit beta or nonpenetrating doses are generally not included in the earlier years even though there were instrument (Norton 1947) and dosimeter (open window) beta response capabilities. This is presumed to be because the radiation protection staff at the time felt that penetrating radiation was the primary hazard and by controlling this hazard to meet regulatory limits any nonpenetrating component would be adequately controlled (i.e., that the shallow dose could not exceed the deep dose by a high enough amount to come close to the higher regulatory limit). The radiation protection staff (LRL 1958e) was aware of the need to monitor for nonpenetrating radiation and the earliest film dosimeter in use had open window and shielded film capabilities. Inasmuch as the limit for WB (deep) dose was 5 rem/yr and for skin (shallow) dose was 15 rem/yr, it is reasonable to assume that the shallow dose could not exceed the deep dose by more than a factor of 3 [43]. For cases where the shallow dose is important to reconstruction and is not reported, dose reconstructors should apply a factor of 3 to the WB dose to estimate the shallow dose. Table 6-1 summarizes recorded dose practices, and Table 6-2 summarizes the interpretation of the reported data.

Table 6-1. Recorded dose practices [44].

Period	Dosimeter measured quantities	Compliance dose quantities
Photon/electron film dosimeter + NTA neutron dosimeter		
1948–1994	Gamma (G) Neutron (N)	WB = gamma + neutron Skin = shallow + photon + neutron Hand = skin + extremity
Photon/electron/neutron–LuxelOSL + CR-39 neutron dosimeter		
1995–present	Skin Photon Neutron	Skin = shallow + photon + neutron WB = photon + neutron

Table 6-2. Interpretation of reported data [45].

Period	Reported quantity	Description	Interpretation of zeroes	Interpretation of blanks (no data)	Rollup of individual and annual data	Monitored/ unmonitored
1948–1981	rem	Reported WB doses include gamma. Neutron doses were designated with "N." Claimant records indicate that some recorded results are expressed as a fraction of the daily dose limit of 100 mrem.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Total deep WB dose	From review of LBNL documents, it is not clear if all employees were continuously monitored. However, the monitoring records appear to be complete. It can be assumed if no monitoring records are included in an employee's file that the individual was not monitored.
1982–1985	rem	Reported WB doses qualified as either photon or neutron.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	
1986–present	rem	Photon deep, neutron deep, and skin dose reported.	Interpret reported zero as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	

6.1.2 LBNL Personnel Dosimetry Technology

LBNL developed beta/photon and neutron personnel dosimetry technologies in the 1940s.

6.1.2.1 Beta/Photon Radiation Personnel Dosimeters

LBNL based its beta/photon film dosimetry methods on the dosimeter design developed at the Metallurgical Laboratory by Pardue, Goldstein, and Wollan (1944) beginning in 1946 (Patterson and Thomas, 1994). Essentially LBNL implemented the identical film dosimetry system used at ORNL and Hanford. Table 6-3 lists beta/photon dosimeter types, periods of use, exchange frequencies, limits of detection (LODs), and potential annual missed doses for LBNL. The LBNL dosimetry methods evolved during the years as improved technology was developed and the complex radiation fields encountered in the workplace were better understood. The adequacy of the respective dosimetry methods to measure radiation dose accurately depends on radiation type, energy, and exposure geometry. Based on inspection of some career dose records, the exchange frequency of the dosimeters was weekly until January 1959 when a monthly exchange was implemented (LBNL 2007) (Attachment A). The dosimeter designs accommodated the numerous beta/photon radiation field types that workers might encounter throughout the LBNL complex. Film dosimeters were used for beta and photon radiation though 1994 (Dinnel 1994) when a commercial optical stimulated luminescence beta/photon dosimetry capability was implemented with CR-39 used for neutron radiation.

Table 6-3. LBNL beta/photon dosimeter type, period of use, exchange frequency, MDL, and potential annual missed dose.

Period of use	Dosimeter	LOD[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
LBNL film dosimeters				
1946–1968	Beta/Photon–DuPont film	0.030	Weekly	0.75
			Biweekly	0.38
			Monthly	0.18
1969–1994	Beta/Photon– film	0.020	Monthly	0.12
			Quarterly	0.04
			Semiannual	0.02
LBNL luminescent dosimeters				
1995–present	Beta/Photon–OSL System	0.010	Monthly	0.06
			Quarterly	0.02
			Semiannual	0.01

a. Estimated LODs for each dosimeter technology in the workplace. LBNL radiological records include dose values recorded at levels less than the LOD.
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.
c. Annual missed dose calculated using the LOD/2 method from NIOSH (2007b).

6.1.2.2 Neutron Radiation Personnel Dosimeters

LBNL implemented its individual worker neutron dosimetry methods beginning in the mid-1940s using PICs with a ^{10}B-enriched lining, portable instruments (Norton 1947) and sometime prior to 1952 the Eastman-Kodak Nuclear Track, Type A (NTA) emulsion (UCRL 1952a, Patterson and Thomas, 1994). NTA was used through 1994 (Dinnel 1994) when a DOELAP accredited Optical Stimulated Luminescent (OSL) beta/photon dosimeter was implemented with CR-39 to measure the neutron dose. Table 6-4 lists neutron dosimeter types, periods of use, exchange frequencies, LODs, and potential annual missed doses for LBNL.

Table 6-4. LBNL neutron dosimeter type, period of use, exchange frequency, LOD, and potential annual missed dose.

Period of use	Dosimeter	LOD[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
1946–1968	Pocket Chamber – thermal neutrons	0.005	Daily	0.65
			Weekly	0.13
1949–1994	NTA film emulsion	0.020	Monthly	0.12
			Quarterly	0.04
			Semiannual	0.02
1995–present	CR-39	0.010	Monthly	0.06
			Quarterly	0.02
			Semiannual	0.01

a. Estimated LODs for each dosimeter technology in the workplace. LBNL radiological records include dose values recorded at levels less than the LOD.
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.
c. Annual missed dose calculated using the LOD/2 method from NIOSH (2007b).

6.1.3 Calibration and Dosimeter Response Characteristics

Potential error in measured radiation dose is dependent on the dosimetry technology response characteristics to each radiation type, energy, and geometry; the methodology used to calibrate the dosimetry system; and the similarity between the radiation fields used for calibration and in the workplace.

6.1.3.1 Beta-Photon Dosimeters

Dosimeters were calibrated using film response to radium, various X-ray spectra, ^{32}P, ^{90}Sr, and uranium metal (Patterson and Thomas 1994). LBNL dosimetrists appear to have been well aware of technical considerations to match calibration and workplace spectra, as noted in Attachment A, and processing quality assurance to achieve accurate measured doses.

6.1.3.2 Neutron Dosimeters

Neutron dosimeters were calibrated using selected neutron sources such as polonium-beryllium or plutonium-beryllium sources (Mather 1952). LBNL staff members conducted substantial measurements of neutron flux and spectra, which are of particular importance to instrument and dosimeter determinations of dose, at various LBNL workplaces (Mather 1952, Stephens 1957). NTA response was found in a study by Kathren, Prevo, and Block (1965) to be a function of the angle of incidence of a neutron with the plane of the film and the energy. A factor of 1.3 was recommended to correct the recorded dose from NTA film for the effects of angular dependence and fast-neutron energy. A documented communication (Fix 2010) with a dosimetry subject expert recommended that the factor of 1.3 also be used to correct the measured neutron dose from TLDs.

6.1.4 Workplace Radiation Fields

The radiation fields at LBNL are highly variable (Patterson and Thomas, 1973, 1994, Casey et al 1988, Coulson et al 1989). They include radiation from a variety of radiation-producing machines such as electron accelerators, X-ray machines, cyclotrons, synchrotron, neutron generators, linear accelerators, Van de Graaff Generator, etc (UCRL 1948). Many different radioactive materials have been handled at LBNL. As noted in Attachment A, measurements of potential workplace radiation hazards in LBNL facilities were done in preparation for operation of various accelerators in the conduct of research.

6.1.4.1 Beta/Photon Radiation

Evaluations of potential beta and photon (gamma and X-ray) radiation hazards in LBNL workplaces have been done on numerous occasions as noted in Attachment A. Table 6-5 lists several of the beta/photon radiation sources potentially encountered at LBNL over the years, the approximate energy category, and the associated dose fraction. All workplace beta radiation energies of potential external radiation exposure significance to workers are greater than 15 keV. If more than one energy range and percentage combination is provided, dose reconstructors should use the combination that is most favorable to claimants.

Table 6-5. Selection of beta and photon radiation energies and dose fraction [46].

Buildings	Functional category	Radiation type	Energy selection (MeV)	Dose fraction
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, Sr-90, fission products, enriched uranium, depleted uranium, natural uranium, and others	Beta	>15	100
		Photon	30–250 > 250	25 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 30–250 > 250	25 50 25
75	**Waste Storage Yard:** fission products, enriched uranium, natural uranium and others	Beta	>15	100
		Photon	30–250 > 250	25 75

Buildings	Functional category	Radiation type	Energy selection (MeV)	Dose fraction
72, 74, 75	**Irradiators**	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

6.1.4.2 Neutron Radiation

Evaluations of potential neutron radiation hazards in LBNL workplaces have also been done on numerous occasions, as noted in Attachment A. Table 6-6 lists neutron radiation sources potentially encountered at LBNL over the years, the approximate energy category, and the associated dose fraction. Workplace neutron radiation energies of potential external radiation exposure significance to workers are between 10 keV and 20 MeV. The default neutron energy selection of 0.1 – 2.0 MeV in Table 6-6 was chosen because according to Moyer (1960) this energy interval contributed neutrons with the greatest dose. This energy range also typically has the highest organ dose conversion factor (DCF; see NIOSH 2007b, Appendix C) that is favorable to claimants.

Table 6-6. Selection of neutron radiation energies and dose fraction [47].

Buildings	Description	Radiation type	Energy selection (MeV)	Dose fraction	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, Sr-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**	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

6.2 MONITORED LBNL WORKERS – MEASURED DOSE

6.2.1 Photon Dose Adjustments

No adjustment to recorded photon doses is recommended. LBNL film and luminescent dosimeters provided reasonably accurate measurement of photon radiation exposure in the facilities and for all years of operation. In the early years, the ratio of the open window (OW) and shielded film dosimeter response was undoubtedly used to evaluate the energy of the incident photon radiation and to distinguish if significant beta radiation was present. Multielement film dosimeters were used later consistent with practices at other DOE sites. PIC and radiation detection instruments were also used, which provided another source of reference for the measured photon exposure.

6.2.2 Photon Organ Dose Conversion Factors

The measured photon dose is used with the DCFs to calculate organ doses of interest using the external dose reconstruction implementation guidelines (NIOSH 2007b). For LBNL measured photon

dose before 1995 (film badge), the DCFs from exposure to organ dose should be used [48]. After 1994, the DCFs from deep dose equivalent to organ dose should be used. This is summarized in Table 6-7. It is recommended that the 100% anterior-posterior (i.e., front-to-back) geometry should be assumed for the irradiation geometry and for conversion to organ dose [49].

Table 6-7. Photon dose adjustment.

Period	Dosimeter	Facility	Adjustment to reported dose
Prior to 1995	Photon dosimeters	All facilities	Use roentgen-to-organ dose conversion factors.
After 1994[a]	Photon dosimeters	All facilities	Use *Hp(10)*-to-organ dose conversion factors.

a. Based on accreditation (Dinnel 1994) of LBL dosimetry system to DOELAP (1986).

6.2.3 Neutron Dose Adjustments

Significant neutron radiation in LBNL facilities would be detected using NTA film and later CR-39 dosimeters because of the general high-energy fields for the neutron radiation energies predominant in dose to people. It is recommended however that a correction for the angular response of the measured neutron dose be applied as noted in Table 6-8.

Table 6-8. Neutron dose adjustment.

Period	Dosimeter	Facility	Adjustment to reported dose
All years	Neutron dosimeters	All facilities	Multiply by an angular correction factor of 1.3

Based on measurements by Moyer (1960), the neutron energy predominant in dose to people is 0.1 to 2 MeV. Considering that NTA has a lower energy response limit of about 0.5 MeV, it is likely that neutron doses were under-estimated in general workplace areas with highly scattered neutron fields and accurately measured in less scattered neutron fields with higher energy neutrons. As such, consideration can be given to estimating the neutron dose using a neutron-to-photon dose (NP) ratio which is described in Section 6.4.3.

6.2.4 Neutron Weighting Factor

The neutron dose must be adjusted to account for the change in neutron quality factors between historical and current scientific guidance as described in NIOSH (2007b). LBNL neutron calibration factors were determined historically from National Institute of Standards and Technology (NIST) calibrated sources. The quality factor is incorporated in the NIST calibration methodology, which used flux-to-dose-rate conversion factors for varying neutron energies for each calibration source. Flux-to-dose-rate conversion factors were typically based on NCRP Report 38 (NCRP 1971). The NCRP report lists both flux-to-dose-rate conversion factors and associated quality factors. Table 6-9 summarizes historical changes in the quality factors, the average NCRP Report 38 quality factor for the neutron energy groups used as input to the Interactive RadioEpidemiological Program (IREP), the associated International Commission on Radiological Protection (ICRP) Publication 60 (ICRP 1991) weighting factor, and the ratio to convert from NCRP Report 38 to ICRP Publication 60 (see ORAUT-OTIB-0055, ORAUT 2006b).

DOE is in the process of incorporating ICRP Publication 60 (ICRP 1991) neutron weighting factors into the routine determination of the recorded neutron dose. For LBNL, the date this is scheduled to begin needs to be determined. Once this change is made, no adjustment in the recorded neutron dose will be necessary thereafter [50].

Table 6-9. Conversion from NCRP Report 38 (NCRP 1971) neutron quality factors to ICRP Publication 60 (ICRP 1991) weighting factors.

Neutron energy	Historical dosimetry guidelines[a]	NCRP Report 38 group averaged quality factor	ICRP Publication 60 neutron weighting factor	Ratio[b]
Thermal	3	2.35	5	2.13
0.5 eV–10 keV	10			
10 keV–100 keV		5.38	10	1.86
100 keV–2 MeV		10.49	20	1.91
2 MeV–20 MeV		7.56	10	1.32
20 MeV–60 MeV		6.96[c]	5	1.00[d]

a. First Tripartite Conference at Chalk River in 1949 (Warren et al. 1949); National Bureau of Standards Handbook 59 (NBS 1954; also known as NCRP Report 17); and Taylor (1971).
b. Ratio of the ICRP Publication 60 weighting factor to the group averaged NCRP 38 quality factor each neutron energy group (ICRP 1991; NCRP 1971).
c. "Not applicable" is usually inserted here rather than the NCRP group averaged value of 6.96, which is larger than the ICRP Publication 60 weighting factor of 5 for 20-to-60-MeV neutrons and results in a non-favorable-to-claimant reduction in the corrected dose for this neutron energy group (ICRP 1991; NCRP 1971).
d. Ratio for adjusting neutron dose from NCRP Report 38 quality factor to ICRP Publication 60 weighting factor is arbitrarily set equal to unity to avoid a non-favorable-to-claimant reduction in the corrected dose for this neutron energy group (ICRP 1991; NCRP 1971).

6.3 MONITORED LBNL WORKERS – MISSED DOSE

Missed doses to LBNL workers are assigned for monitored workers (NIOSH 2007b). The potential for missed dose exists when workers are exposed to radiation at levels below the detection limit of their personnel dosimeters or if dosimeters were not worn for all work involving radiation exposure. LBNL practice (Garden 1950, Nielsen 1954, LBL 1978) was to monitor any significant radiation exposure. Generally in the early years of radiation monitoring, when relatively high detection limits were combined with short monitoring durations, missed doses could be significant. Watson et al. (1994) describes a method to reconstruct doses for any exchange period without a recorded dose. The assignment of a missed dose is based on a determination of (1) the number of dosimeter results with a recorded dose less than the LOD divided by 2, and (2) multiplication of the LOD/2 value by the number of dosimeter results < LOD/2 to include potential unrecorded dose according to the scheduled dosimeter exchange period (NIOSH 2007b). Rich (1969) stated that often no positive neutron dose was measured with NTA film in workplaces with known neutron dose. As such, assigning the missed neutron dose from recorded neutron doses prior to 1995 when CR-39 was implemented (Dinnel 1994) may under-estimate the actual missed neutron dose. To assure a favorable to the claimant evaluation, the missed neutron dose should be determined by multiplying the missed photon dose by an NP ratio. The missed neutron dose measured with the CR-39 beginning in 1995 is based on a determination of (1) the number of CR-39 dosimeter results with a recorded neutron dose less than the LOD divided by 2, and (2) multiplication of the LOD/2 value times the number of dosimeter results < LOD/2 to include potential unrecorded neutron dose according to the scheduled dosimeter exchange period (NIOSH 2007b). A lognormal probability plot of the data in Figure 6-2 is presented in Figure 6-3. The data are best represented by a lognormal distribution with a geometric mean (GM) equal to 0.77, and a geometric standard deviation (GSD = 3.99). This is summarized in Table 6-10.

Table 6-10. LBNL NP ratio from personnel dose measurements.

Description	Values	GM	GSD	95th percentile
Personnel dose data	876	0.77	3.99	7.54

6.4 UNMONITORED LBNL WORKERS

6.4.1 Ambient Neutron Dose

There does appear to be a potential for ambient neutron radiation exposure associated with LBNL Accelerator operations beginning in the 1940s extending over a period of many years. As noted in Attachment A, elevated neutron exposures near the accelerator facilities were measured on many occasions; however measurement of an elevated neutron dose rate, in comparison to normal cosmic background rates, at the fence-line was very difficult. The dose reconstructor can apply an estimate of the ambient neutron dose to an unmonitored worker using guidance in Section 4. Ambient external neutron dose assigned during the SEC is considered to be a partial dose estimate.

6.4.2 Ambient Photon Dose

As described in the preceding sections regarding LBNL practices to assign dosimeters for any significant exposure, there generally should be no significantly exposed unmonitored LBNL workers. The dose reconstructor can apply an estimate of the ambient photon dose to an unmonitored worker using guidance in Section 4. Ambient external photon dose assigned during the SEC is considered to be a partial dose estimate.

6.4.3 Neutron to Photon Dose Ratio

The inability of the NTA film dosimeter to measure the entire neutron spectrum can be considered an example of an unmonitored exposure. The photon dose was reliably measured with LBNL beta/photon dosimeters, and essentially any significant neutron dose in the workplace would be accompanied by significant photon dose. A study was done of recorded dose data for claimants as of March 1, 2010. This data provided paired neutron and photon dose measurements, particularly for annual recorded doses, for which the neutron-to-photon dose ratio was calculated. A total of 1,464 LLNL personnel dose measurements were obtained with measured photon and neutron doses. A box plot of this data is shown in Figure 6-1 which extends from 1947 to 1987.

The data in Figure 6-1 were refined to a total of 876 records for which the recorded photon and neutron doses were equal to or greater than 10 mrem, respectively, to minimize effects in the analysis of measured doses near the LOD. The development of the NP ratio enables the use of the recorded photon radiation dose from an individual's personnel dosimeter to be used to estimate the unmonitored neutron dose. Figure 6-2 illustrates a scatter plot of the measured neutron and photon dose. It is evident that the measured neutron and photon doses are well correlated with a Pearson Correlation of 0.09.

A lognormal probability plot of the data in Figure 6-2 is presented in Figure 6-3.

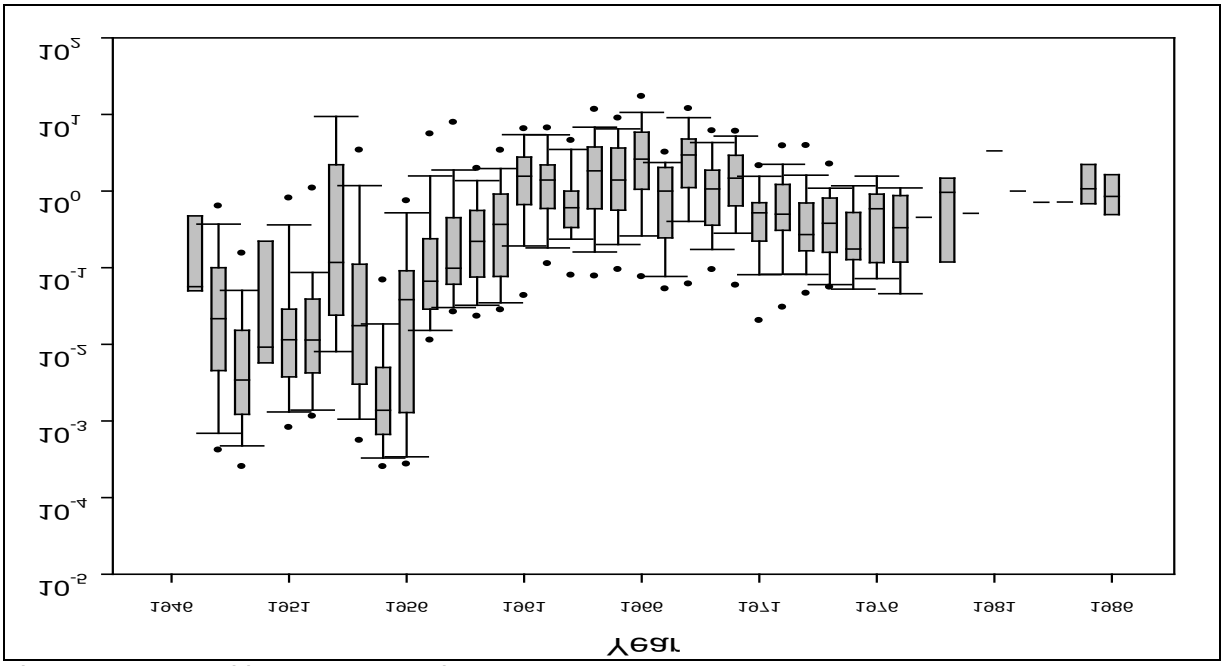

Figure 6-1. Trend in LBNL NP ratios.

6.4.3.1 NP Ratio Application

The combination of the 876 personnel dose data during the period from 1947 through 1987 provide a reasonable sample to evaluate statistical parameters of the NP ratio in LBNL facilities. The recommended lognormal distribution parameters for use in dose reconstruction are summarized in Table 6-10. The lognormal distribution parameters in Table 6-10 may be combined with measured and missed dose distributions using Monte Carlo methods described in ORAUT-OTIB-0012, Monte Carlo Methods for Dose Uncertainty Calculations (ORAUT 2005). The resulting total neutron dose should be partitioned for input to IREP using dose fraction by energy category in Table 6-6 or the default assumption that 100% is from neutrons from 0.1 to 2 MeV [51].

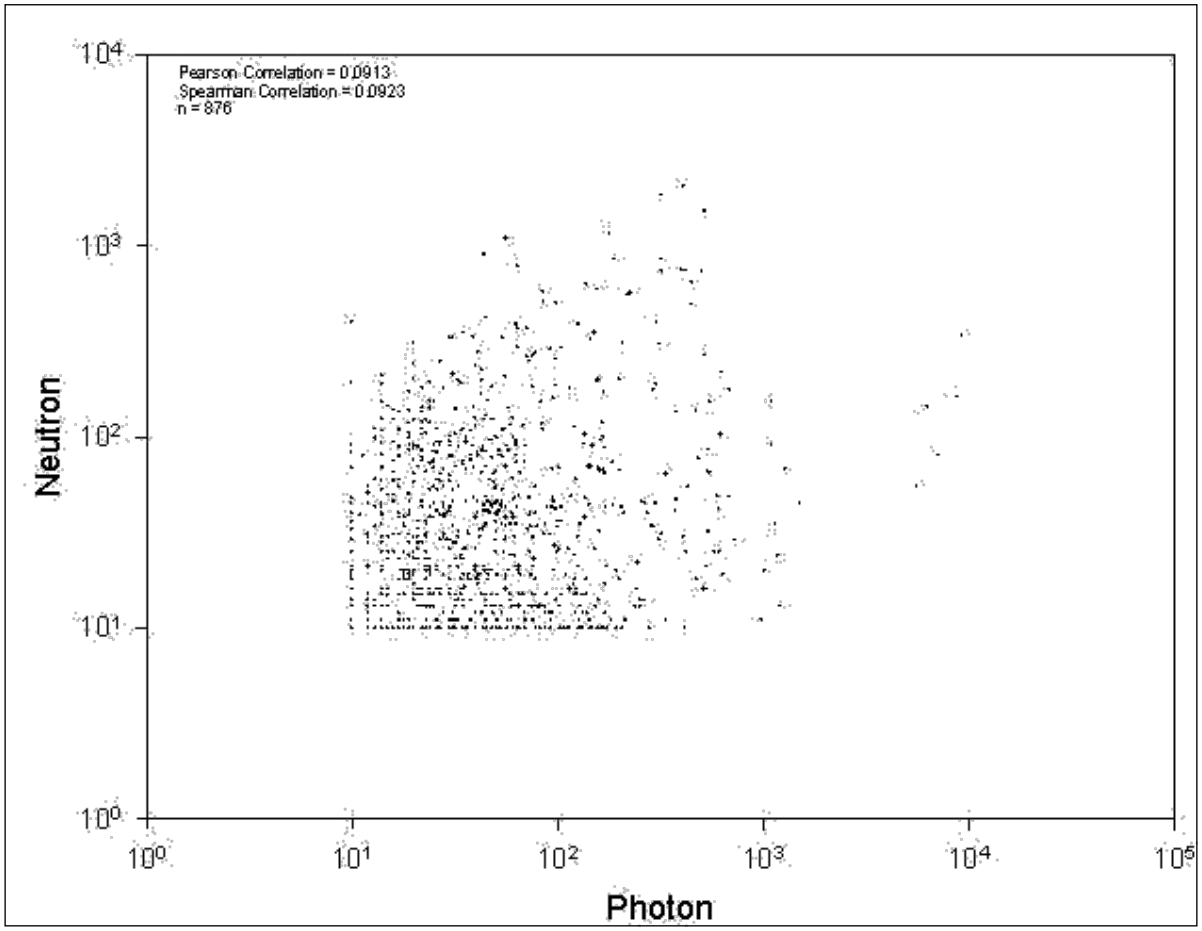

Figure 6-2. LBNL paired personnel neutron and photon doses ≥10 mrem measurements.

6.4.3.2 Construction Workers

If a construction worker received a dosimeter and worked in a facility with significant neutron exposure, this will be detected. In general, the dose reconstructor should assume ambient neutron exposure occurred as described under Section 4 unless there is other information indicating the construction work was conducted only in areas with little or no neutron radiation. As noted in Stephens et al (1974) the "actual fence post dose from operation of most accelerators is a small fraction of the annual dose to the public limit" which at that time was 500 mrem per year. A reference by LBL (1969) provides annual measured doses by facility for 1963 and 1969. The total dose only is provided for 1963 but the respective photon and neutron doses are provided for 1969. The average doses are very much less than 100 mrem but this may provide an alternative to assign a reasonable dose if necessary.

6.5 UNCERTAINTY

A number of factors contribute to uncertainty in measured doses (NCRP 2007). Systematic errors can occur from calibration and processing as well as from extraneous conditions such as moisture, heat, and fading. Random errors arise from variations among workers, the workplace energy spectra, and geometries of their exposures. NIOSH data collections of LBNL documentation have identified studies of uncertainty assessments for LBNL dosimeter systems. Many of these are illustrated in the historical timeline in Attachment A. The LBNL systems have much in common with dosimetry systems used at other DOE accelerator facilities (Casey et al 1988). Reference information to use in an analytical assessment of uncertainty has not been found. As such, in the judgment of the authors [52] of this document, the values in Table 6-11 are reasonable.

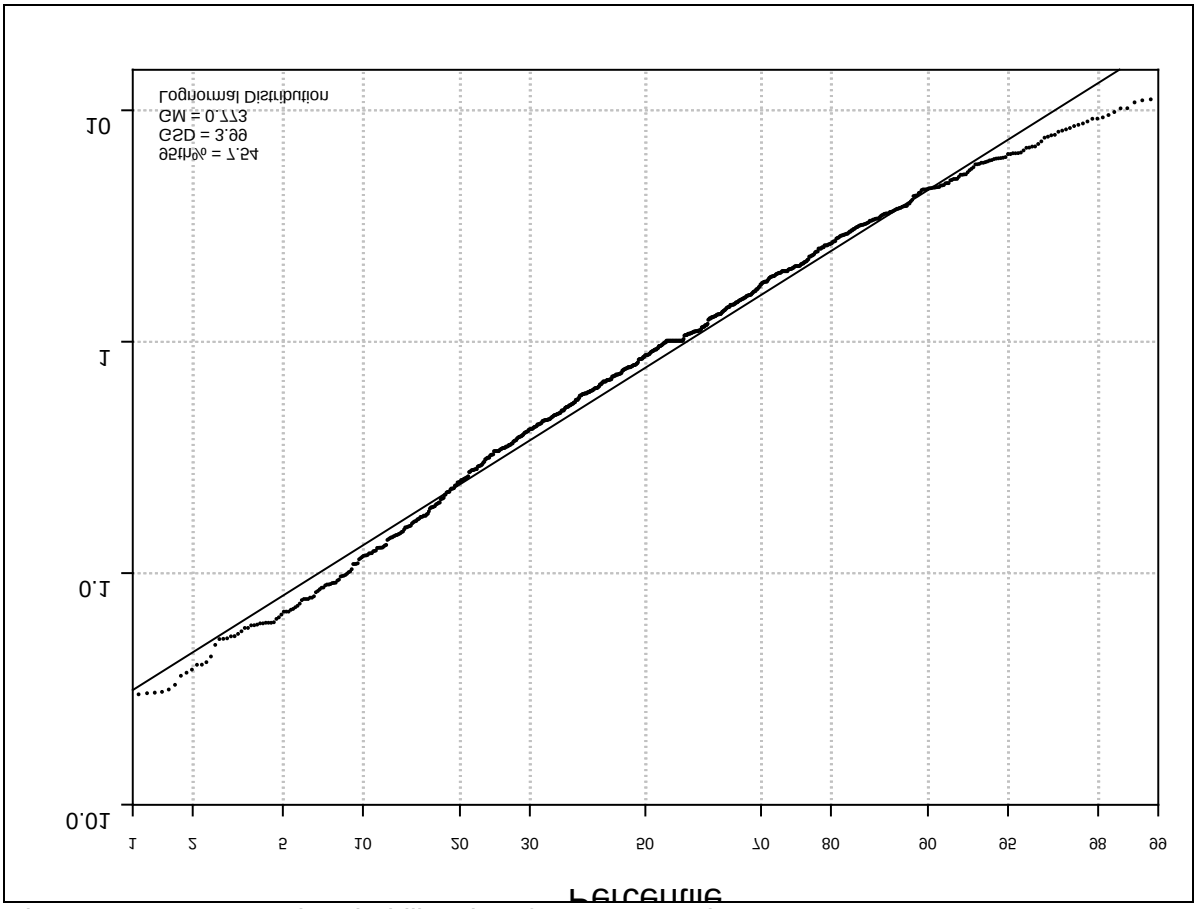

Figure 6-3. Lognormal probability plot of LBNL NP ratios.

Table 6-11. Uncertainty estimates.

Dosimeter	Uncertainty factor[a]
Film dosimeter (1941–59)	1.4
Film dosimeter (1960–94)	1.3
Luminescent (1995–present)	1.2
NTA film (1940s–50s)	1.5
NTA film (1960s–94)	1.3
CR-39 (1995-present)	1.2

a. Estimated variability of measured dose based on dosimeter technology as used in site radiation fields for long term workers.

6.6 SHALLOW DOSE

6.6.1 Assigned Shallow Dose

LBNL dosimeters measured nonpenetrating and penetrating beta/photon radiation exposure. The assignment of shallow dose according to beta, photon, or neutron radiation components can be complex because of mixed radiation fields and site-specific practices used to calculate the WB penetrating, WB skin, and extremity skin dose quantities. LBNL historical records are typically identified as beta, gamma, or neutron doses. The dose reconstructor can validate the reasonableness of the assigned shallow photon dose to the skin of the whole body because it should be equal to or greater than the assigned photon deep dose in essentially all cases. If it is not, the shallow photon dose component should be calculated as equal to the sum of the shallow and deep

photon doses. In cases of assigning a shallow dose to the extremities, such as the hand, which was often evaluated at LBNL, the assigned shallow dose to the extremities should be equal to or greater than the WB shallow photon dose in essentially all cases.

6.6.2 Assigned Extremity Skin Dose

There is uncertainty with respect to reconstructed extremity skin dose because of geometry, shielding, and dosimeter response parameters. A standard monitoring practice is to establish a factor between WB and extremity exposures to determine when the extremity dose would be limiting and, thus, extremity dosimeters should be assigned. The factor is typically based on radiation guidelines for the extremity, skin, and whole body, which have varied over the years as described in Attachment A, Table A-1. As noted in Morgan (1949) dose limits were identified for discussion during the meeting in Chalk River, Canada, among U.S., United Kingdom, and Canadian nuclear weapon development organizations, as follows:

Whole body–0.3 rem/wk;
Skin–0.5 rem/wk; and
Extremity–1.5 R/wk.

Based on comparison of the dose limits, it would not be necessary to monitor the extremity dose unless it was greater than a factor of 3 multiplied by the WB skin dose; otherwise, the WB dose would be limiting. Therefore, it is recommended that the measured WB photon dose be increased by a factor of 3 to assign a dose to the extremities based on the premise that extremity dosimeters would have been assigned and the dose reported for higher exposures [10]. The extremity dose is always equal to or greater than the measured WB skin dose (i.e., an estimated extremity dose is equal to the sum of the WB gamma, neutron, and beta doses). Unless it is clear that the extremity dosimeter is always worn, the measured extremity dose should also be included in the total assigned dose. The dose reconstructor can use guidance in ORAUT-OTIB-0017, Interpretation of Dosimetry Data for Assignment of Shallow Dose (ORAUT 2005b).

7.0 ATTRIBUTIONS AND ANNOTATIONS

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

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

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

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

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

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

[6] Thomas, Elyse. ORAU Team. Principal Medical Dosimetrist. March 2010.
The basis for this assumption is that the reported technique factors for the PA chest projection are the same as those reported in deCastro (1975) and called out as such, and the other technique consists of an exposure time double that of the PA chest projection, which is consistent with the guidance in ORAUT-OTIB-0006 (ORAUT 2005a) for determining the exposure from a LAT chest projection when the exposure for the PA chest projection is known.

[7] Thomas, Elyse. ORAU Team. Principal Medical Dosimetrist. March 2010.
ORAUT-OTIB-0006, Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures. Distances selected for computations are consistent with this document.

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

[10] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix recommended in the absence of other data, that a ratio be used to assign an extremity dose if not measured equal to 3 times the recorded deep dose based on historical radiation protection monitoring guidelines.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

controlled in the later years with aggressive shielding design with steps in power level, see environmental reports for summaries of the shielding efforts for the new and modified accelerator projects.

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

[29] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. Information on the decision to eliminate routine bioassays and use operational bioassays (based on scheduled work) was obtained during a telephone conversation between Elizabeth Langille and James Floyd (LBL Group Leader EH&S), May 6,2006 [SRDB Ref. ID 23402].

Documentation for the approach is also found in:

AIMahamid, I., 2005, Technical Basis Document for Internal Dosimetry, EH&S Procedure 301, Rev.4, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May 12. [SRDB Ref. ID: 21162]

[30] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. "LBNL Electronic Record of Results 1960 – 1996," ORAU Team 2006. [SRDB Ref. ID: 23841]

The electronic record of results was obtained from J. Floyd, LBNL Group Leader EH&S and includes a listing of method codes for the bioassay sample analysis results table. Where specific analyses were found in NOCTS records or in other SRDB records and could be compared to the electronic records, the method codes were verified to match those in the electronic records.

[31] Sargent, Thornton III, 1991, LBNL, Whole Body Counter Facility Operations Manual, January 22. [SRDB Ref. ID: 20900]

The operator aid specifies that a 15 minute count time is used but then provides a step to "assess the need for other counts in other geometries, as per detailed instructions." These instructions implied that special instructions might include an increased count time to achieve a desired detection limit.

[32] Low-Beer, A. DeG., 1963, "Report of Bioassay Program for 1962," memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 31. [SRDB Ref. ID: 21252]

The analysis of special fecal samples was noted in this document for 1962. Earlier special fecal samples are also noted in the electronic record of results found in SRDB Ref. ID 23481.

[33] Low-Beer, A. DeG., 1963, "Report of Bioassay Program for 1962," memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 31. [SRDB Ref. ID: 21252]

The analysis of special blood samples was noted in this document for 1962. Earlier special blood (SB) samples are also noted in the electronic record of results found in SRDB Ref. ID 23481.

[34] LBNL, 1983, Radiochemical Assay Report, July 12. [SRDB Ref. ID: 20880]

The record showed that spot urine collection was used for H-3 analysis during this time period. Spot urine collection may also have been used for H-3 earlier than 1983 at LBNL but of the records reviewed, this was the earliest date noted.

[35] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

This internal dosimetry program document provides information that routine 24 hour urine bioassay samples were obtained and analyzed for certain workers.

[36] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

This internal dosimetry program document provides information that fecal bioassay samples were obtained and analyzed as special bioassays when determined necessary.

[37] LBNL (Earnest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

This internal dosimetry program document provides information that spot urine bioassay samples were obtained and analyzed as determined necessary by EH&S.

[38] LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[39] LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[40] Langille, Elizabeth A. ORAU Team, Task 3. May 31, 2006. A review of the bioassay records in approximately 100 claims on NOCTS showed a file in 1971 (Claim Number Redacted) where the individual was counted on a WBC and an analysis for P-32 was performed. This file was used to establish the beginning time for this method as 1971. Using WBC to analyze for P-32 was also noted in 1995 LBNL Technical Basis document for internal dosimetry and so the method was assumed to be available until LBNL stopped performing WBC in 1996.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995, Technical Basis Document for Internal Dosimetry, University of California, Berkeley, California, May 12. [SRDB Ref. ID: 20926]

The *in vivo* method and detection limits found in the table were taken from this technical basis document.

[41] Langille, Elizabeth A. ORAU Team, Task 3. May, 2006. "LBNL Electronic Record of Results 1960 – 1996," ORAU Team 2006. [SRDB Ref. ID: 23841]

The electronic record of results was obtained from J. Floyd, LBNL Group Leader EH&S and includes a listing of method codes for the bioassay sample analysis results table. Where specific analyses were found in NOCTS records or in other SRDB records and could be compared to the electronic records, the method codes were verified to match those in the electronic records.

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

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

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

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

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

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

[48] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix recommended the respective organ dose conversion factors based on the methods to measure dose historically.

[49] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix recommended the anterior-posterior geometry be used to select the respective organ dose conversion factors based on guidance in IG-0001.

[50] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix identified the need to obtain from LBNL information concerning when ICRP neutron dose weighting factors are used at LBNL to assign personnel neutron dose in accordance with 10 CFR 835 requirements.

[51] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix identified the selection of the default neutron category of 0.1 to 2 MeV based on measurements reported by Moyer (1960) and also this category provides a favorable to the claimant selection.

[52] Fix, John J. ORAU Team. Principal External Dosimetrist. March 2010.
Mr. Fix recommended the uncertainty estimates for LBNL be based on values for similar systems since information from LBNL specific site studies was not available.

REFERENCES

Alloway, D., 1957, "Nose Swipes - [Privacy Act information]," DIA-1027-57, memorandum to J. S. Lichliter, University of California, Lawrence Radiation Laboratory, Berkeley, California, September 11. [SRDB Ref ID: 21162]

AlMahamid, I., 2005, *Technical Basis Document for Internal Dosimetry*, EH&S Procedure 301, Rev. 4, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May 12. [SRDB Ref ID: 22749]

Author unknown, no date, untitled document describing bioassay program. [SRDB Ref ID: 21251]

Author unknown, 2007, *LBNL Response to NIOSH Data Request Letter Dated March 23, 2007*. [SRDB Ref ID: 31508].

Balgobin, D. A., I. Javendel, R. O. Pauer, G. E. Schleimer, and P. A. Thorson, editors, 1993, *Annual Site Environmental Report of the Lawrence Berkeley Laboratory, Calendar Year 1992*, LBL-27170 (1993), University of California, Lawrence Berkeley Laboratory, Berkeley, California, May. [SRDB Ref ID: 23094]

Ball, RH, Chief, Research Service Branch, Atomic Energy Commission, Berkeley Area Office, to W. B. Reynolds, Radiation Laboratory, University of California, dated March 13, 1951, entitled "Permissible Levels of Radiation and Concentrations of Radioactive Isotopes, Attachments to GM Bulletin No. 133," [SRDB Ref ID: 72103].

Bradfield, N. E., 1987, annotated *Operational Safety Procedures for Picker X-Ray Machine 26-126*, September 28. [SRDB Ref ID: 23484]

Bradfield-Montoya, N., 1994, *Activity Hazard Document 163, Picker X-Ray Clinix*, June 22. [SRDB Ref ID: 23486]

Browne, H. 1950, *Outline of Health Chemistry Procedures*, September 22. [SRDB Ref ID: 21068]

Cantelow, H. P., 1973, *Annual Environmental Monitoring Report, 1972*, University of California, Lawrence Berkeley Laboratory, Berkeley, California, March 1. [SRDB Ref ID: 20986, p. 45]

Cantelow, H. P., 1976, "Environmental Sampling Data - 1975," HPC:047:76, memorandum to R. H. Thomas, University of California, Lawrence Berkeley Laboratory, Berkeley, California, February 26. [SRDB Ref ID: 23076]

Casey, W. R. (BNL), A. J. Miller (LANL), J. B. McCaslin (LBL) and L . V. Coulson (FNAL), 1988, "Health Physics Manual of Good Practices at Accelerator Facilities," SLAC-327, US Department of Energy, Washington, DC., April [SRDB Ref ID: 21525]

Cooley, R. C., 1967, "Personnel Radiation Exposures from Medical X-rays – Savannah River Plant – Part II". [SRDB Ref ID: 68124]

Coulson, L. V., A. J. Elwyn, and W. S. Freeman, 1989, "Accelerator Health Physics at DOE Laboratories: A Characterization," Fermi National Accelerator Laboratory, Batavia, IL, April 12, [SRDB Ref ID: 22527]

de Castro, T. M., 1977a, "X-Ray Machine Survey – Building 26, March 1977," memorandum to Dr. H. Stauffer, University of California, Lawrence Berkeley Laboratory, Berkeley, California, October 13. [SRDB Ref ID: 23491]

de Castro, T. M., 1977b, "X-Ray Machine Survey – Building 26, October 14, 1977," memorandum to Dr. H. Stauffer, University of California, Lawrence Berkeley Laboratory, Berkeley, California, October 14. [SRDB Ref ID: 23497]

de Castro, T. M., and S. B. Thomas, 1975, "X-Ray Machine Survey – Building 26, March 19, 1975," memorandum to Dr. T. Budinger, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April 1. [SRDB Ref ID: 23487]

Dinnel, K., 1994, "*LBL's dosimetry program receives accreditation*" Article in LBL Current Events Newsletter dated February 25, 1994, University of California, Lawrence Berkeley Laboratory, Berkeley, California. [SRDB Ref ID: 80033]

DOE (U.S. Department of Energy), 1986, *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems, DOE Laboratory Accreditation Program for Personnel Dosimetry Systems*, DOE/EH-0027, Assistant Secretary for Environment, Safety, and Health, Washington, D.C., December. [SRDB Ref ID: 12294]

DOE (U.S. Department of Energy), 2002, *Radionuclide Air Emission Report (in compliance with 40 C.F.R. 61, subpt. H), Calendar Year 2001*, University of California, Lawrence Berkeley National Laboratory, Berkeley, California.

DOE (U.S. Department of Energy), 2003, *Radionuclide Air Emission Report for 2002 (in compliance with 40 C.F.R. 61, subpt. H)*, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May.

DOE (U.S. Department of Energy), 2004, *Radionuclide Air Emission Report for 2003 (in compliance with 40 C.F.R. 61, subpt. H)*, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May.

DOE (U.S. Department of Energy), 2005, *Radionuclide Air Emission Report for 2004 (in compliance with 40 C.F.R. 61, subpt. H)*, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May.

Fix, J. J., L. Salmon, G. Cowper, and E. Cardis, 1997, "A Retrospective Evaluation of the Dosimetry Employed in an International Combined Epidemiologic Study," *Radiation Protection Dosimetry*, volume 74, pp. 39–53. [SRDB Ref ID: 7769]

Fix, J. J., 2010, "Technical Knowledge of Historical Workplace Surveys for Neutron and Photon Radiation and Options for Neutron Dose Reconstruction," documented communication with Subject Expert, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, November 24. [SRDB Ref ID: 79052]

Garden, N. B., 1950, Letter to E. H. Covey, Control Officer, Naval Radiological Defense Laboratory, dated August 23, 1950 regarding log sheets for persons entering radioactively hazardous areas. [SRDB Ref ID: 21091]

Garden, N. B., 1956, *Tritium Exposure, Worker Name Redacted*, University of California, Lawrence Berkeley Laboratory, Berkeley, California, September 12. [SRDB Ref ID: 21495]

Goldhaber, J., 1981, *Lawrence and His Laboratory, LBL Newsmagazine*, Berkeley, CA, http://www.lbl.gov/Science-Articles/Research-Review/Magazine/1981/index.html

Goldstein, H. A., 1989, letter to H. H. Stauffer, M.D. (Lawrence Berkeley Laboratory), U.S. Food and Drug Administration, Rockville, Maryland, March 2. [SRDB Ref ID: 23502]

Grondona, C. E, 2010, "Re: Question about LBNL X-Ray Equipment," e-mail to E. Thomas (Oak Ridge Associated Universities Team, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, May 2. [SRDB Ref ID: 81017]

Hartsough, W. D., 1974, "Bioassay Programs," letter to R. L. Westby (U. S. Atomic Energy Commission), University of California, Lawrence Berkeley Laboratory, Berkeley, California, August 26. [SRDB Ref ID: 21012]

Heinzelman, K, 2003, "[Privacy Act Information] EEOICPA Request," memorandum to C. Grandona, December 4. [SRDB Ref ID: 23568]

Hickey, E. E., G. A. Stoetzel, D. G. Strom, G. R. Cicotte, C. M. Wiblin, and S. A. McGuire, 1993, *Air Sampling in the Workplace, Final Report*, NUREG-1400, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., September. [SRDB Ref ID: 20129]

Howe, P. W., 1961a, "Bioassay Program," memorandum to W. B. Reynolds, PWH-248-61, University of California, Lawrence Radiation Laboratory, Berkeley, California, March 17. [SRDB Ref ID: 20569]

Howe, P. W., 1961b, untitled letter to Dr. L. B. Werner, PWH-472-61, University of California, Lawrence Radiation Laboratory, Berkeley, California, May 23. [SRDB Ref ID: 20664]

HPS (Health Physics Society), 1996, *An American National Standard, Performance Criteria for Radiobioassay*, ANSI N13.30-1996, American National Standards Institute, New York, New York.

ICRP (International Commission on Radiological Protection), 1991, *1990 Recommendations of the International Commission on Radiological Protection*, Publication 60, Pergamon Press, Oxford, England.

ICRP (International Commission on Radiological Protection), 1998, *Individual Monitoring for Internal Exposure of Workers*, Publication 78, Pergamon Press, Oxford, England.

Kathren, R. L., C. T. Prevo, and S. Block, 1965, "Angular Dependence of Eastman Type A (NTA) Personnel Monitoring Film," *Health Physics*, volume 11, number 10, pp. 1067–1069. [SRDB Ref ID: 6180]

Kaufman, J. A., 1957, "Results of Assay of Nose Swipes of [Privacy Act information] Taken after Spill in Room 143, Bldg. 70 on Sept. 12, 1957," JAK-1050-57, memorandum to J. S. Lichliter, University of California, Lawrence Radiation Laboratory, Berkeley, California, September 27. [SRDB Ref ID: 21161]

Kelly, E. L., 1970, "Environmental Radiation Report for Second Half of 1969 and Annual Summary for 1969," DC-70-159, letter with attachments to E. C. Snute (U.S. Atomic Energy Commission), University of California, Lawrence Radiation Laboratory, Berkeley, California, February 20. [SRDB Ref ID: 20989]

Kelly, E. L., 1972, "Environmental Radiation Report for Second Half of 1971 and the Annual Summary for 1971," DC-72-176, letter with attachments to E. C. Snute (U.S. Atomic Energy Commission), University of California, Lawrence Radiation Laboratory, Berkeley, California, February 23. [SRDB Ref ID: 23072]

LBL (Lawrence Berkeley Laboratory), 1969, Individual Worker Annual Doses, University of California, Berkeley, CA, October. [SRDB 21470]

LBL (Lawrence Berkeley Laboratory), 1978, "Film Badge Office, Letter to Supervisors, dated March 1978 entitled "Update of Persons Requiring Neutron Films for Personnel Dosimetry," Lawrence Berkeley Laboratory, University of California, Berkeley, California. [SRDB Rev ID 21713]

LBL (Lawrence Berkeley Laboratory), 1965–1990, collection of employee bioassay records, University of California, Berkeley, California. [SRDB Ref ID: 21985, 21986]

LBL (Lawrence Berkeley Laboratory), 1980–1993, collection of internal dosimetry evaluations, University of California, Berkeley, California. [SRDB Ref ID: 21871]

Lawrence Berkeley National Laboratory (LBNL), 2007,"Individual Exposure Records (1948-1972)," LBNL, University of California, Berkeley, CA, May 21. [SRDB Ref ID: 32338]

LBNL (Lawrence Berkeley National Laboratory), 1995a, *1994 Site Environmental Report*, LBL-27170 (1995 rev.), University of California, Berkeley, California, May. [SRDB Ref ID: 6448]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1995b, *Technical Basis Document for Internal Dosimetry*, University of California, Berkeley, California, May 12. [SRDB Ref ID: 20926]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1996, *Lawrence Berkeley National Laboratory 1995 Site Environmental Report*, LBL-27170 (1996), University of California, Berkeley, California, July.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1997, *Lawrence Berkeley National Laboratory 1996 Site Environmental Report*, LBL-27170 (1997), University of California, Berkeley, California, July.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1998, *Site Environmental Report for 1997*, LBL-27170 (1998), University of California, Berkeley, California, September.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 1999, *Site Environmental Report for 1998,* LBL-27170 (1999), University of California, Berkeley, California, September.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2000, *Site Environmental Report for 1999,* LBL-27170 (2000), University of California, Berkeley, California, August.

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2001, *Site Environmental Report for 2000*, LBL-27170 (2001), University of California, Berkeley, California, September. [SRDB Ref ID: 23058]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2002, *Site Environmental Report for 2001*, LBL-27170 (2002), University of California, Berkeley, California, August. [SRDB Ref ID: 23063]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2003, *Site Environmental Report for 2002*, LBL-27170 (2003), University of California, Berkeley, California, July. [SRDB Ref ID: 23099, 23100]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2004, *Site Environmental Report for 2003*, LBL-27170 (2004), University of California, Berkeley, California, July. [SRDB Ref ID: 23059, 23060]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2005a, *Site Environmental Report for 2004*, LBL-27170 (2005), University of California, Berkeley, California, September. [SRDB Ref ID: 23061, 23062]

LBNL (Ernest Orlando Lawrence Berkeley National Laboratory), 2005b, *Current RWA Locations Report*, Berkeley, California, November 10. [SRDB Ref ID: 23507]

Lichliter, J. S., 1964, "Revised Radiation Summary," memorandum to Distribution with 1963 radiation measurement attachments, University of California, Lawrence Radiation Laboratory, Berkeley, California. [SRDB Ref ID: 21060]

Low-Beer, A. deG., 1962, “Report of Bioassay Program for 1961,” memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 10. [SRDB Ref ID: 21253]

Low-Beer, A. deG., 1963, “Report of Bioassay Program for 1962,” memorandum to Dr. H. G. Parker, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 31. [SRDB Ref ID: 21252]

LRL (Lawrence Radiation Laboratory), 1958a, collection of nose swipes reports for April 1958, University of California, Berkeley, California. [SRDB Ref ID: 21761]

LRL (Lawrence Radiation Laboratory), 1958b, collection of nose swipes reports for March and April 1958, University of California, Berkeley, California. [SRDB Ref ID: 21762]

LRL (Lawrence Radiation Laboratory), 1958c, collection of nose swipes reports for March 1958, University of California, Berkeley, California. [SRDB Ref ID: 21763]

LRL (Lawrence Radiation Laboratory), 1958d, collection of nose swipes reports for January and February 1958, University of California, Berkeley, California. [SRDB Ref ID: 21764]

LRL (Lawrence Radiation Laboratory), 1958e, "General Radiation Safety Practices (1957)," memorandum from Health Physics Department, UCRL, University of California, Berkeley, California, November. [SRDB Ref ID: 21745]

LRL (Lawrence Radiation Laboratory), 1959a, *Health Chemistry Department Report of Special Analysis*, University of California, Berkeley, California, July 20. [SRDB Ref ID: 21767]

LRL (Lawrence Radiation Laboratory), 1959b, collection of 1959 "Health Chemistry Department Reports of Special Analysis," University of California, Berkeley, California. [SRDB Ref ID: 21768]

LRL (Lawrence Radiation Laboratory), 1960, collection of 1960 "Health Chemistry Department Reports of Special Analysis," University of California, Berkeley, California. [SRDB Ref ID: 21769]

LRL (Lawrence Radiation Laboratory), 1961, collection of 1961 "Health Chemistry Department Reports of Special Analysis," University of California, Berkeley, California. [SRDB Ref ID: 21770]

LRL (Lawrence Radiation Laboratory), 1963, *Lawrence Radiation Laboratory, Environmental Radiation Levels, Berkeley and Livermore*, with attachments, University of California, Berkeley, California. [SRDB Ref ID: 21536]

LRL (Lawrence Radiation Laboratory), 1967, collection of 1966 radiation measurement attachments, University of California, Berkeley, California. [SRDB Ref ID: 21052]

LRL (Lawrence Radiation Laboratory), 1968, *Annual Summary of Environmental Monitoring -1967- Lawrence Radiation Laboratory, Berkeley, California*, with attachment, University of California, Berkeley, California. [SRDB Ref ID: 20996]

LRL (Lawrence Radiation Laboratory), 1969, *Annual Summary of Environmental Monitoring, 1968, Lawrence Radiation Laboratory, Berkeley, California*, with attachment, University of California, Berkeley, California. [SRDB Ref ID: 20994]

LRL (Lawrence Radiation Laboratory), 1970, *Tritium Information and Operational Procedures,* Lawrence Radiation Laboratory, Berkeley, California, University of California, Berkeley, California. [SRDB Ref ID: 20962]

LRL (Lawrence Radiation Laboratory), 1971, *Annual Summary of Environmental Monitoring, 1970, Lawrence Radiation Laboratory, Berkeley, California*, with attachment, University of California, Berkeley, California. [SRDB Ref ID: 20941]

LRL (Lawrence Radiation Laboratory), undated circa 1971, *Early Years of Bioassay at LRL*, University of California, Berkeley, California. [SRDB Ref ID: 21721]

LRL (Lawrence Radiation Laboratory), 1979, Operational Procedures*, Tritium Laboratory, Building 75,* Lawrence Radiation Laboratory, Berkeley, California, University of California, Berkeley, California. [SRDB Ref ID: 20861]

Mansfield, W. G., and A. R. Wood-Zika, 2000, *Technical Basis Manual for Internal Dosimetry*, UCRL-MA-147534, University of California, Lawrence Livermore National Laboratory, Livermore, California, December 1. [SRDB Ref ID: 14840]

Maroncelli, J. M., and T. L. Karpin, 2002, *The Traveler's Guide to Nuclear Weapons: A Journey Through America's Cold War Battlefields*, Silverdale, Washington.

Mather, R., 1952, Radiation Laboratory, documented surveys from 1947 through 1952 of fast neutron energy flux in MeV/cm^2-sec for the 184-inch Cyclotron Area. [SRDB Ref ID: 21537]

McClelland, J., 1958, *Analytical Procedures of the Industrial Hygiene Group*, LA-1858 (2nd Edition), University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, September 1. [SRDB Ref ID: 12948]

Morgan, K. Z., 1949, Letter dated October 11, 1949 regarding “The meeting of the Radiation Protection Committees of the United States, Great Britain and Canada, in Chalk River, Canada, September 29 and 30, 1949.” [SRDB Ref ID: 72103]

Moyer, B. J., 1960, *Radiation Fields of High-Energy Accelerators*, Presented at the Thirteenth International Congress on Occupational Health during July 25-29, 1960, [SRDB Ref ID: 13990]

Moyer, B. J., 1952, *Survey Methods for Neutron Fields*, UCRL-1635, Radiation Laboratory, University of California, January 11. [SRDB Ref ID: 21678]

NBS (National Bureau of Standards), 1954, *Permissible Dose from External Sources of Ionizing Radiation, Recommendations of the National Committee on Radiation Protection*, Handbook 59 (NCRP Report 17), U.S. Department of Commerce, Washington, D.C., September 24. [SRDB Ref ID: 11111, p. 16]

NCRP (National Council on Radiation Protection and Measurements), 1953, *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water,* NCRP Report No. 52, National Academies Press, Bethesda, Maryland.

NCRP (National Council on Radiation Protection and Measurements), 1971, *Protection Against Neutron Radiation*, Report 38, Bethesda, Maryland, January 4.

NCRP (National Council on Radiation Protection and Measurements), 1989, *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies up to 50 MeV (Equipment Design, Performance and Use)*, Report 102, Bethesda, Maryland, February 28.

Nielsen, E., 1954, Letter to D. B. Macfarlane and CL Neadors, dated May 11, 1954, regarding approval for the transfer of the LRL WBNS reactor to UCRL. [SRDB Ref ID: 21371]

NIOSH (National Institute for Occupational Safety and Health), 2007a, *Radiation Exposures Covered for Dose Reconstructions Under Part B of the Energy Employees Occupational Illness Compensation Program Act*, OCAS-IG-003, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 5. [SRDB Ref ID: 35987]

NIOSH (National Institute for Occupational Safety and Health), 2007b, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 21.

NIOSH (National Institute for Occupational Safety and Health), 2010, Special Exposure Cohort, Petition Evaluation Report Petition SEC-00160, Office of Compensation Analysis and Support, Cincinnati, Ohio

Norton, J. S., Memorandum dated June 27, 1947 entitled “Radiation Protection Equipment,”. [SRDB Ref ID: 21132]

ORAUT (Oak Ridge Associated Universities Team), 2004, *Technical Basis Document for the Fernald Environmental Management Project (FEMP)*, ORAUT-TKBS-0017-5, Rev. 00, Oak Ridge, Tennessee, May 28.

ORAUT (Oak Ridge Associated Universities Team), 2004a, ORAUT-OTIB-0014, *Technical Information Bulletin: Assignment of Environmental Internal Doses for Employees Not Exposed to Airborne Radionuclides in the Workplace*, Rev 00, June 22.

ORAUT (Oak Ridge Associated Universities Team), 2005, *Technical Information Bulletin: Monte Carlo Methods for Dose Uncertainty Calculations,* ORAUT-OTIB-0012, *Rev 00*, February 14.

ORAUT (Oak Ridge Associated Universities Team), 2005a, *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures*, ORAUT-OTIB-0006, Rev. 03 PC-1, Oak Ridge, Tennessee, December 21.

ORAUT (Oak Ridge Associated Universities Team), 2005b, *Interpretation of Dosimetry Data for Assignment of Shallow Dose*, ORAUT-OTIB-0017, Rev. 01, Oak Ridge, Tennessee, October 11.

ORAUT (Oak Ridge Associated Universities Team), 2006c, *Y-12 National Security Complex – Occupational Internal Dose*, ORAUT-TKBS-0014-5, Rev. 02 PC-1, Oak Ridge, Tennessee, October 10.

ORAUT (Oak Ridge Associated Universities Team), 2006b, *Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges*, ORAUT-OTIB-0055, Rev. 00, Oak Ridge, Tennessee, June 5.

ORAUT (Oak Ridge Associated Universities Team), 2006c, *Y-12 National Security Complex – Occupational Internal Dose*, ORAUT-TKBS-0014-5, Rev. 02 PC-1, Oak Ridge, Tennessee, October 10.

ORAUT (Oak Ridge Associated Universities Team), 2007a, Calculation of Dose from Intakes of Special Tritium Compounds, ORAUT-OTIB-0066, Rev. 00, Oak Ridge, Tennessee, April 26.

ORAUT (Oak Ridge Associated Universities Team), 2008, *Technical Information Bulletin: Estimating Doses for Plutonium Strongly Retained in the Lung*, ORAUT-OTIB-0049, Rev. 01 PC-1, Oak Ridge, Tennessee, September 26.

ORAUT (Oak Ridge Associated Universities Team), 2010, *Hanford Site – Occupational External Dosimetry*, ORAUT-TKBS-0006-6 Rev. 04, Oak Ridge, Tennessee, January 7.

Pardue, L. A., N. Goldstein, and E. O. Wollan, 1944, *Photographic Film as a Pocket Radiation Dosimeter,* CH-1553-A-2223, University of Chicago, Metallurgical Laboratory, Chicago, Illinois, April. [SRDB Ref ID: 8599]

Parker, H. G., 1963, *Medical Division Examination Information 1961 – 1964.* [SRDB Ref ID: 72126].

Patterson, H. W., 1962, untitled memorandum to J. S. Lichliter, University of California, Lawrence Radiation Laboratory, Berkeley, California, January 15. [SRDB Ref ID: 21085]

Patterson, H. W., 1965, untitled memorandum to J. S. Lichliter with 1964 radiation measurement attachments, University of California, Lawrence Radiation Laboratory, Berkeley, California, February 11. [SRDB Ref ID: 21059]

Patterson, H. W., 1966, untitled memorandum to J. S. Lichliter with 1965 radiation measurement attachments, University of California, Lawrence Radiation Laboratory, Berkeley, California, May 8. [SRDB Ref ID: 21055]

Patterson, H. W., 1965, “Accelerator Radiation Monitoring and Shielding,” UCRL-16445 Rev, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Academic Press, New York, [SRDB 21691]

Patterson, W. H., 1955, "Radiation levels Around UCRL Accelerators," University of California, Radiation Laboratory, Berkeley, CA March 28. [SRDB Ref ID: 72339]

Patterson, H. W., A. deG. Low-Beer, and T. W. Sargent, 1969, *Whole-Body Counting and Bioassay Determinations Made on Accelerator Workers*, UCRL-18683 (Preprint), University of California, Lawrence Radiation Laboratory, Berkeley, California, January 3. [SRDB Ref ID: 21694]

Patterson, H. W., and R. H. Thomas, editors, 1994, *The History of Accelerator Radiological Protection, Personal and Professional Memoirs*, Nuclear Technology Publishing. [SRDB Ref ID: 33209]

Patterson, H. W., and R. H. Thomas, 1973, *Accelerator Health Physics*, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Academic Press, New York. [SRDB Ref ID: 79828]

Pauer, R. O., G. E. Schleimer, and I. Javendel, editors, 1992, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, Calendar Year 1991*, LBL-27170 (1992), University of California, Lawrence Berkeley Laboratory, Berkeley, California, May. [SRDB Ref ID: 23094]

Pickler, D. A., 1975, "Answers to Questions on Bioassays," letter to S. P. Fivozinsky (U.S. Department of Commerce), State of California, Radioactive Materials Licensing, February 21. [SRDB Ref ID: 21276]

Rich, B., 1969, "Lawrence Radiation Laboratory (Livermore)," *AEC Workshop on Personnel Neutron Dosimetry, September 23 to 24, 1969*, BNWL-1340, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, p. 56. [SRDB Ref ID: 11096]

Saunders, G. T., 1950, "Your Request for Air Contamination Data," memorandum to M. D. Thaxter (LRL), June 23. [SRDB Ref ID: 21096]

Schleimer, G. E., editor, 1979, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1978*, LBL-9080, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23080]

Schleimer, G. E., editor, 1980, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1979*, LBL-11192, University of California, Lawrence Berkeley Laboratory, Berkeley, California, June. [SRDB Ref ID: 23082]

Schleimer, G. E., editor, 1981, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1980*, LBL-12604, University of California, Lawrence Berkeley Laboratory, Berkeley, California, June. [SRDB Ref ID: 23083]

Schleimer, G. E., editor, 1982, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1981*, LBL-14553, University of California, Lawrence Berkeley Laboratory, Berkeley, California, June. [SRDB Ref ID: 23084]

Schleimer, G. E., editor, 1983, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1982*, LBL-15978, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23085]

Schleimer, G. E., editor, 1984, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1983*, LBL-17622, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23086]

Schleimer, G. E., editor, 1985, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1984*, LBL-19345, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23087]

Schleimer, G. E., editor, 1986, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1985*, LBL-21447, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23088]

Schleimer, G. E., editor, 1987, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1986*, LBL-23235, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23089]

Schleimer, G. E., editor, 1988, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1987*, LBL-25110, University of California, Lawrence Berkeley Laboratory, Berkeley, California, April. [SRDB Ref ID: 23090]

Schleimer, G. E., editor, 1989, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1988*, LBL-27170 1989, University of California, Lawrence Berkeley Laboratory, Berkeley, California, June. [SRDB Ref ID: 23091]

Schleimer, G. E., and R. O. Pauer, editors, 1990, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, Data for Calendar Year 1989*, LBL-27170 1990, University of California, Lawrence Berkeley Laboratory, Berkeley, California, August. [SRDB Ref ID: 23092]

Schleimer, G. E., and R. O. Pauer, editors, 1991, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, Data for Calendar Year 1990*, LBL-27170 1991, University of California, Lawrence Berkeley Laboratory, Berkeley, California, May. [SRDB Ref ID: 23093]

Soule, H. F., 1962, "Revision to Bioassay Schedule," memorandum to Dr. H. G. Parker, HFS-258-62, University of California, Lawrence Radiation Laboratory, Berkeley, California, March 22. [SRDB Ref ID: 20908]

Stephens, L. D., 1963, *X-Ray Machines (specs, drawings, operations, safety 1956-1977)*, LBL-6405, [SRDB Ref ID: 21715]

Stephens, L. D., editor, 1978, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory, 1977*, LBL-7530 with addendum, University of California, Lawrence Berkeley Laboratory, Berkeley, California, March. [SRDB Ref ID: 23078]

Stephens, L. D., editor, 1977, *Annual Environmental Monitoring Report of the Lawrence Berkeley Laboratory*, LBL-6405, University of California, Lawrence Berkeley Laboratory, Berkeley, California, March. [SRDB Ref ID: 23077]

Stephens, L. D., 1957, Fast Neutron Survey Linear Accelerator Building 10, University of California, Radiation Laboratory, Berkeley, CA, October 15. [SRDB Ref ID: 21942]

Stephens, L. D., and H. Cantelow, 1975, *Annual Environmental Monitoring Report – 1974*, LBL-3821, University of California, Lawrence Berkeley Laboratory, Berkeley, California, March 4. [SRDB Ref ID: 23075]

Stephens, L. D., R. H. Thomas, and S. B. Thomas, 1974, "Population Exposure from High-Energy Accelerators," LBL-3310, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, July [SRDB Rev ID 71786]

Sunderman, D. N., and C. W. Townley, 1960, *The Radiochemistry of Barium, Calcium, and Strontium*, NAS-NS 3010, National Academies Press, Washington, D.C.

Szalinski, P. A., 2006, "E. A. Langille and J. G. Floyd, Discussion on Internal Exposure Monitoring Changes around 1996," documented communication, Oak Ridge Associated Universities, Oak Ridge, Tennessee, May 4.

Taylor, L. S., 1971, *Radiation Protection Standards*, CRC Press, Cleveland, Ohio.

Thaxter, M. D., 1950a, "Hood Design for Radioactive Chemistry," Lawrence Berkeley Laboratory, Berkeley, California, November 3, 1950, MDT-351-50. [SRDB Ref ID: 21039]

Thaxter, M. D., 1950b, "Procedures for Air Monitoring, Filter Queen Specifications," letter to W. Meinke (University of Michigan, Department of Chemistry), May 29. [SRDB Ref ID: 21103]

Thaxter, M D., 1952, "Air Monitoring for Long-lived Alpha Emitters – Criterion for Reportable Concentrations," memorandum to A. Azzalini, March 25. [SRDB Ref ID: 21268]

Thaxter, M D., 1953, "Sampling Methods and Requirements for Estimating Airborne Radioparticulate Hazards," letter to T. Burnett (Oak Ridge National Laboratory), January 19. [SRDB Ref ID: 21357]

Thaxter, M. D., 1958, "Protection Factors for Respirators, Action Levels for Respirator Use," letter to D. Ross (U. S. Atomic Energy Commission), August 28. [SRDB Ref ID: 21995]

Thomas, M., 1991, "Results of FDA Diagnostic Survey," letter to H. Stauffer (Lawrence Berkeley National Laboratory), U.S. Food and Drug Administration, San Francisco, California, September 13. [SRDB Ref ID: 23503]

Thomas, R. H., 1974, untitled letter with attachments to H. Carwell (U.S. Atomic Energy Commission), University of California, Lawrence Berkeley Laboratory, Berkeley, California, March 4. [SRDB Ref ID: 23073]

Thomas, R. H., A. R. Smith, and G. H. Zeman, 2000, "A Reappraisal of the Reported Dose Equivalents at the Boundary of the University of California Radiation Laboratory during the Early Days of Bevatron Operation," LBNL-45224, (2000), Lawrence Berkeley National Laboratory, Berkeley, California, March. [SRDB Ref ID: 26117]

University of California, 1994, *Annual Site Environmental Monitoring Report of the Lawrence Berkeley Laboratory, Calendar Year 1993*, LBL-27170 (1994), Lawrence Berkeley Laboratory, Berkeley, California, May. [SRDB Ref ID: 23097]

University of California Radiation Laboratory (UCRL), 1956, *Medical and Health Physics Quarterly Report, July, August, September 1956*, UCRL-3573, University of California, Radiation Laboratory, Berkeley, CA, February 28. [SRDB Ref ID: 31460]

University of California Radiation Laboratory (UCRL), 1955a, *Medical and Health Physics Quarterly Report, July, August, September 1955*, UCRL-3208, University of California, Radiation Laboratory, Berkeley, CA, February 28. [SRDB Ref ID: 31455]

University of California Radiation Laboratory (UCRL), 1955b, *Medical and Health Physics Quarterly Report, October, November, December 1954*, UCRL-2881, University of California, Radiation Laboratory, Berkeley, CA, February 28. [SRDB Ref ID: 31451]

University of California Radiation Laboratory (UCRL), 1952a, *Medical and Health Physics Quarterly Report, July, August, September 1952*, UCRL-2001, University of California, Radiation Laboratory, Berkeley, CA, November 19. [SRDB Ref ID: 72125]

University of California Radiation Laboratory (UCRL), 1952b, *Medical and Health Physics Quarterly Report, October, November, December, 1951*, UCRL-1694, University of California, Radiation Laboratory, Berkeley, CA, February 28. [SRDB Ref ID: 72124]

University of California Radiation Laboratory (UCRL), 1951, *Medical and Health Physics Quarterly Report, October, November, December, 1950*, UCRL-1143, University of California, Radiation Laboratory, Berkeley, CA February 27. [SRDB Ref ID: 44679]

University of California Radiation Laboratory (UCRL), 1949, *Medical and Health Physics Quarterly Report, July, August, September, 1949*, UCRL-480, University of California, Radiation Laboratory, Berkeley, CA February 27. [SRDB Ref ID: 55796]

University of California Radiation Laboratory (UCRL), 1948, *Medical and Health Physics Quarterly Report, January, February, March*, 1948, UCRL-98, University of California, Radiation Laboratory, Berkeley, CA, March 1948. [SRDB Ref ID: 55802]

University of California Radiation Laboratory (UCRL), 1946, Film Badge Report. [SRDB Ref ID: 32415]

Vargha, P., 1996a, "Cover Letter for QA Manual," memorandum with attachment to K. Dinnel, FS-96-352, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, April 5. [SRDB Ref ID: 20898]

Vargha, P., 1996b, “WBC Records,” memorandum to K. Dinnel, FS-96-334, University of California, Lawrence Berkeley National Laboratory, Berkeley, California, March 27. [SRDB Ref ID: 20902]

Warren, S., 1949, "Minutes of the Permissible Doses Conference held at Chalk River, Canada, September 29-30, 1949." [SRDB Ref ID: 16640]

Watson, J. E. Jr., J. L. Wood, W. G. Tankersley, and C. M. West, 1994, "Estimation of Radiation Doses for Workers without Monitoring Data for Retrospective Epidemiologic Studies," *Health Physics*, volume 67, number 4, pp. 402–405. [SRDB Ref ID: 8601]

GLOSSARY

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

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

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

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

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

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

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

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

bioassay
Determination of kinds, quantities, or concentrations, and in some cases locations of radioactive material in a living body, whether by direct measurement (*in vivo* measurement) or

by analysis and evaluation of materials excreted or removed from the body (*in vitro* measurement). Also called *radiobioassay*.

body burden

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

chronic exposure

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

curie (Ci)

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

dose

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

- Absorbed dose is the amount of energy deposited in a substance by ionizing radiation.
- Collective dose is the sum of the doses to a specific population.
- Committed dose is the dose over time (usually 50 years for workers) to a specific organ or tissue from an intake of radioactive material.
- Cumulative dose is the sum of all doses to the same portion of the body or to the whole body over time.
- Deep dose is the dose at a 1-centimeter depth in tissue (1,000 milligrams per square centimeter).
- Effective dose is the sum of the equivalent doses in the principal tissues and organs of the body, each weighted by a tissue weighting factor that accounts for the probabilities of fatal and nonfatal cancers according to severity and the average length of life lost due to an induced cancer. It indicates the biological effect of the radiation exposure in that tissue.
- Equivalent dose or dose equivalent is the absorbed dose in a tissue or organ multiplied by a weighting factor for the particular type of radiation.
- Organ dose is the dose to a specific organ.
- Penetrating dose is that from higher energy photon (gamma and X-ray) radiation and neutron radiation that penetrates the outer layers of the skin. Nonpenetrating dose is that from beta and lower energy photon radiation.
- Personal dose equivalent is the dose equivalent in soft tissue below a specified point on the body at a specified depth.
- Shallow dose is the dose at a 0.07-millimeter depth in tissue (7 milligrams per square centimeter).

- Skin dose is the dose to the skin.

- Whole-body dose is the dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder.

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

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

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

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

dosimetry
Measurement and calculation of internal and external radiation doses.

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

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

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

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

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

fission products

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

gamma radiation

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

gray (Gy)

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

ionizing radiation

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

intake

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

internal dose or exposure

Dose received from radioactive material in the body.

internal dose assessment

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

in vitro

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

in vivo

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

lung solubility type

See *absorption type*.

minimum detectable activity or amount (MDA)

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

minimum detection level (MDL)

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

missed dose

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

monitoring

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

natural uranium (U, U-nat, NU)

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

neutron

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

neutron film dosimeter

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

nuclear track emulsion, Type A (NTA)

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

occupational dose

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

occupational exposure

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

occupational medical exposure

Exposure to radiation from medical X-ray screening procedures during physical examinations that are required as a condition of employment. For dose reconstruction, occupational medical exposure is a component of occupational exposure.

personal dose equivalent [$H_p(d)$]

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

photon

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

photon radiation

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

probability of causation (POC)

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

rad

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

radiation

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

radioactivity

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

radiograph

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

rem

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

roentgen (R)

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

routine monitoring

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

shallow absorbed dose (D_s)

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

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

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

sievert (Sv)

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

special monitoring

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

spot sample

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

thermoluminescent dosimeter (TLD)

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

transuranic (TRU) elements

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

unmonitored dose

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

uranium (U)

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

Natural uranium contains a minute amount of ^{234}U. See *depleted uranium*, *enriched uranium*, and *natural uranium*.

whole-body (WB) dose

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

X-ray

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

X-ray radiation

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

ATTACHMENT A
HISTORICAL TIMELINE OF RADIATION EXPOSURE ASSOCIATED EVENTS AT LBNL
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Because of the number of relevant references, this section contains a timeline of historical radiation-associated events at LBNL. This was prepared as an aid in examining the various issues and practices. As feasible, pertinent information has been transcribed from the references in the NIOSH Project SRDB. The reference listing and SRDB reference identification (SRDB Ref ID) number are also provided. These references do not necessarily appear in the main reference list for this document.

1940s

Patterson, H. W., 1994, Early Years at the Rad Lab, Chapter 2 in Patterson, H. W., and R. H. Thomas, editors, 1994, The History of Accelerator Radiological Protection, Personal and Professional Memoirs, Nuclear Technology Publishing. [SRDB Ref ID: 33209]

Chapter 2, "Early Days at the Rad Lab" describes radiation protection challenges and practices at LBNL at Berkeley from the earliest days to about 1952 when it is stated that a separate Health Physics Program was begun at Livermore. The beginning of the Radiation Laboratory personnel film dosimetry program is described. The original dosimeter is stated to be holders designed at Oak Ridge (i.e., the two-element dosimeter design adopted at ORNL, Hanford, and many other sites) using DuPont film.

1946

University of California Radiation Laboratory (RL), 1946, Film Badge Report. [SRDB Ref ID: 32415]

This reference is a listing entitled "Film Badge Report" of what appears to be weekly film badge results for respective individuals during the period of April through October 1946. The listing is categorized into work areas such as Bldg #1, ORL-37", CAL-60," Bldg. 10, and Gilman.

1947

Norton, J. S., Memorandum dated June 27, 1947 entitled "Radiation Protection Equipment," [SRDB Ref ID: 21132]

This letter describes the status of various radiation protection equipment activities particularly concerning radiation instrumentation. The list of activities covers many tasks including instrumentation such as hand counter, alpha survey meters, foot counters, etc., being developed at the Radiation Laboratory as well as procurements of instrumentation such as Victoreen portable GM survey meters, Landsverk-Wollan alpha/beta/gamma meters Model L-100, electrometers, etc. The letter states that 48 Landsverk-Wollan pocket electrometers, 6 boron lined pocket electroscopes (slow neutron) , 3 pocket electroscopes (self-charging type), and 12 integrating pocket chambers (neutron) are in use. Sixty-two other boron lined pocket chambers were also received.

1948

University of California Radiation Laboratory (RL), 1948, *Medical and Health Physics Quarterly Report, January, February, March*, 1948, UCRL-98, University of California, Radiation Laboratory, Berkeley, CA, May 1948. [SRDB Ref ID: 55802]

This document beginning on page 50 under Health Chemistry and page 51 Health Physics describes the development of equipment and techniques with the purpose to accomplish the goal of absolute control and trapping of radioactive substances. Monitoring of areas and personnel is underway. A problem was noted regarding the variation of sensitivity among various lots of film used in personnel film badges. It was found necessary to provide each lot of film with a separate calibration curve for

the photometer to convert densities into readings of dosage. Data are being accumulated on the radiation fields of the linear accelerator, and of the cyclotron as its shielding is being augmented.

University of California Radiation Laboratory (RL), 1948, *Monthly Progress Report No. 61 for May 1948*, UCRL-115, University of California, Radiation Laboratory, Berkeley, CA, May 1948, [SRDB Ref ID: 71798]

This document provides a status report on the respective accelerators including 1) 184-inch Cyclotron, 2) 60-inch Cyclotron, 3) Synchrotron, and 4) Linear Accelerators divided into discussion of the Van de Graaff Generator and Linear Accelerators. There is also discussion of the development of the JA Calutron to be used for isotope separation. Health Physics and Chemistry are described on page 11 stating that slow neutron flux densities had been measured by foils placed at various depths in the concrete shielding of the 184-inch cyclotron at particular locations. Air scattering of the neutrons was noted with the flux less than 100 neutrons-cm^{-2}-sec^{-1} under the strongest beam conditions. The fast neutron flux was measured to be much below tolerance.

University of California Radiation Laboratory (RL), 1948, *Monthly Progress Report No. 63 for May 1948*, UCRL-153, University of California, Radiation Laboratory, Berkeley, CA, July 15, [SRDB Ref ID: 71799]

This document provides a status report on the respective accelerators including 1) 184-inch Cyclotron, 2) 60-inch Cyclotron, 3) Synchrotron, and 4) Linear Accelerators divided into discussion of the Van de Graaff Generator and Linear Accelerators. Health Physics and Chemistry are described on pages 11-12 describing the status of efforts to support various research projects such as a specially built box for processing yttrium and strontium with minimum of exposure. Calibration of slow neutron pencils was underway.

1949

Morgan, K. Z., letter dated October 11, 1949 regarding "The meeting of the Radiation Protection Committees of the United States, Great Britain and Canada, in Chalk River, Canada, September 29 and 30, 1949." [SRDB Ref ID: 72103].

This is apparently input to the planned deliberations of the TriPartite meeting in 1949. Proposed maximum permissible tissue dose limits were noted in the following table.

Maximum Permissible Tissue Dose Limits in "Reps" per Week
Based on experience in lack of damage from 200 keV x-rays

Type of radiation	At any point within the body	RBE[a]	In the basal layer of the epidermis	
			Exposure of entire body	Exposure of hands only
x-rays and gamma rays	0.3	1	0.5	1.5
Beta rays	0.3	1	0.5	1.5
Protons	0.03	10	0.05	0.15
Alpha rays	0.015	20	0.025	0.075
Fast neutrons	0.03	10	0.05	0.15
Thermal neutrons	0.06	5	0.1	0.3

a. RBE = relative biological effectiveness.

For purposes of health monitoring, whole body exposure should be assumed when radiation is received to any portion of the body other than hands or forearms. In the light of present knowledge no

manifest permanent injury is to be expected from a single exposure of persons to 25r or less, with the possible exception of pregnant women.

University of California Radiation Laboratory (RL), 1949, *Medical and Health Physics Quarterly Report, July, August, September, 1949*, UCRL-480, University of California, Radiation Laboratory, Berkeley, CA February 27, [SRDB Ref ID: 55796]

This document beginning on page 66 under Health Chemistry and page 67 Health Physics describes improvements to remote handling equipment and extensive surveys of the fast and slow neutron flux densities of a Linear Accelerator. The slow neutron component was stated to be everywhere sufficiently low, extending as high as 1500 neutrons-$cm^{-2}sec^{-1}$ in the worst areas with a beam current of nearly 1/10 microampere. The energy flux density of fast neutrons, in the region of 0.5 to 15 MeV, measured in Mev-$cm^{-2}sec^{-1}$, was measured repeatedly. The document provides a list of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	1,250
Total man-days coverage with pocket chambers	1,594
Total man-days coverage with pocket dosimeters	3,383
Total man-days coverage with pocket chambers (SN)	2,190

A summary of weekly exposures greater than 0.3R as follows:

Exposure above	184" area	60" area	Linear acc.	Synchrotron	Chemistry	Total
0.3R	5	1	9	0	33	48
0.5R	1	0	5	0	16	22
1.0R	1	0	0	0	4	5
1.5R	1(5.0R)[a]	0	0	0	0	1

a. This exposure was received while undergoing a fluoroscopic examination that was in no way connected with the project.

1950

Chew, G. F., and B. J. Moyer, 1950, *High Energy Accelerators at the University of California Radiation Laboratory*, American Journal of Physics, Vol. 18, No. 3, 125-126, March [SRDB Ref ID: 21681]

This is a published paper that describes the operation of the Radiation Laboratory accelerators at that time.

Barrett, R. J., Letter to W. W. Meinke, dated October 25, 1950 regarding description of physical examinations, [SRDB Ref ID: 21067]

Letter contains a description of medical practices at Berkeley involving: 1) a medical examination of the individual, including physical examination, chest x-ray, complete blood count, and urinalysis at the time of employment; 2) periodic blood counts, indicated special studies, and repeated medical examinations every eighteen months; 3) examination at the time the individual terminates employment at the laboratory; 4) maintenance of first aid facilities where job-incurred injuries are initially handled and where limited nursing care and professional medical advice is available for non-job incurred

injuries and illness; and (5) the development of examination methods of special value in regard to radiation injury and other special laboratory hazards.

N. B. Garden, Letter to Health Chemistry Monitors, dated July 27, 1950 entitled "Recent Revisions in Maximum Permissible Radiation Exposure Levels," [SRDB Ref ID: 21093]

This letter describes a review of changes in exposure limits contained in General Industry Safety Orders, Division of Industrial Safety, State of California. Section 3803 states that no employee shall be exposed to a daily dose of ionizing radiation greater than 0.05 roentgen equivalent man, and a total weekly dose of not more than 0.3 roentgen equivalent man. The summation of all types of ionizing radiations shall be used in determining the daily or weekly dose. These values replace the former values stated in the AEC Standard Safety Regulations of 0.1 r/day, from which we obtained the 12.5 mr/hr level for the 8-hour day.

N. B. Garden, 1950, Letter to E. H. Covey, Control Officer, Naval Radiological Defense Laboratory, dated August 23, 1950 regarding log sheets for persons entering radioactively hazardous areas [SRDB Ref ID: 21091]

Letter describes routine Radiation Laboratory radiation protection practices. Log sheets for personnel entering radioactively hazardous areas are not used except during the times of operation of accelerators. Areas have not been set aside as radioactively hazardous. Hazards due to penetrating radiation, or radioactive ingestion, and contamination are evaluated in advance of the run or operation. Then steps are taken to circumvent them. The gloved box technique, secondary containers and a rule of "No Exposure – No Contamination" have served to minimize the time spent in record-keeping and frequent monitoring for contamination. All personnel on the project are issued and required to wear film badges. These are exchanged and read weekly. Badges which show greater than 0.3 roentgen are given special investigation.

University of California Radiation Laboratory (RL), 1951, *Medical and Health Physics Quarterly Report, October, November, December, 1950,* UCRL-1143, University of California, Radiation Laboratory, Berkeley, CA February 27, [SRDB Ref ID: 44679]

This document beginning on page 60 under Health Physics describes implementation of a fast neutron counter with ranges covering a neutron flux of 5 to 10,000 neutrons/cm^2/sec (~0.1 to 40 MeV). Gamma radiation intensities of one r/hr can be discriminated against. The document provides a list of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	1,800
Total man-days coverage with pocket chambers	2,177
Total man-days coverage with pocket dosimeters	4,334
Total man-days coverage with pocket chambers (SN)	3,609

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A summary of weekly exposures greater than 0.3R as follows:

Exposure above	184" area	60" area	Linear acc.	Synchrotron	Chemistry	Total
0.3R	18	18	0	0	11	47
0.5R	3	6	0	0	4	13
1.0R	0	2	0	0	2	4
1.5R	0	2	0	0	1	3
5.0R[a]	0	2*	0	0	0	2

a. In the past three months there have been two exposures exceeding 5 R, one of which was received while undergoing chest fluoroscopy. The other received while undergoing a dental examination. These exposures were in no way project connected.

1951

Ball, RH, Chief, Research Service Branch, Atomic Energy Commission, Berkeley Area Office, to W. B. Reynolds, Radiation Laboratory, University of California, dated March 13, 1951, entitled "Permissible Levels of Radiation and Concentrations of Radioactive Isotopes, Attachments to GM Bulletin No. 133," [SRDB Ref ID: 72103].

This document describes Attachment A entitled "Permissible Levels of External Radiation," and refers to human exposures to beta, gamma and X-rays and Attachment B entitled "List of Permissible Radioisotopes Concentrations for the Guidance of AEC and AEC-Installation personnel, based on Harwell and Chalk River Conferences." The document includes the following:

PERMISSIBLE LEVELS OF EXTERNAL RADIATION

The maximal permissible level for chronic exposure of the total body to penetrating radiation (beta, gamma, X-rays) shall be at the rate of 0.3 rep per week at an effective depth in soft tissue of 5 centimeters, assumed to be the depth of the blood forming organs. A measured dose not exceeding the rate of 0.3 rep per week in air will be assumed to meet these requirements. For soft components of radiation (including beta rays with energy less than 2 MeV), an additional rate of 0.2 rep per week, as measured in air, is permissible. The maximal permissible level for chronic exposure to the basal layer of the skin, at a depth corresponding to 7 milligrams per square centimeter, may thus be at the rate of 0.5 rep per week – but with the restriction that the dose at the depth of the blood-forming organs shall not exceed 0.3 rep per week. In the case of exposures limited to the hands and forearms, the maximal permissible dose shall be 1.5 rep per week, measured in air or at the basal layer of the skin. Weekly (or biweekly) exposure records shall be kept of all personnel who are subject to such exposure. For administration purposes, however, exposure levels may be considered in terms of the average taken over a longer period of time not to exceed three months. A single week's exposure need not be considered excessive if it is not over twice the permissible level of 0.3 rep per week (or twice the level of 0.5 rep per week under the appropriate conditions), provided the average weekly exposure over three months does not exceed the maximal permissible limit.

Bowen, J. E., Letter to N. B. Garden, dated October 8, 1951 entitled, "Status of Health Chemistry Instrumentation," [SRDB Ref ID: 21141]

Letter concerns an itemized report of the progress of instrumentation projects under development for Health Chemistry. Several types of instrumentation are noted including air filter monitoring, scintillation, beta hand counter, alpha, beta gamma pencil probe, etc.

Brown, H., Letter to Mail Room, Bldg. 30 dated December 12, 1950, regarding list of Health Chemistry personnel according to building, [SRDB Ref ID: 21061]

This document describes work assignment of personnel according to Building 5 (room 116), Building 50 (room 326) and Building 3. It is likely to be associated with procedures to provide for the assignment and exchange of dosimeters with personnel.

Nielsen, E., Letter to N. B. Garden, dated September 20, 1951 entitled "Radiation from Uranium Block," [SRDB Ref ID: 21143]

Letter concerns results of film measurements on selected uranium blocks as noted in the following table. Film G-1 to G-8 are film exposures made on a piece of uranium in Garden's office, G-9 is the control, and G-10 is the exposure made from the nickel plated uranium piece used in the ^{24}Na shipping container. Except for G-9 and G-10, each film had two thicknesses of 0.041" aluminum as a beta shield over half of the film.

			Film readings			
			Total (mr)		mr/hr	
Film	Distance(in)	Exposure (hr)	B + G	Gamma	B + G	Gamma
G-1	Contact	1	100	-	100	-
G-2	3	1	-	-	-	-
G-3	12	1	-	-	-	-
G-4	36	1	-	-	-	-
G-5	Contact	48.5	3,550	750	73	15
G-6	3	48.5	1,230	268	25	5
G-7	12	95.5	300	66	3	1
G-8	36	95.5	-	-	-	-
G-9	Control – n/a	n/a	-	-	-	-
G-10	Contact	24	2,500	-	104	-

Comparison between G-1. G-5 and G-10 would indicate that the plating was not thick enough to significantly affect the beta radiation. The number of secondary photons due to stopping of the beta particles in the plating should be less than 1% of the number of beta particles stopped.

Radiation Laboratory (RL), 1951, "Health Chemistry Accident Reports," University of California, [SRDB Ref ID: 30028]

This reference is a collection of Health Chemistry accident reports. The instructions state that this report is to be completed by the monitor and submitted whenever an accident has occurred in his building. The accidents include fire, explosion, spills of radioactive materials, large spills of corrosive or inflammable materials and injury to personnel requiring first aid.

Lawrence Berkeley National Laboratory (LBNL), 2007, "Individual Exposure Records (1948-1972)," LBNL, University of California, Berkeley, CA, May 21, [SRDB Ref ID: 32338]

This reference is one of several examples of a career radiation dose report prepared in this case in 2007 by LBNL. There are individual film dosimeter dose results for nearly every exchange period during the period from 1948 until 1972. Monthly exchange of the film dosimeter occurred effective January 1959 with weekly monitoring prior to this date beginning with the period of 1/12/1948 through 1/14/1948. Slow neutron monitoring results likely from pocket ionization chambers (i.e., boron lined) are also provided from 1/10/1949 through 3/28/1949 for likely each day of use. Electroscope results are provided for identified buildings (i.e., Bldg 6 and 80) during 1949 through 1951 for what appears to be the day the device was used.

University of California Radiation Laboratory (RL), 1952, "Medical and Health Physics Quarterly Report, October, November, December, 1951," UCRL-1694, University of California, Radiation Laboratory, Berkeley, CA February 28, [SRDB Ref ID: 72124]

This document beginning on page 88 under Health Physics describes completion of a portable neutron scintillation counter consisting of a large hollow polyethylene sphere coated on the inside with ZnS:Ag. The document provides a list of the types and quantities of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	1,900
Total man-days coverage with pocket chambers	1,101
Total man-days coverage with pocket dosimeters	3,251
Total man-days coverage with pocket chambers (SN)	2,116

A summary of weekly exposures greater than 0.3r as follows:

Exposure above	184" area	60" area	Linear acc.	Chemistry	Other	Total
0.3r	8	17	3	5	21	54
0.5r		6		1	6	13
1.0r	0	0	0	0	0	0

This report includes a section entitled "Survey Methods for Neutron Fields." The basic methods of neutron interaction with materials and definitions of fast (>~ 15 MeV) and thermal (interaction with nitrogen and protons primary mechanism) are provided along with a discussion of methods of measurement. Monitoring within the permissible dose range using Nuclear Track Film typically involves about one track per two or three microscopic fields of view (i.e. for a one week tolerance exposure of 0.03 rep of fast neutrons). Thus the measurement of typical personnel exposures is tedious and fraught with large statistical errors. There are also important problems of control of the water content of the emulsion, or processing, and of the effects of fading of the latent image.

1952

Moyer, B. J., 1952, Survey Methods for Neutron Fields, UCRL-1635, Radiation Laboratory, University of California, January 11, [SRDB Ref ID: 21678]

This is a technical report concerning methods to survey neutron radiation fields. The difficulty to perform a survey depends accordingly on the stated objectives. For example the measurements may

have three types of objectives such as, 1) only information of the presence of "slow" or "fast" neutrons; 2) a measure of flux densities within known energy intervals; or 3) a direct estimate of the specific rate of energy absorption due to neutron-produced effects in a given medium. Several types of neutron survey instruments are described.

Mather, R., Radiation Laboratory, 1952, documented surveys from 1947 through 1952 of fast neutron energy flux in MeV/cm^2-sec for the 184-inch Cyclotron Area. [SRDB Ref ID: 21537]

This reference is a collection of neutron flux measurements for selected buildings generally associated with the 184-inch cyclotron operation. The details of each survey require review but instrumentation included an argon proportional counter lined with polyethylene from which fast neutrons eject recoil protons. The counter was biased to reject radium gamma ray pulses and to detect pulses from Po-Be and Ra-Be sources.

N. B. Garden to R. L. Dobson, dated July 17, 1952 entitled "Project Personnel Working with Alpha Emitters," [SRDB Ref ID: 21262, 21722]

This letter concerns an effort to develop a complete list of Radiation Laboratory personnel working with alpha emitters. Alpha emitters were identified as Pu, Am, Cm, Ra, and U, and were listed for each of the respective individuals.

University of California Radiation Laboratory (RL), 1952, "Medical and Health Physics Quarterly Report, July, August, September 1952," UCRL-2001, University of California, Radiation Laboratory, Berkeley, CA November 19, [SRDB Ref ID: 72125]

This document beginning on page 129 and 133, respectively, for Health Chemistry (NB Garden) and Health Physics (Moyer) describes monitoring for the increasing number of sources at the University of California and the use of a new gamma survey meter (a Jordan meter) whose range is 20 mr/hr to 500 r/hr for which addition units were ordered. The document provides a list of the types and quantities of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	1,920
Total man-days coverage with pocket chambers	3,364
Total man-days coverage with pocket dosimeters	3,388
Total man-days coverage with pocket chambers (SN)	2,920

A summary of weekly exposures greater than 0.3R as follows:

Exposure above	184" area	60" area	Linear acc.	Chemistry	Other	Total
0.3R	1	15	14	58	12	110
0.5R	0	10	5	19	3	37
1.0R	0	1	0	07	0	8
1.5R	0	0	0	3	0	3
2.0R	0	0	0	2	0	2
2.5R	0	0	0	0	0	0

Nolan, W. E., and H. W. Patterson, 1952, Radiation Hazards from the Use of Dental X-ray Units, UCRL-1882 Rev., Radiation Laboratory, University of California, Berkeley, CA, November 26, [SRDB Ref ID: 71807]

This is a technical report describing the operation of dental X-ray units and summarizes measurements performed at six dentist facilities in the San Francisco area. Measurements were made using DuPont 552 and 558 type personnel monitoring film as well as a portable ionization chamber.

1953

Lawrence Berkeley National Laboratory (LBNL), 2007, "Individual Exposure Records (1952-1956)," LBNL, University of California, Berkeley, CA [SRDB Ref ID: 32989]

This reference appears to be a dose report from Livermore with processing results for each dosimeter processed during the period of what appears to be the employment start date (OSD) on 11-17-1952 with dosimeter assignments beginning March 11, 1953 through approximately the date of termination of May 9, 1956.

Thompson, B. W., 1953, "Fast-Neutron Scintillation Survey Meter," UCRL-2357, Radiation Laboratory, University of California, Berkeley, CA, October 28, [SRDB Ref ID: 21670]

This technical report describes development of a scintillation survey meter to measure neutron energy flux density. To estimate dose, it requires that the neutron distribution be known approximately. The instrument provides significant response at low flux levels, possesses good gamma discrimination, and is non-directional. No field measurements are provided in the report.

N. B. Garden, Health Chemistry, Letter to B. J. Moyer, Health Physics, dated November 11, 1953, entitled "Neutron Monitoring at Livermore, Bldg. 106," [SRDB Ref ID: 21342]

This letter states that work being conducted in building 106, Livermore, was surveyed for neutrons at the time of introduction of the material into the cave. The level indicated at that time that workers might exceed an allowable exposure to neutrons if they worked in certain areas for the several weeks during which the run is expected to continue. Furthermore there is the possibility of materially increasing the neutron flux due to an alpha-n reaction if certain elements are introduced, deliberately or inadvertently. For this reason, it would seem advisable to make a daily check of the neutron flux in front of the cave and we (Health Chemistry) would like a written daily memorandum of this level, so the proper entry can be made in the log of operations.

Radiation Laboratory, personnel annual radiation dose surveys for 1953 through 1958 for the 60-inch Cyclotron Area. [SRDB Ref ID: 21754]

This reference is a collection of personnel doses for selected workers associated with the 60-inch cyclotron operation.

Schneider, R. L., Letter to N. B. Garden, date November 12, 1953, entitled "Inventory of Survey Instruments," [SRDB Ref ID: 21340]

A physical inventory of Health Chemistry survey instruments was completed on October 5, 1953 by location and type of instrument. The survey included buildings 55, 50, 9A, 5, 5A, 14S, 3, 2, 1, Pay Dirt, Lewis Hall and Livermore. The results were:

	Number of instruments at the respective buildings													
Instrument	**4**	**5**	**5A**	**Pay dirt**	**9A**	**50**	**55**	**ORL**	**Donner**	**Crocker**	**Lewis**	**Livermore**	**Off project**	**Total**
Nuclear 2610	3	3	1	1	1	5	-	2	-	1	-	8	-	25
IDL 2610	2	1	1	-	-	1	1	1	-	1\-	-	1	-	8
Jordan AG-15	2	2	-	1	-	3	-	-	-	1	-	4	3	16
PeeWee 2111	3	4	1	1	-	3	-	4	-	-	-	7	1	24
Zeus (black)	-	2	-	-	-	-	-	2	-	-	-	-	-	4
Zeus (red)	2	1	1	-	-	1	-	1	1	-	-	-	-	7
Victoreen	1	-	1	-	-	1	-	3	-	-	-	1	-	7
ABG portable	-	-	1	-	-	-	-	-	-	1	1	-	-	3
Hand & foot, UCRL	1	1	-	-	-	1	-	-	-	-	-	3	-	6
Foot, UCRL	1	1	1	-	-	-	1	-	-	-	-	1	-	5
Austin	1	1	-	-	-	-	-	-	-	-	-	-	-	2
Tritium monitor	-	-	-	-	-	-	-	-	-	-	-	1	-	1

Bennett, J., Letter to W. Nolan, dated December 2, 1953, entitled "Film Badge Testing Program," [SRDB Ref ID: 21337]

This letter describes a test performed on November 23, 1953 using standard personnel film badges, standard film finger rings, and dosimeters (i.e., likely the pocket ionization chamber dosimeters commonly used and listed in the routine reports). To each dosimeter, the standard personnel film and finger ring film were attached using tape and placed equidistant from the gamma source. The results are shown as follows:

Specimen	Finger film	Film badge	Dosimeter	Time
A	1.00	0.800–0.530	Off scale	37 min.
B	1.37	0.465–0.355	0.161	37 min.
C	1.75	0.590–0.440	0.177	37 min.

The letter was concluded with the remark that "one or more of the exposure measuring devices is not too reliable."

1954

Nielsen, E., Letter to D. B. Macfarlane and CL Neadors, dated May 11, 1954, regarding approval for the transfer of the LRL WBNS reactor to UCRL, [SRDB Ref ID: 21371]

This reference reads as an early license transfer of a reactor from LRL to UCRL. Requirements for routine radiological monitoring are specified per the following:

1. Personnel Monitoring

   All persons who enter the Reactor Building will be supplied with:

   a. One film badge with beta gamma and nuclear emulsion films.
   b. Two beta gamma sensitive pocket chambers, one of which will be self-reading.
   c. One slow neutron pocket chamber

The pocket chambers will be read daily; the films weekly. Permanent records of exposure will be kept.

2. Building Monitoring

   The Building will be resurveyed and the results checked against LRL-99 using different instrumentation. Facilities such as the thermal column which have not been reported will be surveyed. Atmospheric and surface contamination will be checked daily, and all activated material will be monitored as it leaves the reactor. Access of other than technical personnel will be controlled by a Health Physics Work Permit.

RCC Letter to J. E. Bowen, dated November 3, 1954, entitled "Meter Performance," [SRDB Ref ID: 21385]

This letter describes discussions concerning reliability of personnel instruments to measure exposure rates. A carton, in the pit-room, containing two capsules of ^{170}Tm had to be opened. Readings were taken with three meters per the following results

#1. Abacus (Yellow) 60 mr
#2. Abacus (Green) 40 mr
#3. Jordan 500 mr (reading with 300 mr standard)

Readings taken through ice-cream carton containing both sources (10 mc, 50 mc) or a total of 60 mc of ^{170}Tm.

	Distance in inches			
Meter	**24**	**18**	**12**	**Surface**
#1	0	0	60 mr	12R
#2	25 mr	50 mr	190 mr	11R
#3	0	0	0	700 mr
Using 50 mc capsule only				
#1	0	0	0	1R
#2	10 mr	20 mr	70 mr	3R
#3	0	0	0	200 mr

Seidel, W. A., Letter to N. B. Garden, dated November 30, 1954, entitled "Location of Health Chemistry Gloved Boxes," [SRDB Ref ID: 21380]

This letter concerns an inventory of Health Chemistry gloved boxes on November 16th and 17th in Berkeley and November 22nd in Livermore. The total number of gloved boxes found was 323 of which 67 were located at Livermore.

Casalina, S. L., Letter to C. L. Linderken, dated November 30, 1954 entitled "Health Chemistry Operations at NPG," [SRDB Ref ID: 21381].

Health Chemistry standards at NPG carried out by Operations and other divisions included assigning personnel handling assemblies, their components, or other active objects with finger rings, Precautions were also specified to keep drinking utensils covered.

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1955

University of California Radiation Laboratory (RL), 1955, "Medical and Health Physics Quarterly Report, October, November, December 1954," UCRL-2881, University of California, Radiation Laboratory, Berkeley, CA February 28, [SRDB Ref ID: 31451]

This document beginning on pages 43 and 46, respectively, for Health Chemistry (NB Garden) and Health Physics (Moyer) describes a large-scale operation in Building 106, Livermore, with processing material that contained multicurie quantities of fission products and multicurie quantities of alpha-emitting substances. The document provides a list of the types and quantities of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	3,256
Total man-days coverage with pocket chambers	8,331
Total man-days coverage with pocket dosimeters	8,331
Total man-days coverage with pocket chambers (SN)	8,168

A summary of weekly exposures greater than 0.3R as follows:

Exposure above	184" area	60" area	Linear acc.	Chemistry	Other	Total
0.3R	0	19	0	17	7	43
0.5R	0	6	0	6	3	15
1.0R	0	0	0	2	0	2
1.5R	0	0	0	1	0	1
2.0R	0	0	0	1	0	1
2.5R	0	0	0	1	0	1
3.0R	0	0	0	0	0	0

Bowen, J. E., Letter to H. J. Browne, dated March 17, 1955, entitled "Lower detection limits of Health Chemistry Instruments," [SRDB Ref ID: 21401]

The following detection levels were noted:

Instrument name	Radiation detected	Lower limit
PeeWee	Alpha	50 c/m
Nuclear 2610 GM	Beta-gamma	Cosmic background ~ 0.05 mr/hr
Juno	Beta-gamma	5 mr/hr
Alpha planchet counter	Alpha	Back ~ 10 c/m
Beta-gamma planchet counter (GM)	Beta	Back ~ 10 c/m
Beta-gamma planchet counter (scintillation)	Beta	Back ~ 100 c/m

Atomic Energy Commission (AEC), 1955, "AEC Standards for Protection Against Radiation," Notice of Proposed Rule Making, July 11 [SRDB Ref ID: 21669]

AEC proposed legislation with dose limits as noted in the following:

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Conditions of exposure		Dose in critical organs (mrem per week)			
Part of body	Radiation	Skin, at basal layer of epidermis	Blood forming organs	Gonads	Lens of eye
Whole body	Any radiation with half-value-layer greater-than 1 mm of soft tissue	600[a]	300[a]	300[a]	300[a]
Whole body	Any radiation with half-value-layer LESS-than 1 mm of soft tissue	1500	300	300	300
Hands and forearms or feet and angles or head and neck	Any radiation	1500[b]			

a. For exposures of the whole body to X or gamma rays up to 3 MeV, this condition may be assumed to be met if the "air dose" does not exceed 300 mr, provided the dose to the gonads does not exceed 300 mrem. "Air dose" means that the dose is measured by an appropriate instrument in air in the region of highest dosage rate to be occupied by an individual, without the presence of the human body or other absorbing and scattering material.
b. Exposure to these limited portions of the body under these conditions does not alter the total weekly dose of 300 mrem permitted to the blood forming organs in the main portion of the body, to the gonads, or to the lens of the eye.

Personnel monitoring whenever there is a potential to exceed 25% of the above stated limits.

University of California Radiation Laboratory (RL), 1955, "Medical and Health Physics Quarterly Report, July, August, September 1955," UCRL-3208, University of California, Radiation Laboratory, Berkeley, CA February 28, [SRDB Ref ID: 31455]

This document is a subset of the entire report beginning on pages 28 and 30, respectively, for Health Chemistry (NB Garden) and Health Physics (Moyer). Health Chemistry monitors supported the dismantling of the 184-inch cyclotron which is to be reconstructed. The document provides a list of the types and quantities of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges	3,716
Total man-days coverage with pocket chambers	8,112
Total man-days coverage with pocket dosimeters	8,112
Total man-days coverage with pocket chambers (SN)	7,947

A summary of weekly exposures greater than 0.3r as follows:

Exposure above	184" area	60" area	Linear acc.	Chemistry	Other	Total
0.3r	0	10	4	19	2	35
0.5r	0	2	2	8	1	13
1.0r	0	0	0	5	0	5
1.5r	0	0	0	3	0	3
2.0r	0	0	0	3	0	3
2.5r	0	0	0	3	0	3
3.0r	0	0	0	3	0	3
4.0r	0	0	0	3	0	3
6.0r	0	0	0	1	0	1
6.5r	0	0	0	0	0	0

The report contains substantial discussion of the Health Physics Program for the Bevatron stating that the initial phase of radiation survey work performed was to determine the maximum radiation levels to

be expected at various locations. The technique of measurement included separate detection of ionizing radiation, slow neutrons and fast neutrons, and then evaluation of this information with respect to maximum operating capabilities of the machine. Building 51 has been rather completely surveyed in this manner. Interlocked safety gates, radiation warning lights, and radiation danger signs have been installed at appropriate locations as determined from these surveys.

University of California Radiation Laboratory (RL), 1955, "The Construction of Concentrated Steel Shielding for Radiation Protection from the 184-inch Cyclotron Accelerator," University of California, Radiation Laboratory, Berkeley, CA February 28, [SRDB Ref ID: 21535]

This reference is a job number 7900-22 that describes construction of the 184-inch cyclotron meson cave shielding beginning June 1955.

Patterson, W. H., 1955, "Radiation levels Around UCRL Accelerators," University of California, Radiation Laboratory, Berkeley, CA March 28, [SRDB Ref ID: 72339]

Radiation levels around the accelerating machines at UCRL vary widely and are dependent on conditions determined by experimental requirements. The exposure levels below should be interpreted as being the highest levels to which people are exposed in the ordinary course of their work. For brief periods, of the order of minutes, unusual jobs may require people to be exposed to higher rates. The radiation level averaged over a forty-hour work week is of the order of 0.1 times these maximum levels, and the person with the highest average exposure at the laboratory has less than the maximum of 300 mrep per week as determined by the AEC.

	Measuring device		
Accelerator	**Ion chamber**	**BF_3 proportional counter**	**Polyethylene lined proportional counter**
Bevatron	0.3-0.7 mr/hr	10–100 cm^{-2} sec^{-1}	10 MeV cm^{-2} sec^{-1}
184-inch Cyclotron	0.2–0.4 mr/hr	25–50 cm^{-2} sec^{-1}	18 MeV cm^{-2} sec^{-1}
32 MeV Linear	5–10 mr/hr	25–50 cm^{-2} sec^{-1}	20 MeV cm^{-2} sec^{-1}
320 MeV Synchrotron	See UCRL-1916 and 1917 revised for gamma-neutron cross sections for various elements up to 320 MeV. In general, the radiation levels in inhabited areas around the synchrotron are hardly measurable above normal background.		

1956

University of California Radiation Laboratory (RL), 1956, "Medical and Health Physics Quarterly Report, July, August, September 1956," UCRL-3573, University of California, Radiation Laboratory, Berkeley, CA February 28, [SRDB Ref ID: 31460]

This document beginning on page 17 Health Chemistry (N. B. Garden) and page 20 Health Physics (B. J. Moyer) describes renovations for a 2500-curie ^{60}Co source. The document provides a list of the types and quantities of survey instruments maintained and also a summary of personnel dosimeter use as follows:

Description	Quantity
Total people covered with film badges (Berkeley and Livermore)	4,434
Total man-days coverage with electroscopes (Berkeley only)	4,475
Total man-days coverage with dosimeters (Berkeley only)	2,675
Bevatron:	

Electroscopes, man-days	1,800
Bldgs. 10 and 53	
Slow Neutron Chambers, man-days	1,325
Dosimeters, man-days	1,325
Electroscopes, man-days	1,325
Crocker	
Slow Neutron Chambers, man-days	900
Dosimeters, man-days	900
Electroscopes, man-days	900
Bldg. 70	
Slow Neutron Chambers, man-days	450
Dosimeters, man-days	450
Electroscopes, man-days	450

A summary of weekly exposures greater than 0.3r as follows:

Exposure above	184" area	60" area	Linear acc.	Chemistry	Other	Total[a]
0.3r	0	15	17	7	3	42
0.5r	0	5	1	2	2	10
1.0r	0	1	0	0	0	1
1.5r	0	0	0	0	0	0
2.0	0	0	0	0	0	0
2.5	0	0	0	0	0	0
3.0	0	0	0	0	0	0
4.0r	0	0	0	0	0	0
6.0r	0	0	0	0	0	0
6.5r	0	0	0	0	0	0

a. Excluding Livermore

Eastman Kodak Company, 1956, "Availability of Personnel Dosimetry Film," Rochester, NY, December 14, [SRDB Ref ID 21706].

This reference documentation includes an advertisement from Eastman Kodak regarding their beta/photon and neutron radiation personnel dosimeter film choices. The reference also includes response data apparently from the Radiation Laboratory concerning DuPont 558 film.

1957

Stephens, L. D., 1957, Fast Neutron Survey Linear Accelerator Building 10, University of California, Radiation Laboratory, Berkeley, CA, October 15, [SRDB Ref ID: 21942]

This reference describes measurements performed at several times and for different accelerator operations. The first survey in the reference concerns a measurement on October 15, 1957 after roof shielding timbers were in place which duplicate earlier measurements performed on June 10, 1957. Operating conditions were duplicated as nearly as possible. A moderated BF_3 counter with an outer cadmium shield as a neutron detector was used to perform both sets of measurements. A facility schematic was used to record results of both sets of measurements. A series of similar measurements is included in the reference with typically neutron flux measurements recorded on a facility schematic.

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Bevatron Neutron Survey, 1957, University of California, Radiation Laboratory, Berkeley, CA, December 5, [SRDB Ref ID: 21549]

Fast and slow neutron levels were measured on 12/4/1957 in the area Bay 9 – Bay 14 inclusive to compare results of new shielding placed in this area with previous measurements conducted on 11/15/1957. A paper is also included in the reference by B. J. Moyer, entitled "Shielding at Berkeley Bevatron," for delivery at High-Energy Accelerator Shielding Conference during April 11-13, 1957 in New York. The reference also includes results of a cloud chamber neutron survey.

1958

Majitani, T., Letter to N. B. Garden, dated November 20, 1958 entitled "Personnel Exposures and 60" Cyclotron Operations," University of California, Radiation Laboratory, Berkeley, CA, [SRDB Ref ID: 21389]

This letter describes an evaluation of exposures to work crews from selected operations as noted in the weekly film badge readings. During the year 1957, the average exposure received by a crew member was 101 mr per week. The high man average was 132 mr/wk. The average received in 1957 was lower than the previous years starting from 1953. Radiation was noted as originating from two sources as follows;

- Cyclotron – the machine itself-which increased the environmental radiation in specific areas where work was conducted.
- Target

Based on this evaluation, recommendations were noted regarding a use of a remote viewing system for operators, adequate instruments for operational monitoring, target handling, and design consideration.

1960

Moyer, B. J., 1960, "Radiation Fields of high-Energy Accelerators," Presented at the Thirteenth International Congress on Occupational Health during July 25-29, 1960, [SRDB Ref ID: 13990]

This reference authored by the person who managed the Radiation Laboratory Health Physics program from about 1946 to 1952 and subsequently the Livermore Health Physics program beginning in 1952. This reference describes experiences during the past 15 years of operations of high-energy accelerators throughout the world. Operations at the Bevatron in Berkeley are often described. A characteristic of the Bevatron was the acceleration of protons to collide with selected target materials. The protons collide with atomic nuclei and disrupt them, knocking out many neutrons and protons, so that the energy of the primary beam is converted into the release and motion of a large number of secondary particles, the majority of which are neutrons. Neutrons without an electrical charge can diffuse through many materials and as such the accelerator becomes a diffuse emitter of neutrons degraded in energy over a large extent of its structure. An interesting feature of the Bevatron is the operation, similar to other accelerators of this type in the world, without a complete enclosure. These types of accelerators were constructed at a time when anticipated beam levels and the contemporary understanding of shielding did not seem to demand enclosure over the top of the device but only an outside-wall shield. At Berkeley, a complete enclosure system was installed prior to increases in the beam level. Radiation measurements, pertaining to a configuration with a side-wall shield 16 feet high, and 5 to 10 feet thick, with no roof shield; 2/3 to 3/4 of the dose is attributable to neutrons,

primarily fast neutrons of a few tenths MeV energy. The gamma radiation content of the field is primarily from neutron capture (largely in hydrogen in concrete) in materials close to the location of the measurement. Measurements have been made of neutron flux densities, and mean neutron energies, at mean body height, as a function of radial distance from the external face of the shield into the experimental areas. The mean neutron energy contributing the major biological damage is 0.1 to 0.2 MeV. Experimenters are allowed to work in these areas. No continuing activities of a long-term nature are located in the regions near the accelerator where the radiation level is more than 2.5 mrem/hr (which corresponds to a neutron flux density of 30/cm^2-sec for 0.5 MeV neutrons, or 80/cm^2-sec for 0.1 MeV neutrons). There is evidence that the fast neutron radiation is primarily due to downward scattering by air and the building roof, and a large yield of low-energy neutrons which diffuse upward from the whole machine.

1962

Lawrence Berkeley National Laboratory (LBNL), 2007,"Tabulated Individual Exposure in 60" Cyclotron (1947-1962)," LBNL, University of California, Berkeley, CA [SRDB Ref ID: 14003]

This reference provides a tabulation of quarterly doses for selected individuals at the 60" cyclotron. For one worker, the tabulation extends from the 3rd quarter 1947 through the 2nd quarter 1962.

1965

Patterson, H. W., 1965, "Accelerator Radiation Monitoring and Shielding," UCRL-16445 Rev, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Academic Press, New York, [SRDB Ref ID: 21691]

This reference provides an overview stating that since the late 1940s the Health Physics Department has been responsible for accelerator radiation monitoring and shielding at the Lawrence Radiation Laboratory in Berkeley. During this time, radiation measurements and shielding studies have been made on the 60-inch cyclotron, the 184-inch cyclotron, the electron synchrotron, the electron linear accelerator, the Bevatron, the heavy-ion linear accelerator, the proton linear accelerator, and the 88-inch cyclotron. The measurements have mostly been made with the purpose of identifying the various components of the radiation field and determining their energy distributions. A general rule that has emerged from these studies is that fast neutrons (0.1 to 10 MeV) dominate the biological hazard of the radiation field existing near a well-shielded particle accelerator by contributing more than half of the rem dose. Gamma rays and low-energy neutrons contribute 10 to 20%, and high-energy neutrons make up the balance. The development and use of neutron detectors that allow an estimation of the neutron spectrum have been emphasized in order to determine the rem dose. The document describes the various instruments and applications. For area dosimetry, representative locations are near each of the accelerators and at four stations near the boundary of the laboratory. The rate of exposure and integrated amount are recorded. For personnel monitoring, nearly every employee of the Laboratory is issued a beta-gamma film badge; in addition, about 900 employees have Eastman Type A neutron films. The films are developed and interpreted monthly. The beta-gamma film is calibrated with radium while the NTA is calibrated with neutrons of various energies. Each person's neutron exposure is recorded in terms of proton recoil tracks per microscope field of view, and this is translated into neutrons/cm^2 and rem, based on knowledge of the neutron spectrum. Whenever a personnel film indicates an exposure above 400 mrem in any one month, an investigation is made, the exposure is re-evaluated if necessary, and the results are given to the individual and his supervisor and also recorded. Pocket ionization chambers are worn by some individuals, and by everyone in certain areas. At present, no Laboratory employee has exceeded the maximum permissible exposure given by (age – 18) 5 rem formula.

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1966

McCaslin, J. B., H. W. Patterson, A. R. Smith and L. D. Stephens, 1966, "Some Recent Developments for Monitoring High-Energy Accelerator Radiation," UCRL-16769, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Academic Press, New York, [SRDB 71899]

This reference describes methods to interpret separate components in the radiation field and to determine their energy spectrum. This is important to an accurate evaluation of exposures received by individuals working near high-energy accelerators. No single instrument or detector can do this alone so a variety of different detectors and instruments must be used. Three recent methods for monitoring particulate radiation above 20 MeV include: 1) nuclear emulsion, 2) elemental mercury, and 3) ^{7}Be production in light elements; below 20 MeV, the use of moderated foils of In, Au, and Co has been extended to include Ta.

1969

Stephens, L. D., and A. J. Miller, 1969, "Radiation Studies at a Medium Energy Accelerator," UCRL-19386, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, October [SRDB Ref ID: 72354]

The 88-inch Cyclotron is one of the new generation of sector-focused cyclotrons which has been built since 1960. These third generation machines combine the advantages of high beam intensities of 1st generation cyclotrons with the high energies of 2nd generation synchrocyclotrons to produce beams of excellent quality and stability. Monitoring of the radiation outside the shield as well as inside the vault areas was done concurrently with the beam developments. Effective attenuation lengths were measured through the shielding walls at several angles from a target. Attenuation of neutrons was measured for walls composed entirely of concrete, as well as of concrete and iron, or of concrete, iron, and sand. Variations in shielding efficiency were determined. Neutron flux measurements have been made along an extended beam line in an effort to improve beam transport and reduce personnel irradiation. This has included a nearly complete picture of the external radiation field produced by the accelerator. The document includes a description of measured fields under a variety of circumstances.

Lawrence Berkeley Laboratory, 1969, "Individual Worker Annual Doses," University of California, Berkeley, CA, October [SRDB Ref ID: 21470]

This reference contains 1966 and for comparison 1969 annual gamma and neutron dose summaries for several classes of workers.

	Dose, mrem				
	1966	1969			No. of
Facility	Total	Gamma	Neutron	Total	persons
184-inch Synchrotron	14.4	15.2	7.5	22.7	25
Bevatron	58.2	35.4	16.5	51.9	43
88-inch Cyclotron	19.0	16.6	0.091	16.691	24
Hilac	8.7	12.2	0.25	12.45	30

The reference also contains 1969 annual neutron and photon doses for each individual according to identified buildings. This data was selected for analysis of neutron to photon dose ratios.

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1971

Miller, A. J., and M. W. Patterson, 1971, "Measurement of Induced Activity to Estimate Personnel Exposures Received from Accelerator Beams," UCRL-20262, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, June [SRDB Ref ID: 71915, 21694].

This reference describes a method developed at Lawrence Radiation Laboratory to estimate the dose received by an individual accidentally exposed to an accelerator particle beam. The dose estimate is based on measurement of the gross induced activities, primarily ^{11}C, resulting from nuclear interactions of the particle beam with the body tissues of the exposed individual. Experimental work has been done by exposing two tissue-equivalent phantoms, one simulating an arm and the other a torso, to particle beams (protons, mesons and neutrons) of various energies. Under favorable conditions the lower limit of sensitivity in the estimated dose is less than one rem.

1973

Patterson, H. W., and R. H. Thomas, 1973, Accelerator Health Physics, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, Academic Press, New York, [SRDB Ref ID: 79828]

This textbook is a classic reference in accelerator health physics describing fundamental principles, methods of measurement and personnel dosimetry associated with the LBNL accelerators.

1974

Stephens, L. D., R. H. Thomas, and S. B. Thomas, 1974, "Population Exposure from High-Energy Accelerators," LBL-3310, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, July [SRDB Ref ID: 71786]

This paper describes the transport of neutrons from high-energy electron and proton accelerators as representing the dominant source of radiation exposure to the population. The stated limit of permissible dose in the environment is 500 mrem/year. The actual fence post dose from operation of most accelerators is a small fraction of this limit. The neutron dose rates in the environment are so low that it is very difficult to accurately measure the dose rate.

1977

Lawrence Berkeley Laboratory, 1977, "Accidental Accelerator Beam Exposure Dosimetry Procedure," UCID-3905, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, April [SRDB Ref ID: 21550]

This document appears to be the first issue of a document that describes the potential serious consequences of an accidental exposure, the significance of particle accelerators as a source of accidental exposures within DOE, and steps to follow if an accidental exposure is suspected.

1978

Lawrence Berkeley Laboratory, Film Badge Office, Letter to Supervisors, dated March 1978 entitled "Update of Persons Requiring Neutron Films for Personnel Dosimetry," Lawrence Berkeley Laboratory, University of California, Berkeley, CA, [SRDB Ref ID: 21713]

This correspondence requests an update to the list of employees to be routinely assigned a neutron film dosimeter. The criteria of persons requiring a neutron film badge are described as follows:

- Person works inside any shielded area of any accelerator, such as experimenters or technicians.
- Person is permanently assigned to an accelerator area.
- For persons who work at accelerators only occasionally, the duration at the site should be about 20% (i.e., 4-5 days per month or greater).
- Any questionable cases should be badged.

1981

Lawrence Berkeley Laboratory, 1981, "Accidental Accelerator Beam Exposure Dosimetry Procedure," LBID-493, Lawrence Berkeley Laboratory, University of California, Berkeley, CA [SRDB Ref ID: 21584]

This document describes the potential serious consequences of an accidental exposure, the significance of particle accelerators as a source of accidental exposures within DOE, and steps to follow if an accidental exposure is suspected.

1984

Taylor, C. A., DOE, "Functional Appraisal of the Personnel Dosimetry Program at Lawrence Berkeley Laboratory November 1983 – January 1984," dated March 21, 1984, [SRDB Ref ID: 21727]

This is a transcript of a DOE quality assurance evaluation involving many individuals. Basically the report states that many of the observed problems are attributable to a lack of senior line management attention and support for the personnel dosimetry program.

Hyde E. K., Director, Lawrence Berkeley Laboratory, Letter to D. E. Neely, Director, DOE/SAN-LBL, DOE, dated April 26, 1984, entitled "LBL Personnel Dosimetry Program," [SRDB Ref ID: 21446]

This reference is the LBL response to the foregoing assessment.

1987

Greenhouse, N. A., T.M. de Castro, J.B. McCaslin, A.R. Smith, R.K. Sun and D.E. Hankins, 1987, *An Evaluation of NTA Film in an Accelerator Environment and Comparisons with CR-39,* Radiation Protection Dosimetry (1987) 20 (3): 143-147.

The Lawrence Berkeley Laboratory (LBL) has enjoyed decades of successful experience with NTA film because of the relatively energetic neutron spectra in the workplace and a cool, low humidity environment. The recognized existence of softer neutron spectra at some locations at LBL, and the availability of CR-39 as a possible alternative dosemeter prompted this study to determine neutron dosemeter adequacy in these areas. CR-39 offers several advantages over NTA film, including lack of latent track fading, the potential for automated readout, and improved response to lower energy neutrons. The CR-39 detection threshold of 0.1 MeV or less made it a particularly attractive possible alternative for neutron dosimetry at LBL's lower energy accelerators. A dosimetry study was conducted at one location at the SuperHILAC where the average neutron energy was about 0.5 MeV and the maximum was about 20 MeV. Neutron fluence, energy spectrum and dose equivalent measurements were made with a variety of active instruments at this accelerator during exposure of a

rotating phantom, upon which NTA film and CR-39 dosemeters were attached. The results indicated that with standard calibration techniques both dosemeter types responded adequately to at least half of the total measured dose equivalent.

1988

Casey, W. R. (BNL), A. J. Miller (LANL), J. B. McCaslin (LBL) and L . V. Coulson (FNAL), 1988, "Health Physics Manual of Good Practices at Accelerator Facilities," SLAC-327, US Department of Energy, Washington, DC., April [SRDB Ref ID: 21525]

This document presents guidance to be used to develop and conduct radiation protection programs at DOE accelerator facilities. It is noted that the diversity of accelerator types, their size, design, and beam properties require varying strategies for radiation safety. Section 6.5 describes personnel dosimetry (p 41) considerations. Beta and photon dosimetry are generally similar to other types of DOE facilities. Neutron dosimetry however is more complicated because of a greater range in energy from thermal to several GeV.

1989

Coulson, L. V., A. J. Elwyn, and W. S. Freeman, 1989, "Accelerator Health Physics at DOE Laboratories: A Characterization," Fermi National Accelerator Laboratory, Batavia, IL, April 12, [SRDB Ref ID: 22527]

This document describes the role of the Fermilab as being designated during January 1986 as the DOE lead laboratory for Accelerator Health Physics Research with the primary purpose to advise DOE of those areas of accelerator health physics research which should be pursued, and to help in prioritization. Section V, "Personnel Dosimetry," provides an overview of the status of personnel dosimetry methods used by the respective DOE accelerator sites. At the time this document was prepared, film and thermoluminescent personnel dosimetry methods were generally used. The description in this document of LBL personnel dosimetry is the current use of film, exchanged monthly, and processed in-house, for both beta-gamma and neutron dosimetry. There are about 1200 gamma (Kodak Type II) and 600 neutron (NTA) films used each month. There were plans to switch to a Panasonic TLD system, but using NTA, or CR-39, for actual neutron dosimetry (i.e., Panasonic system used to "flag" persons with potential neutron exposure for processing of NTA or CR-39). Dosimeter intercomparison studies were being done in neutron fields associated with heavy ion accelerators. All DOELAP performance tests have been passed.

1991

Sun, Rai-Ko S., 1991, "Review of Measurement at Accelerators and Application to Dosimeter Calibration," LBL-30883, Lawrence Berkeley Laboratory, University of California, Berkeley, CA [SRDB Ref ID: 20875]

The reference describes multisphere spectrometer measurements at Lawrence Berkeley Laboratory accelerator facilities (the SuperHILAC, the BEVALAC, and the 88-inch Cyclotron). The multisphere spectrometer has a broad energy response from 0.025 ev to several GeV. From the measured response, the neutron spectrum, neutron average energy, absorbed dose, dose equivalent and fluence can be calculated. There is also some information regarding comparison of the calculated doses with those determined with personnel dosimeters such as CR-39.

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1994

Dinnel, K, 1994, "Article in LBL Currents dated February 25, 1994," Lawrence Berkeley Laboratory, University of California, Berkeley, CA [SRDB Ref ID: 80033]

LBL's thermoluminescent dosimetry (TLD) program has been accredited by the U.S. Department of Energy, reported Kathleen Dinnel, the Dosimetry Unit leader. DOE accreditation makes it possible for the Laboratory to phase out film badges and, over the next six months, replace them with TLDs. Up until now, LBL has issued TLDs only on a limited basis. The dosimeter is processed in a reader in Bldg. 90. Dinnel said the TLDs are able to provide remarkable detail about the nature of any given dose. They allow LBL's health physicists to discriminate between shallow and deep penetrating doses and between gamma, x-ray, beta, and slow neutron exposures. "In the next six months," Dinnel said, "virtually everybody with a dosimeter here--other than people working in neutron fields--will be issued a TLD. We'll be seeking accreditation on another TLD for use in high-energy neutron fields, and at that stage, we'll phase over these workers to TLDs as well."

Patterson, H. W., and R. H. Thomas, editors, 1994, The History of Accelerator Radiological Protection, Personal and Professional Memoirs, Nuclear Technology Publishing, [SRDB Ref ID: 33209]

This textbook is a collection of articles covering a wide range of topics at accelerators throughout the US and the world. Since the editors were associated with LBNL for many years and considering their earlier textbook "Accelerator Health Physics" published in 1973, there is substantial information concerning radiation protection challenges and practices at LBNL. Chapter 2, "Early Days at the Rad Lab" authored by H. W. Patterson describes activities at Berkeley from the earliest days to about 1952 when it is stated that a separate Health Physics Program was begun at Livermore. The beginning of the Radiation Laboratory personnel film dosimetry program is described. The original dosimeter is stated to be a holder designed at Oak Ridge (i.e., the two-element dosimeter design adopted at ORNL, Hanford, and many other sites) using DuPont film. The process of calibrating the film response using a National Bureau of Standards calibrated radium source is described. A similar process was used to calibrate film response to various X-ray spectra, ^{32}P, ^{90}Sr, and uranium metal. The earliest doses were apparently noted as "daily doses", or 0.10 roentgen. In 1950 when the maximum permissible dose limit was lowered to 0.3 r per week the records were converted from "daily doses" to roentgen. The 60-inch cyclotron is stated to be the largest source of radiation and many dosimeters were located at this facility. Preparations for the startup of the 184-inch cyclotron in 1946 are described in terms of making sure everyone had a film dosimeter and that there were sufficient radiation survey meters. The text also describes the formation of the Health Chemistry and Health Physics radiation protection organizations. Patterson states in his text (p 39) that he personally exchanged all of the film dosimeters. He and Bill Nolan conducted all of the routine healthy physics duties at the Radiation Laboratory including radiation surveys in three dimensions around the accelerators with ion chambers and various neutron counters.