ORAU TEAM
Dose Reconstruction Project for NIOSH

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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.
02/26/2010	02	Revision to incorporate LLNL measured personnel doses, LLNL document collections and to respond to comments. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Stephen Spanos and Ralph W. Kenning.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ALARA	as low as reasonably achievable
amp	ampere
AVLIS	Atomic Vapor Laser Isotope Separation
CFR	Code of Federal Regulations
Ci	curie
cm	centimeter
CR-39	allyl diglycol carbonate or Columbia Resin
CTW	construction trade worker
d	day
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
DOT	U.S. Department of Transportation
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ERDA	U.S. Energy Research and Development Administration
eV	electron-volt
FN	fast neutron
g	gram
GM	geometric mean
GSD	geometric standard deviation
Hp(d)	personal dose equivalent at depth *d* (deep dose, *d* = 10 mm; shallow dose, *d* = 0.07 mm) in tissue
HE	high-explosive
hr	hour
ICRP	International Commission on Radiological Protection
ICT	Insulated Core Transformer
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LINAC	linear accelerator
LLL	Lawrence Livermore Laboratory
LLNL	Lawrence Livermore National Laboratory
LOD	limit of detection
LPTR	Livermore Pool Type Reactor
LRL	Lawrence Radiation Laboratory
m	meter
MeV	megaelectron-volt, 1 million electron-volts

mm	millimeter
mR	milliroentgen
mrem	millirem
mSv	millisievert
MW	megawatt
n	neutron
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology
NIOSH	National Institute for Occupational Safety and Health
NP	neutron-to-photon
ns	nanosecond
NTA	nuclear track emulsion, type A
NTS	Nevada Test Site
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
OSP	Operational Safety Procedure
OW	open window
PIC	pocket ionization chamber
PNL	Pacific Northwest Laboratory
POC	probability of causation
R	roentgen
RBE	relative biological effectiveness
RTNS	Rotating Target Neutron Source
S	radiation response in the shielded region of film
s	second
SEC	Special Exposure Cohort
SN	slow neutron
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
TED	track-etch dosimetry
TLD	thermoluminescent dosimeter
TRIGA	Training, Research, Isotopes, General Atomics
UCRL	University of California Radiation Laboratory
U.S.C.	United States Code
WB	whole-body
wk	week
yr	year
μrem	microrem
γ	gamma
§	section or sections

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

The statute also includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2007a):

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

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

6.1.1 Purpose

The Lawrence Livermore National Laboratory (LLNL) was established in 1952 as a major government-owned scientific and nuclear weapons research site. Later operations included nonmilitary applications of nuclear energy. The purpose of this TBD is to describe the external radiation dosimetry systems and protection practices at LLNL. This document discusses historical and current practices in relation to the evaluation of external radiation exposure of monitored and unmonitored workers. It documents historical practices at LLNL and provides information for the evaluation of external radiation exposed workers. It can serve as a supplement to, or substitute for, individual monitoring data.

6.1.2 Special Exposure Cohort Petition Information for LLNL

Classes Added to the SEC

NIOSH has determined, with concurrence from the Secretary of Health and Human Services (HHS), that MFP doses at LLNL cannot be reconstructed with sufficient accuracy between 1950 and 1973, inclusive. For this reason, the following class of LLNL employees has been added to the SEC (Leavitt 2008).

Employees of the DOE, its predecessor agencies, and DOE contractors or subcontractors who were monitored for radiation exposure while working at the Lawrence Livermore National Laboratory from January 1, 1950, through December 31, 1973, for a number of workdays aggregating at least 250 workdays or in combination with workdays within the parameters established for one or more other classes of employees in the Special Exposure Cohort.

Class Recommended by NIOSH for addition to the SEC

NIOSH has subsequently determined that MFP doses for workers not monitored for radiation exposure at LLNL also cannot be reconstructed with sufficient accuracy between 1950 and 1973, inclusive. For this reason, NIOSH has recommended that the following class of LLNL employees be added to the SEC (NIOSH 2009).

All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Lawrence Livermore National Laboratory in Livermore, California from January 1, 1950 through December 31, 1973, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort.

The NIOSH-recommended SEC class includes all workers during the SEC period. Because of the identified dose reconstruction infeasibility, all dose reconstructions for all workers having employment during the SEC period are considered partial dose reconstructions. If monitoring data are available for workers included in the SEC, dose is to be assigned as appropriate based on such data; however, such dose reconstructions are still considered partial dose reconstructions because the HHS has determined that exposure to mixed fission and activation products during the SEC period cannot be bounded.

6.1.3 Scope

Workers at LLNL were exposed to radiation from a variety of radioactive materials and radiation-producing machines. LLNL workers were assigned beta/photon dosimeters apparently from the beginning of operations. LLNL workers also worked at the Nevada Test Site (NTS) 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 significant occupational radiation exposure. As illustrated in Attachment A, Section A.2, the operations and radiation safety staff routinely reviewed LLNL workplace hazards and dosimeter results for compliance with radiation control limits and investigated doses approaching weekly, quarterly, or annual radiation dose limits. LLNL radiation dosimetry practices were based on experience at other DOE laboratories such as Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL). The collective DOE radiation protection experience also included 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 6.10.

6.2 LLNL OPERATIONS

LLNL in Livermore, California, is a DOE scientific laboratory. The University of California managed and operated LLNL until October 1, 2007, when a partnership of the University of California, Bechtel Corporation, Babcock and Wilcox, the URS Corporation, and Battelle Memorial Institute assumed this role. LLNL was established in 1952 as the Lawrence Radiation Laboratory (LRL) at Livermore as an associated operation of the University of California Radiation Laboratory (UCRL) at Berkeley (now LBNL). The University of California-administered LBNL and LLNL had close working relationships. In historical official planning documents and records, LBNL is designated as Site 100, LLNL as Site 200, and LLNL's remote test location as Site 300. This TBD addresses LLNL operations at the historical Site 200 and Site 300 operations. LBNL radiation protection practices are expected to have been adopted at LLNL during the earliest years of LLNL operation. Personnel dosimetry at LLNL was provided by the LBNL dosimetry laboratory initially until LLNL developed capabilities to process staff and visitor assigned dosimeters. There is ongoing collaboration between these two laboratories.

6.2.1 Radiation Safety Practices

Information regarding routine LLNL radiation safety practices historically is available from the various references and policies noted in Attachment A. Table A-1 contains a detailed summary of radiation protection whole-body (WB), skin, and extremity (hand) dose limits applicable to DOE and predecessor agencies historically along with LLNL site-specific guidance. Section A.2 contains a historical timeline of radiation associated reports and events that illustrate LLNL practices and policies. LLNL workers were assigned personnel dosimeters provided by LBNL in 1952 based on the LLNL dose records, and according to policy (Thompson 1953; Block 1954) all workers were issued personnel film and pocket dosimeters by LLNL beginning in March 1953. Available LLNL radiation protection guidance to monitor and control worker exposure to radiation is summarized in Table 6-1.

Table 6-1. LLNL radiation protection guidance.

Reference	Description
Block 1954; LRL ca. 1954	Block, S., 1954, "Personnel Monitoring Procedure for UCRL, Livermore," memorandum to All Department Heads, University of California, Lawrence Radiation Laboratory, Livermore, California, July 19. [SRDB Ref ID: 16949] LRL (Lawrence Radiation Laboratory), ca. 1954, *Personnel Monitoring Procedure for UCRL, Livermore*, University of California, Livermore, California. [SRDB Ref ID: 23478] These references described features and requirements of LLNL personnel monitoring as follows: • Film badges were provided for all personnel employed at UCRL, Livermore site. Each film badge was identified with a number assigned to an individual. • PICs would be provided at the Film Badge Office for those who did not have access to them. The PICs would be read and a record kept of the individual's exposure. Because one of the chambers was a self-reading type, the exposure could be read by the individual concerned. • For those who worked in radiation areas, the film badges were exchanged once a week. • For personnel who did not work in a radiation area, film badges were exchanged monthly. • Persons who routinely visited radiation areas would have film badges exchanged weekly. This group included laboratory guards and custodians and some installation and maintenance personnel. • Any person who suspected a significant exposure had to have their dosimeter processed as soon as possible on delivery to Health Physics. • Measured exposures exceeding 0.3 rem/wk required an investigation.
LLL 1977	LLL (Lawrence Livermore Laboratory), 1977, *Health and Safety Manual*, M-010, Change 10, University of California, Livermore, California, November 1. [SRDB Ref ID: 15756] This manual described the radiation safety regulations and LLNL practices to monitor, measure, and control worker exposure to comply with Chapter 0524 of the *ERDA Manual* (ERDA 1977).
Straume 1980	Straume, T., 1980, *Radiation Safety Program for Site 300*, University of California, Lawrence Livermore Laboratory, Livermore, California, September. [SRDB Ref ID: 72845]

Personnel film beta/photon dosimeters and pocket ionization chambers (PICs) were made available beginning at least as early as 1953, and records were maintained of only the measured positive doses (Block 1954). Recorded doses began in 1952. Trends in the number of monitored workers are shown in Figure 6-1, which is based on analysis of a copy of LLNL radiological records (Shingleton 2007). The analysis was of dose records with beginning and ending wear dates less than 18 months apart (i.e., multiyear transfer doses from previous employers for new employees are often recorded in subsequent employer records with a single dose entry covering a multiyear period) to minimize the impact from transfer doses from other facilities on the analysis. Figure 6-1 illustrates the number of monitored workers and the number of workers with positive recorded WB dose from photon and neutron radiation, respectively. The trend in the number of monitored workers and the number of workers with positive recorded photon dose is nearly identical before the early 1980s, which confirms the LLNL stated practice to record positive measured doses only. The trend in the number of workers with a measured positive neutron dose illustrates a gradual increase beginning in the 1980s. The situation concerning technical limitations to measure neutron radiation dose in many workplaces is discussed below in this TBD. Basically, LLNL workers were monitored and the positive dose results recorded before the mid-1980s approximately, and thereafter all doses (including zero doses) were recorded.

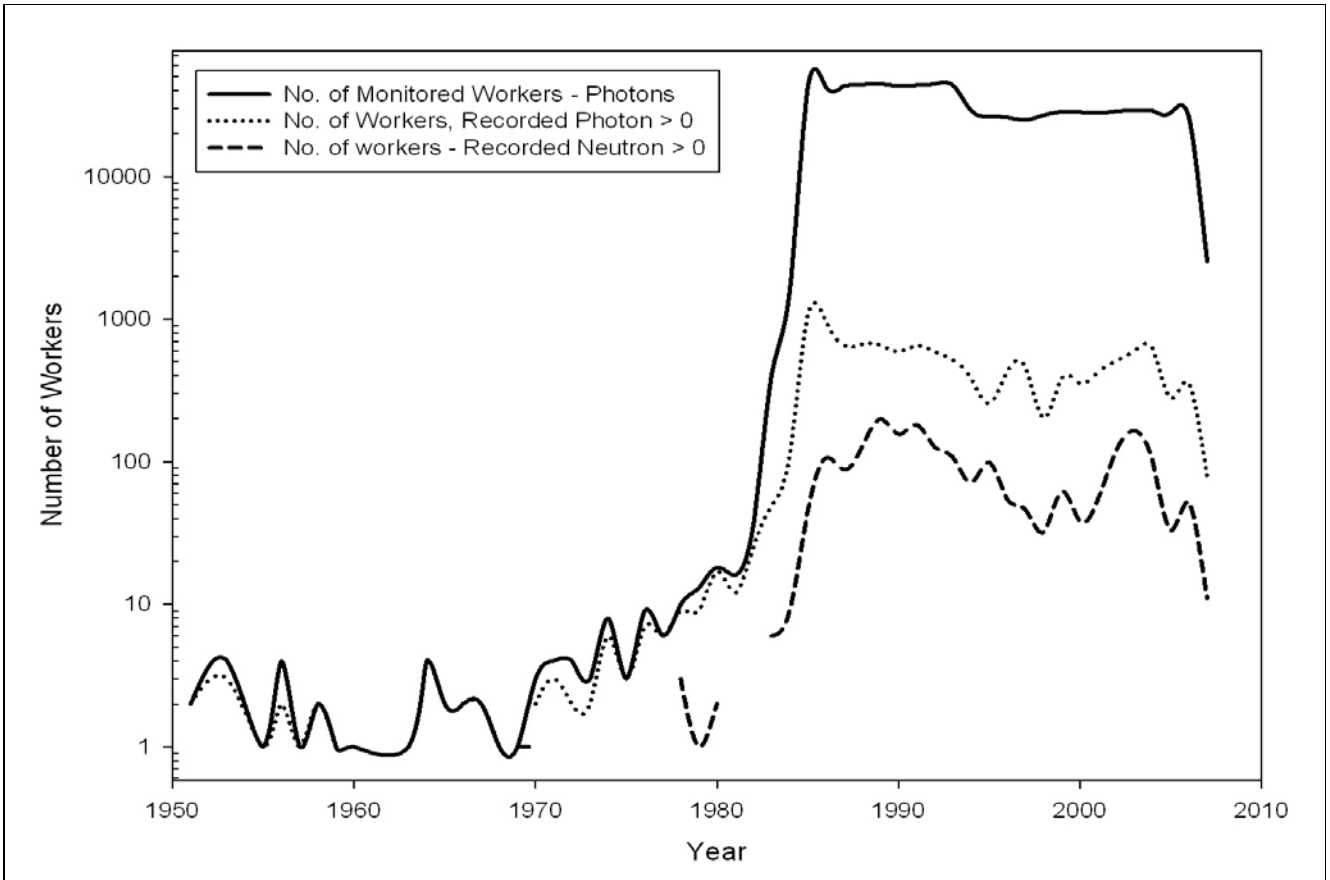

Figure 6-1. Trend in the number of LLNL monitored workers, the number of workers with recorded photon doses >0 and the number of workers with recorded neutron doses >0, 1952–2006.

6.2.2 <u>Radiological Records</u>

LLNL maintains a computerized radiological record system. There are many thousands of images of hard-copy dosimetry cards containing worker name, identification number, date, dosimeter badge assigned, and film processing result shown as the ratio of the dose for the film open-window (OW) to shielded (S) film regions (LRL 1952–1959). Practices to calculate the LLNL recorded WB, skin (SK) and extremity hand (HN) doses from the measured dosimeter dose components are summarized in Table 6-2. The measured neutron dose has been included in the WB dose for all years. Dose reconstructors can use the information in Table 6-2 and the additional information in Table 6-3 to assist in the interpretation of LLNL external dosimetry summary reports.

Table 6-2. Determination of LLNL recorded dose [1].

Period	Dosimeter measured quantities	Compliance dose quantities*
Beta/photon film dosimeter + NTA neutron film dosimeter		
1952–1963	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron SK = WB + beta HN = hand extremity dose (HN = hands)
1963–1969	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron SK = shallow (SK = skin) = gamma + neutron + beta HN = hand extremity dose (HN = hands)
Beta/photon/neutron–LLNL TLD		
1969–1985	Beta (B) Gamma (G) Neutron (N)	WB = gamma + neutron SK = shallow (SK = skin) = gamma + neutron + beta HN = hand extremity dose (HN = hands)
Beta/photon/neutron–Panasonic TLD + CR-39 neutron dosimeter		
1985–present	B/G/N	SK = NPEN + WB WB = PEN + SN + FN
1995–2003	Shallow (SH or SK) Deep photon (PH DP) Deep neutron (NU DP)	SK = beta + photon + neutron (B/G/N) WB = photon deep + neutron deep
* WB = Whole Body, SK = Skin, HN = extremity (Hand), NPEN = nonpenetrating, PEN = penetrating, SN = Slow Neutron, FN = Fast Neutron.		

During the early 1950s, the National Council on Radiation Protection and Measurements (NCRP) introduced the concept of permissible dose to replace the tolerance dose concept. As noted in Attachment A, the NCRP recommended that the maximum permissible dose to the gonads and blood-forming organs be 0.3 rem (3 mSv) per week in 1954, which corresponds to an annual WB dose limit of 15 rem (150 mSv). In the later 1950s, the potential significance of cumulative radiation exposure to genetic and cancer risks became a concern leading to implementation of the WB dose limit of 5 × (N-18) rem, where N is measured in years. In the later 1980s, changes in the WB dose limit were associated with an NCRP recommendation to limit WB dose to a maximum of 10 rem averaged over 5 years (i.e., average of 2 rem/yr). The historical trend in LLNL WB photon dose, dose limits, and in comparison with the median and 95th-percentile LLNL recorded WB annual photon doses are presented in Figure 6-2. The recommended annual dose limits by applicable scientific and regulatory agencies are shown in Figure 6-2. Attachment A provides a more detailed history of official and LLNL radiation dose control limits. The reasons for the dramatic improvement in the variability of the measured doses in 1985 are likely associated with the implementation of the Panasonic dosimetry system, capabilities to utilize individual element radiation calibration factors, preparations for DOE Laboratory Accreditation Program (DOELAP) dosimeter performance testing that became mandatory in 1985 (DOE 1986), and the assignment of dosimeters to a much larger number of workers.

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

Table 6-3. Interpretation of LLNL reported dose data [2].

Period	Reported quantity	Description	Interpretation of zeroes	Interpretation of blanks (no data)	Rollup of individual and annual data	Monitored/ unmonitored
1952–1968	rem	Reported WB doses qualified with "G" for gamma and "N" for neutron. Skin and extremity (hand) doses are also reported	Zeroes were generally not recorded. Reported zero should be interpreted as meaning less than LOD.	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 for beta/gamma radiation. Selected employees were monitored for neutron radiation.
1969–1985	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 recorded before 1980. However, for any year, a blank or reported zero result should be interpreted as meaning less than LOD.	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 for beta/gamma and neutron exposure.
1985–present	rem	Photon deep, neutron deep, and shallow dose reported.	Zeroes were typically reported. Reported zero should be interpreted as meaning less than LOD.	Blanks should be interpreted as individual was monitored with zero result.	Photon WB dose. Neutron WB dose. Shallow skin dose. Total deep WB dose.	

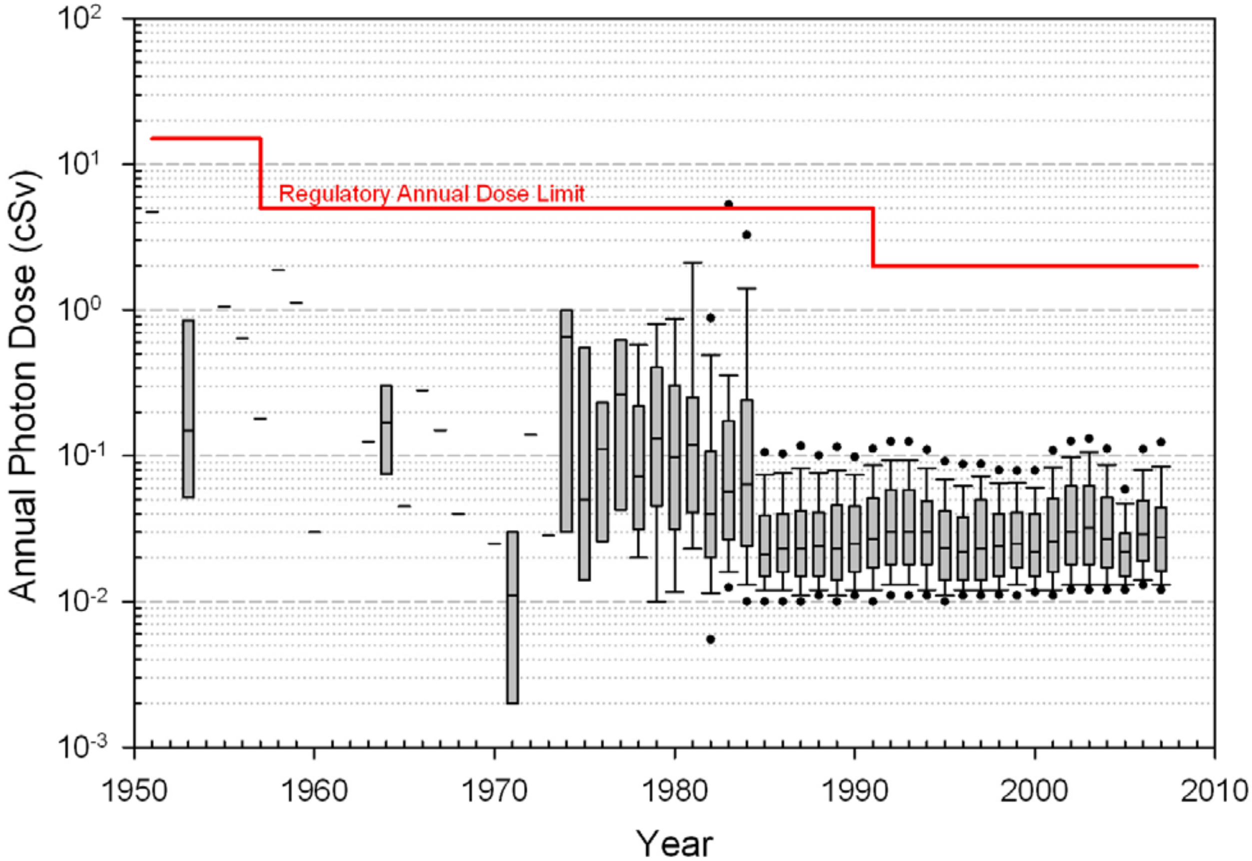

Figure 6-2. Box plot of historical measured LLNL worker whole-body photon doses showing median, whiskers at 25th and 75th percentiles, respectively, and bullets at 95th percentile compared to official dose limits.

important to the assessment of the original recorded dose in relation to the radiation dose equivalent quantity *Hp(d),* where d = 10 mm or d = 0.07 mm for WB deep and shallow dose, respectively. Dose reconstructors can compare earlier dosimetry systems to current systems to evaluate their performance based on the premise that current systems have more stringent criteria, as indicated in DOELAP dosimeter performance testing.

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

- Administrative practices that facilities adopted to calculate and record personnel dose based on technical, administrative, and statutory compliance considerations.

- Dosimetry technology, which includes the physical capabilities of the dosimetry system, such as the response to different types and energies of radiation, in particular in mixed radiation fields.

- Calibration and dosimeter response characteristics of the respective monitoring systems and similarity of the methods of calibration to sources of exposure in the workplace.

- Workplace radiation fields, which can include mixed types of radiation, variations in exposure geometries, and environmental conditions.

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

6.3.1 Historical Administrative Practices

As noted in Attachment A, Section A.2, references of historical LLNL radiation associated events, LLNL used personnel dosimeters to measure and record doses from external radiation to workers throughout the history of its operations. These dosimeters include one or more of the following:

- Personnel WB film and thermoluminescent beta/photon dosimeters
- PIC (electrometers, etc.) dosimeters for photon and thermal neutron detection
- Personnel extremity (particularly hand) dosimeters
- Personnel neutron nuclear track emulsion, type A (NTA) film, thermoluminescent and track-etch 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 apparently in place for all these parameters. From its inception, LLNL had policies to monitor individuals with significant potential for radiation exposure. The practice of providing film and pocket ionization dosimeters to all workers has been in effect since March 1953 (Thompson 1953) and in 1958 film badges became part of the security badge (Nolan 1958), which effectively mandated that all workers wear their film dosimeters at all times. Dosimeter exchange frequencies varied over the years depending on the dosimeter type in use at the time and on the exposure potential of the individual being monitored. Individuals with lower exposure potential tended to have less frequent exchange frequencies than those with higher exposure potential. Neutron dose results are observed in the early 1950s, as noted in Attachment A, Section A.2. Individual worker dose histories typically include recorded dose at LLNL from the early 1950s. As noted above, LLNL recorded only positive doses until the early 1980s. As evident in Figure 6-1, there was comparably little recorded dose in the earlier years and comparatively very little recorded neutron dose. Certainly this trend in recorded dose is in part an indication of the establishment of a new laboratory with personnel dosimetry originally provided by LBNL with little potential for significant worker exposures. Doses increased with time as new facilities were constructed and became operational and, at least for neutron radiation, as improved dosimetry methods became available.

6.3.2 LLNL Personnel Dosimetry Technology

LLNL began operations in 1952 using dosimeter and processing technical support provided by LBNL. LLNL developed its own capabilities to process dosimeters in 1953 and proceeded to improve capabilities adopting multielement film, thermoluminescent, and track-etch dosimetry technology.

6.3.2.1 Beta/Photon Radiation Personnel Dosimeters

Initially, LBNL provided LLNL with beta/photon film dosimeters and processing, and PICs (Thompson 1953). These film dosimeters were similar in design to those developed at the Metallurgical Laboratory at the University of Chicago (Pardue, Goldstein, and Wollan 1944) and widely adopted at many other DOE sites (ORNL, Hanford, etc.). LLNL had developed its own fully functional personnel dosimetry film and PIC program with in-house processing by March 1953 (Thompson 1953). Early exposure records, likely from LBNL, provided “electrometer” results (designated by “E” in selected claimant files), which supplemented the film dosimeter results. For purposes of dose reconstruction, the electrometer or E results should be used in a qualitative manner in the same manner as PIC data. The film dosimeter recorded dose results should be used to estimate the actual dose to workers until the thermoluminescent dosimeter (TLD) was implemented in 1969 (Rich 1969).

Table 6-4 summarizes the personnel beta/photon dosimeters used at LLNL over the years, along with their periods of use, exchange frequencies, limits of detection (LODs), and estimated annual missed doses. 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 depends on radiation type, energy, and exposure geometry. The exchange frequency of the dosimeters was gradually lengthened and corresponded generally to downward reductions in the radiation protection guidelines (Attachment A; Morgan 1961; Taylor 1971). The dosimeter designs accommodated the numerous beta/photon radiation field types that workers might encounter throughout the LLNL complex. In 1969, TLDs, which had been under development for many years, fully replaced film dosimeters. LLNL constructed the TLDs used from 1969 through 1984, using 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.

Table 6-4. LLNL beta/photon dosimeter type, period of use, exchange frequency, LOD, and potential annual missed dose [3].

Period of use	Dosimeter	LOD[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
LLNL film dosimeters				
1952–1968[d]	Beta/Photon–DuPont 558 film	0.030	Weekly (n = 50)	0.75
			Biweekly (n = 25)	0.38
			Monthly (n = 12)	0.18
LLNL thermoluminescent dosimeters				
1969–1984	Beta/Photon/Neutron–Harshaw TLD-100, TLD-200, TLD-600, and TLD-700 phosphors	0.020	Monthly (n = 12)	0.12
			Quarterly (n = 4)	0.04
			Semiannual (n = 2)[e]	0.02
1985–present	Beta/Photon–Panasonic 810AS and 802AS TLD	0.010	Monthly (n = 12)	0.06
			Quarterly (n = 4)	0.02
			Semiannual (n = 2)	0.01

a. Estimated LODs for each dosimeter technology in the workplace. LLNL radiological records include dose values recorded at levels less than the LOD.
b. Exchange frequencies were dependent on work assignment. If the exchange frequency is not evident based on trends in an individual’s personnel records, assume a monthly exchange frequency.
c. Annual missed dose calculated using the LOD/2 method from NIOSH (2007b).
d. Initially LBNL provided and processed LLNL beta/photon film dosimeters.
e. From January 1974 to June 1978, the site began a test semiannual badge exchange monitoring program for about 2,000 employees. The semiannual badge exchange program was implemented after this for certain buildings (Hoots 1978).

6.3.2.2 Neutron Radiation Personnel Dosimeters

Table 6-5 summarizes the personnel neutron dosimeters used at LLNL over the years, along with their periods of use, exchange frequencies, LODs, and estimated annual missed doses. Initially, LBNL supplied and processed NTA film dosimeters and thermal neutron-sensitive pencil dosimeters. LLNL had implemented capabilities for the thermal neutron-sensitive pencil dosimeters by March 1953 (Thompson 1953) but it is not certain when LLNL had fully implemented in-house NTA processing capabilities. Neutron dosimeters were assigned to LLNL workers according to need as noted in several Attachment A historical record notes. It appears clear from the record that workers should be assigned neutron dosimeters for any significant exposure; for example, 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.” However, as illustrated in Figure 6-1, there is relatively little recorded neutron dose for LLNL workers until the latter 1980s when TLDs were being used. Rich (1969) noted the inability of NTA dosimeters to measure known neutron doses during workplace comparisons with TLDs (see Section 6.6.4).

Table 6-5. LLNL neutron dosimeter type, period of use, exchange frequency, LOD, and potential annual missed dose [4].

Period of use	Dosimeter	LOD[a] (rem)	Exchange frequency[b]	Annual missed dose[c] (rem)
LLNL NTA Film Dosimeters				
1952–1968	Kodak NTA film	(b)	Weekly (n = 50)	1.25
			Biweekly (n = 25)	0.625
			Monthly (n = 12)	0.30
LLNL TLD				
1969–1984	Beta/Photon/Neutron - Harshaw TLD-100, TLD-200, TLD-600, and TLD-700 phosphors	0.020	Monthly (n = 12)	0.12
			Quarterly (n = 4)	0.04
LLNL Track-Etch Dosimeter				
1985–present	Neutron–CR-39	0.010	Monthly (n = 12)	0.06
			Quarterly (n = 4)	0.02

a. Estimated LODs for each dosimeter technology in the workplace. LLNL radiological records include dose values recorded at levels less than the LOD.
b. The estimated LOD for NTA based on laboratory studies is 50 mrem. However, as noted in Rich (1969) often no positive neutron dose was measured in workplaces with known neutron dose. As such, it is recommended that the missed neutron dose be determined by multiplying the missed photon dose by a NP ratio.
c. Annual missed dose calculated using the LOD/2 method from NIOSH (2007b).

TLDs fully replaced NTA film dosimeters by 1969 (Rich 1969). 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 included the thermal neutron response of TLD-100 phosphors and, as such, the percent of thermal radiation was incorporated into the neutron dose evaluation (Hankins 1982a). Later dosimeter modifications introduced a design with cadmium-shielded 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. A further design change incorporated shielding on all sides of the TLD-600 and TLD-700 elements, which minimized the over-response of the earlier designs and was in use until 1985 when LLNL implemented CR-39 track-etch neutron dosimeters. The combination of the Panasonic System and CR-39 is currently in use.

6.3.3 Calibration and Dosimeter Response Characteristics

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

6.3.3.1 LLNL Beta/Photon Dosimeters

Dosimeters were calibrated using a variety of beta radiation sources and photon beams as noted in the studies in Attachment A. LLNL dosimetrists appear to have been well aware of technical considerations to match calibration and workplace spectra, and processing quality assurance (Hoots and Landrum 1981), to achieve accurate measured doses. Hankins (1982a) reported a retrospective study of LLNL dosimeter response characteristics to reconstruct an exposure to beta and gamma radiation that occurred in 1963. Typical higher energy photon-emitting nuclides such as ^{226}Ra, ^{137}Cs, or ^{60}Co were used to irradiate dosimeters in air (i.e., no phantom) until the early 1980s when DOELAP personnel dosimeter performance testing (Roberson et al. 1983) was imminent with on-phantom exposures. Since 1986, photon calibrations have been to ^{137}Cs with dosimeters placed on a phantom. Beta calibrations were routinely to ^{90}Sr.

6.3.3.2 LLNL Neutron Dosimeters

Neutron dosimeters were calibrated using selected neutron sources such as polonium-beryllium or plutonium-beryllium sources before about 1970. In later years, unmoderated and moderated ^{252}Cf has been used. LLNL staff members (Hankins 1967, 1975a,b; Griffith et al. 1977, 1978a,b; Hankins 1978a,b; Griffith and Hankins 1980; Hankins 1982b, 1984a, Hankins, Homann and Buddemeier 1989) provide substantial information on considerations of calibration of albedo neutron dosimeters for various workplace neutron spectra. LLNL archive records provide a history of neutron calibration sources and tolerance limits from 1953 through 1955 as well as monitoring results (LRL 1953–1955). Kathren, Prevo, and Block (1965) described LLNL studies of NTA response characteristics. NTA response was found to be a function of the angle of incidence of a neutron with the plane of the film and the energy. A factor of 1.3 was recommended to correct the recorded dose from NTA film for the effects of angular dependence and fast-neutron energy. A documented conversation (Fix 2010) with a subject and site expert recommended that the factor of 1.3 also be used to correct the recorded neutron dose from TLDs.

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. As noted in Attachment A, reviews of potential workplace hazards in LLNL facilities, including radiological, were often done. These reviews provided a summary listing of potential radiation hazards in the respective facilities.

6.3.4.1 Beta/Photon Radiation

Evaluations of potential beta and photon (gamma and X-ray) radiation hazards in LLNL workplaces have been done on numerous occasions as noted in Attachment A, Section A.2. Table 6-6 lists several of the beta/photon radiation sources potentially encountered at LLNL over the years, the approximate energy category, and the associated dose fraction. All workplace beta radiation energies of potential external radiation exposure significance to workers are greater than 15 keV.

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

Buildings–old numbers[a]	**Buildings–new numbers[a]**	**Description**	**Radiation type**	**Energy selection (keV)**	**Dose fraction**
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	Laboratory 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 (Plutonium Facility)	Beta	>15	100
			Photon	<30 30–250	50 50
172	331	Gaseous Chemistry (Tritium Facility)	Beta	>15	100
			Photon	<30[b]	100
182	162, 165, 166	Laboratory 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. Trost (2005).
b. Bremsstrahlung X-ray radiation from tritium beta radiation.

6.3.4.2 Neutron Radiation

Evaluations of potential neutron radiation hazards in LLNL workplaces have also been done on numerous occasions, as noted in Attachment A, Section A.2. Table 6-7 lists neutron radiation sources potentially encountered at LLNL over the years, the approximate energy category, and the associated dose fraction. Workplace neutron radiation energies of potential external radiation exposure significance to workers are between 10 keV and 20 MeV. The default neutron energy selection of 0.1 – 2.0 MeV in Table 6-7 was chosen because sources of neutron radiation were normally shielded. This energy range also typically has the highest organ dose conversion factor (DCF; see NIOSH 2007b, Appendix C) that is favorable to claimants.

Table 6-7. Selection of workplace neutron radiation energies and dose fractions [6].

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, 235, 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	Laboratory 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: (Tritium Facility)	Neutron	0.1–2.0	100
182	162, 165, 166	Laboratory 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
	255	Radiological Calibration and Instrument Repair Facility	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.

The NTA dosimeter (1952–1968) exhibited a lower neutron energy threshold of approximately 500 keV and consequently underestimated the neutron exposure (Rich 1969; Griffith and Hankins 1980; NCRP 2007). The photon dose was measured adequately and all LLNL neutron dose was accompanied by a significant photon dose. For neutron dose received before 1969, the dose should be adjusted by using a neutron-to-photon (NP) ratio. The ratio varies by operation and task (Hankins 1982b). Neutron spectral and dose measurements in LLNL facilities were done in later years, as noted in Attachment A, Section A.2.

6.4 MONITORED LLNL WORKERS – MEASURED DOSE

6.4.1 Photon Dose Adjustments

No adjustment to recorded photon doses is recommended. LLNL film and thermoluminescent dosimeters provided reasonably accurate measurement of photon radiation exposure in the facilities and for all years of operation. In the early years, the ratio of the OW film dosimeter response and the shielded film response was used to evaluate the energy of the incident photon radiation and to distinguish if significant beta radiation was present. Multielement film dosimeters were used later consistent with practices at other DOE sites. PIC and radiation detection instruments were also used, which provided another source of reference for the measured photon exposure. Kathren (1965) reported results of a workplace comparison of film and thermoluminescent dosimeters. Approximately 60% of the compared results showed good agreement defined as dose results differing by the greater of 20 mR or ≤20% of the higher dose interpretation.

6.4.2 Photon Organ Dose Conversion Factors

The measured photon dose is used with the DCFs to calculate organ doses of interest using the external dose reconstruction implementation guidelines (NIOSH 2007b). For LLNL measured photon dose before 1986 (film badge and TLD), the DCFs from exposure to organ dose should be used [7]. After 1985, the DCFs from deep dose equivalent to organ dose should be used. This is summarized in Table 6-8. It is recommended that the 100% anterior-posterior (i.e., front-to-back) geometry should be assumed for the irradiation geometry and for conversion to organ dose [8].

Table 6-8. Photon dose conversion factors.

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.

6.4.3 Neutron Dose Adjustments

There is very little recorded neutron dose before the mid-1980s according to Figure 6-1. Based on evaluations by Rich (1969) and by the U.S. Atomic Energy Commission (AEC) at other DOE plutonium facilities (Vallario, Hankins, and Unruh 1969; Biles 1972; Fix, Wilson, and Baumgartner 1997b), the NTA-measured neutron dose underestimated the actual neutron dose. As such, adjustments to the LLNL recorded neutron dose are necessary to arrive at a favorable to claimant dose considering the uncertainty associated with the recorded dose as follows [9]:

- Neutron doses determined before January 1, 1969, with the NTA film dosimeter are likely too low and an NP ratio should be multiplied by the measured photon dose to assign a favorable neutron dose to the claimant. It should be noted that if the Energy Employee has recorded neutron dose, the assigned neutron dose should be compared with the recorded neutron dose and the assigned dose used only if it is higher [10].

- Neutron dose measurements with the workplace performance-validated TLD implemented in 1969 should be multiplied times an angular correction factor of 1.3.

6.4.4 Neutron Weighting Factor

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

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

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

a. First Tripartite Conference at Chalk River in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994); National Bureau of Standards Handbook 59 (NBS 1954; also known as NCRP Report 17); and Taylor (1971).
b. Ratio of the ICRP Publication 60 weighting factor to the group averaged NCRP 38 quality factor each neutron energy group (ICRP 1991; NCRP 1971).
c. "Not applicable" is usually inserted here rather than the NCRP group averaged value of 6.96, which is larger than the ICRP Publication 60 weighting factor of 5 for 20-to-60-MeV neutrons and results in a non favorable to claimant reduction in the corrected dose for this neutron energy group (ICRP 1991; NCRP 1971).
d. Ratio for adjusting neutron dose from NCRP Report 38 quality factor to ICRP Publication 60 weighting factor is arbitrarily set equal to unity to avoid a non favorable to claimant reduction in the corrected dose for this neutron energy group (ICRP 1991; NCRP 1971).

DOE is in the process of implementing ICRP Publication 60 (ICRP 1991) neutron weighting factors into the routine determination of the recorded neutron dose. For LLNL, the date this is scheduled to begin will need to be determined. Once this change is made, no adjustment in the recorded neutron dose will be necessary thereafter [11].

6.5 MONITORED LLNL WORKERS – MISSED DOSE

Missed doses to LLNL workers are assigned for monitored workers (NIOSH 2007b). Thompson (1953) documented that all workers at LLNL were monitored for radiation exposure however as noted in Block (1954) only positive measured doses were recorded. The potential for missed dose exists when workers are exposed to radiation at levels below the detection limit of their personnel dosimeters or if dosimeters were not worn for all work involving radiation exposure. Nolan (1958) documented the experience that new or additional low-level exposure was observed for some workers when the LLNL security and dosimeter badge were combined in 1958. LLNL policy was to monitor any significant radiation exposure. Generally in the early years of radiation monitoring, when relatively high detection limits were combined with short monitoring durations, missed doses could be significant. Watson et al (1964) describes a method to reconstruct doses for any exchange periods without a recorded dose. The assignment of a missed dose is based on a determination of (1) the number of dosimeter results with a recorded dose less than the LOD divided by 2, and (2) multiplication of the LOD/2 value by the number of dosimeter results < LOD/2 to include potential unrecorded dose according to the scheduled dosimeter exchange period (NIOSH 2007b). Rich (1969) stated that often no positive neutron dose was measured with NTA film in workplaces with known neutron dose. As such, the missed dose from neutron radiation before 1969 should not be based on the NTA dosimeter results but rather the missed neutron dose should be determined by multiplying the missed photon dose by an NP ratio. For neutron dose measured with the TLD, the assignment of a missed neutron dose is based on a determination of (1) the number of dosimeter results with a recorded neutron dose less than the LOD divided by 2, and (2) multiplication of the LOD/2 value times the number of dosimeter results < LOD/2 to include potential unrecorded neutron dose according to the scheduled dosimeter exchange period (NIOSH 2007b).

6.6 UNMONITORED LLNL WORKERS

There should generally not be any occupationally exposed unmonitored LLNL workers because workers were assigned a dosimeter. However, there might be some situations regarding unrecorded dose for work activities that involved comparatively low-level exposure, considering only positive doses were recorded before about 1980. LLNL workers who were apparently unmonitored for external radiation are assigned either external onsite ambient doses, if they were nonradiological workers and would not have been exposed to workplace radiation sources, or unmonitored doses using coworker studies or some other evaluation if a potential for exposure was evident. As noted in the historical timeline of dosimeter assignment practices in Attachment A, LLNL policy was to assign dosimeters to all workers. This policy was clearly stated in 1954 (Block 1954) and might have existed earlier because there are records of earlier measured photon and neutron dose (see Attachment A, Section A.2). As such, the potential for a significant unmonitored beta/photon radiation exposure appears minimal.

6.6.1 Ambient Neutron Dose

There does appear to be a potential for ambient neutron radiation exposure associated with ICT Building 212 operations beginning in about 1966 extending over a period of many years. As noted in Attachment A, Section A.2, elevated neutron exposures at the fence and at a nearby bus stop were evaluated on many occasions. LLNL-measured annual neutron dose at the perimeter fence from this facility is presented in Table 6-10. Documentation by Myers (1984) and various references noted in Attachment A indicate that elevated neutron exposure from this facility existed at least through 1986.

Table 6-10. Perimeter fence neutron doses from Building 212.

Year	Maximum annual dose (mrem)	SRDB reference
1972	250	Gudiksen et al. 1973
1973	250	Silver et al. 1974
1974	370	Silver et al. 1975
1975	700	Silver et al. 1976
1976	600	Silver et al. 1977
1977	550	Silver et al. 1978
1978	137	Silver et al. 1979
1979	80	Silver et al. 1980
1980	85	Toy et al. 1981
1981	33	Auyong, Griggs, and Buddemeier 1982
1982	36	Griggs, Gonzales, and Buddemeier 1983
1983	113	Griggs, Meyers, and Buddemeier 1984
1984	45	Griggs, Meyers, and Buddemeier 1985
1985	7	Griggs and Buddemeier 1986
1986	30	Holland, Buddemeier, and Brekke 1987
1987	9	Holland and Brekke 1988
1988	5	Kamelgarn 1989
1989	6	Sims et al. 1990
1990	6	Sims et al. 1991
1991	7	Gallegos et al. 1992
1992	7	Gallegos et al. 1993
1993	7	Gallegos et al. 1994

The annual doses in Table 6-10 would generally relate to a comparably low dose rate per hour. Considering that all LLNL workers were assigned neutron-sensitive TLDs beginning at least in 1969 (Rich 1969), any occupationally significant ambient neutron dose would have been detected and measured by these dosimeters. However, it is possible that low-level neutron exposures were not measured. As such, the dose reconstructor can consider whether to assign a comparatively low ambient neutron dose to a worker in comparison with typically much greater measured and assigned occupational dose components.

6.6.2 Coworker Assigned Photon Dose

As noted above, there generally should be no unmonitored LLNL workers.

6.6.3 Neutron-to-Photon Dose Ratio

The inability of the NTA film dosimeter to measure the neutron dose (Rich 1969) can be considered an example of an unmonitored exposure. The photon dose was reliably measured with LLNL film and thermoluminescent dosimeters, and essentially any significant neutron dose would be accompanied by significant photon dose. The LLNL TLDs provide paired neutron and photon dose measurements. A total of 554 LLNL TLD personnel dose measurements were obtained with measured photon and neutron doses equal to or greater than 20 and 40 mrem, respectively, to minimize effects in the analysis of measured doses near the LOD. The development of the NP ratio enables the use of the recorded photon radiation dose from an individual's personnel dosimeter to be used to estimate the unmonitored neutron dose. Figure 6-3 illustrates the NP ratio for each of the 554 measured neutron and photon dose measurements. The range in NP values appears similar for all years without a distinctive trend. The neutron and photon doses are not, however, well correlated, as shown in Figure 6-4 with a Pearson Correlation of 0.38, likely because photon radiation exposure of workers occurred in many workplaces whereas neutron exposure occurred primarily in plutonium facilities with variable NP dose ratios.

The 554 NP values of paired measured photon and neutron doses are well represented by a lognormal distribution (i.e., Kolmogorov–Smirnov test = 0.076). The statistical parameters are summarized in Table 6-11.

Beginning in 1994, the LLNL Radiation Exposure (REX) database records often included the facility to which each worker was assigned and presumably, in the case of measured neutron dose, the facility where the neutron exposure occurred. Analyses of the collective dose for this subset of the 554 TLD paired neutron and photon doses according to year and building are summarized in Table 6-12. Four LLNL buildings (i.e., 235, 332, 335 and 3340) respectively had a collective neutron dose exceeding 1 rem during this 12-year period. The majority of the collective neutron dose is associated with work in the LLNL Plutonium Facility Building 332 (i.e., Buildings 335 and 3340 are office buildings used by personnel working at Building 332).

Analyses of statistical parameters for each of these buildings are presented in Table 6-13. These facilities would be expected to comprise all of the facilities with significant potential for neutron exposure during the period of 1994 to 2006. Statistical parameters for the subset of the 554 paired measurement data shown in Table 6-13 with an identified facility (i.e., 215 values) are very similar to the parameters shown in Table 6-11 for the analysis of all 554 paired measurements.

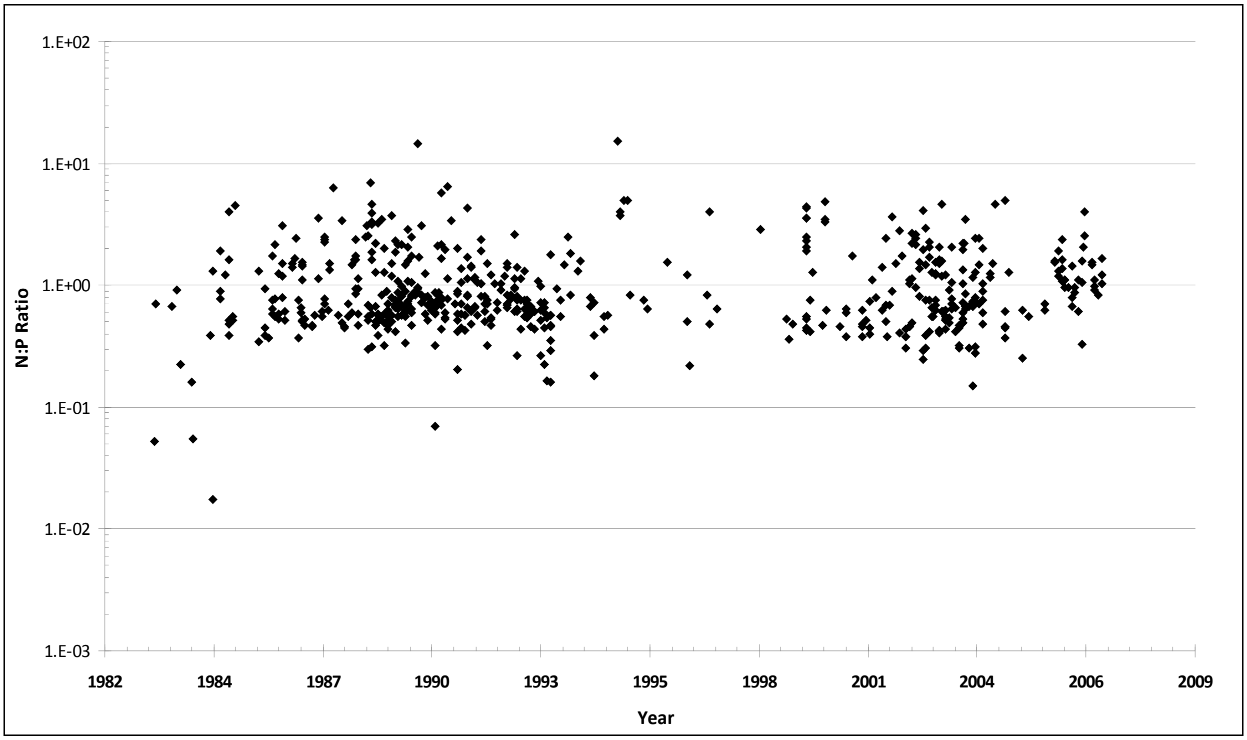

Figure 6-3. Trend of TLD measured LLNL worker NP dose ratio with respective neutron ≥40 mrem and photon ≥20 mrem dose components.

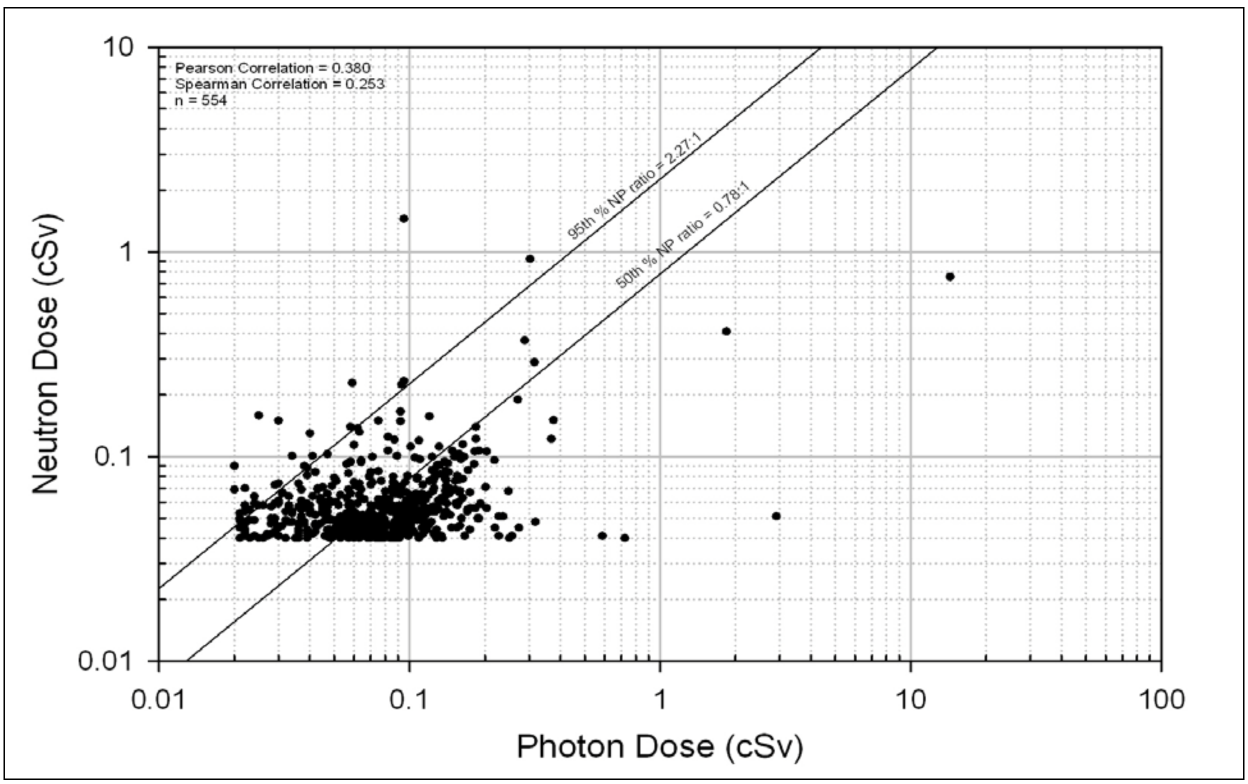

Figure 6-4. LLNL paired TLD neutron ≥40 mrem and photon ≥20 mrem dose measurements.

Table 6-11. LLNL NP ratio from TLD measurements.

Description	Values	GM	GSD	95th percentile	Fit[a]
TLD personnel dose data	554	0.78	1.91	2.27	0.076

a. Kolmogorov–Smirnov test is used as a measure of goodness of fit to a lognormal distribution.

Table 6-12. Collective TLD measured photon and neutron dose (person-rem).

	Collective dose[a]									
	Building 332		Building 3340		Building 335		Building 235		Totals	
Year	Neut.	Phot.	Neut.	Phot.	Neut.	Phot.	Neut.	Phot.	Neut.	Phot.
1994	0.105	0.294			0.090	0.118	0.000	0.000	0.195	0.412
1995	0.294	0.608			0.182	0.299	0.023	0.000	0.499	0.907
1996	0.222	0.777			0.049	0.396	0.000	0.064	0.271	1.237
1997	0.182	1.132			0.050	0.456	0.000	0.017	0.232	1.605
1998	0.242	0.493			0.000	0.180	0.000	0.000	0.242	0.673
1999	0.346	0.825			0.224	0.353	0.053	0.042	0.623	1.220
2000	0.303	0.900			0.121	0.490	0.000	0.100	0.424	1.490
2001	0.395	0.807			0.292	1.128	0.025	0.193	0.712	2.128
2002	0.217	0.551	0.328	0.791	0.482	1.211	0.505	0.298	1.532	2.851
2003	0.187	0.430	0.646	1.220	0.567	1.420	0.321	0.290	1.721	3.360
2004	0.149	0.222	0.467	0.913	0.432	1.615	0.090	0.596	1.138	3.346
2005	0.072	0.115	0.247	0.524	0.037	0.256	0.000	0.033	0.356	0.928
2006	0.167	0.153	0.769	1.045	0.073	1.638	0.035	0.469	1.044	3.305
Totals	2.881	7.307	2.457	4.493	2.599	9.560	1.052	2.102	8.989	23.462

a. Neut. = neutron; Phot. = photon.

Table 6-13. Statistical parameters for facility-specific TLD neutron and photon dose data, 1994–2006.

	LLNL facility					
Statistical parameters	231	235	332	335	3340	Overall
Points	1	9	52	53	99	214
Fit[a]		0.23	0.22	0.13	0.09	0.07
GM		1.86	0.55	1.07	0.74	0.79
GSD		1.44	1.42	1.92	1.68	1.86
95th percentile		3.38	0.97	3.14	1.73	2.18
Maximum	1.22	2.97	1.31	2.67	2.52	2.97
average		1.97	0.58	1.27	0.85	0.96
Minimum	1.22	1.03	0.39	0.15	0.25	0.15

a. Kolmogorov–Smirnov test is used as a measure of goodness of fit to a lognormal distribution.

Hankins (1982b) provides 236 paired neutron and photon measurements for numerous LLNL facilities. The statistical analysis results are summarized in Table 6-14. Again, for 1982, these buildings are apparently the only facilities with a potential for significant neutron exposure. These data illustrate a slightly higher NP geometric mean (GM) and geometric standard deviation (GSD) compared to the statistical parameters determined from the personnel TLD measurements in Tables 6-11 through 6-13.

6.6.3.1 NP Ratio Application

The combination of the 554 personnel TLD data during the period from 1982 to 2004 and the 236 points from the 1982 measurements provides a reasonable sample to evaluate statistical parameters of the NP ratio for the majority of workers. The 1982 workplace measured data however in Table 6-14 better represent the variability in workplace (Fix 2010) and the recommended lognormal distribution parameters for use in dose reconstruction are summarized in Table 6-15 [12]. This distribution is combined with measured and missed dose distributions using Monte Carlo methods described in ORAUT-OTIB-0012, *Monte Carlo Methods for Dose Uncertainty Calculations* (ORAUT 2005c). The resulting total neutron dose should be partitioned for input to IREP assuming that 100% is from neutrons from 0.1 to 2 MeV.

Table 6-14. Statistical parameters for facility-specific measured neutron and photon dose data, 1982 (Hankins 1982b).

Statistical parameter	LLNL facility								
	131	212(ICT)	231	233	251	281	332	Site 300	Overall
No. of values	3	9	31	24	20	34	81	34	236
Fit	0.29	0.26	0.22	0.13	0.15	0.14	0.08	0.16	0.09
GM	5.28	3.08	0.87	0.52	2.43	0.63	1.58	1.21	1.19
GSD	5.02	1.94	1.91	2.99	2.56	4.38	2.91	2.22	3.18
95th percentile	75.15	9.17	2.51	3.16	11.42	7.13	9.12	4.52	7.96
Maximum	19.33	7.50	5.91	5.00	25.00	7.50	20.29	3.33	25.00
Average	9.67	3.59	1.09	0.92	4.06	1.40	2.73	1.53	2.20
Minimum	0.87	0.67	0.09	0.09	0.75	0.03	0.03	0.10	0.03

a. Kolmogorov–Smirnov test is used as a measure of goodness of fit to a lognormal distribution.

Table 6-15. Recommended NP ratio for Dose Reconstruction.

Description	GM	GSD	95th percentile
LLNL Dose Reconstruction	1.19	3.18	7.96

6.6.3.2 Construction Workers

If a construction worker received a TLD and worked in a facility with significant neutron exposure, this will be detected by the TLD. The NTA film dosimeter assigned to some workers before 1969 might not detect significant neutron exposure (Rich 1969) and, therefore, a favorable to claimant option must be selected to reconstruct potential neutron exposure. As such, the dose reconstructor should assume neutron exposure occurred unless there is other information indicating the construction work was conducted only in areas with little or no neutron radiation.

6.6.3.3 Specific Locations

Generally the standard NP ratio with a GM of 1.19 and a GSD of 3.18 (Table 6-15) should be used for workers unless the individual's records indicate that they worked in a specific facility and time where measurements are available in Tables 6-13 (1994–2004) and 6-14 (1982), respectively, or the facility has only photon exposure. An examination of LLNL recorded dose records shows only a few buildings with positive TLD-measured neutron dose as shown in Tables 6-13 and 6-14. Hankins (1982b) provided a summary of calibration factors for each of the facilities according to workplace measurements of the neutron radiation dose fraction. The neutron dose from the TLD results is divided by the calibration factor shown in Table 6-16 to obtain the neutron dose for the various workplaces. The calibration factor is indicative of the effective neutron energy (i.e., the lower the value of the calibration factor, the higher the effective energy of the neutron spectrum).

6.7 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, the workplace energy spectra, and geometries of their exposures. NIOSH data collections of LLNL documentation have identified studies of uncertainty assessments for LLNL dosimeter systems. Many of these are illustrated in the historical timeline in Attachment A, Section A.2. The LLNL systems have much in common with dosimetry systems used at other DOE facilities.

6.7.1 Measured Photon Dose

NIOSH (2007b) 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

Table 6-16. Summary of neutron calibration factors for LLNL buildings (Hankins 1982a).

Facility	Building	Rooms/sources		Calibration factor
LLNL Plutonium Facility	332	Room 1378		0.4
		Other rooms		0.3
		Vaults		0.4
		Room 1378 during PuBe work		0.2
		Shielded PuBe work		0.2
Vault	231	Inside vault		0.45
Chemistry	233	Building 233		0.45
Rotating target neutron source	212	ICT – Building 212		0.9
		Top of ICT Shielding		0.5
Chemistry Heavy Elements Facility	251	Shielded boxes		0.8
		Unshielded work:	Cm-244 tracers	0.3
			Cf-252 tracers	0.2
			Boxes (top-bottom-no shield)	0.3
Reactor	281	Reactor		1.6[a]
Weapons Engineering Calibration Laboratory Site 300	131 255 Site 300	Shielded sources:	Cf-252 PuBe	0.4 0.2
		Unshielded sources:	Cf-252 PuBe	0.14 0.1
		Berm shielded accelerator		0.8
		255 Control Room		1.0

a. An additional correction for over-response of the 9-in. sphere must also be applied.

uncertainty at 95% confidence should not be less than the LOD, which for LLNL was about 0.03 rem for beta/gamma film dosimetry in the 1950s. LLNL researchers have published several articles on evaluations of personnel photon dose measurements and evaluations as follows:

- Wilcox (1956) reported on test exposures of DuPont 555 film from 5 mR to 1,000 mR with some testing in excess of 1,000 mR (Wilcox 1956). The ranges of this film for mixed photon energies at LLNL were stated to be:

^{60}Co	0.010 – 2,000 R
30 keV	0.001 – 200 R

- Table 6-17 presents a summary of intercomparison results described in a memorandum by Kathren (1965) between film- and TLD-measured doses in LLNL workplaces. Film badge interpretations and TLD-100 dose evaluations were compared over the April-to-August 1965 interval. During this period, there were 176 pairs of dosimeters that could be compared. Table 6-17 gives the results of the comparison. Good agreement was defined as interpretations differing by the greater of 20 mR or ≤20% of the higher interpretation. The June-to-August period was separated because special precautions were taken to ensure that the two dosimeters were changed at the same time and that no overlapping intervals occurred. Of the 40 cases in which the film readings were higher that the LiF, at least 32 were with persons known to have been exposed to low-energy X-rays; an additional 3 had possible low-energy X-ray exposure. In these cases, the developed film generally showed a typical low-energy X-ray pattern. Thus, the higher film badge results can be attributed to the lack of response by the TLD-100; the film badge data are more indicative of actual exposure. By contrast, there is no obvious explanation in which the TLD interpretations are higher than those for the film.

Table 6-17. Summary of LLNL measured TLD and film doses (Kathren 1965).

	April–August		June–August	
Condition	**Number**	**Percent**	**Number**	**Percent**
Good agreement	105	60	58	57
Film higher	40	23	22	22
TLD-100 higher	31	18	22	22
Total	176	100	102	100

- LRL and PNL (1966–1967) prepared documentation of LLNL dosimeter performance in the DOE-sponsored study in 1967 to evaluate a complex-wide dosimeter performance standard, which is described in BNWL-542, *The Establishment and Utilization of Film Dosimeter Performance Criteria* (Unruh et al. 1967). The criteria in this document were used to develop performance testing criteria used in a study of 35 government, military, and commercial dosimeter processors at that time. LLNL-reported doses in comparison with the given doses are summarized in Table 6-18.

Table 6-18. LLNL participation in DOE dosimeter performance testing (LRL and PNL 1966–1967).

Dosimeter No.	Given dose	LLNL dose	Dose difference	Percent
Gamma radiation				
1	1.000	1.050	0.050	5.0
2	1.000	1.050	0.050	5.0
3	1.000	1.050	0.050	5.0
4	1.000	1.050	0.050	5.0
5	1.000	1.010	0.010	1.0
6	1.000	1.100	0.100	10.0
7	0.240	0.245	0.005	2.1
8	0.240	0.280	0.040	16.7
Beta radiation				
1	0.500	0.530	0.030	6.0
2	0.500	0.520	0.020	4.0
3	0.500	0.500	0.000	0.0
4	0.500	0.530	0.030	6.0
5	0.500	0.520	0.020	4.0
6	0.500	0.510	0.010	2.0
7	0.500	0.510	0.010	2.0
Neutron radiation				
1	0.262	0.291	0.029	11.1
2	0.787	0.862	0.075	9.5
3	0.262	0.280	0.018	6.9

- Hankins (1982a) reported results of a retrospective study of LLNL dosimeter response characteristics in a study to reconstruct an LLNL worker 1963 exposure at the Nevada Test Site (NTS) using beta and gamma irradiations from the LANL Godiva IV Critical Assembly. This study concluded that for the evaluated beta irradiations the film dosimeter without the security badge is reasonably accurate and about a factor of 2 too low when the security credential is in place. The gamma irradiations were accurate within about ±20%. The LLNL TLDs used at the time of this study (i.e., 1982) showed a similar accuracy (±20%) for gamma radiation and a factor of 2 too low for beta irradiations.

6.7.2 Measured Neutron Dose

LLNL researchers (Hankins 1967; Hankins and Nealy 1971; Hankins 1976; Griffith et al. 1977; Hankins 1977a; Griffith et al. 1978a,b; Hankins et al. 1978a,b; Slaughter et al. 1978; Griffith and Hankins 1980; Hankins 1982a,b, 1984b; Hankins, Homann, and Buddemeier 1989) have prepared numerous documents regarding neutron dose evaluation. A few selected documents follow:

- LRL and PNL (1966–1967) documentation of LLNL dosimeter performance in the DOE-sponsored study in 1967 included neutron radiation, as shown in Table 6-18.

- Hankins (1978b) described studies of albedo neutron dosimeter performance. As described in this report, a neutron survey inside containment of the Farley Nuclear Plant was made to determine the spectra of leakage neutrons and to evaluate the accuracy of a 9-in.-diameter sphere remmeter (PNR-4) and of albedo-neutron dosimeters. Variations in the neutron spectra, the ratio of gamma-to-neutron dose rates, and the thermal neutron component of the neutron dose were also studied. The results indicated the neutron spectra were constant throughout the reactor with a 25-keV component on a 1/E spectrum. The albedo-neutron dosimeter performed within about ±25% of the measured dose. A neutron survey was also made at a neutron radiography facility with an accuracy of the albedo-neutron dosimeter within approximately ±33% of the measured dose.

- Hankins (1982a) described techniques to evaluate the neutron exposures received by personnel at the LLNL. Two types of evaluations are discussed covering the use of the routine personnel dosimeter and of the albedo-neutron dosimeter. Included in the report are field survey results that were used to determine the calibration factors to be applied to the dosimeter readings. Calibration procedures were discussed and recommendations were made on calibration and evaluation procedures. The document described methods used to develop workplace-specific dose calibration factors. The techniques used were stated to typically agree within ±30%. For the lower calibration factors, low readings of up to 50% were observed. At these points, the neutrons were known to be approximately isotropic and a low calibration factor was expected from the badge results. The calibration factor obtained by using the 9/3-in. sphere ratio is accurate to within ±30%.

6.7.3 Measured Beta Dose

LLNL researchers have prepared documents regarding beta dose evaluation as noted in Attachment A, Section A.2. A few selected documents follow:

- LRL and PNL (1966–1967) documentation of LLNL dosimeter performance in the DOE-sponsored study in 1967 included beta radiation as shown in Table 6-18.

- Hankins (1984a) reported results of a retrospective study of LLNL dosimeter response characteristics to reconstruct a LLNL worker 1963 exposure at the NTS using beta and gamma irradiations from the LANL Godiva IV Critical Assembly. This study concluded that for the evaluated beta irradiations the film dosimeter without the security badge is reasonably accurate and about a factor of 2 too low when the security credential is in place. The gamma irradiations were accurate within about ±20%. The LLNL TLDs used at the time of this study (i.e., 1984) showed a similar accuracy (±20%) for gamma radiation and a factor of 2 too low for the beta irradiations used in this study.

6.8 SHALLOW DOSE

6.8.1 Assigned Shallow Dose

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

6.8.2 Assigned Extremity Skin Dose

There is uncertainty with respect to reconstructed extremity skin dose because of geometry, shielding, and dosimeter response parameters. According to LLNL dose records, extremity dosimeters were assigned to LLNL radiation workers. A standard monitoring practice is to establish a factor between WB and extremity exposures to determine when the extremity dose would be limiting and, thus, extremity dosimeters should be assigned. The factor is typically based on radiation guidelines for the extremity, skin, and whole body, which have varied over the years as described in Attachment A, Table A-1. At the 1949 meeting in Chalk River, Canada, among U.S., United Kingdom, and Canadian nuclear weapon development organizations, several aspects of operational health physics were defined (Taylor 1971). The identified limits were:

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

Based on comparison of the dose limits, it would not be necessary to monitor the extremity dose unless it was greater than a factor of about 5 multiplied by the WB dose; otherwise, the WB dose would be limiting. Therefore, it is recommended that the measured WB photon dose be increased by a factor of 5 to assign a dose to the extremities based on the premise that extremity dosimeters would have been assigned and the dose reported for higher exposures [13]. The extremity dose is always equal to or greater than the measured WB skin dose (i.e., an estimated extremity dose is equal to the sum of the WB gamma, neutron, and beta doses). Unless it is clear that the extremity dosimeter is always worn, the measured extremity dose should also be included in the total assigned dose. The dose reconstructor can use guidance in ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (ORAUT 2005d). An example is shown in Table 6-19.

Determination of assigned Extremity Dose
Assigned Whole Body (WB).Dose = Gamma + Neutron
Assigned WB Skin = WB Penetrating + Beta
Assigned Extremity Dose = WB Skin + extremity dose
Assign greater of: 1) 5 x Gamma dose 2) Assigned Extremity dose

Table 6-19. Examples of extremity skin dose assignments (assuming no clothing correction) (mrem).

LLNL reported dose				Assigned extremity skin dose
Beta	**Gamma**	**Neutron**	**Extremity**	
50	0	0	0	= (0 + 0) + 50 + 0 = 50
0	50	25	0	= 5 × (50) = 250
100	20	0	60	= (20 + 0) + 100 + 60 = 180
100	50	0	100	= 5 × 50 = 250 = (50 + 0) + 100 + 100 = 250

6.9 NON-SITE-SPECIFIC FACTORS

6.9.1 Adjustment for Glovebox Workers

There is uncertainty with respect to the reconstructed organ dose in the lower abdomen for workers working substantially in a chemical benchtop environment such as the LLNL plutonium facility glovebox operations. Guidance in OCAS-TIB-0010, *Best Estimate External Dose Reconstruction for Glovebox Workers* (NIOSH 2005), should be used to adjust the measured photon dose to workers in identified LLNL plutonium facilities where extensive and long-term glovebox work was conducted. In general, this correction should be considered for any worker with a glovebox checked on the Computer Assisted Telephone Claim form and whether the identified places of work included glovebox or other benchtop work environments.

6.9.2 Lead Vests Worn By Vault Operations Technicians

During 1990, LLNL Vault Operations technicians wore lead vests when conducting some of their tasks in the vault (Shingleton 1991). The technicians wore two dosimeters, one on the inside and the other on the outside of the vest. The lead vest resulted in a significant reduction of the recorded photon dose ranging from 9 to 44%. Dose reconstruction must consider the site of the cancer to ensure a favorable to claimant reconstructed dose. LLNL practices for wearing lead vests appear to vary from facility to facility and, even for the vault operations described in Shingleton (1991), the wearing of a lead vest was for only some tasks. The fraction of the measured photon dose for the dosimeter worn under the vest is dependent on the radiation field and the lead vest specifications. Passmore (1992, 1995a,b) has reported similar measurements of the effect of lead vests on recorded photon doses at Pantex and Rocky Flats Plant plutonium facilities. Until the specific details of LLNL practices to require workers to wear lead vests and to ensure integrity of the vests, the recommended option is to incorporate a correction factor depending on the cancer site, as shown in Table 6-20. If the dosimeter location is not known, the most clamant-favorable dosimeter locations should be assumed. Table 6-20 values were derived from the LLNL measurements (Shingleton 1991) to represent a maximizing best estimate of the correction factor based on the available measurement results and are applied as a constant. The lead vest did not affect the neutron dose component.

Table 6-20. Correction factors for application to photon dose received while wearing a lead vest [14].

Dosimeter location	Cancer location	Neutron dose	Deep photon dose	Shallow photon dose[a]
Under apron	Protected area	1	1	1
	Outside vest	1	2	1
Outside apron	Protected area	1	(b)	1
	Outside vest	1	1	1

a. Shallow dose would be based on dosimeter worn outside the vest.
b. In this case, the measured dose will be too high and will be favorable to the claimant.

Adjustment to dose for use of protective lead vests depends on the location of the cancer site in relation to the lead vest. The vests covered the torso of the body but did not cover the head, neck, arms, or lower portion of the legs. If the cancer site is under the vest, there is no adjustment (i.e., the factor is 1.0), because a dosimeter under the vest will reasonably measure a dose to the cancer site. If the cancer site is in an area not protected by the lead vest, and for which the dosimeter-measured dose might be too low, the recommended adjustment factor as listed in Table 6-19 should be applied.

6.10 ATTRIBUTIONS AND ANNOTATIONS

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

[1] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
Mr. Fix reviewed the historical LLNL claimant dose reports to evaluate methods used to determine the WB penetrating, WB skin, and extremity (hand) skin doses from the dosimeter results.

[2] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006.
Mr. Thomas reviewed DOE dose reports for Energy Employee claims to evaluate trends in the types of dose data.

[3] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
Mr. Fix reviewed the historical documentation to estimate the types of beta/photon dosimeters, exchange frequencies, and associated LODs used to monitor LLNL workers. The LODs were estimated according the type of dosimeter technology and typical capabilities. Kathren (1964) provides LLNL beta/photon film LOD estimates for 1963. The annual potential missed dose was calculated using the method in OCAS-IG-001 (NIOSH 2007b).

[4] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
Mr. Fix reviewed the historical documentation to estimate the types of neutron dosimeters, exchange frequencies, and associated LODs used to monitor LLNL workers. The LODs were estimated according the type of dosimeter technology and typical capabilities. Kathren (1964) provides LLNL NTA LOD estimates for 1963. The annual potential missed dose was calculated using the method in OCAS-IG-001 (NIOSH 2007b).

[5] 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.

[6] 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 was chosen because the DCF is typically favorable to claimants.

[7] Thomas, Bill R. Integrated Environmental Management. Health Physicist. April 2006.
The precise date LLNL implemented on-phantom photon radiation calibrations is not known. It is expected that this was done for beta/photon dosimeters certainly no later than 1986 when

DOELAP dosimeter performance testing was required. This is a favorable to claimant judgment pending information regarding the precise date this was done.

[8] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
The selection of the geometry is described in OCAS-IG-001 (NIOSH 2007b).

[9] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
This represents the judgment of Mr. Fix and is consistent with statements in Rich (1969). This position is also substantially based on information in Fix, Wilson, and Baumgartner (1997b) and the similarity between LLNL and Hanford workplace radiation in plutonium facilities.

[10] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The recommendation to use the claim-specific NP dose ratio if higher than the recommended default values is to ensure that the neutron dose of record for the claimant is not reduced.

[11] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
DOE has informed NIOSH by letter that DOE contractors have a 3-year window to implement the ICRP Publication 60 weighting factors (ICRP 1991). Therefore, it will be necessary for the NIOSH Office of Compensation Analysis and Support points of contact with each site to obtain the planned implementation date. This information will need to be requested from LLNL.

[12] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. February 2010.
The information in this section is based on the judgment of a LLNL Subject and Site expert (Fix 2010) regarding options to assure favorable to claimant neutron dose reconstruction as documented by Mr. Fix.

[13] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. October 2009.
The information in this section is based on the judgment of Mr. Fix recommending to the dose reconstructor, depending on the target tissue, consideration to assign an extremity dose in the event that monitoring for extremity dose is not performed or is incomplete or the extremity dose is not reported by DOE.

[14] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. November 2009.
The tabled values of the recorded photon dose correction factor for wearing a lead vest was based on the dose response measurements in the Shingleton (1991) reference. The maximum value in this reference stated a 44% reduction in the gamma dose. A favorable to claimant value of 50% was assumed, resulting in the tabled correction factor of 2 for a cancer site on the whole body such as the head or upper arm, not under the lead vest, but for which the dosimeter is located under the vest.

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GLOSSARY

albedo dosimeter
Thermoluminescent dosimeter that measures the thermal, intermediate, and fast neutrons scattered and moderated by the body or a phantom from an incident fast neutron flux.

ampere (A)
International System unit of electrical current equal to 1 coulomb per second.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

claimant
Individual who has filed for compensation under the Energy Employees Occupational Illness Compensation Program. This individual can be the energy employee (worker), a survivor, or the legal representative of the energy employee.

class
A "class of employees" is defined in the EEOICPA rule as a group of employees who work or worked at the same DOE facility or AWE facility, and for whom the availability of information and recorded data on radiation exposures is comparable with respect to the informational needs required to complete a radiation dose reconstruction.

Columbia Resin Number 39 (CR-39)
Radiosensitive material used in track-etch neutron dosimeters.

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

deep dose equivalent (H_d)
Dose equivalent in units of rem or sievert for a 1-centimeter depth in tissue (1,000 milligrams per square centimeter). See *dose*.

DOE Laboratory Accreditation Program (DOELAP)
Program for accreditation by DOE of DOE site personnel dosimetry and radiobioassay programs based on performance testing and the evaluation of associated quality assurance, records, and calibration programs.

dose
In general, the specific amount of energy from ionizing radiation that is absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays

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

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose

received by an individual. See *albedo dosimeter*, *film dosimeter*, *neutron film dosimeter*, *pocket ionization chamber*, *thermoluminescent dosimeter*, and *track-etch dosimeter*.

dosimetry
Measurement and calculation of internal and external radiation doses.

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

Energy Employees Occupational Illness Compensation Program Act of 2000, as amended (EEOICPA; 42 U.S.C. § 7384 *et seq.*)
Law that provides for evaluation of cause and potential compensation for energy employees who have certain types of cancer.

exchange period
Period (weekly, biweekly, monthly, etc.) for routine exchange of dosimeters. Also called exchange frequency.

external dose
Dose received from radiation emitted by sources outside the body.

film
In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*.

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

gamma radiation
Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

glovebox
Enclosure with special rubber gloves through which an operator can handle radioactive or toxic material without risk of injury or contamination normally operated at a slightly reduced pressure so that air leakage, if any, is inward.

limit of detection (LOD)
Minimum level at which a particular device can detect and quantify exposure or radiation. Also called lower limit of detection and detection limit or level.

linear accelerator (LINAC)
Straight single-pass particle accelerator in which radio frequencies accelerate the beam over the length of the accelerator.

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

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

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

nuclear track emulsion, Type A (NTA)
Film sensitive to fast neutrons made by Eastman Kodak. The developed image has tracks caused by neutrons that are visible under oil immersion with about 1,000-power magnification.

occupational dose
Internal and external ionizing radiation dose from exposure during employment. Occupational dose does not include that from background radiation or medical diagnostics, research, or treatment, but does include dose from occupationally required radiographic examinations that were part of medical screening.

on-phantom
Exposure of a dosimeter on a phantom to simulate the dosimeter's response when worn on a person.

open window (OW)
Area of a film dosimeter that has little to no radiation shielding (e.g., only a holder and visible light protection). See *film dosimeter*.

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

photon
Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

pocket ionization chamber (PIC)
Cylindrical monitoring device commonly clipped to the outer clothing of an individual to measure ionizing radiation. A PIC may be self-reading or require the use of a outside device to be able to read the dosimeter. Also called pencil, pocket pencil, pencil dosimeter, and pocket dosimeter.

rad

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

radiation

Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer.

radioactivity

Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei. See *radionuclide*.

rem

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

roentgen

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

shallow absorbed dose (D_s)

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

shallow dose equivalent (H_s)

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

sievert (Sv)

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

thermoluminescence

Property that causes a material to emit light as a result of heat.

thermoluminescent dosimeter (TLD)

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

track-etch dosimeter

Device for evaluation of fast neutron dose through examination of traces left by the neutrons on the Columbia Resin Number 39 emulsion.

unmonitored dose

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

whole-body (WB) dose

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

X-ray radiation

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

ATTACHMENT A
HISTORICAL TIMELINE OF RADIATION EXPOSURE ASSOCIATED EVENTS AT LLNL

TABLE OF CONTENTS

LIST OF TABLES

This attachment contains a summary of LLNL Radiation Protection practices and an abbreviated historical timeline used in the preparation of the LLNL radiation protection practices and workplace measurements and controls.

A1. RADIATION PROTECTION

The basic elements of DOE and predecessor radiation protection policies were generally well defined at the beginning of LLNL operations.

Radiation Protection Standards
The basic elements of LLNL radiation protection practices were defined in the earliest years of operating LLNL facilities. In the earliest years of LLNL operations, the AEC used radiation protection guidance provided by national and international organizations. The limits and chronology are shown in Table A-1. To demonstrate compliances of workplace beta, photon, and neutron radiation exposure to workers, doses have been monitored by health physics personnel using personnel dosimeters, PICs, and portable radiation detection instruments. Personnel dosimeters represent the primary method to measure and record the official dose for a worker. However, personnel dosimeters are assigned to workers typically for a specified period (i.e., weekly, monthly, quarterly, or semiannually at LLNL beginning in 1974 depending on potential for radiation exposure), and exchanged for new dosimeters according to an established monthly or quarterly schedule. Dosimeters on return are typically processed and doses assigned. Typically, the official dose based on the dosimeter was not received by the worker or their supervision until many days after a dosimeter has been routinely exchanged and certainly well after radiation exposure to the worker has occurred. Administrative control of worker exposures is based on workplace controls or the results of dose measurements using PICs or portable instruments and timekeeping. These instrument measurements represent the real methods used day-to-day to limit worker radiation exposures. Basically, a cumulative administrative radiation exposure record is maintained for each worker for use in tracking and, as necessary, limiting exposures. Dose results from the personnel dosimeters for each exchange cycle are used to update the administrative exposure record. The dosimeter exchange cycle is selected based on the exposure potential for each worker and, in case of an incident, personnel dosimeters can be special-processed at any time. This process requires close attention by supervision and radiation safety personnel to the total exposure accumulated by each worker.

Table A-1. Chronology of radiation standards: occupational external WB dose equivalent limits.

Year	ICRP		NCRP		AEC/ERDA/DOE		LLNL radiation protection guidance	
	Criteria	**Ref.**	**Criteria**	**Ref.**	**Criteria**	**Ref.**	**Criteria**	**Ref.**
1950	0.3 rad/wk		0.3 rad/wk		0.3 rad/wk 3.9 rad/13 wk	NBS Handbook 47 (NBS 1950)		
1954	0.3 rad/wk		3.0 rad/13 wk 0.3 rad/wk 15 rem/yr	NBS Handbook 59 (NBS 1954)	3.0 rad/13 wk 0.3 rad/wk max, 15 rem/yr	NBS Handbook 59 (NBS 1954)	0.3 rem/wk	LRL ca. 1954
1955							Neutron weekly allowable exposure is 1.3 tracks per field based on 30 n/cm^2/s for 40 hr	LRL 1955
1957	0.3 rad/wk		5 rem/yr avg 12 rem/yr max	Addendum to NBS Handbook 59 (NBS 1958)	3.0 rad/13 wk 0.3 rad/wk max 15 rem/yr			
1958	0.1 rem/wk, 3.0 rem/13 wk, 5 (N-18) rem*	ICRP Publication 1 (ICRP 1959)	0.3 rem/wk 3 rem/13 wk, 12 rem/yr max, 5 (N-18) rem*	Addendum to NBS Handbook 59 (NBS 1958)	0.3 rem/wk, 3.0 rem/13 wk 12 rem/yr 5 (N-18) rem*	NBS Handbook 59 (NBS 1954)		
1960	0.1 rem/wk, 3.0 rem/13 wk, 5 (N-18) rem*		0.3 rem/wk 3 rem/13 wk, 12 rem/yr 5 (N-18) rem*		3 rem/13 wk, 5 rem/yr avg 5 (N-18) rem*	Federal Radiation Council Report 1 (FRC 1960)		

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1963					Prospective: Qtr–3 rem Year–5 rem Retrospective Accumulated Dose: 5(N-18)	*AEC Manual*, Chapter 0524 (AEC 1963)		
1965	3 rem/13 wk 5 rem/yr	ICRP Publication 9 (ICRP 1966)	0.3 rem/wk 3 rem/13 wk 12 rem/yr 5 (N-18) rem*		3 rem/13 wk 5 rem/yr avg 5 (N-18) rem*			
1971	3 rem/13 wk 5 rem/yr		3 rem/13 wk 5 rem/yr	NCRP Report 38 (NCRP 1971)	3 rem/13 wk 5 rem/yr avg 5 (N-18) rem*			
1974	3 rem/13 wk 5 rem/yr		3 rem/13 wk 5 rem/yr		3 rem/13 wk 5 rem/yr	NCRP Report 38 (NCRP 1971)		
1977	5 rem/yr acceptable risk	ICRP Publication 26 (ICRP 1977)	3 rem/13 wk 5 rem/yr		3 rem/13 wk 5 rem/yr			
* N refers to age of the worker in years.								

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A2. HISTORICAL TIMELINE

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

1952

Powell, F., 1952, untitled letter to E. O. Lawrence (University of California Radiation Laboratory), California Research and Development Company, San Francisco, California, June 24. [SRDB Ref ID: 15231]

Provided film dosimeter dose results for all film badge readings recorded in the permanent files for Radiation Laboratory personnel at Livermore. Unless exposures are noted by date, it is understood that the film indicated no exposure. There are slightly more than two pages of dose results for identified personnel.

Block, S. 1952, "Personnel Monitoring for Thermal Neutrons by the Cd (n, γ) reaction," memorandum to F. P. Cowan, University of California Radiation Laboratory, Livermore, California, September 17. [SRDB Ref ID: 15717]

Described a sensitive method for detecting low-level integrated doses of slow neutrons in the presence of gamma radiation using Cd(n,γ) reaction and film. This reaction showed good promise to provide a method for personnel monitoring of slow neutrons.

1953

Thompson, D. R., 1953, "Film Badge and Pocket Dosimeter Information," memorandum to All Livermore Employees, University of California Radiation Laboratory, Livermore, California, March 9. [SRDB Ref ID: 15709]

Stated the film badge and PIC dosimeter program was in place at Livermore. All personnel whose daily work might expose them to ionizing radiation of any kind were requested to start wearing their film badges. With few exceptions, there was a film badge for each employee at Livermore. Supervisors were asked to insist that each employee under his supervision wear his or her film badge if and when it was required. PICs of the gamma or slow neutron type were available to scientific personnel on request.

LRL (Lawrence Radiation Laboratory), 1954, collection of memoranda from B. Lagiss and S. Block, March through December, University of California, Livermore, California. [SRDB Ref ID: 36304]

These memoranda reported measured film badge doses for LLNL groups and film dosimeter exchange weeks. The weekly tolerance was 0.3 R.

LLNL (Lawrence Livermore National Laboratory), 1953–1985, collection of external radiation dose records, University of California, Livermore, California. [SRDB Ref ID: 23463]

Contained external radiation dose records from 1953 through 1985 for selected personnel.

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LRL (Lawrence Radiation Laboratory), 1953–1955, collection of film badge reports, University of California, Livermore, California. [SRDB Ref ID: 36349]

These reports provided a history of neutron calibration sources and tolerance limits.

<u>1954</u>

Block, S., 1954, "Personnel Monitoring Procedure for UCRL, Livermore," memorandum to All Department Heads, University of California, Lawrence Radiation Laboratory, Livermore, California, July 19. [SRDB Ref ID: 16949]

Described features and requirements of personnel monitoring as follows:

- Film badges were provided for all personnel employed at UCRL, Livermore site. Each film badge was identified with a number assigned to an individual.
- PICs were also provided at the Film Badge Office for those who did not have access to them. The PICs were read and a record kept of the individual's exposure. Because one of the chambers was a self-reading type, the exposure could be read by the individual concerned.
- For those who worked in radiation areas, the film badges were exchanged once a week.
- For personnel who did not work in a radiation area, film badges were exchanged monthly.
- Persons who routinely visited radiation areas had film badges exchanged weekly. This group included laboratory guards and custodians and some installation and maintenance personnel.
- Any person who suspected a significant exposure had his dosimeter processed as soon as possible on delivery to Health Physics.

LRL (Lawrence Radiation Laboratory), 1954, *Livermore Film Badge Report, NTA Films, Week of Nov. 3-10, 1954*, University of California, Livermore, California. [SRDB Ref ID: 36087]

Indicated tolerances as follows:

- One weekly tolerance (PoBe) = 1.38 tracks per field
- Ten week tolerances (PoBe) = 13.6 tracks per field
- Background = 0.05 tracks per field

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

Described radiation protection limits and the requirement for all persons entering a radiation area to wear a film badge. Film badges were provided for all personnel at the UCRL Livermore Site. The badges were for the most part hung on a rack in the Film Badge Office in Building 162. A radiation area was defined as an area in which precautions against radiation exposures were required, usually designated by a sign bearing the standard radiation symbol. PICs could also be assigned for areas with higher exposure levels. Film badges with neutron-sensitive film and boron-lined PICs could also be assigned to persons working in areas with the potential for significant neutron radiation exposure. The radiation areas were described as general areas with a film badge board to further designate the

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area and for use to obtain and leave monitoring instruments on entering or exiting a radiation area. Measured exposures exceeding 0.3 mrem/wk required an investigation.

1955

LRL (Lawrence Radiation Laboratory), 1955, collection of memoranda from Health Physics and Film Badge Office on neutron exposures, University of California, Livermore, California, January 26, October 10, and October 28. [SRDB Ref ID: 15693]

These memoranda discussed assignment of positive neutron dose based on neutron tracks recorded on neutron film. Memoranda stated the neutron dose was based on a PoBe calibration and the percent of the allowable tolerance dose (i.e., weekly allowable exposure is considered to be 1.3 tracks per field based on 30 n/cm^2/s for 40 hours. The January 26 memorandum states that all significant neutron exposures would be brought to the attention of supervision. Two workers were apparently exposed to 14-MeV neutrons.

1956

Wilcox, G. E., 1956, "New Film - 555 for 1956 - 1957," memorandum to W. E. Nolan and S. Block, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 19. [SRDB Ref ID: 15705]

Reported test exposures of DuPont film 555 from 5 mR to 1,000 mR with some results in excess of 1,000 mR. The range of this film for mixed photon energies extent at LLNL was stated to be:

Co-60	0.010 – 2,000 R
30 keV	0.001 – 200 R

Author unknown, ca. 1957, untitled analysis of film badges during 33-week period beginning January 1, 1956. [SRDB Ref ID: 15230]

Analysis of recorded positive doses identified several patterns as follows:

Considering all workers with a film badge since 1/1/1956	
Total number of workers receiving exposures	251
Total number of positive film exposures	1,316
Average positive exposures/worker	5.2
Considering workers with repeated positive exposure only	
Total number of workers receiving exposures	183
Total number of positive film exposures	1,248
Average positive exposures/worker	6.8

The percentages of positive exposures by work group were:

- Chemists–42%
- Health Chemists–35%
- Tuballoy Shop–11%
- Pratt & Whitney–11%
- Miscellaneous–2%

Ten workers were identified with 20 or more positive weekly doses, and the curium operation appeared to contribute the highest measured doses.

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Lindeken, C. L., 1956, "Film Badge Coverage at Site 300," memorandum to G. E. Wilcox, University of California, Lawrence Radiation Laboratory, Livermore, California, March 14. [SRDB Ref ID: 15703]

Stated that UCRL personnel assigned to Site 300 were issued film badges. Health Chemistry staff members were involved in all operations at Site 300 involving radioisotopes and toxic materials; it was proposed in this memorandum that Health Chemistry staff members take responsibility for routine exchange of Site 300 dosimeters.

1957

LRL (Lawrence Radiation Laboratory), 1957, "Radiation Exposures," memorandum from Health Physics to R. Jopson, University of California, Livermore, California, April 9. [SRDB Ref ID: 15667]

Reported exposure results of Building 157 personnel for April 2 to April 8, 1957. The maximum permissible exposure was 0.3 R/wk.

1958

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

Stated that the film-and-security badge had been in use for 6 months. The philosophy of having every person wear a film badge identified a number of workers handling uranium with low-level exposures that were not being measured. There were also some recorded doses from badges for workers in nonradiological areas, but the badges recorded positive doses because the badge board was receiving low-level radiation.

In general, the data received had improved in quality and quantity. LLNL now changed badges for approximately 90% of the personnel every month, 99% within 2 months, and only three to five people had gone 3 months without an exchange. The readings indicated personnel rather than board exposures. The quality seemed better because LLNL could differentiate beta and gamma types more easily by the density ratios with less intuition involved.

Wilcox, F. W., 1958, "Personnel Exposures," letter to W. E. Nolan (Lawrence Radiation Laboratory), Reynolds Electrical & Engineering Company, Las Vegas, Nevada, December 22. [SRDB Ref ID: 15235]

Reported measured doses to several LLNL workers participating in nuclear tests at NTS.

LRL (Lawrence Radiation Laboratory), 1960–1962, "Site 300," University of California, Livermore, California. [SRDB Ref ID: 35162]

Listed Site 300 staff members from 1960 to 1962.

1959

Wilcox, F. W., 1959, "Personnel Exposures," letter to W. E. Nolan (Lawrence Radiation Laboratory), Reynolds Electrical & Engineering Company, Las Vegas, Nevada, January 6. [SRDB Ref ID: 15234]

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Reported measured doses to several LLNL workers participating in nuclear tests at NTS.

1961

LRL (Lawrence Radiation Laboratory), 1962, *Hazards Control Quarterly Report No. 7 (October through December, 1961)*, UCRL-6818, University of California, Livermore, California. [SRDB Ref ID: 33001]

States that the distribution and use of portable survey meters was restricted to persons familiar with the limitations of the instruments. In most instances if a meter was required a Monitor was also needed. The Hazards Control Field Representative was responsible for the radiation instruments issued in his area. Three survey instruments of each type required were generally issued to each Monitor. Additional instruments were issued in the event that more were necessary for adequate day-to-day monitoring.

LRL (Lawrence Radiation Laboratory), 1961, "Portable Radiation Survey Instruments," *H.C. Manual*, Part I, Procedure 1106, University of California, Livermore, California, October 16. [SRDB Ref ID: 15711]

Described each instrument and limitations. For example, the portable instrument used at LRL to detect and measure thermal and fast neutron fluxes was called the Nemo. This instrument was made by Nuclear-Chicago Corporation as its Portable Neutron Survey Meter Model 2715. It detected fast, slow, or mixed fluxes from 10 to 10^4 n/cm^2/s.

1962

Montgomery, D., 1962, "Neutron Film List," memorandum to B. Smales, Lawrence Radiation Laboratory, University of California, Livermore, California, February 6. [SRDB Ref ID: 15731]

Reported several personnel were placed on the Neutron Film List for Building 171 because of work with neutron-emitting radioactive materials apparently in Room 1232. The list was to be reviewed monthly and changes made accordingly.

Kathren, R. L., 1962, "Evaluation of Personnel Dosimetry Program," memorandum to J. J. Balanda, Lawrence Radiation Laboratory, University of California, Livermore, California, October 31. [SRDB Ref ID: 16145]

Discussed several areas of the LLNL film dosimetry program including badge design and calibration. The LOD with the LLNL badge was typically assumed to be 20 mrem for ^{60}Co gamma radiation but could be a low as 10 mrem.

1963

Kathren, R. L., W. C. Day, and D. E. Denham, 1963, "Preliminary Health Physics Analysis, Building 110 Criticality Incident," memorandum to J. J. Balanda, University of California, Lawrence Livermore Laboratory, Livermore, California, April 4. [SRDB Ref ID: 15228]

Personnel dosimeters showed gamma doses of 70, 100, and 120 mrem, respectively, for three workers and no recorded neutron dose. The lower limits of detectability were about 10 mrem for gamma and 50 mrem for fast neutrons.

1964

Block, S., and K. F. Petrock, 1964, "Evaluation of a Neutron Rem Dosimeter," p. 17, *Hazards Control Quarterly Report No. 18 (July–December 1964)*, UCRL-12167, University of California, Lawrence Livermore Laboratory, Livermore, California, February. [SRDB Ref ID: 72280]

Described evaluation of an LLNL-modified neutron rem counter capable of reading RBE dose rate to ±10% in the intermediate neutron energy region.

1965

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

Described NTA response as a function of the angle of incidence of neutron radiation with the plane of the film. The angle of maximum response was a function of the energy of the incident neutrons. A factor was found that corrected for the effects of angular dependence and fast-neutron energy on the track-per-field dose. A factor of 1.3 was recommended to multiply the measured neutron dose to compensate for angular response.

Block, S., and C. T. Prevo, 1965, "A Source of Intermediate Energy Neutrons for Dosimeter Calibration," p. 8, *Hazards Control Quarterly Report No. 22 (July–September 1965)*, UCRL-14534, University of California, Lawrence Radiation Laboratory, Livermore, California. [SRDB Ref ID: 13888]

An Sb-Be neutron source moderated with D_2O was used to provide intermediate-energy neutrons for dosimetry calibrations.

Kathren, R., 1965, "Preliminary Evaluation of TLD-100-Film Badge Field Comparison," memorandum to D. Jones, Lawrence Radiation Laboratory, Livermore, California, November 2. [SRDB Ref ID: 15227]

Film badge interpretations and TLD-100 dose evaluations were compared over the April to August 1965 interval. During this period, there were 176 pairs of dosimeters that could be compared. The following table gives the results of the comparison. Good agreement was defined as interpretations differing by the greater of 20 mR or ≤20% of the higher interpretation. The period from June to August was separated out because special precautions were taken to ensure that the two dosimeters were changed at the same time, and that no overlapping leaving intervals occurred.

Condition	April–August		June–August	
	Number	Percent	Number	Percent
Good agreement	105	60	58	57
Film higher	40	23	22	22
TLD-100 higher	31	18	22	22
Total	176	100	102	100

Of the 40 cases in which the film readings were higher than the LiF readings, at least 32 were for persons known to have been exposed to low-energy X-rays; an additional 3 had possible low-energy X-ray exposure. In these cases, the developed film generally showed a typical low-energy X-ray pattern. Therefore, the higher film badge results could be attributed to the lack of response by the

TLD-100; the film badge data were more indicative of actual exposure. By contrast, there was no obvious explanation in which the TLD interpretations were higher than the film interpretations.

<u>1966</u>

Bolstad, J. W., G. E. Cummings, J. L. Eagan, and H. F. Finn, 1966, *Safety Analysis Report for the Livermore Pool Type Reactor*, UCRL-50147, University of California, Lawrence Radiation Laboratory, Livermore, California, November 20. [SRDB Ref ID: 13890]

Much of the shielding around the reactor was portable and was arranged so continuous work areas received no more than 100 mrem/wk. Radiation surveys were made weekly and high-radiation areas noted with signs and in some cases with flashing lights. The movement of portable shielding was strictly controlled and normally done only with the reactor shut down. Shielding effectiveness was carefully checked during the subsequent reactor startup.

<u>1967</u>

Radcliffe, J. B. Jr., E. E. Hill, and G. E. Cummings, 1967, *The Livermore Pool Type Reactor (LPTR)*, UCRL-4919, Rev II, University of California, Lawrence Radiation Laboratory, Livermore, California, January. [SRDB Ref ID: 13889]

Contained general information for an eventual 3-MW reactor that first achieved criticality during December 1957.

LRL (Lawrence Radiation Laboratory), 1968, *Hazards Control Progress Report No. 29 (September-December 1967), and Index to Hazards Control Progress Reports, Nos. 27 through 29*, UCRL-50007-67-3, University of California, Livermore, California. [SRDB Ref ID: 33012]

<u>1969</u>

Myers, D. S., and C. T. Prevo, 1969, "Personnel Dosimetry Associated with the Handling of a Large Numbers of 3-Kg ^{239}Pu Billets," unknown journal, pp. 505–517. [SRDB Ref ID: 53745]

Described the process for measuring WB neutron doses using a neutron-to-gamma dose rate ratio. Because the neutron-to-gamma ratio was dependent on the size, spacing, and moderation of the array, a new ratio was determined for each array. A neutron-to-gamma dose ratio was also established for billet surface radiation using computer techniques. The neutron dose was then established by applying the measured neutron-to-gamma ratio to the WB gamma dose as measured by film badges, and to the gamma hand dose as measured by TLDs. The monthly neutron-to-gamma dose ratio ranged from 2 to 5 and the hand dose was about a factor of 2 greater than the WB dose.

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

Stated that all of the approximately 6,200 employees and other permanently badged personnel at LRL were monitored by TLDs in an automated system. In addition, approximately 1,700 visitors and other temporary TLD personnel dosimeters were processed each month. Approximately 85% of monitored personnel received no measurable exposure and these were placed on a quarterly exchange with plans to go to a longer exchange cycle. The overview stated that TLD-100 was used to provide thermal neutron response for personnel potentially exposed to neutrons. The studies showed that any significant neutron dose was detected and then investigated, evaluated, and reported by a professional health physicist. In specific applications, the neutron-to-gamma dose ratio approach had proven effective. The Anderson-Braun neutron meter was used for neutron dose equivalent rate measurements, and the Victoreen Model 400 survey meter was used for gamma rate measurements. Ratios in the range of 0.46 to 3.0 were observed for most work locations. Measurements of neutron dose equivalent with NTA film were ineffective (i.e., no dose indicated in fields calculated to give easily detectable doses.).

1971

LLL (Lawrence Livermore Laboratory), 1968–1971, *Site 300 Radiation Safety Program*, University of California, Livermore, California. [SRDB Ref ID: 16188]

Described radiation safety practices for several Site 300 facilities with an emphasis on the monitoring program. The principal radiation safety hazards at Site 300 were summarized in general terms as follows:

- X- or gamma-ray exposures to personnel at Buildings 809, 823, 851 and 874.
- Chronic internal deposition of natural uranium, thorium, depleted uranium, and their alloys from firing table high-explosive (HE) tests.
- Occasional exposure to other nuclides in HE tests, and
- Massive contamination and possible internal deposition from plutonium, uranium, and tritium in static and dynamic tests in the 832, 834, 836, 854, and 857 test facilities.

Activities with hazardous materials at Site 300 were covered by guidelines in the LRL Health and Safety Manual and the Site 300 Safety and Operational Manual. Operations beyond the scope of these manuals were supplemented by special OSPs.

1972

Crites, T. R., 1972, collection of three memoranda to D. Jones, “Interpretation of the Special Dosimeter in Use in Building 281,” University of California, Lawrence Livermore Laboratory, Livermore, California, July 19, August 11, and October 12. [SRDB Ref ID: 14080]

These memoranda described the use of a special dosimeter for LPTR Operations and Experiment personnel at B-281. Bonner sphere neutron spectra from two calibration sources and several workplace locations showed similarity to ^{252}Cf with various thicknesses of D_2O. Neutron-to-gamma dose ratios in the general reactor areas varied from 0.1 to 1.0. The TLD-100 neutron response to 1 rem ^{252}Cf in 30-cm D_2O was an indicated 1.1 rem if no reflecting phantom was used and 2.4 rem if in contact with a phantom. The TLD neutron response to 1 rem ^{252}Cf in 50-cm D_2O was an indicated 7 rem if no reflecting phantom was used and 10.3 rem if in contact with a phantom. Runs with TLD-100, unbacked, in two of the reactor beams yielded an indicated 520- to 850-mrem dose compared to a remmeter measured dose of 1 rem.

Singh, M., and C. Slater, 1972, untitled memorandum to P. Hoff, University of California, Lawrence Livermore Laboratory, Livermore, California, October 5. [SRDB Ref ID: 15037]

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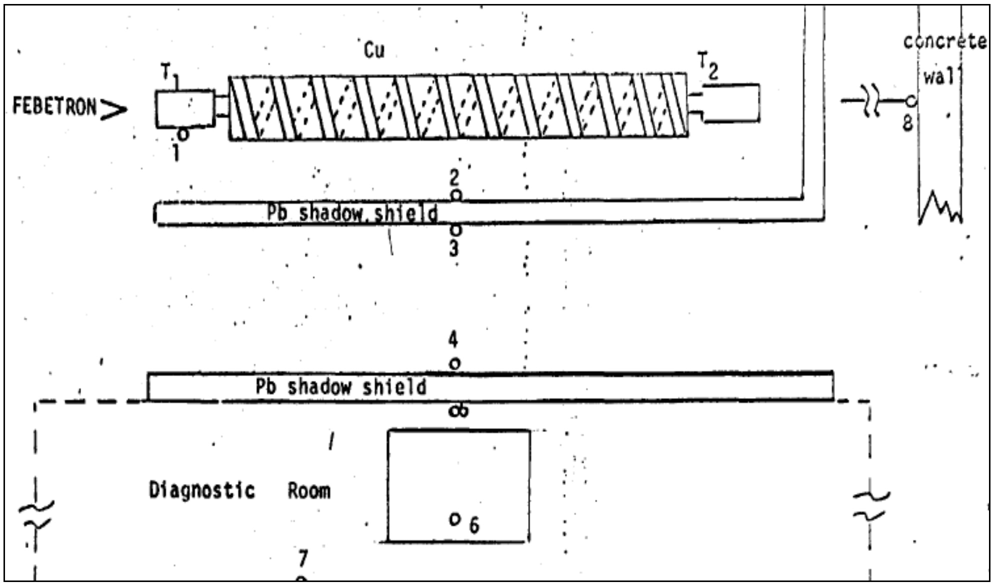
Reported additional measurements for the Febetron electron beam in Building 166. The operational mode of the Febetron was (1) peak energies of 2.5 MeV, (2) pulse duration of 40 ns, (3) 10,000 amps, and (4) operated with and without the magnets on.



The following table lists the measured integrated doses for the positions in the figure.

Position	Dose (mrem) per pulse
1	19,500
2	330
3	<2
4	8
5	0.29
6	0.004
7	0.83
8	<2

Singh, M. S., 1972, “Febetron Calculations,” memorandum to E. P. Sims and P. Hoff, University of California, Lawrence Livermore Laboratory, Livermore, California, October 20. [SRDB Ref ID: 15035]

1973

LLL (Lawrence Livermore Laboratory), ca. 1973, “Table 1. Radiation Dosimetry Measurements at the 100 MeV LINAC,” and handwritten notes, University of California, Livermore, California. [SRDB Ref ID: 15062]

1974

Hankins, D. E., 1975, “The Energy Response of TLD Badges Located on Personnel,” *Health Physics*, volume 28, number 1, pp. 80–81.

Described studies of various filter combinations to achieve a tissue-equivalent energy response with LiF dosimeter as would be worn by personnel.

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Crites, T. R., 1974, untitled letter to H. W. Dicksen (Oak Ridge, Tennessee), Lawrence Livermore Laboratory, Livermore, California, June 14. [SRDB Ref ID: 72712]

Discusses LLNL participation in an intercomparison study of the performance of personnel dosimeters.

1975

Hankins, D. E., 1975a, "Evaluation of Personnel TLD Badges Exposed to Neutrons in the Vault of Building 231," memorandum to Distribution, Lawrence Livermore Laboratory, Livermore, California, March 12. [SRDB Ref ID: 15111]

Hankins, D. E., 1975b, "Evaluation of Personnel TLD Badges Exposed to Neutrons in Building 332," memorandum to Distribution, Lawrence Livermore Laboratory, Livermore, California, February 4. [SRDB Ref ID: 15520]

Hankins, D. E., 1975c, *Studies of Neutron Dosimetry at the Lawrence Livermore Laboratory*, UCRL-76808, University of California, Lawrence Livermore Laboratory, Livermore, California, November. [SRDB Ref ID: 72225]

These reports described workplace evaluations of the LLNL albedo dosimeter system that employed a Harshaw TLD-100 thermal neutron-sensitive phosphor and methods to provide workplace-dependent calibration.

Odell, B. N., and A. J. Toy, Jr., 1975, *Safety Analysis Report for Building 331 at Lawrence Livermore Laboratory*, UCRL-51816 Draft, University of California, Lawrence Livermore Laboratory, Livermore, California, October 15. [SRDB Ref ID: 13891]

States the primary nuclide handled was tritium. There could have been small quantities of ^{239}Pu, ^{233}U, and ^{235}U.

Leahy, E. J,, and G. E. Williams, 1975, "Radiation Survey of Building 239 with 4 MeV Linatron in Operation," memorandum to K. C. MacMillan, University of California, Lawrence Livermore Laboratory, Livermore, California, December 15. [SRDB Ref ID: 15080]

A survey was conducted with the Linatron operating at its rated output of 400 R/hr at 1 m. Exterior measurements were made using portable radiation instruments. Interior spaces were monitored using TLDs over a 6-hour period.

The exterior of Building 239 was found to have radiation exposure rates less than 0.1 mR/hr, with the exception of the exterior ramp door. The dose rate at the exterior ramp door would have to be determined for operations where the Linatron was positioned in the western portion of the B 9 cell. The observed doses for 6 hours of exposure were:

Location	Unshielded (mR)	Shielded (mR)	Reduction factor
North	494	16	30
Center	545	21	25
South	438	33	13

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The reduction factors indicated that a lead shield about 0.25-in. thick was all the shielding necessary to isolate scattered radiation originating in cell B 9. Scattered radiation into cell B 11 and up the ramp area were the only exposure problems that would require continued vigilance.

LRL (Lawrence Livermore Laboratory), undated, "Building 239 Principal Radiation Hazards and Their Safety Control," University of California, Livermore, California. [SRDB Ref ID: 15078]

Contained radiation safety procedures for external and internal radiation monitoring. The primary external radiation hazards included several X-ray units and a large (10^8 n/s) neutron source.

1976

Held, B. J., and M. S. Singh, 1976, "UF_6 Operation, Building 177, Room 130," memorandum to B. Roth, University of California, Lawrence Livermore Laboratory, Livermore, California, March 2. [SRDB Ref ID: 15051]

Described a review of an experiment using a laser and a maximum of 10 g of enriched (perhaps 93%) UF_6. The primary potential hazard identified concerned the potential for inhalation.

Hankins, D. E., 1976, "Survey Results in Buildings 231 and 233," memorandum to Distribution, University of California, Lawrence Livermore Laboratory, Livermore, California, February 2. [SRDB Ref ID: 15100]

Described results of instrument surveys made in the 231 vault, outside the vault, and in the Building 233 source storage area using the PNR-4 neutron remmeter. The instrument was used with the 9- and 3-in. spheres and with the bare probe. The survey was made to confirm that calibration factors to TLD readings, determined earlier, were still applicable. The following table provides measurement results.

Location	9- to 3-in. ratio	% Thermal	Calibration factor
1. In vault	0.63	0.69	0.55
2. In vault	0.72	0.62	0.5
3. In vault	0.84	0.37	0.4
4. In vault	0.59	0.48	0.45
5. In vault	0.64	0.88	0.6
6. In vault	0.67	0.64	0.55
7. In vault	0.63	0.59	0.5
8. In vault	0.59	0.59	0.5
9. In vault	0.67	0.67	0.55
10. Outside vault	0.41	2.7	1.2
11. Outside vault	0.47	2.7	1.2
12. Outside vault	0.33	2.7	1.2
13. Bldg. 233	0.71	2.0	1.0
14. Bldg. 233	0.58	2.0	1.0
15. Bldg. 233	0.54	2.1	1.0
16. Bldg. 233	0.63	1.7	0.9
17. Bldg. 233	0.84	1.8	1.0
18. Bldg. 233	0.43	3.2	1.5
19. Bldg. 233	0.84	1.7	0.9

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Hankins, D. E., 1976, “Planted TLD Badge Results,” memorandum to Distribution, University of California, Lawrence Livermore Laboratory, Livermore, California, February 2. [SRDB Ref ID: 15519]

Described results of TLD badges taped to gallon jugs placed in various locations in Buildings 332, 233, and 255. The results were used to confirm that TLD calibration factors determined previously were correct for current conditions. Measurement results were:

Location	% Thermal	Calibration factor	
		From curve	**Experimental**
1. Bldg. 233	1.7	0.95	1.35
2. Bldg. 332 Shannon Office	2.1	1.0	1.32
3. Bldg. 332 Walden Office	5.3	2.25	2.57
4. Bldg. 332 Room 1378	0.46	0.43	0.28
5. Bldg. 332 Room 1378	0.31	0.33	0.40
6. Bldg. 255 PuBe storage	0.53	0.48	0.53

Stated that a calibration factor of 2.5 would continue to be used for the office area outside the Building 332 source storage vault per a February 4, 1975, memorandum. For an unknown workplace, a calibration factor of 0.5 was used.

Graham, C. L., 1976, “Off-Site Radiation Dose from B-212 for 1975,” memorandum to D. S. Myers, University of California, Lawrence Livermore Laboratory, Livermore, California, March 24. [SRDB Ref ID: 15081]

The results of the neutron and gamma doses for 1975 at the fence south of the ICT target room are shown below. The results represented the maximum radiation levels at the fence. Gamma dose measurements and two neutron measurements were begun on May 15, 1975.

Annual fenceline dose (mrem)			
Dates	**Neutron 1**	**Neutron 2**	**Gamma**
01/07/75–02/14/75	130		
02/14/75–03/31/75	75		
03/31/75–05/15/75	70		
05/15/75–06/30/75	30	43	21
06/30/75–08/12/75	100	109	49
08/12/75–10/01/75	120	142	51
10/01/75–10/16/75	40	25	21
10/16/75–11/04/75	40	59	24
11/04/75–12/31/75	30	25	22
Totals	685	403	188

From these data, it was estimated that the neutron-to-gamma ratio was 2. Therefore, the gamma measurements from January 7 to May 15 could be estimated to be 162 mrem. The total gamma dose was then 162 + 188 mrem = 380 mrem. The total neutron and gamma dose above natural background for 1975 was 1,035 mrem. Natural background was estimated to be 60 mrem.

Sundbeck, C. W., 1976, “TLD Results,” memorandum to T. Madden, University of California, Lawrence Livermore Laboratory, Livermore, California, June 8. [SRDB Ref ID: 15077]

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On March 30, 1976, TLDs were prepared for gamma and neutron measurements at the Building 212 fenceline. TLDs were read on June 2, 1976. The results were:

Neutron exposure	0.068 rem
Gamma exposure	0.029 R

Fisher, J., 1976, "Periodic Area Rem Meter Readings," memorandum to J. Powell, University of California, Lawrence Livermore Laboratory, Livermore, California, October 14. [SRDB Ref ID: 15072]

Quarterly reported neutron doses at the fenceline south of Building 212 were as follows:

06/01/76–08/02/76	82 mrem
08/02/76–10/07/76	81 mrem

These neutron doses were measured by recording neutron fission tracks in Lexan™.

Myers, D. S., 1976, "Personnel Dosimetry Requirements for Visitors and Contractors," memorandum to Support Team Leaders, University of California, Lawrence Livermore Laboratory, Livermore, California, June 3. [SRDB Ref ID: 16189]

Described the implementation effective July 1, 1976, of a revised TLD badging program for visitors and contractors. Under this new program, only the facilities in the following table required TLD badges for access by visitors and contractors.

Livermore Site		**Site 300**	
194	281	809	851
212	321	823	812E
231 (Vault)	327		
233	332		
239	431		
251			

The list of facilities would be reviewed quarterly. The logistics of issuing the TLD badges for visitors and contractors would remain the same; namely, the Personnel Dosimetry Laboratory would provide the visitor TLD badges to the Security Department, which would issue them at the Pass Office. LLNL would supplement the revised TLD badging requirements with an increased number of area TLDs in various facilities as appropriate. In general, if it was likely that visitors or contractors would receive measurable radiation doses (>10 mrem), they should have been issued a TLD badge.

1977

Powell, T. J., 1977, "Personal Radiation Dosimetry Requirements for LLL Visitors," memorandum to J Dixson, University of California, Lawrence Livermore Laboratory, Livermore, California, January 27. [SRDB Ref ID: 16078]

Stated that Building 431 should be deleted from the list of buildings requiring the issue of personal dosimeters to LLNL visitors.

Hankins, D. E., 1977, "A Modified A-B Remmeter with Improved Directional Dependence and Thermal Neutron Sensitivity," *Health Physics*, volume 34, pp. 249–254.

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Fisher, J., 1977, "Site Perimeter Neutron Monitoring," memorandum to T. J. Powell, University of California, Lawrence Livermore Laboratory, Livermore, California, January 25. [SRDB Ref ID: 15071]

The following neutron doses were recorded on the site perimeter remmeters during the indicated periods:

Location	Period	Dose (mrem) Total	Monthly average
1	07/15/76–01/07/77	2.4	<1
2	07/15/76–01/07/77	2.8	<1
3	10/07/76–01/07/77	136	45.4
4	07/15/76–01/07/77	3.2	<1
5	07/15/76–01/07/77	2.4	<1
6	07/15/76–01/07/77	2.9	<1
7	07/15/76–01/07/77	2.5	<1
8	07/15/76–01/07/77	2.8	<1

Graham, C. L., 1977, "Off-Site Radiation Dose From Building 212 for 1976," memorandum to T. J. Powell, University of California, Lawrence Livermore Laboratory, Livermore, California, March 3. [SRDB Ref ID: 15070]

The results of the neutron and gamma doses for 1976 at the fence south of the ICT target room are shown below. The results represented the maximum radiation levels at the fence. Neutron No. 1 and No. 2 measurements were made with ^{235}U fission foils in an Anderson-Braun remmeter and with TLDs in a 10-in. polyethylene sphere, respectively.

Annual fenceline dose (mrem)			
Dates	**Neutron 1**	**Neutron 2**	**Gamma**
12/29/75–02/02/76	Unavailable	125	62
02/02/76–04/02/76	Unavailable	35	25
04/02/76–06/02/76	54	68	29
06/02/76–08/04/76	82	136	58
08/04/76–10/18/76	81	112	52
10/18/76–01/06/77	136	163	58
Totals	353	639	284

The annual neutron dose was determined by averaging Neutron No. 1 and No. 2 measurements where applicable, and by using the No. 2 measurements when the No. 1 measurements were unavailable. The annual neutron dose result was 576 mrem. The total neutron and gamma dose above natural background for 1976 was 860 mrem. Natural background was estimated to be 60 mrem.

Slaughter, D. R., and D. W. Rueppel, 1977, *Environmental Neutron Spectrum Outside the LLL High-Intensity 14-MeV Neutron Facility*," UCRL-78946, University of California, Lawrence Livermore Laboratory, Livermore, California, June 9. [SRDB Ref ID: 15065]

Results of field spectra measurements showed that the transmitted neutron energy spectrum was concentrated in two rather strong peaks. Dose equivalent conversion with these spectra could be difficult. A standard polyethylene-moderated remmeter or 22.8-cm (9-in.) spherical remmeter would seriously underestimate the 14-MeV transmission peak. However, due to the small contribution from energetic neutrons, the measured total dose rate would be only 10% to 15% low.

Hankins, D. E., 1977, "Radiation Survey in Office Areas of Building 233," memorandum to D. S. Myers, University of California, Lawrence Livermore Laboratory, Livermore, California, March 24. [SRDB Ref ID: 15099]

Described photon radiation survey using a Reuter Stokes high-pressure ion chamber and an SPA-3 scintillation probe assembly. The ion chamber results were considered to be more accurate. The highest readings obtained were 350 µR/hr in the hallway and 430 µR/hr at the source storage cabinet.

Madden, T. W., 1977, "Total Man-Rem at Major Facilities," memorandum to T. J. Powell, University of California, Lawrence Livermore Laboratory, Livermore, California, October 11. [SRDB Ref ID: 16928]

Estimates of person-rem were taken from personnel dosimetry files, and they did not include any dose less than 100 mrem/yr. The following table lists collective doses in person-rem and totals for each major facility and year in the report.

Bldg.	1973	1974	1975	1976	Total
194	17.60	5.80	7.4	5.82	36.62
212	6.50	7.06	8.0	7.35	28.91
332	3.30	5.18	4.74	6.29	19.51
331	4.20	3.54	0.74	2.38	10.86
251	4.20	6.95	6.13	1.83	19.16
281	3.90	6.24	4.11	1.80	16.05
231	5.50	3.47	1.98	2.62	13.57
233	0.78	2.35	5.73	2.12	10.98
Total	45.98	40.59	38.83	30.26	155.66

The recommendation was made that Buildings 231 and 233 be considered one facility because most of the exposures were to Materials Management personnel who worked in both buildings.

Graham, C. L., and S. G. Homann, 1977, *Gamma-Ray Dosimetry Errors with TLDs*, UCRL-80183, University of California, Lawrence Livermore Laboratory, Livermore, California, October 13. [SRDB Ref ID: 6184]

Described studies of dosimeter response for selected sources of photon radiation and the potential to overestimate the dose based on issues about lack of electronic equilibrium and nonuniform energy deposition throughout the TLD phosphor.

Griffith, R. V., D. R. Slaughter, H. W. Patterson, J. L. Beach, E. G. Frank, D. W. Rueppel, and J. C. Fisher, 1977, *Multi-Technique Characterization of Neutron Fields From Moderated* ^{252}*Cf and* ^{238}*PuBe Sources*, UCRL-79483, University of California, Lawrence Livermore Laboratory, Livermore, California, November 7. [SRDB Ref ID: 55790]

Bare and moderated neutron sources were used to calibrate survey instruments and personnel neutron dosimeters in the Hazards Control Department radiation calibration facility at LLNL. Specifically, ^{252}Cf and ^{238}PuBe sources were used in spheres of water, polyethylene, deuterium oxide, and aluminum.

1978

Griffith, R. V, D. E. Hankins, R. B. Gammage, L. Tommasino, and R. V. Wheeler, 1978, *Recent Developments in Personnel Neutron Dosimeters – A Review*, UCRL-80928, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 17. [SRDB Ref ID: 72237]

Described primary methods of neutron personnel dosimetry.

Griffith, R. V., J. C. Fisher, D. E. Hankins, and D. E. Miller, 1978, *Personnel Neutron Monitoring Developments at LLL*, UCRL-81897, University of California, Lawrence Livermore Laboratory, Livermore, California, November 14. [SRDB Ref ID: 72238]

Stated that approximately 40 employees at LLNL worked in areas where personnel neutron monitoring was necessary. The dose rate in these areas was low, rarely exceeding 0.5 rem/yr. There was a wide variety of neutron environments (i.e., DT neutron generators, 3-MW pool type reactor, 100-MeV LINAC, and a number of vaults and glovebox work areas where alpha, neutron, and spontaneous fission sources were stored) that made neutron monitoring difficult. The following table reproduces a comparison of instrument and dosimeter measured doses.

	NP Ratio					
	Method of measurement[a]					
Facility[b]	**AB**	**9–in. SP**	**TLD**	**NTA**	**FT-Np**	**FT-Th**
Pu-238/Be (unmoderated)	0.9	0.9	0.7	1.2	1.2	1.6
High flux neutron generator	1.0	1.3	8.0	0.9	1.1	1.1
Cm-244 handling facility						
Location 1	1.1	1.3	5.0	0.8	0.9	0.7
Location 2	1.0	1.5	11.0	0.8	1.0	0.8
Location 3	1.0	1.5	11.0	0.7	1.0	0.5
Cf-252 calibration cell						
Source unmoderated	1.1	1.4	7.0	0.6	0.8	0.4
Source in 25 cm H_2O	1.0	1.3	7.0	0.7	0.9	0.5
Source in 25 cm D_2O	1.0	1.6	14.0	0.5	0.9	0.4
Source in 25 cm Al	1.1	1.7	11.0	0.4	0.8	0.2
3-MW pool type reactor						
Location 1	0.9	2.0	28.0	0.5	1.2	0.6
Location 2	1.0	1.4	13.0	0.7	1.0	0.6
850-MW pressurized power reactor						
Location 1	1.2	2.5	23.0	0.2	0.7	0.1
Location 2	1.2	2.8	31.0	0.2	0.8	0.1
250-keV TRIGA reactor						
Location 1	1.1	1.6	12.0	0.5	0.8	0.3
Location 2	1.1	1.7	10.0	0.5	0.8	0.3
Location 3	1.1	1.8	13.0	0.5	0.8	0.4
Location 4	1.1	1.8	15.0	0.3	0.7	0.1

a. AB = Anderson Braun remmeter, 9–in. Sp = 9–in. spherical remmeter, TLD = Hankins albedo dosimeter, NTA = nuclear track emulsion, type A; FT-Np = fission track Np-237, FT-Th = fission track Th-232.
b. Typically shielded such as in the workplace unless noted as unshielded.

Hankins, D. E., 1978a, "Calibration Factors for Albedo Neutron Dosimeters," memorandum to Distribution, University of California, Lawrence Livermore Laboratory, Livermore, California, February 28. [SRDB Ref ID: 72437]

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This memorandum described the results of measurements to develop calibration factors for LLNL workplaces as shown in the following table.

Facility	Building	Rooms/sources		Calibration factor
LLNL Plutonium Facility	332	Room 1378		0.4
		Other rooms		0.3
		Vaults		0.4
		Room 1378 during PuBe work		0.2
		Shielded PuBe work		0.2
Vault	231	Inside vault		0.45
Chemistry	233	Building 233		0.45
Rotating target neutron source	212	ICT–Building 212		0.9
		Top of ICT shielding		0.5
Chemistry Heavy Elements Facility	251	Shielded boxes		0.8
		Unshielded work:	Cm-244 tracers	0.3
			Cf-252 tracers	0.2
			Boxes (top-bottom-no shield)	0.3
Reactor	281	Reactor		1.6[a]
Weapons Engineering	131	Shielded sources:	Cf-252	0.4
			PuBe	0.2
Calibration Laboratory	255	Unshielded sources:	Cf-252	0.14
			PuBe	0.1
Site 300	Site 300	Berm-shielded accelerator		0.8
		255 control room		1.0

a. Additional correction for over-response of 9-in. sphere needs to be applied.

Gibson, T. A., 1978, "Off-Site Radiation Dose from Building 212 for 1977," memorandum to T. J. Powell and W. J. Silver, University of California, Lawrence Livermore Laboratory, Livermore, California, March 20. [SRDB Ref ID: 15067]

The results of the neutron and gamma doses for 1976 at the fence south of the ICT target room are shown below.

Annual fenceline dose (mrem)			
Quarter	**Neutron 1[a]**	**Neutron 2[b]**	**Gamma**
1	198	134	79
2	111	111	56
3	72	67	32
4	170	138	72
Totals	551	450	239

a. Neutron No.1 measurements with TLDs in a 10-in. poly sphere,
b. Neutron No.2 measurements from fission tracks in polycarbonate.

The annual neutron dose was taken to be the average of the two measurements, which was 500 mrem. The total neutron plus gamma dose (above natural background taken to be 60 mrem) for 1977 was, therefore, about 680 mrem (i.e., 500 + 239 – 60 = 679 mrem).

Hankins, D. E., 1978b, *Albedo-Neutron Dosimetry Studies at Lawrence Livermore Laboratory*, UCRL-81889, University of California, Lawrence Livermore Laboratory, Livermore, California, November. [SRDB Ref ID: 6186]

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Described various studies of albedo neutron dosimeter performance. A neutron survey inside containment of the Farley Nuclear Plant was made to determine the spectra of leakage neutrons and to evaluate the accuracy of a 9-in.-diameter sphere remmeter (PNR-4) and of albedo-neutron dosimeters. Variations in the neutron spectra, the ratio of gamma-to-neutron dose rates, and the thermal neutron component of the neutron dose were also studied. The results indicated the neutron spectra were constant throughout the reactor with a 25-keV component on a 1/E spectrum. The albedo-neutron dosimeter performed within about ±25% of the measured dose. A neutron survey was also made at a neutron radiography facility with an accuracy of the albedo-neutron dosimeter within approximately ±33% of the measured dose.

Hoots, S. S., 1978, "Semiannual Dosimeter Exchange Program," memorandum to D. S. Myers, University of California, Lawrence Livermore Laboratory, Livermore, California, December 7. [SRDB Ref ID: 14089]

Described results of testing of semiannually exchanged dosimeters to selected personnel that began in 1974 with the following results.

Period	Total no. assigned	No. of positive doses (mrem)		
		0–50	51–100	>100
Jun 1974	1,582	84	9	10
Dec 1974	1,683	67	14	10
Jun 1975	1,686	69	6	2
Dec 1975	1,678	94	10	7
Jun 1976	1,824	134	15	6
Dec 1976	1,824	33	11	6
Jun 1977	1,899	86	6	5
Dec 1977	1,977	45	8	3
Jun 1978	1,959	81	5	1
Totals	15,982	693	84	50

As a result of this testing, LLNL implemented a routine semiannual dosimeter exchange for personnel without potential for significant exposure in routine work activities. Based on this analysis, it was concluded that all workers in the following buildings could be placed on a semiannual dosimeter exchange:

111	123	219	523
113	125	310	592-594
115	141	311	616
116	215	312-319	618
117	216	322-328	622
119	217	401-411	651
122	218	515-519	

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Personnel in the following buildings or areas could be placed on a semiannual dosimeter exchange on the basis of work assignment:

121	231 complex	361 complex	615
131	241 complex	381	661
151	253	412	Site 300
160 complex	255	418	
170 complex	261	431-435 complex	
222 complex	271	511	

Personnel in the following buildings should not be on the semiannual exchange:

194	281	331	419
212 complex	292	332	514
251	321	341 complex	612

1979

Hankins, D. E., 1979, untitled letter to R. Medioni (Centre de' Etudes Nuclearies), University of California, Lawrence Livermore Laboratory, Livermore, California, February 26. [SRDB Ref ID: 72746]

While I was at LASL we performed a study with about 30 personnel at the Pu facility over a period of 6 months. In addition to gamma and NTA film each worker was given bare Li 6 and Li 7 TLDs and one of the Hankins-type albedo dosimeters was taped to the bottom of his film badge. We were using a calibration factor of 24 mrem/track for the NTA film.

The results of this study indicated that if the person's neutron exposure exceeded about 70 mrem/month, we had reasonably good agreement between the NTA and albedo results. If the exposure was less than 70 mrem, the NTA only occasionally would record any exposure. This is obviously a reader problem. If there were a fairly large number of tracks they were evaluated accurately but when few tracks were present, the [track counters] *would not see any tracks. Occasionally a zero albedo result would be obtained when the NTA badge was positive (up to 70 mrem) but this was infrequent.*

The 24 mrem/track was based on field calibrations in the facility and was considerably higher than the 8 mrem/track usually used. Background was about 3 tracks/film. The total time from removal from the refrigerator until developed was about 6 weeks.

For neutron exposures above 70 mrem/months the agreement became better as the exposure increased and at ~400 mrem was reasonably good. No effort was made to reevaluate an NTA film if poor agreement was obtained since this was a study of routine evaluation techniques.

The gamma component of the dose was being overestimated by the film badge by a factor of two. This resulted in the total exposure as determined by TLDs and film being about equal even though the NTA film saw nothing at the lower neutron exposures.

Hoots, S., 1979, "Investigation Requirements and Analysis of TLD Readings," memorandum to Procedure File, University of California, Lawrence Livermore Laboratory, Livermore, California, October 12. [SRDB Ref ID: 13884]

Describes criteria to be effective as of October 1, 1979, for assigning skin and deep dosimeter doses.

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Leahy, E. J., D. E. Hankins, and T. Straume, 1979, "Radiation Survey, Bldg. 851," memorandum to W. M. Halladay, University of California, Lawrence Livermore Laboratory, Livermore, California, November 15. [SRDB Ref ID: 72588]

Describes neutron and gamma ray dose rate measurements made on October 25 and 26 and November 7, 1979, in the areas in and around Building 851 that might normally be occupied while the LINAC was in operation. Thirty measurement locations were surveyed using PNR-4 neutron and Victoreen 440 photon dose meters. NP dose ratios for the 30 locations were determined to range from 0.6 to 3.3. NP dose ratios were also determined for three health physicists wearing the standard LLNL dosimeter and one person who wore an albedo dosimeter, as shown in the following table.

	Dose (mrem)		
Person	**Gamma**	**Neutron**	**NP ratio**
1	15	19	1.3
2	15	22	1.5
3	14	14	1.0
3 (albedo)	13	10	0.8

Roberts, R. S., 1979, "Radiation Safety Practices in the Bldg. 823 Area," memorandum to D. Dufek, University of California, Lawrence Livermore Laboratory, Livermore, California, September 5. [SRDB Ref ID: 72599]

Described recommendation to place administrative controls on occupancy of office trailer T-48 and outside areas during operation of the LINAC, or to place shielding in the trailer to reduce personnel exposure to measured radiation fields between 5 and 8 mR/hr gamma and 1 and 2.5 mrem/hr neutron. The control trailer had adequate shielding but the office trailer did not. It was considered that exposure of personnel in the office trailer was not necessary and should be eliminated.

Singh, M. S., 1979, *Laser Program Radiation Safety Program*, University of California, Lawrence Livermore Laboratory, Livermore, California, December. [SRDB Ref ID: 15049]

Provided an assessment of potential sources of radiation exposure associated with the LLNL Laser Program.

Willhoite, S. B., 1979, *Determination of Gamma and Neutron Yearly Doses at the Building 212 Bus Stop*, University of California, Lawrence Livermore Laboratory, Livermore, California, December 12. [SRDB Ref ID: 15066]

Described an assessment of the yearly dose at the bus stop 91 m west of the environmental monitoring station south of the Building 212 RTNS. Based on this study, the gamma dose at the bus stop in 1978 was estimated to be 3 mrem (factor of 0.03 times environmental monitoring station measured photon dose) and the neutron dose was estimated to be 52 mrem (factor of 0.37 times environmental monitoring station measured neutron dose).

It was stated that the RTNS was operating at a neutron yield of 1.5×10^{12} n/s when the operational surveys were made. This was approximately half of the yield at which the RTNS was often run. Therefore, the yearly doses would be approximately a factor of 2 greater.

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1980

Willhoite, S. B., 1980, "Survey to Determine Yearly Neutron Dose at the 212 Bus Stop Due to Operation of the RTNS," University of California, Lawrence Livermore Laboratory, Livermore, California, February 22. [SRDB Ref ID: 15087]

Described measurements of the neutron and gamma dose at the bus stop. The average neutron dose rates observed for the locations and operating conditions surveyed were:

RTNS neutron yield	Average neutron dose rate (μrem/hr)	
	RTNS	Bus stop
2×10^{12} n/s	257	14
3×10^{12} n/s	410	20

Based on this study, the conversion factor for determining the yearly neutron dose at the 212 bus stop gave the yearly neutron dose at the RTNS environmental monitoring, which was 5% of the RTNS fenceline neutron dose. Neutron energy spectra measurements noted in the report indicated that 17% of the total neutron dose was attributable to neutrons of approximately 14 MeV and 18% of the was the result of neutrons below 1 MeV.

LLL (Lawrence Livermore Laboratory), 1980, "Neutron Survey of 3MeV Van de Graff," University of California, Livermore, California, June 30. [SRDB Ref ID: 15086]

Contained measurement results of surveys done with the LLNL remmeter. The meter was positioned directly below the target changer.

Straume, T., 1980, *Radiation Safety Program for Site 300*, University of California, Lawrence Livermore Laboratory, Livermore, California, September. [SRDB Ref ID: 72845]

External radiation hazards identified include:

Location	Radiation source	Normal exposure potential (mR/hr)
B 809	1-MeV LINAC	0
B 809	300-kV X-ray	0
	150-kV X-ray	0
	50-kV X-ray	0
	110-kV X-ray	0
	Co-60, 310-Ci source	0
B 812E	Co-60, 56 Ci	0
	Co-60, 77 Ci	0
B 823	13-MeV LINAC	< 2.5[a]
B 851	LINAC	<10[a]
	Klystrons[b]	0

a. Time personnel spent in these areas is controlled.
b. Dose rate is from one klystron only—there were a total of five in the LINAC room.

Ozaki, C., 1980–1981, notes pertaining to the cyclotron and ICT, University of California, Lawrence Livermore Laboratory, Livermore, California. [SRDB Ref ID: 15090]

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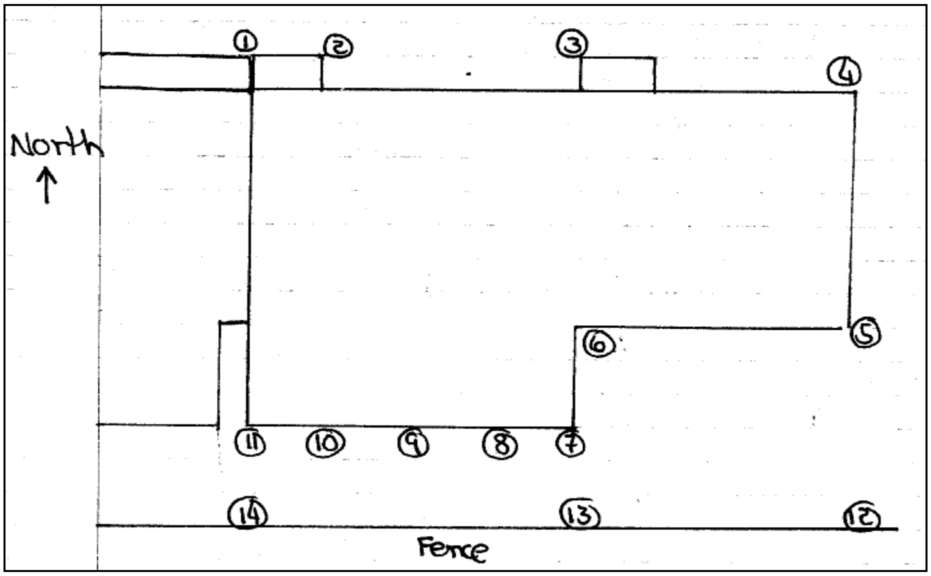
There are results of a November 4, 1980, area survey with the ICT beam output of 2×10^{12} n/s. The measurement locations and results follow:



Position	Dose	
	Gamma (mR/hr)	Neutron (mrem/hr)
1	0.5	8
2	0.4	1
3	0.5	0
4	0.2	0
5	0.3	0
6	0.3	0.3
7	0.3	0.2
8	0.5	0.7
9	0.5	2.0
10	1.3	4.0
11	0.3	0.1
12	0	0.1
13	0	0.1
14	0.1	0.2

Griffith, R. V., and D. E. Hankins, 1980, "A Systematic Approach to Personnel Neutron Monitoring," March, UCRL-82658, University of California, Lawrence Livermore Laboratory, Livermore, California. [SRDB Ref ID: 72240]

Described personnel neutron dosimetry methods and the use of workplace neutron dose and spectra measurements to calibrate dosimetry system.

1981

Ozaki, C. 1981, [TLD Radiation Survey of] "ICT Rabbit System, Trailer 939-940," University of California, Lawrence Livermore Laboratory, Livermore, California, April 7. [SRDB Ref ID: 15084]

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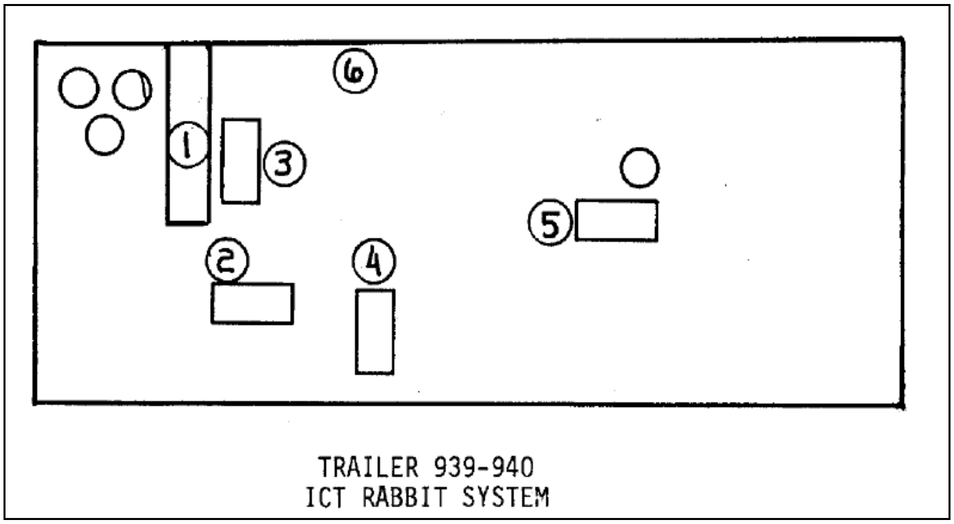
Contained measurements of the Trailer 939-940 ICT Rabbit System per the following diagram.



The measurements were made by placing six TLD packets at the locations noted above on March 16, 1981, and collecting these packets on March 27, 1981. The ICT Rabbit System was operated for approximately 80 hours. The results are:

Location	Dose (rem)
1	0.003
2	0.002
3	0.002
4	0.002
5	0.001
6	0.002

Lascurettes, N., 1981, "Audit Report No. 1230 – Use of Dosimeters," letter to D. Nielsen (Lawrence Livermore National Laboratory), University of California Systemwide Administration, Berkeley, California, August 31. [SRDB Ref ID: 21458]

Included a cover letter, an attached audit report, and an attached response to audit findings.

<u>1982</u>

Leahy, E. J., 1982, "4 MeV X-Ray Dose Rate Measurements," memorandum to R. Hoblitzell, University of California, Lawrence Livermore National Laboratory, Livermore, California, April 1. [SRDB Ref ID: 15076]

Measurements were made using the 4-MeV X-ray unit in space B-9 of Building 239. The measurements were made with a Victoreen 660 Digital Exposure Measurement and Compliance Meter. The following figure shows measurements that were made for the condition.

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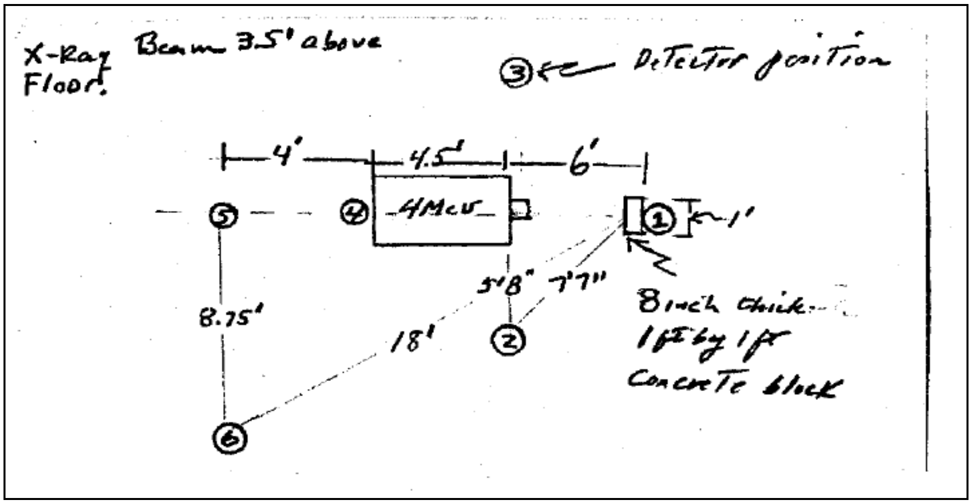

The results were:

Detector position	Detector indication (R/hr)
1	1608
2 & 3	13.8
4	5.6
5	1.9
6	1.3

Hankins, D. E., 1982, *Evaluation of the Neutron Dose Received by Personnel at the LLNL*, UCID-19385, University of California, Lawrence Livermore Laboratory, Livermore, California, May 1. [SRDB Ref ID: 72180]

Documented the techniques being used to evaluate the neutron exposures received by personnel at LLNL. Two types of evaluations were discussed covering the use of the routine personnel dosimeter and of the albedo neutron dosimeter. Included in the report are field survey results that were used to determine the calibration factors applied to the dosimeter readings. Calibration procedures were discussed and recommendations were made on calibration and evaluation procedures. This report contained substantial workplace measurement data and analysis.

1983

Leahy, E. J., 1983, “Dosimetry System Cycle Changes,” memorandum to All Health Physicists, University of California, Lawrence Livermore National Laboratory, Livermore, California, October 3. [SRDB Ref ID: 14026]

Described a planned change in LLNL dosimetry system to a Panasonic system. Only personnel on monthly and quarterly dosimeter exchange cycles would receive a Panasonic dosimeter with a window to measure beta and low-energy photons. The inventory of new dosimeters was limited. To provide adequate dosimetry coverage, personnel dosimetry exchange cycles had to be altered. Those persons on a quarterly exchange cycle who were not receiving significant exposures of penetrating radiation and no skin exposures could be changed to semiannual dosimeter exchange. Those on a semiannual cycle receiving “skin”-type exposures or having the potential for such exposure would be changed to quarterly.

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Meadors, O. L., J. P. Harris, and A. J. Toy, 1983, "LLNL Incident Analysis Report," memorandum to C. Gatrousis, University of California, Lawrence Livermore National Laboratory, Livermore, California, July 5. [SRDB Ref ID: 15031, p. 2]

Described expectations of shipments between LLNL and NTS. External radiation levels and removable (nonfixed) radioactive contamination levels should conform to DOT regulations 49 CFR 173.393 and 173.397. Containers with external contamination (any detectable quantity above background) were not to be shipped.

<u>1984</u>

Myers, D. S., 1984, "Neutron Doses @212," University of California, Lawrence Livermore National Laboratory, Livermore, California, February 16. [SRDB Ref ID: 15083]

Noted neutron dose rates for Building 212 as follows:

	212 ③	⑤
1979	46 mrem	85 mrem
1980	33 mrem	6.2 mrem
1981	36 mrem	6.6 mrem
1982	36 mrem	6.2 mrem
1983	113 mrem	10 mrem

A note stated that according to measurements by Willhoite in February 1980, the neutron dose from the ICT was 20 times higher at station 5 than station 3.

Davis, J., 1984, "Fence Line Doses at Building 212," memorandum to J. Shearer, University of California, Lawrence Livermore National Laboratory, Livermore, California, July 5. [SRDB Ref ID: 15064, p. 3]

Described events that led to the increase in dose at the 212 Building fenceline monitors during 1983. Apparently water-filled cans that had been fabricated and installed over the target in the early 1970s for purposes of reducing the dose rate had been removed, resulting in the increased dose. High-flux runs had been made generally off-shift to minimize exposure to personnel. The high-flux experiment was stated to be finished and the cans replaced over the target assembly.

Myers, D. S., 1984, "Neutron Doses at the Building 212 Perimeter Fence," memorandum to W. J. Silvers, University of California, Lawrence Livermore National Laboratory, Livermore, California, June 22. [SRDB Ref ID: 15064, p. 5]

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A table of annual neutron doses was included as follows:

Perimeter neutron doses at Building 212	
Year	**Annual dose (mrem)**
1983	113
1982	36
1981	33
1980	85
1979	80
1978	137
1977	550
1976	600
1975	700

Myers, D. S., 1984, “Summary of Radiation Levels at the Fence Adjacent to Building 212,” memorandum to J. C, Davis, Lawrence Livermore Laboratory, Livermore, California, October 15. [SRDB Ref ID: 15074]

Described quarterly measured neutron and photon doses as follows:

Radiation doses at Building 212 fence		
	Dose equivalent (mrem)	
Quarter	**Neutron**[a]	**Gamma**[b]
1	38.0	15
2	2.8	11
3	3.0	11

a. The normal neutron background was approximately 1 to 1.5 mrem per quarter.
b. The normal gamma background was approximately 11 to 12 mrem per quarter.

The DOE fenceline maximum allowed dose per year was 500 mrem but also needed to comply with as-low-as-reasonably-achievable (ALARA) objectives. Achieving the lower fenceline dose of about 2 mrem per quarter over background likely represented meeting the ALARA objective.

<u>1985</u>

Thorngate, J. H., and R. V. Griffith, 1985, “Neutron Spectrometers for Radiation Monitoring at Lawrence Livermore National Laboratory,” *Radiation Protection Dosimetry*, volume 10, number 1, pp. 125–135.

Described a system for measuring neutron spectra developed at LLNL that combined a liquid scintillation detector for neutrons above 0.3 MeV with a multisphere system for lower energies. The resultant combination provided spectra suitable for radiation protection purposes from thermal energies to 20 MeV. Measurements using these techniques were made at LLNL and several other locations.

LLNL (Lawrence Livermore National Laboratory), 1985, *Radiation Safety Program – Building 251, Heavy Elements Facility*, University of California, Lawrence Livermore National Laboratory, Livermore, California, August 21. [SRDB Ref ID: 15034]

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Described the LLNL ALARA program and the external dosimetry monitoring program. All employees and visitors at LLNL were issued a TLD. The TLD change frequency was dependent on the amount of time an individual was expected to work with sources of ionizing radiation. The LLNL Panasonic TLD allowed selection of phosphors to measure neutron as well as beta and gamma radiations. CR-39 track-etch neutron badges were assigned to workers at Building 251 who worked with neutron-emitting radionuclides. All dosimeter results that had a positive reading were reported to the appropriate health physicist. Any neutron exposure, monthly dosimeter reading higher than 300 mrem, or quarterly dosimeter reading higher than 100 mrem had to be investigated by the health physicist. A written report was issued to document the investigation results. The facility Health and Safety Technician also reviewed all doses for people working in Building 251. Nuclear accident dosimeters were used at Building 251.

LLNL (Lawrence Livermore National Laboratory), 1985, *Radiation Safety Program, Building 151*, University of California, Livermore, California, August 21. [SRDB Ref ID: 15030]

Same external radiation monitoring program wording for this facility as shown above for Building 251.

1986

Griffith, R. V., 1986, "LLNL Site Perimeter Neutron Dose Results for the Period January 3 to March 31, 1986," memorandum to R. Buddemeier, University of California, Lawrence Livermore National Laboratory, Livermore, California, April 14. [SRDB Ref ID: 15064, p. 7]

Reported dose equivalent measurement results at the indicated site perimeter locations during the first quarter of calendar year 1986 as follows:

	Dose equivalent (mrem)	
Location	**Dose**	**Monthly dose rate**
1	0.9	0.3
2	1.1	0.4
3	14.0	4.8
4	1.1	0.4
5	2.1	0.7
6	1.3	0.5
7	0.9	0.3
8	1.4	0.5

The measurements were made using fission track foils in Anderson Braun remmeters. The result for location 3 raised the question of whether the water-filled cans had been removed.

1987

Gordon, L. E., 1987, "1986 Chemistry and Materials Science Radiation Safety Report of the Tritium Facility," memorandum to A. L. Buerer, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 16. [SRDB Ref ID: 14070]

This facility was in Building 331 and tritium constituted the primary radiological hazard. This memorandum described briefly the Hazards Control Department Hazards Information, Recording and Control (HIRAC) database for safety recommendations received from the various disciplines regarding potential hazards.

Mansfield, W. G., 1987, "1986 Summary Annual Report – AVLIS Radiological Safety," memorandum to M. Chew, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 16. [SRDB Ref ID: 15044]

The highest individual doses to the hand, skin, and whole body by AVLIS personnel during 1987 were 0.379, 0.12, and 0.05 rem, respectively. Doses to the hand received during uranium handling and pod cleaning continued to dominate.

1988

Hankins, D. E., S. Homann, and J. Westermark, 1988, "The LLNL CR-39 Personnel Neutron Dosemeter," *Radiation Protection Dosimetry*, volume 23, number 1, pp. 195–198.

Described a personnel neutron dosimetry system based on the electrochemical etching of CR-39 plastic at elevated temperatures. The system, relative to others, was more accurate for varied neutron spectra, had less energy dependence and less fading, and had fewer reading problems.

Trent, M., 1988, "Nuclear Chemistry Radiation Safety Program; 1987 Annual Report," memorandum with attachments to S. Velen, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 8. [SRDB Ref ID: 15028]

Buildings 151 and 281 were covered in one report while Building 251 was reported separately because operations in Building 251 were very different from those in the rest of Nuclear Chemistry.

The total WB dose assigned to Building 151 and 281 during 1987 was 2.344 person-rem. The total is almost evenly divided with 1.22 rem assigned to Building 151 and 1.124 rem from operations in Building 281. As in the past, most of the dose in Building 151 resulted from weapons debris analysis in the Dissolving Wing. However 0.529 rem resulted from heavy elements research conducted in Building 251. In Building 281, most of the WB dose resulted from experiments conducted at Building 292, the RTNS II facility. There were some individuals working in Building 151 who received most of their doses while working in Building 251.

LLNL (Lawrence Livermore National Laboratory), *Operational Health Physics Program for the 170 Complex*, Revised, University of California, Livermore, California, April 1. [SRDB Ref ID: 15043]

Described monitoring requirements and frequency for several types of radiation safety activities.

Mansfield, W. G., 1988, "1987 Annual Radiological Safety Report – Building 331," memorandum to R. M. Latimer University of California, Lawrence Livermore National Laboratory, Livermore, California, April 5. [SRDB Ref ID: 14071]

Described collective dose, which was essentially all from tritium.

1989

Shingleton, K. L., 1989 "Radiation Dose Summary for Nuclear Chemistry, 1988," memorandum to C. Lagerquist, University of California, Lawrence Livermore National Laboratory, Livermore, California, May 3. [SRDB Ref ID: 15029]

In summary, 29 people received WB doses, the largest of which was 435 mrem. A total of 2.429 person-rem was accrued. Twenty-six people received hand doses, the largest of which was 2.666 rem. The collective annual dose to the hands was 11.781 rem. Three people received skin doses, the largest of which was 99 mrem. The total skin dose received by these three workers was 129 mrem.

Hankins, D. E., S. G. Homann, and B. Buddemeier, 1989, *Personnel Neutron Dosimetry Using Electrochemically Etched CR-39 Foils*, UCRL-53833, Revision 1, University of California, Lawrence Livermore National Laboratory, Livermore, California, December. [SRDB Ref ID: 72184]

Described LLNL personnel neutron dosimetry system based on the CR-39 track-etch dosimeter. The CR-39 system had several advantages in comparison with other systems, especially when varied neutron spectra were encountered. CR-39 did not have the severe energy dependence that existed with albedo neutron dosimeters, and it did not have the fading and reading problems encountered with NTA film. The energy response of CR-39 to neutrons was fairly flat from about 150 keV to 5 MeV, but dropped by about 60% in the 13- to 16-MeV range. The sensitivity of the dosimetry system was about 4.5 tracks/cm^2-mrem, with a background equivalent to about 3 mrem for new CR-39 foils. The limit of sensitivity was approximately 6 mrem.

1991

Hankins, D. E., 1991, "LLNL Neutron Dosimetry," *Eleventh DOE Workshop on Personnel Neutron Dosimetry, June 3-7, 1991, Las Vegas, Nevada*, PNL-SA-21596, U.S. Department of Energy, Assistant Secretary for Environment, Safety and Health, Washington, D.C., p. 5. [SRDB Ref ID: 10804]

Article stated that at LLNL only a small number of workers received neutron exposure. With few exceptions, the exposure was to workers at the LLNL plutonium facility. The exposures were primarily to neutrons from (1) the spontaneous fission of fissile materials and (2) oxides of fissile material. The neutron energies ranged from a fission spectrum, due to work with plutonium without shielding, down to a lightly moderated spectrum, due to work in shielded gloveboxes. Personnel who worked in the plutonium vaults were exposed to a neutron spectrum containing a large component of room-scattered and thermal-energy neutrons.