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Dose Reconstruction
Project for NIOSH

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ACRONYMS AND ABBREVIATIONS

CR-39   Canadian Resin Number 39, a polycarbonate material used for neutron dosimetry

DCF   dose conversion factor
DOE   U. S. Department of Energy
DOELAP   DOE Laboratory Accreditation Program
DOL   U.S. Department of Labor

EEOICPA   Energy Employees Occupational Illness Compensation Program Act

$Hp(d)$ 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

LBNL   Lawrence Berkeley National Laboratory
LLNL   Lawrence Livermore National Laboratory

MDL   minimum detection level
MED   Manhattan Engineer District

NVLAP   National Voluntary Laboratory Accreditation Program
NIOSH   National Institute for Occupational Safety and Health
NTA   nuclear track emulsion, type A

TBD   technical basis document
TLD   thermoluminescent dosimeter

U.S.C.   United States Code

WB   whole body

6.1   <u>INTRODUCTION</u>

Site Profiles, which include Technical basis documents (TBDs), 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 when additional relevant information is obtained about the affected site(s). These documents may be used to assist the 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 facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 (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 DOE employees 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 [probability of causation] 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 radiation exposures 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 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.

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

Workers at the Lawrence Livermore National Laboratory (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. The *External Dose Reconstruction Implementation Guideline* (NIOSH 2002) identified dosimeter records as the highest quality records for a retrospective dose assessment.

Radiation dosimetry practices were initially based on experience gained during several decades of radium and X-ray medical diagnostic and therapy applications. These methods were generally well advanced at the start of the Manhattan Engineer District (MED) program to develop nuclear weapons beginning about 1940 (Morgan 1961; Taylor 1971).

6.2   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.

6.3   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):

- Administrative practices that facilities adopt 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 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.

6.3.1   <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
- 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). By 1956, LLNL had its own fully functional personnel dosimetry program with in-house processing.

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.

Period of use	Dosimeter	MDL[a] (rem)	Exchange frequency[b]	Max. 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	Semi-annual (n=2)	0.025
	Neutron – CR-39	0.010	Monthly (n=12)	0.06
		0.010	Quarterly (n=4)	0.02

a.   Estimated MDLs for each dosimeter technology 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.   Maximum annual missed dose calculated using the MDL/2 method from NIOSH (2002).
d.   From 1952 to 1955, LBNL processed film dosimeters.

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.

6.3.2   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 accurately measure radiation dose as discussed in later sections depends on radiation type, energy, exposure geometry, etc. The dosimeter 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.

6.3.2.1   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 1955. 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.

6.3.2.2   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 1955 through 1969. At some atomic weapons employer facilities or Department of Energy 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" (Block, 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 Lawrence Berkeley National Laboratory to develop the Technical Basis Documents may provided 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." No where 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 design, which minimized the over-response of the earlier design, was in use until 1985 when LLNL adopted Panasonic TLDs. Also in 1985, CR-39 neutron dosimeters were introduced and used with the Panasonic TLDs. This system continues in use at present.

6.3.3   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.

6.3.3.1   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.

6.3.3.2   Neutron Dosimeters

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

6.3.4   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 CFR 835.2, which is claimant favorable.

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

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	50
				> 250	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	25
				> 250	75
103, 114, 125, 127, 174, 175	215, 321, 419, 514, 243, 253	**Lab Services:** radioactive materials	Beta	>15	100
			Photon	30–250	75
				> 250	25
110	261	Criticality Test Facility	Beta	>15	100
			Photon	30–250	50
				> 250	50
115	327	Radiography	Beta	>15	100
			Photon	30–250	25
				> 250	75
121	412	**Hot cells**: high beta waste, Sr-90	Beta	>15	100
			Photon	30–250	75
				> 250	25
170	131	Weapons	Beta	>15	100
			Photon	<30	50
				30–250	50
171	332	Metallurgical Chemistry: AKA **Plutonium Facility**	Beta	>15	100
			Photon	<30	50
				30–250	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	25
				> 250	75
190	251	Chemistry **Heavy Elements Facility**: Cm-244, Am-241, U-233, Pu-239, others	Beta	>15	100
			Photon	<30	25
				30–250	50
				> 250	25
193	281	**Reactor**	Beta	>15	100
			Photon	30–250	25
				> 250	75
Site 300	Site 300	**Explosives Testing**: linear accelerators, depleted uranium, H-3, radiography	Beta	>15	100
			Photon	30–250	25
				> 250	75

a. LLNL 2005

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

Buildings - old numbers[a]	Buildings - new numbers[a]	Description	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.   LLNL 2005

6.3.5   <u>Recorded Dose Practices</u>

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

Table 6-4. Recorded dose practices.

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 Oct. 18, 1963, beta exposures were recorded as a component of the whole-body dose.

6.3.6 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 1963 was not adequately defined to directly report shallow and neutron doses the dose reconstructor should use the guidance found within *External Dose Reconstruction* (NIOSH 2003a), *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (NIOSH 2005a) and *Assignment of Missed Neutron Doses Based on Dosimeter Records* (NIOSH 2005b.)

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.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	All employees with significant exposure potential were monitored (more than 95% of employees were monitored before 1958). After 1958, all employees were monitored continuously.
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. Reported zero should be interpreted as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	All employees were monitored continuously.
1985 - present	rem	Photon deep, neutron deep, and shallow dose reported.	Zeroes were typically reported. Reported zero should be interpreted as meaning less than MDL.	No data or blanks should be interpreted as individual was monitored with zero result.	Photon WB dose Neutron WB dose Shallow skin dose Total deep WB dose	All employees were monitored continuously.

6.4 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.

Neutron Dose
To ensure claimant favorability, 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 1990). The associated dose correction factor is 1.91, which is rounded to 2. Dose reconstructors should apply this factor to measured neutron dose equivalent and missed neutron dose equivalent. See Table 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 2 to account for ICRP 60 weighting factors (ICRP 1990).

6.5   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. This situation existed at LLNL only before May 1958, when dosimeters were incorporated in the security badges and worn by all employees regardless of exposure potential. Prior to May 1958, workers with little potential for occupational radiation exposure were not generally monitored.

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 (2002) describes options to calculate missed dose for this situation. The preferred option estimates a claimant-favorable maximum potential missed dose as MDL/2 multiplied by the number of zero-dose results. Table 6-1 lists the results of these calculations.

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.

6.6   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 (2002) 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 (2002) 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.

An uncertainty factor of 1.2 is appropriate for dosimetry results based on the simplified dosimetry i=uncertainty modeling for film contained within NIOSH (2002). 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 claimant-favorable for doses measured with both film and TLDs.

Relatively little information is available on uncertainty for shallow dose. In view of the similar mechanisms between photon and beta film dosimetry, NIOSH (2002) 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.

	Bias magnitude and range	
Site-specific dosimetry system	Overall bias[a]	Range in bias[b]
Photon/electron film (1952 - 1969)	1.0	0.7 - 1.3
Neutron NTA film (1952 - 1969)	1.0	0.5 – 2.0
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.

6.7   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 nonpenetrating 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 claimant-favorable energy range of 30 to 250 keV.

- Radionuclides used in the various buildings and facilities are described in the LLNL site description (NIOSH 2005c.) 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, a claimant favorable approach 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 client favorable.

- 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 (2002). This approach is conservative based on a review of historical data.

- For unmonitored workers, dose reconstructors should solicit and use coworker data. In general, assign the maximum reasonable coworker dose as a claimant-favorable estimate. As an alternative, use population data.

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

- Prior to 1963, the reported whole body dose is a good estimate of the skin dose, since it includes both the penetrating and shallow components (both of which would contribute to skin dose). Prior to 1963, the reported "whole body" dose represents an overestimate of the deep dose because it included a shallow-only component. The recommendation for pre-1963 dosimetry records would be to accept the reported whole body dose as both shallow and deep. This would be claimant-favorable and reasonable since it will not be possible for a dose reconstructor to break the reported whole body dose down into deep and shallow components. Also see NIOSH (2005a) for additional guidance on reconstructing 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 (NIOSH 2003b.)

6.8 ORGAN DOSE

NIOSH (2002) discusses the conversion of measured doses to organ dose equivalent, and Appendix B of that document contains the appropriate dose conversion factors 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.

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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 exposure to background radiation, as a patient from medical practices, from voluntary participation in medical research programs, or as a member of the general public.

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 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.