Document Title:	Document Number:	ORAUT-TKBS-0035-6
	Revision:	01
Lawrence Livermore National Laboratory – Occupational External Dose	Effective Date:	04/26/2007
	Type of Document	TBD
	Supersedes:	Revision 00

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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
10/07/2005	00	New technical basis document for the Lawrence Livermore National Laboratory – Occupational External Dose. First approved issue. Initiated by Jay J. Maisler.
04/26/2007	01	Approved revision to respond to comments by ORAU and Task 5. This revision specifically does not respond to Worker Outreach comments received; which will be addressed in a future revision. Constitutes a total rewrite of the document. Incorporates formal internal and NIOSH review comments. Adds Attributions and Annotations section. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Paul A. Szalinski.

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ACRONYMS AND ABBREVIATIONS

CFR	Code of Federal Regulations
CR-39	Columbia Resin – 39 or as polyallyl diglycol carbonate (PADC or CR-39), a polycarbonate material used for neutron dosimetry
DCF	dose conversion factor
DOE	U. S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
GSD	Geometric standard deviation
Hp(d)	personal dose equivalent at tissue depth *d* (*d* = 10 mm or 0.07 mm)
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
keV	kilovolt-electron
LBNL	Lawrence Berkeley National Laboratory
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MDL	minimum detection level
MED	Manhattan Engineer District
MeV	megaelectron-volt
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
NVLAP	National Voluntary Laboratory Accreditation Program
ORAU	Oak Ridge Associated Universities
POC	probability of causation
RFETS	Rocky Flats Environmental Technology Site
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
WB	whole body

6.1 INTRODUCTION

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

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

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

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

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

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

6.1.1 Purpose

This Site Profile documents historical practices at the Lawrence Livermore National Laboratory (LLNL) and provides information for the evaluation of external dosimetry data for monitored workers; it can serve as a supplement to, or substitute for, individual monitoring data.

This document provides a uniform and consistent approach to assessing occupational external dose at LLNL for dose reconstructions in relation to the EEOICPA. It provides guidance to dose reconstructors on input parameters that are specific to LLNL employees, as well as the approach for employees with either missing or no monitoring information.

LLNL workers handled a variety of radionuclides as part of their routine work. The key elements in the source term were plutonium and tritium although others were used at various times and in various forms. For the purposes of dose reconstruction, it can be assumed that internal source terms were introduced at LLNL's inception on September 2, 1952.

6.1.2 Scope

Workers at LLNL were exposed to radiation from a variety of radioactive materials and radiation-producing machines. In addition, many LLNL workers worked at the Nevada Test Site or were involved with other weapons tests where they could have received radiation exposures. Personnel dosimeter records are generally available for all periods at LLNL for workers who had any potential for occupational radiation exposure. The operations and radiation safety staff routinely reviewed dosimeter results for compliance with radiation control limits and investigated doses approaching annual or quarterly dose limits.

Radiation dosimetry practices were initially based on experience gained during several decades of radium and X-ray medical diagnostic and therapy applications.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 6.8.

6.1.3 Basis of Comparison

Various radiation dose concepts and quantities have been in use to measure and record occupational dose since the initiation of the MED in the early 1940s. The basis of comparison for reconstruction of dose is the personal dose equivalent, *Hp(d)*, where *d* identifies the depth in millimeters and represents the point of reference for dose in tissue. *Hp(d)* is an operational quantity used to determine the worker's actual dose equivalent from a dosimeter reading. International Commission on Radiological Protection (ICRP) Publication 74 (ICRP 1996) and International Commission on Radiation Units and Measurements (ICRU) Report 57 (ICRU 1998) both define it as a practical method for calibration of instruments and dosimeters to dose equivalent. Weakly penetrating radiation is significant to shallow dose equivalent, which is defined at *d* equal to 0.07 mm and noted as *Hp(0.07).* Penetrating radiation is significant to deep dose equivalent, which is defined at *d* equal to 10 mm and noted as *Hp(10). Hp(0.07)* and *Hp(10)* are the radiation quantities used in the DOE Laboratory Accreditation Program (DOELAP) used to accredit DOE personnel dosimetry systems since the 1980s (DOE 1986). The National Voluntary Laboratory Accreditation Program (NVLAP), which is the U.S. Nuclear Regulatory Commission equivalent to DOELAP, uses the same operational quantities. This TBD uses *Hp(10)* and *Hp(0.07)* as deep and shallow dose equivalents, respectively.

6.2 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 LLNL dosimeter responses are important to the assessment of bias and uncertainty of the original recorded dose in relation to the radiation quantity *Hp(d)*. 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 the DOELAP and NVLAP programs.

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

- <u>Administrative practices</u> that facilities adopt to calculate and record personnel dose based on technical, administrative, and statutory compliance considerations.
- <u>Dosimetry technology</u>, 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.
- <u>Calibration</u> of the respective monitoring systems and similarity of the methods of calibration to sources of exposure in the workplace.
- <u>Workplace radiation fields</u>, 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.

6.2.1 <u>Historical Administrative Practices</u>

LLNL used personnel dosimeters to measure and record doses from external radiation to designated workers throughout the history of its operations. These dosimeters include one or more of the following:

- Personnel whole-body (WB) beta/photon dosimeters
- Pocket ionization chamber dosimeters (i.e. electrometers, etc.)
- Personnel extremity dosimeters
- Personnel neutron dosimeters

LLNL began operations in 1952 using dosimeter and processing technical support provided by the Lawrence Berkeley National Laboratory (LBNL), which was then known as the University of California Radiation Laboratory. LBNL had implemented its dosimetry methods based on the personnel beta/ photon dosimeter design developed at the Metallurgical Laboratory at the University of Chicago (Pardue, Goldstein, and Wollan 1944). From 1952 to 1955, LBNL provided LLNL with photon/electron film dosimeters and nuclear track emulsion, type A (NTA) film; technical details regarding the capabilities of the external dosimetry system are provided in the LBNL site profile (ORAUT 2006a). By 1956, LLNL had its own fully functional personnel dosimetry program with in-house processing. Early exposure records also provided “electrometer” results (designated by “E” in selected claimant files), which supplemented the official results measured by film. For purposes of dose reconstruction, the “electrometer” or “E” results should be used in a qualitative manner because no data was found on the calibration or energy response of these devices; the film or TLD results should be used to estimate the actual exposure.

Table 6-1 summarizes the personnel dosimeters used at LLNL over the years, along with their periods of use, exchange frequencies, minimum detection levels (MDLs), and estimated annual missed doses.

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

Period of use	Dosimeter	MDL[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
1952–1969[d]	Photon/electron–DuPont 558 and 519 film	0.015	Weekly (n = 50)	0.375
		0.020	Biweekly (n = 25)	0.25
		0.030	Monthly (n = 12)	0.18
	Neutron–Kodak NTA film	0.050	Weekly (n = 50)	1.25
		0.050	Biweekly (n = 25)	0.625
		0.050	Monthly (n = 12)	0.30
1969–1985	Photon/electron/neutron - Harshaw TLD (TLD-100, TLD-200, TLD-600, and TLD-700)	0.010	Monthly (n = 12)	0.06
		0.020	Quarterly (n = 4)	0.04
1985–present	Photon/electron–Panasonic 810AS and 802AS TLD	0.010	Monthly (n = 12)	0.06
		0.015	Quarterly (n = 4)	0.03
		0.025	Semiannual (n = 2)	0.025
	Neutron–CR-39	0.010	Monthly (n = 12)	0.06
		0.010	Quarterly (n = 4)	0.02

a. Estimated MDLs for each dosimeter technology in the workplace. Dose values were recorded at levels less than the MDL.

b. Exchange frequencies were dependent on work assignment. If the exchange frequency is not evident based on trends in an individual's personnel records, assume a monthly exchange frequency.

c. Annual missed dose calculated using the MDL/2 method from NIOSH (2006).

d. From 1952 to 1955, LBNL processed film dosimeters. Dosimetry records in LLNL database prior to 1952 were processed by LBNL.

Dose reconstruction parameters concerning LLNL administrative practices significant to dose reconstruction involve policies to:

- Assign dosimeters to workers.
- Exchange dosimeters.
- Estimate dose for missing or damaged dosimeters.
- Replace destroyed or missing records.
- Evaluate and record dose for incidents.
- Obtain and record occupational dose to workers for other employer exposure.

LLNL policies were in place for all these parameters. From its inception, LLNL had policies to monitor individuals with any significant potential for radiation exposure. The current practice of monitoring all workers entering the site, regardless of exposure potential, has been in effect since May 1958, when film badges became part of the security badge (Nolan 1958). Dosimeter exchange frequencies varied over the years depending in part on the dosimeter type in use at the time and in part on the exposure potential of the individual being monitored; individuals with low exposure potential tended to have less frequent exchange frequencies than those with high exposure potential. Doses below the detection limit were either recorded as zero or not recorded at all; a review of representative claimant files indicates some inconsistencies. It was apparent that some individuals did not return their dosimeter for processing; the record indicates the term “missing.”

6.2.2 Dosimetry Technology

The LLNL 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 as discussed in later sections depends on radiation type, energy, exposure geometry, etc. The exchange frequency of the dosimeters was gradually lengthened and corresponded generally to downward reductions in the radiation protection guidelines (Morgan 1961; Taylor 1971). The dosimeter designs accommodated the numerous radiation field types that workers might encounter throughout the LLNL complex.

6.2.2.1 Beta/Gamma Dosimeters

From 1952 through 1955, LBNL supplied and processed beta/gamma dosimeters. These film dosimeters were similar in design to those developed at the Metallurgical Laboratory at the University of Chicago (Pardue, Goldstein, and Wollan 1944). LLNL used a similar design when it began its in-house dosimetry program in 1956. These film dosimeters, which were in use until 1969, used DuPont 558 and 519 film.

In 1969, thermoluminescent dosimeters (TLDs) replaced film dosimeters. LLNL constructed the TLDs used from 1969 through 1985, which contained Harshaw TLD-100, TLD-200, TLD-600, and TLD-700 elements. The use of Panasonic 802 and 810 dosimeters began in 1985 and has continued to the present.

6.2.2.2 Neutron Dosimeters

From 1952 through 1955, LBNL supplied and processed neutron dosimeters, which used Kodak NTA film. LLNL-provided dosimeters used the same film from 1956 through 1969. At some atomic weapons employer facilities or DOE facilities, neutron dosimeters were not read out unless a minimum gamma exposure threshold was reached. There is no evidence that this was practiced at LLNL. In *Personnel Monitoring Procedure for UCRL, Livermore* (LRL ca. 1954) it is stated that: “A film badge containing fast neutron sensitive film shall also be provided for persons who will be working within areas where significant neutron exposures are possible.” No definition of "significant" was provided; at this time there are no clear criteria for how neutron dosimeters were assigned. If available, coworker data should be used. It is clear that all unmonitored workers did not have the potential for exposure to neutrons based on buildings worked in and job classifications, but the criteria for monitoring has not been quantified. Research into dosimetry practices at LBNL to develop the TBDs may provide additional information on dosimetry practices. This document will be revised if additional evidence is found.

As far as badge exchange and processing, the document states that: “For those who work in radiation areas, the film badges are exchanged once a week and fresh film is installed. The old film is developed and the radiation dosage is recorded.” Nowhere in this document is it mentioned that not all neutron film badges were processed. However, only values above the limit of detection were reported.

In 1969, TLDs replaced film dosimeters. LLNL constructed the TLDs used from 1969 through 1985, which contained Harshaw TLD-100, TLD-200, TLD-600, and TLD-700 elements. From 1969 through 1975, the neutron dosimeter used a non-Albedo-type design. Badge modifications in 1975 used the Albedo design whereby cadmium shielded the TLD-600 and TLD-700 components on all sides except the side facing the wearer’s body. This design effectively shielded incident thermal neutrons from the TLD-600 and TLD-700 elements and detected only thermal neutrons reflected from the wearer’s body.

The change in design did not modify the detection limit. The change provided a more precise result compared to the over-estimate which was observed prior to 1975. The design, which minimized the over-response of the earlier design, was in use until 1985 when LLNL adopted Panasonic TLDs. Also in 1985, Columbia Resin-39 (CR-39) neutron dosimeters were introduced and used with the Panasonic TLDs. This system continues in use at present.

6.2.3 Calibration

Potential error in recorded dose is dependent on the dosimeter response characteristics to each radiation type, energy, and geometry; the methodology used to calibrate the dosimetry system; and the extent of similarity between the radiation fields used for calibration and the field present in the workplace. The potential error is much greater for dosimeters with significant variations in response, such as film dosimeters for low-energy photon radiation and the NTA film and TLDs for neutron radiation.

6.2.3.1 Beta/Photon Dosimeters

Dosimeters were calibrated using ^{226}Ra, ^{137}Cs, or ^{60}Co in air (i.e., no phantom) until the 1986 adoption of DOELAP procedures requiring calibration with phantoms. Since 1986, photon calibrations have been to ^{137}Cs with a phantom. Beta calibrations were routinely to ^{90}Sr.

6.2.3.2 Neutron Dosimeters

Neutron dosimeters were calibrated using PuBe sources prior to 1970. Since 1970, unmoderated and moderated ^{252}Cf has been used.

6.2.4 Workplace Radiation Fields

The radiation fields at LLNL are highly variable. They include radiation from a variety of radiation-producing machines such as electron accelerators, X-ray machines, cyclotrons, neutron generators, and a research nuclear reactor. In addition, many different radioactive materials have been used at LLNL. Tables 6-2 and 6-3 list many of the radiation sources that might have been encountered at LLNL over the years. All beta particle energies are greater than 15 keV. In general, beta and/or charged particle exposure around the accelerators is limited to shallow dose. Due to the manner in which accelerated charged particles were contained, individuals would not have been exposed to energetic charged particles. The neutron energy selection of 0.1 – 2.0 MeV indicated in Table 6-3 was chosen because neutron sources were shielded and moderated to this energy range; the energy range of 0.1 – 2.0 MeV has the highest quality factor, as provided in 10 C. F. R. § 835.2, which is favorable to claimants.

6.2.5 Recorded Dose Practices

Table 6-4 summarizes the terminology used to describe dosimeter measured and compliance dose quantities.

6.2.6 Interpretation of Reported Data

Dose reconstructors can use the information in Table 6-5 to assist in the interpretation of LLNL external dosimetry summary reports. Because much of the data prior to 1958 was not adequately defined to directly report shallow and neutron doses, the dose reconstructor should use the guidance found within *External Dose Reconstruction* (ORAUT 2006b), *Interpretation of Dosimetry Data for*

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

Buildings–old numbers[a]	Buildings–new numbers[a]	Description	Radiation type	Energy selection (keV)	Percentage
101, 102, 106, 117, 118, 147, 176, 192	222, 221, 223, 224, 234, 232, 233, 167, 168, 169	**Chemistry:** radioactive materials including Co-60, fission products, enriched uranium, depleted uranium, natural uranium, U-233, Cm-244, Pu-239, Am-241, others	Beta	>15	100
			Photon	30–250 >250	50 50
153, 154, 157, 173, 180, 194	210, 212; 171, 173-177; 241, 243; 435, 442, 443; 194	**Physics:** accelerators, activation products, H-3, others	Beta	>15	100
			Photon	30–250 >250	25 75
103, 114, 125, 127, 174, 175	215, 321, 419, 514, 243, 253	**Lab Services:** radioactive materials	Beta	>15	100
			Photon	30–250 >250	75 25
110	261	Criticality Test Facility	Beta	>15	100
			Photon	30–250 >250	50 50
115	327	Radiography	Beta	>15	100
			Photon	30–250 250	25 75
121	412	Hot cells: high beta waste, Sr-90	Beta	>15	100
			Photon	30–250 >250	75 25
170	131	Weapons	Beta	>15	100
			Photon	<30 30–250	50 50
171	332	Metallurgical Chemistry: AKA Plutonium Facility	Beta	>15	100
			Photon	<30 30–250	50 50
172	331	Gaseous Chemistry: AKA Tritium Facility	Beta	>15	100
			Photon	<30 (tritium brems)	100
182	162, 165, 166	Lab Services: 55 Ci Co-60 (1958)	Beta	>15	100
			Photon	30–250 >250	25 75
190	251	Chemistry Heavy Elements Facility: Cm-244, Am-241, U-233, Pu-239, others	Beta	>15	100
			Photon	<30 30–250 >250	25 50 25
193	281	Reactor	Beta	>15	100
			Photon	30–250 >250	25 75
Site 300	Site 300	Explosives Testing: linear accelerators, depleted uranium, H-3, radiography	Beta	>15	100
			Photon	30–250 >250	25 75

a. LLNL (2005).

Assignment of Shallow Dose (ORAUT 2005a), and *Assignment of Missed Neutron Doses Based on Dosimeter Records* (ORAUT 2005b). A review of the claimant files indicated an inconsistency in the manner in which shallow dose was reported. In some cases, the reported shallow dose includes the shallow and penetrating dose. In other cases, the shallow dose excludes the penetrating dose. For purposes of dose reconstruction, it is assumed that if the reported shallow dose exceeds the penetrating dose, the shallow dose is the sum of the shallow and penetrating doses. If the reported shallow dose is less than the penetrating dose, the shallow dose should be derived as the sum of the shallow dose and the penetrating dose.

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

Buildings–old numbers[a]	Buildings–new numbers[a]	Description[b]	Radiation type	Energy selection (MeV)	Percentage
101, 102, 106, 117, 118, 147, 176, 192	222, 221, 223, 224, 234, 232, 233, 167, 168, 169	Chemistry: radioactive materials including Co-60, fission products, enriched uranium, depleted uranium, natural uranium, U-233, Cm-244, Pu-239, Am-241, others	Neutron	0.1–2.0	100
153, 154, 157, 173, 180, 194	210, 212; 171, 173-177; 241, 243; 435, 442, 443; 194	Physics: accelerators, activation products, H-3, others	Neutron	0.1–2.0	100
103, 114, 125, 127, 174, 175	215, 321, 419, 514, 243, 253	Lab Services: radioactive materials	Neutron	0.1–2.0	100
110	261	Criticality Test Facility	Neutron	0.1–2.0	100
115	327	Radiography	Neutron	0.1–2.0	100
121	412	Hot cells: high beta waste, Sr-90	Neutron	0.1–2.0	100
170	131	Weapons	Neutron	0.1–2.0	100
171	332	Metallurgical Chemistry: AKA Plutonium Facility	Neutron	0.1–2.0	100
172	331	Gaseous Chemistry: AKA Tritium Facility	Neutron	0.1–2.0	100
182	162, 165, 166	Lab Services: 55 Ci Co-60 (1958)	Neutron	0.1–2.0	100
190	251	Chemistry Heavy Elements Facility: Cm-244, Am-241, U-233, Pu-239, others	Neutron	0.1–2.0	100
193	281	Reactor	Neutron	0.1–2.0	100
Site 300	Site 300	Explosives Testing: linear accelerators, depleted uranium, H-3, radiography	Neutron	0.1–2.0	100

a. Trost (2005).
b. The facilities listed in this table represent the buildings where there was a potential for exposure to neutron radiation.

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

Year	Dosimeter measured quantities	Compliance dose quantities
Photon/electron film dosimeter + NTA neutron dosimeter		
1952–1963	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron + beta[a] H = hand extremity dose (HN = hands)
1963–1969	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron S = shallow (SK = skin) = gamma + neutron + beta H = hand extremity dose (HN = hands)
Photon/electron/neutron–Harshaw TLD		
1969–1985	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron S = shallow (SK = skin) = gamma + neutron + beta H = hand extremity dose (HN = hands)
Photon/electron/neutron–Panasonic TLD + CR-39 neutron dosimeter		
1985–present	B/P/N	Skin = NPEN + WB WB = PEN + SN + FN
1995–2003	Shallow (SH or SK) Deep photon (PH DP) Deep neutron (NU DP)	Skin = beta + photon + neutron (B/P/N) WB = photon deep + neutron deep

a. Prior to 1958, beta exposures were recorded as a component of the whole-body dose.

The NTA dosimeter (1952-1969) exhibited a lower neutron energy threshold of approximately 500 keV and consequently underestimated the neutron exposure (Griffith et al. 1979; NIOSH 2006; ORAUT 2006c). The photon dose was measured adequately and all LLNL neutron dose was accompanied by a significant photon dose. For neutron dose received prior to 1969, the dose should be adjusted by using a neutron to photon ratio. The ratio varied by operation and task. There was no comprehensive study of neutron flux at LLNL; the neutron to photon ratio cannot be established using existing data from LLNL. A review of other DOE facilities that handled plutonium reported a neutron to photon ratio

Table 6-5. Interpretation of reported data.

Period	Reported quantity	Description	Interpretation of zeroes	Interpretation of blanks (no data)	Rollup of individual and annual data	Monitored/ unmonitored
1952–1963	rem	Reported WB doses include gamma and beta, sometimes qualified with "G" for gamma only. Neutron doses were designated with "N."	Zeroes were generally not reported. Reported zero should be interpreted as meaning less than MDL.	Blanks should be interpreted as individual was monitored with zero result.	Photon WB dose. Neutron WB dose. Shallow skin dose. Total deep WB dose.	All employees with significant exposure potential were monitored for both gamma and neutron radiation (more than 95% of employees were monitored before 1958).
1963–1985	rem	Reported WB doses qualified as either "G" for gamma or "N" for neutron. Beta reported with "S" and/or "SK" for skin.	Zeroes were generally not reported before 1980. However, for any year, a blank or reported zero result should be interpreted as meaning less than MDL.	Blanks should be interpreted as individual was monitored with zero result.	Photon WB dose. Neutron WB dose. Shallow skin dose. Total deep WB dose.	All employees with significant measurable exposure potential were monitored continuously.
1985–present	rem	Photon deep, neutron deep, and shallow dose reported.	Zeroes were typically reported. Reported zero should be interpreted as meaning less than MDL.	Blanks should be interpreted as individual was monitored with zero result.	Photon WB dose. Neutron WB dose. Shallow skin dose. Total deep WB dose.	All employees with significant measurable exposure potential were monitored continuously.

to range from 0.7 to 0.91. The study at Savannah River indicated the greatest ratio and a value of 1 is recommended for use for LLNL while the NTA film was used (ORAUT 2005c). The neutron to photon ratio applicable to LLNL was determined to have a geometric mean of 1.0, geometric standard deviation of 3.0, and an upper 95th percentile of 6.1.

6.3 ADJUSTMENTS TO RECORDED DOSE

Photon Dose

No adjustment to recorded photon doses is recommended. Prior to 1986, dosimeters might have been calibrated in air (i.e., no phantom). Dose reconstructors should use roentgen-to-organ dose conversion factors (DCFs) when assessing reported photon doses prior to 1986. Since 1986, deep dose equivalents at LLNL have been based on DOELAP calibration to *Hp(10)*. Use *Hp(10)*-to-organ DCFs beginning in 1986. Table 6-6 lists adjustments to recorded dose [5].

Neutron Dose

Neutron exposure reported prior to 1969 was likely under-estimated. The NTA film was inadequate to retrospectively assess an estimate of the neutron dose that is assuredly favorable to claimants. The use of a neutron to photon ratio is described in Section 6.2.6 of this document.

To ensure favorability to the claimant, dose reconstructors can generally consider the neutron energies at LLNL to be between 0.1 and 2.0 MeV, for which the ICRP Publication 60 radiation weighting factor is 20 (ICRP 1991). The associated dose correction factor is 1.91. Dose reconstructors should apply this factor to measured neutron dose equivalent and missed neutron dose equivalent. See Table 6-6 [6].

Table 6-6. Adjustments to recorded dose.

Period	Dosimeter	Facility	Adjustment to reported dose
1952–1985	Photon dosimeters	All facilities	Use roentgen-to-organ dose conversion factors.
1986–present	Photon dosimeters	All facilities	Use *Hp(10)*-to-organ dose conversion factors.
All years	Neutron dosimeters	All facilities	Multiply reported doses by factor of 1.91 to account for ICRP 60 weighting factors (ICRP 1991; ORAUT 2006d).

6.4 MISSED AND UNMONITORED DOSE

The potential for missed dose exists when workers are exposed to radiation at levels below the detection limit of their personnel dosimeters. In the early years of radiation monitoring, when relatively high detection limits are combined with short monitoring durations, missed doses can be significant. This section discusses methodologies for estimating missed doses.

Unmonitored dose pertains to the potential dose received by workers who did not wear personnel dosimetry. LRL (ca. 1954) documented that all workers at Livermore were monitored for dose beginning in 1954. However, review of individual worker's files indicates gaps in monitoring. This is evident for employees with low dose potential [7].

Watson et al. (1994) examined methods analysts can consider when there is no recorded dose for a period during a working career. The missed dose for dosimeter results less than the MDL is particularly important for earlier years when MDLs were higher and dosimeter exchange was more frequent. NIOSH (2006) describes options to calculate missed dose for this situation. The preferred option estimates a potential missed dose favorable to claimants as MDL/2 multiplied by the number of zero-dose results. Table 6-1 lists the results of these calculations. The analysis of co-worker data is the best estimate of unmonitored dose however, the analysis is not available at this time. A review of the co-worker study at the Los Alamos National Laboratory (LANL) indicated that exposure data exhibited a lognormal distribution and a geometric standard deviation (GSD) ranging from 2.7 to 5.82 (ORAUT 2005d). The dose reconstructor should assume the LLNL results to have a lognormal distribution and a geometric standard deviation (GSD) of 4.0. The use of data from LANL provides an example of similar work performed with similar materials where the same type of controls were applied. The regulations for personnel exposure were the same for LLNL and LANL. In the absence of actual data from LLNL, the use of data from LANL is a reasonable attempt at providing estimates of dose distributions. The geometric mean and associated GSD for external exposures were provided in Table 6E-2 of the LANL TBD (ORAUT 2005d). The data were provided by each year of operation. It should only be used when no other LLNL specific data are available.

Specific incident reports might address significant nonroutine worker doses, such as skin contamination events. The dose assessments in such reports, based on investigations conducted at the time of the incident, should be the best estimates of dose received.

6.5 BIAS AND UNCERTAINTY

A number of factors contribute to uncertainty in measured doses. 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 and the energy spectra and geometries of their exposures. This TBD analysis found no specific uncertainty assessments for LLNL dosimeter systems. However, the systems have much in common with systems used at other facilities, such as the DOE Hanford Site, for which extensive studies have been performed (Wilson et al. 1990; Fix, Gilbert, and Baumgartner 1994). The similarities enable reasonable comparisons for the LLNL systems based on experience at Hanford and elsewhere.

NIOSH (2006) provides guidance for estimating uncertainty in external dose reconstruction. Under good laboratory conditions, film-badge uncertainty can be at the level of 10% to 15%. The absolute uncertainty at 95% confidence should not be less than the MDL, which for LLNL, was as high as 0.03 rem for beta/gamma film (Table 6-1). Figure 2.1 of NIOSH (2006) shows the results from two methods of calculating the uncertainty factor. In the absence of any other site-specific data, dose reconstructors should use numerical values employed for film-badge dose reconstruction [8].

An uncertainty factor of 1.2 is appropriate for dosimetry results based on the simplified dosimetry uncertainty modeling for film contained within NIOSH (2006). The uncertainty for TLDs is generally smaller than that for film and somewhat less dependent on energy. Dose reconstructors should use an uncertainty factor of 1.2, which is favorable to claimants for doses measured with both film and TLDs [9]. A reasonable option consistent with other TBDs and in dose reconstruction is to assume an uncertainty of ±30% for film and of ±20% for TLD. It is recommended that dose reconstructors assume a constant input to IREP by multiplying the measured dose by 1.3 for film and 1.2 for TLD.

Relatively little information is available on uncertainty for shallow dose. In view of the similar mechanisms between photon and beta film dosimetry, NIOSH (2006) recommends applying the methodology described above to the beta dose.

Table 6-7 lists bias and uncertainty factors for LLNL.

Table 6-7. Bias and uncertainty [10].

Site-specific dosimetry system	Bias magnitude and range	
	Overall bias[a]	**Range in bias[b]**
Photon/electron film (1952–1969)	1.0	0.7–1.3
Neutron NTA film (1952–1969)	c	c
Harshaw photon/electron/neutron TLD (1969–1985)	1.0	0.8–1.2
Panasonic photon/electron TLD (1986–present)	1.0	0.8–1.2
CR-39 neutron (1986–present)	1.0	0.6–1.5

a. Based on the distribution of energy levels and geometry judged most likely. Divide recorded dose by the table's bias value to calculate deep dose.
b. Range of overall bias factors based on alternative distributions of energy levels and geometry.
c. Neutron dose for this time period should be based on the neutron to photon dose ratio. There is documentation that NTA film cannot provide reliable estimates of neutron dose.

6.6 DOSE RECONSTRUCTION

As much as possible, the basis for dose to individuals should be the dosimetry records. It is important to distinguish between the recorded non-penetrating and penetrating doses and the actual *Hp(0.07)* and *Hp(10)*. The following list contains appropriate guidance:

- Worker dosimetry records that provide nonzero beta-photon values for *Hp(10)* and *Hp(0.07)* are adequate. Dose reconstructors should consider beta energies to be greater than 15 keV and, unless known to be otherwise, photon energies to be within the energy range of 30 to 250 keV which is favorable to claimants [11].

- Radionuclides used in the various buildings and facilities are described in the LLNL site description (ORAUT 2005e.) These will give the dose reconstructor additional evidence as to whether shallow doses are primarily from beta or low-energy X-rays if a particular building is cited in the workers' history files. If no evidence can be found as to the source of shallow dose, an approach that is favorable to claimants should be taken. In general, for most non-skin cancers, this results in assigning shallow dose to the 30- to 250-keV photons; for skin cancers on exposed skin, assigning the dose to beta particles is more favorable to claimants [12].

- Dose reconstructors should assign missed dose for workers for whom dosimetry records provide zero beta-photon values for *Hp(10)* and *Hp(0.07)* as identified in NIOSH (2006). This approach is conservative based on a review of historical data [13].

- For unmonitored workers, dose reconstructors should use the guidance in ORAUT-OTIB-0020 (ORAUT 2005f) to apply a dose based on coworker data [14].

- For unmonitored workers whose exposure potential has been determined to be low, assign the environmental dose [15].

- The LLNL dosimetry programs were designed to measure the non-penetrating exposure to workers. The guidance in ORAUT-OTIB-0017 (ORAUT 2005a) should be used to reconstruct the non-penetrating dose.

- No evidence could be found to indicate whether elevated ambient levels of external radiation were subtracted from workers' doses. However, because of the LLNL's facility type, it is unlikely that there would have been a significant elevated ambient dose (ORAUT 2003b).

6.7 ORGAN DOSE

NIOSH (2006) discusses the conversion of measured doses to organ dose equivalent; Appendix B of that document contains the appropriate DCFs for each organ, radiation type, and energy range based on the type of monitoring performed. In some cases, simplifying assumptions are appropriate. For periods when calibrations were performed in free air, prior to 1986, dose reconstructors should use the exposure-to-organ DCF. For recorded doses from 1986 to the present, use the *Hp(10)*-to-organ DCF.

6.8 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations to assist in the process of worker dose reconstruction. These callouts are listed in this section with information that identifies the source and justification for each item. Conventional references are provided in the next section that link data, quotations, and other information to documents available for review on the Oak Ridge Associated Universities (ORAU) Team servers.

[1] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006.
Mr. Thomas reviewed the types of activities described in ORAUT (2005e) to establish the type of dosimeter, exchange frequency, and associated MDL and missed dose. The MDL was estimated by the dosimeter technology and the exchange period. When possible, the annual missed dose was calculated using the method selected by MDL/2 in OCAS-IG-001 (NIOSH 2006). From 1952 to 1955, the dosimeters were issued and processed by LBNL.

[2] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006.
Mr. Thomas reviewed the types of activities described in ORAUT (2005e). Given the type of operations and the types of radioactive isotopes reported for each building, the energy fractions were selected in a manner similar to those for the LANL facilities.

[3] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. Mr. Thomas reviewed the types of activities that involved isotopes and tasks in which neutron radiation could be encountered as described in ORAUT (2005e). Given the type of operations and the types of radioactive isotopes reported for each building, the neutron energy selection of 0.1 – 2.0 MeV indicated in Table 6-3 was chosen because neutron sources were shielded and moderated to this energy range; the energy range of 0.1 – 2.0 MeV has the highest quality factor, as provided in 10 CFR 835.2, which is favorable to claimants.

[4] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 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.

[5] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. Before 1986, external dosimeters were calibrated in air without the use of a phantom. The "roentgen to organ" dose is adequately calculated using the DCFs used by the dose reconstructors. In 1986, LLNL changed its calibration procedures to use DOELAP requirements. The adjustments listed in Table 6-6 are consistent with other site technical basis documents, including those for LANL and RFETS.

[6] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. Adjustments to neutron exposure are described in ICRP Publication 60 for neutron energies between 0.1 and 2.0 MeV (ICRP 1991). The dose correction factor of 1.91, reported in ICRP Publication 60, should be used to provide a correction to reported exposures and the calculation of missed dose.

[7] Szalinski, Paul A. Integrated Environmental Management. Health Physicist. March 2007. Review of NIOSH-Office of Compensation Analysis and Support Claims Tracking System (NOCTS) cases, which included the Position/Titles of "Computer Administrator," "Administrative Assistant," "Administrative Specialist," and "Secretary," all showed unmonitored periods.

[8] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. The uncertainty factor for film badge dose reconstruction is provided by OCAS-IG-001 (NIOSH 2006). This approach provides a series of consistent, assumptions for each DOE site, including LLNL, that are favorable to claimants. In the event that LLNL provided specific uncertainty factors for a particular film badge or batch of dosimeters, dose reconstructors should use the NIOSH assumptions.

[9] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. OCAS-IG-001 (NIOSH 2006) indicates that the uncertainty for TLD results is lower than the uncertainty assumed for film. The uncertainties of 1.3 for film and 1.2 for TLDs were derived from OCAS-IG-001 and should be assigned to film and TLD results at LLNL.

[10] Smith, Matthew H. ORAU Team. Health Physicist. May 2006. Mr. Smith reviewed the bias described for the types of dosimeters and LLNL facilities. He recommended a revision of the table to be consistent with the Hanford TBD (ORAUT 2006c).

[11] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. Some dosimetry results do not distinguish between penetrating and nonpenetrating dose. The dose reconstructor is reminded to use an energy range dose that is favorable to claimants for nonpenetrating photons and a beta energy that will penetrate the outer layer of skin.

[12] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. The guidance provided describes two calculations by the dose reconstructor, exposed skin and covered skin. Some dosimetry results do not distinguish between penetrating and nonpenetrating dose. The dose reconstructor is reminded to assign a dose estimate dose which is favorable to claimants.

[13] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. Some dosimetry results do not distinguish between penetrating and nonpenetrating dose. The assignment of missed dose that is described in OCAS-IG-001 is considered to be conservative. A review of historical data in NOCTS indicates that the missed dose assigned in OCAS-IG-001 (NIOSH 2006) is higher than the dose that would be assigned using the coworker data.

[14] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. The purpose of ORAUT-OTIB-0020 (ORAUT 2005f) is to provide general information to enable ORAU Team dose reconstructors to assign doses to workers at DOE sites who have little or no individual monitoring data.

[15] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006. The radiation dose for unmonitored workers is characterized by ORAUT-OTIB-0020 (ORAUT 2005f) and the external dose assigned by the environmental dose described in ORAUT (2005g). A low exposure potential is assumed to be a task in which an employee did not routinely handle radioactive materials and might have worked in an office environment and/or an administrative role.

REFERENCES

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]

Fix, J. J., E. S. Gilbert, and W. V. Baumgartner, 1994, *An Assessment of Bias and Uncertainty in Recorded Dose from External Sources of Radiation for Workers at the Hanford Site*, PNL-10066, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, August. [SRDB Ref ID: 305]

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]

Griffith, R. V., D. E. Hankins, R. B. Gammage, and L. Tommasino, 1979, “Recent Developments in Personnel Neutron Dosimeters - A Review,” *Health Physics*, volume 36, number 3, pp. 235–260. [SRDB Ref ID: 7965]

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), 1996, *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, Publication 74, Pergamon Press, Oxford, England.

ICRU (International Commission on Radiation Units and Measurements), 1998, *Conversion Coefficients for Use in Radiological Protection Against External Radiation*, Report 57, Bethesda, Maryland.

LRL (Lawrence Radiation Laboratory), ca. 1954, *Personnel Monitoring Procedure for all UCRL, Livermore*, University of California, Livermore, California. [SRDB Ref ID: 23478]

Morgan, K. Z., 1961, “Dosimetry Requirements for Protection from Ionizing Radiation,” *Selected Topics in Radiation Dosimetry, Proceedings of the Symposium on Selected Topics in Radiation Dosimetry, Sponsored by and Held in Vienna 7-11 June 1960*, International Atomic Energy Agency, Vienna, Austria, pp. 3–23. [SRDB Ref ID: 8345]

NIOSH (National Institute for Occupational Safety and Health), 2006, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 2, Office of Compensation Analysis and Support, Cincinnati, Ohio, August 25.

Nolan, W. E., 1958, “Progress Report on Film Badge Program,” memorandum to D. C. Sewell, 1958, University of California, Lawrence Radiation Laboratory, Livermore, California, November 13. [SRDB Ref ID: 23005]

ORAUT (Oak Ridge Associated Universities Team), 2003, *Technical Information Bulletin: Occupational Dose from Elevated Ambient Levels of External Radiation*, ORAUT-OTIB-0007, Rev. 00, Oak Ridge, Tennessee, November 12.

ORAUT (Oak Ridge Associated Universities Team), 2005a, *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), 2005b, *Assignment of Missed Neutron Doses Based on Dosimeter Records*, ORAUT-OTIB-0023, Rev. 00, Oak Ridge, Tennessee, March 7.

ORAUT (Oak Ridge Associated Universities Team), 2005c, *Savannah River Site*, ORAUT-TKBS-0003, Rev. 03, Oak Ridge, Tennessee, April 5.

ORAUT (Oak Ridge Associated Universities Team), 2005d, *Los Alamos National Laboratory – Occupational Internal Dose*, ORAUT-TKBS-0003, Rev. 02, Oak Ridge, Tennessee, May 10.

ORAUT (Oak Ridge Associated Universities Team), 2005e, *Lawrence Livermore National Laboratory – Site Description*, ORAUT-TKBS-0035-4, Rev. 00 PC-1, Oak Ridge, Tennessee, October 26.

ORAUT (Oak Ridge Associated Universities Team), 2005f, *Use of Coworker Dosimetry Data for External Dose Assignment*, ORAUT-OTIB-0020, Rev. 01, Oak Ridge, Tennessee, October 7.

ORAUT (Oak Ridge Associated Universities Team), 2005g, *Lawrence Livermore National Laboratory – Occupational Environmental Dose*, ORAUT-TKBS-0035-4, Rev. 00, Oak Ridge, Tennessee, November 18.

ORAUT (Oak Ridge Associated Universities Team), 2006a, *Site Profile for the Lawrence Berkeley National Laboratory*, ORAUT-TKBS-0049, Rev. 00, Oak Ridge, Tennessee, August 7.

ORAUT (Oak Ridge Associated Universities Team), 2006b, *External Dose Reconstruction*, ORAUT-PROC-0006, Rev. 00 PC-3, Oak Ridge, Tennessee, December 11.

ORAUT (Oak Ridge Associated Universities Team), 2006c, *Hanford Site – Occupational External Dosimeter*, ORAUT-TKBS-0006-6, Rev. 02, Oak Ridge, Tennessee, November 21.

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]

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

Trost [illeg.], M., 2005, "LLNL Building Index: Pre 1966 and Post 1966," facsimile to J. J. Maisler (Integrated Environmental Management), University of California, Lawrence Livermore National Laboratory, Livermore, California, February 15. [SRDB Ref ID: 16948]

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]

Wilson, R. H., J. J. Fix, W. V. Baumgartner, and L. L. Nichols, 1990, *Description and Evaluation of the Hanford Personnel Dosimeter Program from 1944 through 1989*, PNL-7447, Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, September. [SRDB Ref ID: 4793]

GLOSSARY

beta radiation
Radiation consisting of electrons emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) direct fission products emit beta radiation. The beta particle is physically identical to an electron moving at high velocity.

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

deep dose equivalent (H_d)
The dose equivalent at a depth of 10 millimeters in tissue.

dose equivalent (*H*)
The product of the absorbed dose (*D*), the quality factor (*Q*), and any other modifying factors. The special unit is the rem. When *D* is expressed in grays, *H* is in sieverts (1 sievert equals 100 rem).

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

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

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

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

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

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

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

missed dose

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

neutron

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

neutron film dosimeter

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

nuclear track emulsion, Type A (NTA)

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

occupational dose

The radiation dose resulting from a claimant's exposure to radiation and/or to radioactive material while working at the LLNL site. Occupational dose does not include, for example, exposure to background radiation (including radon), dose as a patient from medical practices (including for treatment of work related injuries), dose from voluntary participation in medical research programs, or dose received as a member of the general public.

personal dose equivalent $H_p(d)$

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

photon

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

rad

The traditional unit of absorbed dose (one rad equals 100 ergs per gram of material absorbing the radiation energy). The word derives from *radiation absorbed dose*.

radiation

Alpha, beta, neutron, and photon radiation.

radioactivity

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

rem

The traditional unit of dose equivalent, which is equal to the product of the absorbed dose in rad and the quality factor of the radiation. The word derives from *roentgen equivalent in man*.

roentgen

A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kilogram of dry air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (more than about 100 kilovolts-electron) energy photons.

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

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

sievert (Sv)
The International System unit for dose equivalent (1 sievert equals 100 rem).

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

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

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

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

X-ray
(1) Ionizing electromagnetic radiation of external nuclear origin. (2) A radiograph.