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☐ New ☐ Total Rewrite ☒ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/10/2005	00	New Technical Basis Document for the Los Alamos National Laboratory – Occupational External Dose. First approved issue. No training required. Initiated by Jack E. Buddenbaum.
05/30/2007	01	Approved revision to update document. Adds Purpose and Scope sections. Constitutes a total rewrite of document. Adds Attributions and Annotations section. Incorporates formal internal and NIOSH review comments. This revision results in an increase in assigned dose and a PER is required due to the addition of median photon adjustment values in Tables 6-22 and A-8; otherwise, the maximum values were replaced with lower 95th percentiles, and therefore would lower doses. An exception to the lower 95th-percentile values is the value for Other Operations, which is higher than the previously reported maximum value of annual geometric means. This change will result in a higher dose. Changes in Table A-7 will increase skin/shallow dose for LAMPF/LANSCE workers. Training required: As determined by the Task Manager. Initiated by Jack E. Buddenbaum.
11/23/2009	02	Approved revision was initiated to make the following changes: updated NIOSH references in Sections 6-1, 6-2, A-6 and Reference Section. Added details to the Scope in Section 6.1. In Section 6.2, "Reporting Practices" was modified to distinguish between LANL records with non-penetrating dose listed as "SHALLOW" vs. those listed as "SKIN." Several changes were made to remove dose reconstruction methods and information relating to periods when it has been determined to be infeasible to estimate external doses. Specifically, according to the HHS letter adding a class of LANL employees to the SEC (1943-1975), partial dose reconstructions may include external doses from gamma emitters in the years 1946-1975, neutrons from 1946-1975, and beta-emitters in the years 1949-1975. Incorporates formal internal and NIOSH review comments. No sections were deleted. Training required: As determined by the Objective Manager. Initiated by Donald N. Stewart.

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ACRONYMS AND ABBREVIATIONS

ABS	acrylonitrile butadiene styrene
AEC	U.S. Atomic Energy Commission
CHP	Certified Health Physicist
Ci	curie
CIH	Certified Industrial Hygienist
cm	centimeter
CMR	Chemistry and Metallurgy Research (Building or Division)
CMR-12	early radiochemistry group
d	day
DCF	dose conversion factor
DE	dose equivalent
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DP	DP Site[1], or TA-21. The site of plutonium processing at LANL from 1945 until 1978; also housed polonium processing.
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ERDA	U.S. Energy Research and Development Administration
eV	electron-volt
GSD	geometric standard deviation
GMX-1	early radiography group
H Division	Health Division
HT	Heat Treatment (building)
HYPO	Water Boiler Reactor in high-power configuration
ICRP	International Commission on Radiological Protection
in.	inch
keV	kiloelectron-volt, 1,000 electron-volts
kVp	applied kilovoltage
LAMPF	Los Alamos Meson Physics Facility
LAMPRE	Los Alamos Molten Plutonium Reactor Experiment
LANL	Los Alamos National Laboratory
LAPRE I	First Los Alamos Power Reactor Experiment
LAPRE II	Second Los Alamos Power Reactor Experiment
LOPO	Water Boiler Reactor in low-power configuration
m	meter
MDL	minimum detection level
MED	Manhattan Engineer District
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
min	minute
mm	millimeter
mo	month

[1] Although undocumented, there are several theories about the origin of the "DP Site" name for TA-21. The most logical are that it stands for D-Prime, since it replaced D Building, or that it stands for "D Plant," "Displaced Persons," "D-Plutonium," or "D-Production" (Martin 1998).

mrad	millirad
mrem	millirem
mSv	millisievert
n, or n unit	an early unit of neutron dose used with pocket ionization chambers; the quantity of neutron radiation producing the same ionization in a 100-R PIC as 1 R of gamma.
NADE	neutron ambient dose equivalent
NBS	National Bureau of Standards
NCF	neutron correction factor
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NTA	nuclear track emulsion, type A
NTP	nuclear track plate
ORNL	Oak Ridge National Laboratory
PIC	pocket ionization chamber (i.e., pencil dosimeter)
PN3	LANL track-etch neutron dosimeter
PNNL	Pacific Northwest National Laboratory
PNL	Pacific Northwest Laboratory
POC	probability of causation
PTB	*Physikalisch-Technische Bundesanstalt*
PVC	polyvinylchloride
R or r	roentgen, an early unit of radiation exposure
SEC	Special Exposure Cohort
Site Y	code name for Los Alamos Laboratory from April 1943 to December 1946
SNM	Special Nuclear Material
SUPO	Water Boiler Reactor in highest (Super) power configuration
TA	Technical Area
TBD	technical basis document
TED	track-etch dosimetry or dosimeter
TLD	thermoluminescent dosimeter
UHTREX	Ultra High-Temperature Reactor Experiment
U.S.C.	United States Code
WB	whole-body
wk	week
yr	year
µm	micrometer
§	section or sections

6.1 INTRODUCTION

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

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

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[2]] 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 structure

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

- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

6.1.1 Purpose

When Los Alamos became operational in 1943, it had a single mission – the design and manufacture of the first nuclear weapons (Hoddeson et al. 1993). In 1947, Los Alamos Laboratory (Project Y) became Los Alamos Scientific Laboratory, which in 1981 became Los Alamos National Laboratory (LANL; University of California 2001); for simplicity, except in reference citations, this TBD uses LANL for all periods. LANL assignments in the early 1940s included:

- Performing the final purification of plutonium received at LANL
- Reducing plutonium to its metallic state
- Determining the relevant physical and metallurgical properties of plutonium
- Developing weapon component fabrication technologies (Hammel 1998)

Processes undertaken included nuclear fuel fabrication; nuclear criticality experimentation; nuclear reactor operations; radiochemical separations; refining, finishing, and storing plutonium and various enrichments of uranium; processing large quantities of other nuclear materials such as tritium, polonium, and lanthanum; testing nuclear device components and the devices themselves; and handling the associated radioactive waste (Widner et al. 2004). After World War II, LANL scientists and engineers were involved in development and testing of nuclear devices that were more and more powerful, compact, reliable, and dependably deployable in the field, and that were contained in a variety of delivery vehicles suited to various combat objectives.

LANL was the lead site for U.S. nuclear component fabrication until 1949, when the Hanford Plutonium Finishing Plant in Washington began making *pits*, the central cores of the primary stages of nuclear devices (DOE 1997). Plutonium processing at LANL took place in D Building in 1944 and 1945, then relocated to DP Site, which housed a variety of plutonium research, design, and fabrication activities for more than 30 years until Technical Area (TA)-55 became operational in 1978 (Widner et al. 2004). After 1949, LANL was a backup production facility that designed, developed, and fabricated nuclear components for test devices. From time to time, LANL performed special functions in its backup role. For example, due to a 1984 accident at Hanford, plutonium oxide was sent to LANL for conversion to metal (DOE 1997).

Operations, facilities, and capabilities that were needed to support development and production of the various types of nuclear devices expanded in many cases to support other missions after World War II (Widner et al. 2004). Programs in chemistry, metallurgy, and low-temperature physics expanded into nonmilitary development and fundamental research. The Health Division (H Division) grew significantly and expanded into many areas of health physics, industrial hygiene, medicine, safety, and biomedical research related to people and radiation. Early reactors built to confirm critical masses for fissionable materials and to study properties of fission and the behavior of the resulting neutrons were the forerunners of a variety of reactors designed and in some cases built and operated at LANL. While some of these reactors served as sources of neutrons for nuclear research or materials testing, other designs were pursued for potential applications in power generation and propulsion of nuclear rockets into deep space. During World War II, accelerators were used to determine the critical masses for each proposed nuclear weapon design. After the war, other accelerators were used, including one of the world's largest at the Los Alamos Meson Physics Facility (LAMPF). Some of the first significant steps toward controlled nuclear fusion as a power source occurred at LANL, and the plasma thermocouple program explored methods for direct conversion of fission energy to electricity for potential application in propulsion of spacecraft.

In more recent decades, LANL has been a large multidiscipline research institution that utilizes a wide variety of radioisotopic sources, radiation-producing machines, and critical assemblies (Hoffman and Mallett 1999a). Employees could have received occupational radiation exposure from beta, photon, and neutron radiation. Most occupational external radiation exposure at LANL (at least during the 1980s and 1990s) has been due to neutron radiation, which has accounted for about 60% of the external collective dose equivalent (DE) (Hoffman and Mallett 1999a). Neutron radiation exposures at LANL originate from radioisotope sources, nuclear materials handling, critical assemblies, and accelerators. Although they are a smaller part of the total, beta and photon radiation exposures occur from a larger variety of source types. In addition to those for neutron radiation, these sources include radiation-producing machines, medical isotopes for research and production, and others.

LANL has used facility and individual worker monitoring methods to measure and control radiation exposures. Records of radiation doses to individual workers from personnel dosimeters worn by the worker and coworkers are available for LANL operations beginning in 1943. Doses from these dosimeters were recorded at the time of measurement and routinely reviewed by operations and radiation safety personnel for compliance with radiation control limits. The NIOSH *External Dose Reconstruction Implementation Guidelines* NIOSH (2007c) has identified these as the highest quality records for retrospective dose assessments. The information in this TBD pertains to analysis of these records.

Radiation dosimetry practices were initially based on experience gained during several decades of radium and X-ray medical diagnostic and therapy applications. These methods were generally well advanced at the start of the Manhattan Engineer District (MED) program to develop nuclear weapons in about 1940. The primary challenges encountered by MED, and later U.S. Atomic Energy Commission (AEC, MED's successor agency), operations to measure worker dose to external radiation involved:

- Comparatively large quantities of high-level radioactivity
- Mixed radiation fields involving beta, photon (gamma and X-ray), and neutron radiation with low, intermediate, and high energies
- Neutron radiation

Many details about policies, procedures, practices, and issues dealing with external radiation monitoring at LANL are documented in a compilation of correspondence and reports called the *Photodosimetry Evaluation Book*. Informally, this compilation, which has eight volumes, has been referred to as "the Bible" of external radiation dosimetry at LANL. It was first assembled in 1956, and was expanded until around 1970 (Widner 2004). Table 6-1 lists the volumes that currently compose this resource.

6.1.2 Scope

Section 6.2 discusses the program for measuring skin and whole-body (WB) doses to the workers. The methods for evaluating external doses to workers have evolved over the years as new techniques and equipment have been developed. Concepts in radiation protection have also changed. The dose reconstruction parameters, LANL practices and policies, and dosimeter types and technology for

Table 6-1. Volumes of *Photodosimetry Evaluation Book*.

Volume	Approximate date range	Reference
I	01/19/44–07/28/58	LASL 1959
II	01/02/60–12/23/69	LASL 1969
III	02/18/70–07/26/77	LASL 1977
IV	01/27/78–10/21/86	LANL 1986
V	06/05/45–02/08/79 Misc. docs.	LASL 1979
VI	04/08/85–12/15/89	LANL 1989
VII	02/02/90–02/15/96	LANL 1996
VIII	02/08/96–12/05/01	LANL 2001
IX (active)	02/14/02–05/28/03	LANL 2003

measuring the dose from the different types of radiation are discussed. Attention is given to the valuation of doses measured from exposure to beta, gamma, and neutron radiation. Test results are tabulated for various dosimeters exposed at different geometries and radiation energies.

For photon and neutron dose, Sections 6.3 and 6.4, respectively, discuss the sources of bias, workplace radiation field characteristics, responses of the different beta/gamma and neutron dosimeters in the workplace fields, and the adjustments to the recorded dose measured by these dosimeters during specific years.

Section 6.5 presents sources of potential dose that could be missed because of the limitations of dosimetry systems and the methods of reporting low doses. This missed dose is discussed as a function of facility location, dosimeter type, year, and energy range. Section 6.6 and Attachment A describe the use of the external dosimetry technical basis parameters to facilitate the efforts of the dose reconstructors.

It has been determined that it is not feasible to reconstruct some doses at LANL during the period from 1943 to 1975, and a class of LANL employees has been added to the Special Exposure Cohort (SEC) (NIOSH 2007b). Partial dose reconstructions may be performed for those individuals not qualifying for compensation under the SEC class. From an occupational external dose reconstruction perspective, partial dose reconstructions may include, and are limited to, external dose from gamma emitters from 1946 onward; dose from beta emitters from 1949 onward, and neutron dose from 1946 onward.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 6.7.

6.2 DOSE RECONSTRUCTION PARAMETERS

Examinations of the beta, photon (X-ray, gamma ray), and neutron radiation type, energy, and geometry of exposure in the workplace, and the characteristics of the respective LANL dosimeter response are crucial to the assessment of bias and uncertainty of the original recorded dose in relation to the radiation quantity *Hp(10)*. The bias and uncertainty for current LANL dosimetry systems are well documented for *Hp(10)* (Hoffman and Mallett 1999a,b; LANL 1989, 1996, 2001, 2003). The performance of current dosimeters can often be compared with performance characteristics of historical dosimetry systems in the same, or highly similar, facilities or workplaces. In addition, current performance testing techniques can be applied to earlier dosimetry systems to achieve a consistent evaluation of historical dosimetry systems. Dosimeter response characteristics for radiation types and energies in the workplace are crucial to the overall analysis of error in recorded dose. Accuracy and precision of recorded worker doses and the comparability of the recorded dose types depend on the following considerations (Fix et al. 1997; Fix, Wilson, and Baumgartner 1997):

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

An evaluation of the original recorded doses based on these parameters is likely to provide the best estimate of *Hp(10)* and, as needed, *Hp(0.07)* for individual workers with the least overall uncertainty.

6.2.1 Administrative Practices

Historically, LANL had an extensive radiation safety monitoring program using portable radiation instruments, contamination surveys, zone controls, and personnel dosimeters to measure dose in the workplace (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003). This program was conducted directly by or under the guidance of a specially trained group of radiation monitors or radiation protection technologists. Results from the dosimeters were used to evaluate and record doses from external radiation exposure to workers throughout the history of LANL operations. Dosimeters that have been used fall into the following categories:

- Personnel WB beta/photon
- Pocket ionization chamber (PIC)
- Personnel extremity
- Personnel WB neutron

Shortly after operations began in 1943, some workers were monitored with PICs alone. In 1943, the phase-in of photon film dosimetry methods began at LANL. More and more groups started using film badges for photon dosimetry, and in 1949 a new badge was introduced to support evaluation of beta exposures. Beta/gamma film badge designs changed several times through the 1950s, 1960s, and 1970s as filters of various types were used to address the energy-dependent response of film. LANL officially switched to the use of thermoluminescent dosimeters (TLDs) in 1980 and is currently using its second generation of TLD badge.

Before 1949, the Laboratory implemented neutron dosimetry for selected workers beginning with the use of PICs that incorporated Bakelite chambers and graphite coatings. In 1949, nuclear track plates (NTPs) were first used, and badges incorporating Eastman Kodak nuclear track emulsion, type A (NTA) film were first used in 1951. While TLD badges were used for neutron dosimetry beginning in 1980, NTA film continued to be used in a “piggyback” fashion with TLD badges for some workers. Track-etch dosimeters (TEDs) have been used for evaluation of fast neutron doses since 1995.

LANL administrative practices significant to dose reconstruction include policies to:

- Assign dosimeters to workers

- Exchange dosimeters
- Use control 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

6.2.1.1 Assignment of Dosimeters to Workers

When monitoring for external radiation exposures started in 1943, PICs were assigned to “a few persons thought to have the highest potential for receiving exposures at or above the ‘tolerance’ limit” [LANL 1986 (10/6/81 questionnaire)]. At that time, the tolerance limit was 0.1 R/day based on a National Bureau of Standards (NBS) Recommendation [LASL 1959 (3/21/44 industrial hygiene survey and 2/26/48 LASL memorandum)]. By 1945, when film badges were in use by a number of LANL groups, only workers with the “higher exposure potentials” were issued dosimeter badges [LANL 1986 (10/6/81 questionnaire)]. At the time of the earliest criticality experiments and accidents at LANL, workers who received the highest exposures had not yet been issued film badges. Their exposures were calculated from activation measurements and area film badges [LANL 1986 (10/6/81 questionnaire)].

In some cases, considerable evaluation went into the determination of whether groups of workers should wear dosimeters. In June 1948, it was reported that workers in DP East were not wearing film badges [LASL 1959 (June 7 and 8 memoranda)]. After a trial period of 3 months showed no exposure, workers stopped wearing film badges in the spring of 1947. An assessment concluded that the gamma-ray intensity from polonium sources at DP East was very low in comparison to their alpha activity, and that film badges would only be needed for those who worked in and around the storage vault if it were to contain about 2,000 Ci or more [LASL 1959 (June 8 memorandum)]. For “urchin”-type initiators [1], gamma exposure to the fingers determined allowable exposure times. Wrist badges would record perhaps 1% of the dose to the fingertips, and total-body dose would be negligible. Because of this, tolerance times were specified as 100 Ci-min at 1 cm, and it was recommended that studies involving use of impressions of the ridges on the fingertips as indicators of radiation exposure be continued [LASL 1959 (June 7 and 8 memoranda)]. For preparation of polonium-beryllium (PoBe) neutron sources, fast neutron exposure was limiting. Around October 1948, the need for film monitoring at the DP West plutonium facilities was recognized because of low-level gamma exposure from spontaneous fission in plutonium and the possibility of a criticality accident. It was emphasized at the time that AEC Safety Regulation 3 required that film badges be worn in any area where radioactive materials were handled.

As of April 1960, the brass-cadmium film badge was being worn by about half of University of California employees, all of the Security Force, and 75% of Zia employees (LASL 1969). At most sites, film badges were reportedly issued "only to personnel who need them" (LASL 1969). At that time, the plan was to combine the film badge with the site security badge to increase compliance with the requirement to wear dosimeter badges, and it was proposed that badges be issued to all LANL and AEC personnel on a regular basis.

In October 1962, the new multi-element Cycolac film badge was issued to about 100 persons who had “histories of appreciable or out of ordinary radiation exposures” [LASL 1969 (3/5/63 memorandum)]. The Cycolac badge was used for all film dosimetry from about 1963 to about 1977, when the use of some TLD badges began (Widner 2003). Between 1943 and late 1981, the number of persons monitored for external exposures increased from less than 100/yr to more than 5,000/yr, but personnel monitoring for external radiation still had not been extended to all workers at LANL.

During the time film badges were in use, about 15,000 gamma and neutron films were developed each month. By June 1981, fewer than 40 NTA films were developed each month. By December 1990, approximately 7,800 TLD badges were processed each month, plus about 200 NTA film badges per month that were issued to workers at LAMPF for high-energy dosimetry during accelerator operations (about 7 mo/yr) (LANL 1996).

Table 6-2 lists the reported numbers of workers monitored by LANL from 1944 to 2008 along with total and average doses calculated from those data (LANL 2004). Estimates of the total number of workers employed at LANL each year are also presented [2]. "Average total dose" for each year is calculated as the total dose (person-rem) divided by the number of workers monitored (that is, in Table 6-2, column 2 divided by column 3). Figure 6-1 shows the number of workers monitored each year over the same period (LANL 2004). The data on which Table 6-2 and Figure 6-1 are based have not been corrected for potential missed doses.

Table 6-2. Annual external radiation doses, 1944 to 2008 (LANL 2004, updated 2009).

Year	Total dose (person-rem)	No. of workers		Average total dose (rem)
		Monitored	Total	
1944	7.89	9	1,235	(0.88)[a.]
1945	2,153.37	812	1,235	(2.65)[a,b.]
1946	3,819.95	508	2,750	7.52[a]
1947	464.62	1,237	2,750	0.38
1948	343.05	2,080	1,570	0.16
1949	466.42	3,177	1,940	0.15
1950	552.49	3,895	2,420	0.14
1951	2,503.80	4,257	2,700	0.59
1952	812.72	2,366	2,790	0.34
1953	717.16	1,878	2,900	0.38
1954	920.18	2,068	2,970	0.44
1955	763.25	1,984	3,040	0.38
1956	1,280.80	2,287	3,000	0.56
1957	585.75	2,539	3,150	0.23
1958	5,704.65	3,032	3,223	1.88[a]
1959	447.09	2,930	3,214	0.15
1960	541.02	3,622	3,300	0.15
1961	299.22	3,973	3,450	0.08
1962	386.62	4,119	3,632	0.09
1963	251.83	4,176	3,428	0.06
1964	250.63	4,103	3,740	0.06
1965	364.67	4,222	3,800	0.09
1966	241.24	4,446	3,930	0.05
1967	268.31	4,072	4,050	0.07
1968	285.12	3,861	4,250	0.07
1969	388.69	3,980	4,350	0.10
1970	408.92	4,031	4,100	0.10
1971	341.21	3,775	4,100	0.09
1972	338.66	3,877	4,300	0.09
1973	436.00	3,866	4,450	0.11
1974	409.64	4,337	4,860	0.09
1975	452.67	4,716	5,757	0.10
1976	393.26	5,254	6,224	0.07
1977	432.81	5,624	6,519	0.08
1978	364.53	7,045	7,162	0.05
1979	320.88	7,549	7,398	0.04
1980	375.54	7,638	5,317	0.05
1981	588.55	7,966	8,028	0.07
1982	672.83	7,997	7,639	0.08
1983	673.33	8,144	7,912	0.08
1984	798.77	8,622	8,467	0.09
1985	715.19	9,487	9,025	0.08
1986	531.67	9,612	9,265	0.06
1987	400.48	9,202	9,075	0.04
1988	391.98	9,469	9,128	0.04
1989	326.93	10,605	9,665	0.03
1990	228.85	10,796	10,806	0.02
1991	163.25	11,284	11,037	0.01
1992	132.49	11,560	11,377	0.01
1993	141.81	11,772	11,371	0.01
1994	178.44	11,783	11,386	0.02
1995	234.93	12,448	11,382	0.02
1996	188.70	10,958	11,603	0.02
1997	182.02	10,860	12,146	0.02
1998	158.21	11,167	12,829	0.01
1999	128.89	11,212	13,294	0.01
2000	87.45	10,456	12,987	0.01
2001	114.28	10,443	13,284	0.01
2002	160.06	10,871	14,332	0.01
2003	218.83	10,660	10,015	0.02
2004[c]	113.29	10,192		0.01
2005	149.06	10,826		0.01
2006	161.88	10,104		0.02
2007	150.50	9,745		0.02
2008	72.51	8,148		0.01

a. In accordance with the designation adding a class of LANL employees to the SEC, it is not feasible to reconstruct photon doses to LANL workers prior to 1956; nonpenetrating doses may not be reconstructed prior to 1949; and neutron doses may be reconstructed only from 1946 onward (NIOSH 2007b).

b. A criticality accident during this year delivered large doses to a small number of people, driving the average total dose up significantly.

c. For years 2004-2007, an update to LANL (2004) was received during preparation of the Evaluation Report for SEC petition SEC-00109; for 2004-2007 (and part of 2008) only the numbers of employees monitored were available.

6.2.1.2 Dosimeter Exchange Frequencies

Dosimeters were exchanged on routine schedules. In the earliest operations, daily measurements with PICs were performed, but results are generally not available in employee records. After film badges came into use in 1943, daily PIC measurements continued, but film measurements provided a

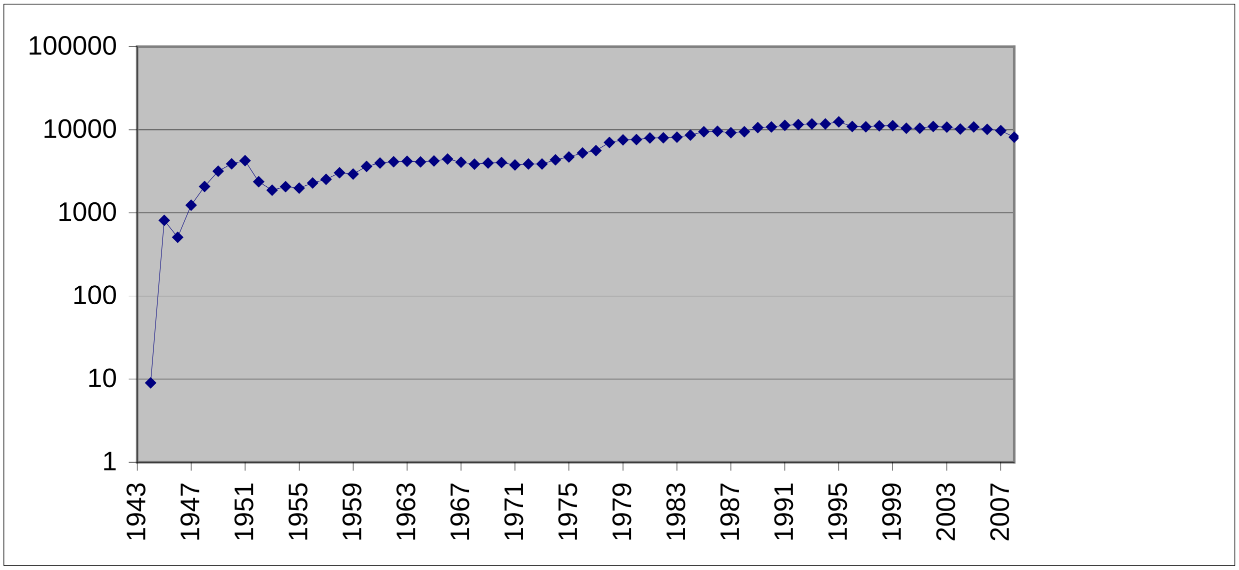


Figure 6-1. Number of workers monitored as a function of time (LANL 2004, updated January 2009).

check of the daily measurements and formed a permanent record of worker exposures. Film packets were exchanged and processed monthly for most workers, but were exchanged more frequently (as often as daily) for certain operations with high exposure potential. In February 1948, it was reported that brass film badges (film placed directly in a brass container, with no window of any sort or filters of any other metal) had been issued to all Sigma and Heat Treatment (HT) Building personnel in October 1947 to monitor beta and gamma exposures and had been exchanged and reissued every 2 weeks since that time [LASL 1959 (2/26/48 memorandum)]. Health Group personnel were then considering the exchange of badges more often than every 2 weeks for personnel who were handling "abnormally large amounts" of ^{235}U during certain periods at these facilities [LASL 1959 (2/26/48 memorandum)].

In October 1956, beta/gamma dosimeters were exchanged at 1- or 2-week intervals, with 2-week intervals predominating [LASL 1959 (10/4/56 memorandum)]. NTPs were exchanged at 4-week intervals. There was a desire to use 2-week intervals for NTPs and read all plates, but the H-1 monitoring group was unable to support this due to labor considerations. At that time, only half the issued plates were read [LASL 1959 (10/4/56 memorandum)]. In September 1988, LANL evaluated changing from monthly to monthly/quarterly badge issue (LANL 1989). The HSE-1 section leader recommended against changing to monthly/quarterly issuance, stating that problems with fading supported continuation of monthly exchange. Monthly exchange continued to be the most common.

In February 1992, LANL temporarily switched to quarterly badge exchange due to installation startup problems with a new data management system, with the exception of 22 employees who were involved in a special project that required weekly exchange. Monthly exchange was reinstated in April 1992. LANL began phasing in a quarterly dosimeter exchange frequency for personnel who received low occupational radiation exposure beginning in April 1996 (LANL 2001). The cutoff was a less-than-

10-mrem collective dose for a work group (mailstop) based on 1995 exposure records. Beginning in July 1996, mailstops with collective doses of 50 mrem or less for 1995 were placed on quarterly exchange. As of February 2002, quarterly periods were used for about 40% of dosimeter issues (LANL 2003).

Exchange frequencies for LANL dosimeters are summarized in Table 6-3 and later in the discussion of methods for estimation of missed dose.

Table 6-3. Typical exchange frequencies for dosimeters in use during different periods.

Dosimeter type	Date range	Exchange frequency
PIC	Before 1945	Daily
Film badge	1943–1979[a]	Monthly for most, biweekly for some, up to daily for some operations such as radioactive lanthanum processing
TLD	1980–1995	Monthly
TLD	1996–present	Monthly for most, quarterly for some
NTP	1949–approx. 1951	4-wk interval
NTA film	1951–1995	4-wk interval
TED	1995–present	Quarterly

a. According to the designation adding a class of LANL workers to the SEC, it is not feasible to reconstruct photon doses prior to 1946, and infeasible to reconstruct nonpenetrating doses prior to 1949 (NIOSH 2007b).

6.2.1.3 Use of Control Dosimeters

A review of the documents in the *Photodosimetry Evaluation Book* from 1944 to the present yielded little information on how control dosimeters were used over time at LANL. The information that was found is as follows:

- An October 1944 report (in LASL 1959) received at LANL from the MED about the use of lead cross dental film packets to monitor gamma, X-ray, and beta exposure mentioned that "each group of test films is developed with a calibration film. One unexposed test film is included in the group as a check. After processing, if the unexposed film shows evidence of radiation fog, as indicated by an image or shadow of the lead cross, the evaluation of exposures received by films carried by personnel is questionable, if not useless."

- A November 2, 1944, report (in LASL 1959) about film monitoring conducted at an unidentified MED warehouse said that "[c]ontrol badges (or, in this case, films) are to be mailed from, and returned to, Rochester with the others but are not to be issued to any worker. Indeed, they are to be kept in a place which is known to be free of radiation. Such a control badge will then reveal whether anything goes wrong with the films (badges) during shipment or at any other time except while they are actually being worn."

The existence of the two documents cited above indicates that the use of control badges was a concept that LANL personnel were familiar with from the early years of operations.

- A Los Alamos "Nuclear Track Plate Evaluation Procedure" dated February 27, 1956 (in LASL 1979), stated that: "It has been found that NTPs which are not worn, but are processed and 'read,' will indicate some exposure. This exposure varies somewhat with the seasons, etc., and is attributed to cosmic radiation. Therefore, whenever a group of NTPs are packaged for issue, a 'blank' NTP is also packaged and immediately sent to P-10 for processing and reading. Then the blank's exposure will be subtracted from the personnel's neutron exposure during the process of evaluating the NTPs."

- A November 1974 sheet of potential values for the Remarks Code used in dosimetry records (in LASL 1974) had a Code 025 that signified "Used as Blank," and an August 1976 revision had a Code 247 that signified "Control film inadvertently issued to a visitor- D. P. 4/7/76."

- A July 23, 1991, memorandum from to the Dosimetry Evaluation Book (in LANL 1996) indicated that, in response to a finding from a DOE Laboratory Accreditation Program (DOELAP) onsite audit, "several 'unirradiated dosimeters' have been added to the blind audit program since January, 1991."

- An April 29, 2003, memorandum (in LANL 2003) from Jeffrey Hoffman to Michael McNaughton, both LANL employees, discussed two environmental dosimeters that had been labeled "vault dosimeters" in error.

- LA-UR-03-1037, "LANL 8823 Neutron Blind Audits at TA-36" (in LANL 2003), indicated that the blind-testing protocol at that time included 19 WB TLDs, 13 extremity TLDs, and 13 TEDs each quarter, of which four, three, and three, respectively, were "non-irradiated controls."

Based on the above excerpts and information from a former worker in the LANL dosimetry group (Widner 2003), a set of calibration films was developed when a batch of personnel films was developed. A control that had been kept in the dosimetry offices along with the calibration films (apparently in a vault in later years), and other controls that had been kept in the film badge racks with the personnel films, were photographically developed at the same time. These badge racks, which were for storage of dosimeter badges when the badges were not being worn by the persons to whom they were issued (e.g., overnight or over weekends), were in areas where only background radiation was expected under normal circumstances; control badges were also kept in these racks for the normal film badge issue periods. The developed “calibration film control” was used to zero the densitometer before the densities of the calibration film were read. The density readings of the calibration film were plotted against the exposure given to the calibration film to permit the evaluation of the personnel film. The control accompanying the personnel film was used to zero the densitometer before the densities of the personnel films were read. On rare occasions when the personnel control film showed some exposure due to fallout from Nevada Test Site operations, the control film was evaluated and its exposure was subtracted from all personnel film for the period.

On rare instances, the personnel control films were “lost” or removed from the film badge racks by persons unknown. On such occasions, a personnel film badge that had been issued to a person who <u>never</u> entered the radiation work areas during the film badge issue period was used as the control for zeroing the densitometer before the other personnel films were read (Widner 2003). In those cases, Remark Code 25 would be attached to the zero dose reading recorded for the person whose badge was used as the blank. Remark Code 247 was appended to the evaluated exposure of the person (probably a visitor) to whom the control film had been inappropriately given.

6.2.1.4 Reporting Conventions

Monitoring for external radiation exposures at LANL began in 1943 with the use of PICs. Gamma exposures were recorded in units of roentgen. Before 1949, some Laboratory personnel who worked with the cyclotron and other neutron sources wore Victoreen pencil PICs for determination of their neutron dose [LASL 1969 (11/12/68 memorandum)]. The results were recorded in n units, which were defined as “the quantity of neutron radiation that will produce the same ionization in a 100-R Victoreen chamber (red Bakelite) as 1 R of gamma radiation.” While n-unit data were recorded in medical records of some individuals, they were apparently never converted to the computerized database of exposure records and will probably not be available with information provided for claimants (Widner 2004). See Section 6.2.2.2 for more details about the n unit.

When brass film badges (film placed directly in a brass container, with no window of any sort or filters of any other metal) came into use by more and more LANL groups between 1943 and 1945, only gamma exposure in roentgens was evaluated.

Starting in January 1949, the following values were recorded on personnel exposure sheets:

- PIC readings (R)
- Gamma exposure (R)
- Beta exposure (rep)

Beta exposure was reported only when "it forms a significant part of the total exposure" [LASL 1959 (1/10/49 memorandum)]. No entry in the beta exposure column indicated that a negligible amount of beta exposure was present. For DP Site personnel working with plutonium and for soft X-ray evaluations, special calibration curves were used, and gamma roentgen exposures were multiplied by 0.6 to convert to gamma rem [LASL 1959 (7/1/56 document)]. [The comparable DOELAP roentgen-to-rem dose conversion value is 0.38 for 16-keV photons (DOE 1986)].

Starting in 1949, NTPs came into use. As of February 1956, NTPs were evaluated by assuming all 10- to 100-µm tracks represented 3.75-MeV neutrons and all longer tracks represented the maximum average energy of the higher energy neutrons in the workplace. NTA film came into use in the brass-cadmium badge in 1951. While tolerances for neutrons were stated in terms of neutrons per square centimeter per second in the early years, neutron doses were reported in terms of rem in 1953 and possibly earlier [LASL 1959 (Jan. 1953 document)].

Before April 1957, exposures for HT shop and Sigma areas (where uranium was handled) were recorded as pure beta exposures, but some gamma exposures should have been recorded for workers at those facilities [LASL 1959 (4/3/57 document)]. Based on film badge data from early 1953, a factor of 0.1 was used in the conversion of radiation exposure records for IBM entry to calculate retrospectively the gamma exposure from the gamma-plus-beta exposure measured by the dosimeter. The theoretical ratio of gamma to beta plus gamma was reported to be about 1:17 for normal uranium [LASL 1959 (4/3/1957 document)].

The roentgen-to-rem dose conversion factor (DCF) was changed to 0.5 from July 1957 to March 1963 for body badges exposed to low-energy X-rays and plutonium; the use of this factor was discontinued around March 20, 1963 [LASL 1969 (3/20/63 memorandum)].

As of 1960, the following external radiation dose data were recorded (Littlejohn 1961):

- Gamma dose (rem)
- Beta dose (rad)
- Thermal neutron dose (from cadmium optical density minus brass optical density, rem)
- Fast neutron dose (from NTA film, rem)

On January 1, 1972, the Laboratory evaluated assignment of neutron dose equal to TLD-measured gamma dose for workers who handled ^{238}Pu [LASL 1974 (12/3/71 memorandum)]. This appears to have been a special study for a relatively small group of workers, possibly using hand-fabricated badges with loose chips, because TLDs were in relatively short supply at that time (Widner 2003).

Starting in early 1980 with the conversion to the Model 7776 TLD badge, the following external radiation dose data were recorded [LASL 1980 (3/21/80 memorandum, page 66 of the PDF file)]:

- "Non-penetrating Rad" represented the total skin dose from external ionizing radiation; it was equal to old beta-rad plus gamma-rem or old gamma-R.
- "Penetrating-rem" represented the total WB dose from external ionizing radiation; it was equal to old gamma-rem dose. Evaluated based on the copper-filtered TLD chip.
- "Neutron-rem" was typically equal to the albedo (body-scattered) neutron dose from the TLD badge; when piggyback NTA film was used, the fast neutron dose from NTA film was added to the albedo neutron dose, and "NTA" was entered in the Remarks field.
- "Total-rem" was equal to penetrating-rem plus neutron-rem plus tritium-rem (where tritium-rem was calculated from tritium urine assays).

Since the implementation of the Model 8823 TLD badge in 1998, the following dose quantities have been evaluated and recorded (Hoffman and Mallett 1999a,b):

- Beta shallow DE (mrem)
- Beta eye DE (mrem)
- Gamma shallow DE (mrem)
- Gamma deep DE (mrem)
- Gamma eye DE (mrem)
- Neutron deep DE (mrem)
- Total shallow DE (mrem)
- Total deep DE (mrem)
- Total eye DE (mrem)
- Total deep neutron DE (mrem)

Shallow doses, which are reported to a tissue depth of 7 mg/cm^2, correspond to the old nonpenetrating doses. Doses to the lens of the eye are reported to a tissue depth of 300 mg/cm^2. Deep doses, which are reported to a tissue depth of 1,000 mg/cm^2, correspond to the old penetrating doses. Neutron DE values correspond to albedo neutron DE (rem).

Table 6-4 summarizes quantities that have been recorded in LANL worker exposure records over time.

In the reporting of doses for LANL workers to NIOSH for the Dose Reconstruction Project, LANL personnel have used the following conventions (Widner 2005):

- Blank entries or “----” entries in tables of doses indicate a “null value” (i.e., no monitoring was performed for the subject individual for that period).
- Dose entries that are all zeros (0.00 or 0.000) indicate that monitoring was performed for the subject individual during that period, but that results were below the minimum detectable dose.
- The SHALLOW doses as reported by LANL are the shallow dose as measured by TLDs or film badges; they do not include neutron dose or tritium dose. This contrasts with those records

Table 6-4. Quantities recorded in exposure records over time (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003).

Period	Values recorded in personnel exposure records
1943–1948	PIC reading (R) Gamma exposure (R)
1949–1950	PIC reading (R) Gamma exposure (R) Beta exposure (rep)
1951–1959	PIC reading (R) Gamma exposure (R) Beta exposure (rep) Fast neutron dose (rem)
1960–1979	Gamma dose (rem) Beta dose (rad) Thermal neutron dose (rem) Fast neutron dose (rem)
1980–1997	"Non-penetrating Rad" "Penetrating-rem" "Neutron-rem" "Total-rem"
1998–present	Beta shallow DE (mrem) Beta eye DE (mrem) Gamma shallow DE (mrem) Gamma deep DE (mrem) Gamma eye DE (mrem) Neutron deep DE (mrem) Total shallow DE (mrem) Total deep DE (mrem) Total eye DE (mrem) Total deep neutron DE (mrem)

reported as “SKIN” doses, which were reported in records submitted for dose reconstruction through late 2005.[3]

- Early LANL case records contain a column labeled “SKIN.” The SKIN doses reported are derived by LANL as shallow dose plus neutron dose plus tritium dose.

- When, for a given month, the dose report form identifies “Badge Type” as “Monthly,” but there are up to five lines of data (see example below), that indicates that multiple badges were worn during the month. The doses for the individual badges should be added to obtain the dose totals for the month.

External dose (rem)		Skin	Deep	Neutron	Tritium
June	Monthly	0.000	0.000		
June	Monthly	0.000	0.000		
June	Monthly	0.010	0.010		
June	Monthly	0.000	0.000		
June	Monthly	0.040	0.020		

3 When an automated tool is used for assigning doses to appropriate radiation types, the dose reconstructor must choose whether non-penetrating doses were assigned as “SHALLOW” or “SKIN.”

- When the dose reported is as follows, it reflects that the badge in use had two elements – dental X-ray film and NTA film. In the case below, the first line of data is from the NTA film and the second is from the dental X-ray film. In these cases, the neutron dose entry on the second line for the month is essentially a placeholder, and should not be corrected for missed dose.

External dose (rem)		Skin	Deep	Neutron	Tritium
April	Monthly	0.010		0.010	
April	Monthly	0.060	0.010	0.000	

6.2.1.5 Recordkeeping

From 1943 through 1952, external radiation evaluation results were recorded in standard "LA notebooks" that eventually found their way to the document room for permanent filing [LASL 1959 (1/20/51 document)]. December 9, 1946, was the first date for which a record of visitor badge issuance was found in LA notebooks, and the use of the notebooks for visitor badge data ended in January 1951 [LANL 1986 (10/30/79 memorandum)].

In August 1950, H Division started supplying PICs and film badges for use by the GMX-1 group in "extraordinary work" [LASL 1959 (February 1956 memorandum)]. Before that, dosimetry for the GMX-1 group was reportedly handled by GMX-1 personnel at GT Site, and apparently no long-term records of these early measurements were retained.

In January 1953, a Cardex system for filing exposure data on paper cards was put into use [LASL 1959 (2/16/56 memorandum)]. In January 1956, LANL started noting all NTPs issued on Personnel Exposure Cardex records. Before that, only plates that were read were recorded [LASL 1959 (2/27/56 document)].

In 1957, a computerized system was first employed at LANL to record personnel exposures to radiation [LASL 1959 (4/3/57 memorandum)]. In 1959, IBM equipment was first used to evaluate film exposures (Littlejohn 1961). This recordkeeping has been computerized since that time.

In September 1978, it was reported that for the previous 10 years no entry was made for a visitor's film badge in the computerized records system for film badge exposures less than 0.04 rem [LANL 1986 (9/28/78 document)]. For purposes of reporting to the primary employer of visitors, nonzero exposures recorded by the LANL Cycolac film badge were defined to be total exposures of 0.04 rem or more. (For regularly issued film badges, all measured values from 0.00 rem upward were recorded and attributed to the worker in the H-1 dosimetry records system.) This procedure for visitor film badges was used so reporting of doses less than 0.04 rem was not required, which would have been an enormous undertaking due to the need to find each visitor to obtain employer name and address for reporting purposes. On January 1, 1976, LANL had to start reporting zero exposures for all U.S. Energy Research and Development Administration (ERDA) visitors because ERDA had just established a radiation exposure record system for all its employees [LANL 1986 (10/30/79 memorandum)].

As of October 1989, the policy for NTA film dose entries was as follows: For workers who wore piggyback NTA dosimeters with their TLDs, NTA doses were summed with TLD neutron doses for monthly and annual reports. Before implementation of the new external dosimetry data management system, entry of NTA neutron doses used the same guidelines as those for TLD neutron doses: doses less than or equal to 4 mrem were entered as 0 rem, 5 to 14 mrem were entered as 0.01 rem, 15 to 24 mrem were entered as 0.02 rem, 25 to 34 mrem were entered as 0.03 rem, 35 to 44 mrem were entered as 0.04 rem, and so on (LANL 1989; Widner 2004).

Between 1981 and September 1990, shallow, deep, or neutron exposures less than 10 mrem were reduced to 0 mrem [LANL 1996 (9/14/90 document)]. LANL decided to change associated procedures such that shallow doses, deep doses, and neutron doses less than 5 mrem were rounded to 0 mrem, and doses between 5 and 10 mrem were rounded to 10 mrem effective with September 1990 TLD evaluations. These changes were not fully implemented until 1991 [LANL 1996 (2/5/91 and 4/19/91 memoranda)].

In early 1992, LANL installed and started a new data management system called the External Dosimetry Badge System.

6.2.1.6 Quality of External Dosimetry Data

At LANL, dosimeters were selected, issued to workers, and processed; the resulting measurements were recorded and used to estimate doses. There appears to be no use of recorded notional doses, although there are issues of missed dose for low-dosed dosimeters (see Section 6.5) and recorded doses for individual dosimeters at levels less than the statistical minimum detection level (MDL).

LANL dosimetry capabilities during the early years were in line with the stage of development of associated technologies at the time. Radiation dosimetry technology developed considerably during the period of LANL operations, and LANL kept up with technological developments as they became accepted. Administrative practices are described in the *Photodosimetry Evaluation Book* (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003) and LANL technical reports, and detailed information for each worker is in the NIOSH claim documentation. The claim documentation provides specific information to be evaluated on the recorded dose of record. There do not appear to have been significant administrative practices that jeopardized the integrity of the dose of record.

6.2.2 Dosimetry Technology

LANL health physicists learned from experiences at other MED sites that followed the general evolution in dosimeter technology using PICs in addition to one- or two-element dosimeters in the 1940s and early 1950s, multielement film dosimeters in the later 1950s, and TLDs from the 1970s to the present. LANL dosimeter designs differed somewhat from the designs at the MED Metallurgical and Clinton Laboratories in the early to mid-1940s, but capabilities to measure doses were similar.

The adequacy of the dosimetry methods to measure radiation dose accurately is determined from the radiation type, energy, exposure geometry, etc., as described in later sections. The dosimeter exchange frequency was gradually lengthened, and generally corresponded to the period of regulatory dose controls (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003). At the beginning of Laboratory operations, a dose control of 1 mSv/d (100 mrem/d) was in effect. This was changed to 3 mSv/wk (300 mrem/wk) and later to 50 mSv/yr (5,000 mrem/yr) in the late 1950s. These changes were in accord with AEC regulations at the time and with the appropriate NBS handbooks (Widner 2003). Table 6-5 summarizes major events in the LANL personnel dosimetry program.

Table 6-5. External dosimetry events (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003).

Period	Event
1943	Monitoring for external radiation exposures began, using PICs.
1943	Film badges first used at LANL by the GMX-1 Radiography Group. These badges apparently used Lead Cross Type K dental film in a brass holder.
Early 1944	LANL H Division health physicists gathered information about film monitoring practices from other MED sites.
May 1944	Film badges, made at LANL, distributed to some workers by H Division on a trial basis.
Feb 1945	System of monitoring exposure of personnel with photographic film was established by the H Division, with badges exchanged monthly. Continued to use PICs.
Late 1945	After Omega Site criticality accident, "catastrophe badges" were developed and assigned to workers who could be involved in criticality accident.
Aug 1947	“Brass Film Badge” in use included three types of film in a brass container with no windows or filters of other metals.
Sep 48–Mar 49	New badge phased in. Brass clip provided only partial shielding of film surface.
29 Aug 1949	First NTPs issued for evaluation of fast neutrons.
20 Apr 1950	Started changeover to new badge that used brass and lead filters plus unfiltered area.
7 Mar 1951	Studied ring badges and wrist badges and variability of ratios between them.
24 Mar 1951	New finger film badge developed. Used Eastman Kodak Type K or DuPont sensitive Type 552, brass and cadmium filters.
Apr 1951	Change to brass and cadmium badge. Brass and cadmium filters, plus open window. Used DuPont 502 dental film and Eastman Kodak Type B packet that contained NTA fast film and Fine Grain Positive.
1954	Thermal neutron measurements started.
1955	Routine measurement of thermal neutrons was discontinued.
1956	Routine evaluation of thermal neutron exposures restarted.
Oct 1962	Multi-element Cycolac film badge put into use. It included multi-element filter, another multi-element filter with Li-6, and unfiltered area. Two film packets: DuPont 543 (with DuPont 502 film), Kodak Type B (with NTA fast film and Fine Grain Positive).
31 Jan 1963	Practice of using wrist-to-finger ratios greater than 1 discontinued.
Mar 1963	Comparison of Cycolac and brass-cadmium badges conducted.
Aug 1968	LANL tried to duplicate Battelle PNL badge performance study of 1966, in which it did not participate.
Sep 1970	Started issuing film badges with TLD-ribbon containing plastic insert to selected individuals at DP Site. Purpose of these badges with TLD-600 and TLD-700 ribbons was to evaluate individual exposures between film development and evaluation.
1971–1972	Prototype albedo-neutron TLD badge studied at DP West, compared to Cycolac film badge data.
Jul–Dec 1972	Performance of film badges, NTA film, and prototype albedo-neutron-TLDs compared at DP West plutonium facilities over a 6-month period.
May 1978	Began issuing Model 7776 TLD badges to visitors. Certain LANL groups got them starting in September. Additional LANL groups changed from film to TLD throughout 1978–1979, as TLD cards and badges were acquired.
1978–1979	LANL participated in National Research Council/University of Michigan pilot dosimeter testing program.
1980	At LAMPF, TLD badge was supplemented by Kodak NTA film placed in a Cycolac piggyback holder attached to TLD badge.
1 Jan 1980	Dosimetry section completed changeover from film dosimetry badges to TLD badges as dosimeter of record. Model 7776 badge had cadmium and non-cadmium versions. Cadmium version was initially used at LAMPF.
Late 1980	Changed to use of non-cadmium badge at LAMPF to gain sensitivity.
Jun 1981	Concurrent monitoring with NTA film and TLDs was conducted.
Jun 1981	Discontinued routine issue of NTA film for LAMPF personnel.
Dec 1984	LANL applied to participate in pilot testing of DOELAP.
16 Jan 1985	LANL selected for participation in pilot testing of DOELAP.
Jul 1987	TLD plus NTA badges used with other detectors during special neutron spectral measurements at LAMPF.
May 1988	Neutron measurements made at seven locations in TA-55 Room 209 using ESP-2 neutron instrument and TLD badges on Lucite phantom.
Jun 1991	LANL expressed interest in participating in some categories of DOELAP testing of extremity dosimeters (not the categories with low-energy beta emitters or neutrons).

Period	Event
Aug 1992	Comparison conducted of bubble dosimeters with Model 7776 TLDs.
1993	LANL purchased automated reader for use with chemically etched CR-39 detectors.
1995	LANL introduced TED as replacement for NTA film as high-energy neutron dosimeter at LAMPF.
22 Feb 1996	Moved up deployment of new eight-element TLD (worn with 7776 TLD badge) for use in dynamically determining employee-specific NCFs.
Apr 1996	Began to phase in quarterly dosimeter exchange frequency for personnel who received "low" occupational radiation exposure.
1996	LANL submitted track-etch neutron dosimeters for irradiation at PSI in Europe.
Feb 1998	Review of Model 8823 TLD as neutron dosimeter issued.
1 Apr 1998	Model 8823 became dosimeter of record. Eight-element TLD (called Model 8823 by manufacturer Harshaw/Bicron) uses Model 7774 TLD cards.
Oct 1998	Began using wrist dosimeter for routine monitoring.
1999	LANL TED passed DOELAP performance testing for neutrons.
1999	LANL participated in 4th Intercomparison of Personal Dosimeters Used in U.S. DOE Accelerator Facilities.
2000	LANL submitted TLDs and track-etch badges for irradiation by monoenergetic, accelerator-produced neutrons from 0.144 MeV to 19 MeV at PTB in Germany.

6.2.2.1 Beta/Photon Dosimeters

The following paragraphs describe LANL dosimeters and periods of routine use to provide the recorded dose of record.

Pocket Ionization Chambers. Monitoring for external radiation exposures at LANL began in 1943 when PICs were issued to a few persons thought to have the highest potential for receiving exposures at or above the "tolerance" limit [LANL 1986 (10/6/81 document)]. As of January 19, 1944, Victoreen PICs were in use. In August 1950, H Division furnished Keleket Pocket Chambers along with film badges for use by GMX-1 in “extraordinary work.”

Brass Film Badge, 1943 to 1948. Before 1951, external dosimetry was provided by three different organizations at LANL – H Division, the CMR-12 Radiochemistry Group, and the GMX-1 Radiography Group (CMR indicates *Chemistry and Metallurgical Research*, and also refers to a building). The first use of film badges at LANL was apparently in 1943 by the GMX-1 Radiography Group (Widner 2004).

On January 19, 1944, H Division personnel inquired with Colonel Stafford Warren of MED at Oak Ridge National Laboratory (ORNL) about using strips of film to check exposures to radiation. They requested film and instructions for use in checking their Victoreen PICs. By May 18, 1944, LANL had started to distribute film monitors to various people [LASL 1959 (5/18/44 memorandum)]. On June 14, 1944, Colonel Warren gave authorization to order Lead Cross Type K Dental Film from Eastman Kodak Company. In February 1945, H Division instituted a system to monitor exposure of workers with photographic film [LASL 1959 (2/17/45 memorandum)]. The badges apparently used Eastman Kodak Lead Cross Type K Dental Film in a brass holder. Film packets of that type were ordered with a 0.5-mm-thick lead cross over one face (covering about 60% of that face), with the edges of the cross folded over to cover a small portion of the opposite side of the packet [LASL 1959 (6/13/44 drawing attached to 10/27/44 memorandum)]. In the MED method for use of this film, penetrating photon doses were estimated from the areas on the edge of the film packets where the ends of the lead cross folded over the edge of the packet; the combined thickness of the lead and the 0.033-in.-thick brass holder absorbed beta rays [LASL 1959 (report attached to 10/27/44 memorandum)].

In the film badge in use in August 1947, film was placed directly in a 0.4- to 0.5-mm-thick brass container with no window or filters of other metal [LASL 1959 (8/4/47 memorandum)]. These badges, which were intended to measure only gamma radiation, were made at LANL. Three types of film were initially used together: Eastman Kodak Industrial Type K X-Ray Safety Film (0.01 to 6.0 R), DuPont

D-2 Special Type X-Ray Film (two films, together covering 0.13 to 30 R, and DuPont Adlux Film (65 to 1,500 R). Beginning around July 1947, only Eastman Kodak Type K film was used routinely, but all films continued to be used "in cases where an operation is considered at all hazardous" [LASL 1959 (8/4/47 memorandum)].

There is some uncertainty about the point in time when LANL switched from the film badge that used the lead cross film to the version in use in August 1947 that used films with no windows or filters of any type.

Early LANL film packets were collected and read once a month, and new films were supplied. Film badges did not replace the daily measurements of the PICs; they provided a check of daily measurements and formed a permanent record of exposure. About 1 week after the August 8, 1945, fatal criticality accident at TA-2, "catastrophe badges" that could measure up to 3,000 R with film, red phosphorous capsules for measuring fast neutron flux, and brass in the badge itself for measuring slow neutron flux were assigned to "anyone who could be involved in a criticality accident" [LASL 1959 (6/14/45 document)].

Brass Clip Badge, 1949 to 1950. About January 1949, there were changes in the type of film badge used at the Laboratory. The new badge had a DuPont film packet inserted in a brass clip that provided only partial shielding of the film surface. The brass absorbed almost all beta radiation while having negligible effect on gamma radiation. By comparing the optical densities under brass with those not under brass, a separate evaluation of beta exposure could be made.

Brass-Lead Film Badge, 1950 to 1951. On April 20, 1950, the Laboratory started changeover to a new film badge. It used brass and lead filters plus an unfiltered area. The two-filter system was used to support energy determination for beta and gamma radiation so appropriate correction factors could be applied. This badge was used until April 1951.

Brass-Cadmium Film Badge, 1951 to 1962. In April 1951, the Laboratory initiated changeover to a brass and cadmium film badge. This badge incorporated brass and cadmium filters and an open window. It used two film packets: a DuPont 543 packet that contained DuPont 502 dental film and an Eastman Kodak Type B packet that contained NTA fast neutron film and Fine Grain Positive film.

Cycolac Film Badge, 1962 to 1978. In October 1962, a new multielement Cycolac film badge was issued to about 100 persons who had histories of appreciable or out-of-ordinary radiation exposures. More widespread use followed. Named after the brand of plastic used in its holder, the Cycolac badge used a multielement filter, a second multielement filter with ^{6}Li, and an unfiltered area. It used two film packets: a DuPont 543 packet that contained DuPont 502 dental film and an Eastman Kodak Type B packet that contained NTA fast neutron film and Fine Grain Positive film. In addition, it contained indium, gold, and sulfur foils for accident dosimetry. The Cycolac badge was seen to have the advantages of relative gamma and X-ray energy independence (within 30%) from about 30 keV to 1,400 keV, the ability to evaluate thermal neutrons in the presence of X- and gamma radiations below 400 keV, and improved directional independence.

Model 7776 Thermoluminescent Dosimeter Badge, 1978 to 1998. A prototype albedo-neutron TLD was studied at DP West in the last half of 1972. The Laboratory began issuing TLD badges to visitors in May 1978. Certain Laboratory groups began to receive them in September because it took several months for complete conversion. The Model 7776 TLD badge had cadmium and noncadmium versions. It incorporated copper, Cycolac plastic, and cadmium filters, and used three TLD-700 chips (one covered with copper, one with thin Cycolac plastic, and the third with thicker plastic) and one TLD-600 chip (enriched in ^{6}Li). In the cadmium badge, the third TLD-700 chip and the TLD-600 chip were shielded by cadmium pockets, as opposed to plastic covers in the noncadmium badge. The Dosimetry section completed the changeover from film dosimetry badges to TLD badges as the dosimeter of record on January 1, 1980. The Model 7776 dosimeter was not designed to perform low-penetrating beta dosimetry and was not accredited by DOELAP for low-energy beta particles or beta and low-energy photon mixtures (Hoffman and Mallett 1999a).

Model 8823 Eight-Element Thermoluminescent Dosimeter, 1998 to Present. The Model 8823 TLD is a custom LANL design that contains two Harshaw/Bicron-NE TLD cards (Hoffman and Mallett 1999a,b). The Model 8823 cardholder is made of black acrylonitrile butadiene styrene (ABS) plastic to prevent the exposure of light-sensitive TLD elements. The holder contains a 21-mil-thick cadmium box that is painted red in which the neutron TLD card is placed. The cadmium box has an open window under positions 7 and 8 (next to the body of the wearer) and over positions 5 and 6 (toward the incident radiation) to facilitate the combined albedo and anti-albedo design. The technical advantage of the moderating box is that it reduces the dependence of TLD neutron response on the distance of the dosimeter from the worker's body. The holder is designed to provide 600 mg/cm^2 ABS plastic filtration over positions 1 and 4, mainly to determine photon deep dose. Positions 2 and 3 are beta windows that are covered with one and two layers of aluminized Mylar, respectively. The aluminized Mylar is coated with black paint on the back to maximize light attenuation.

The photon and beta dosimeters used over time at Los Alamos are summarized in Table 6-6.

Table 6-6. Photon and beta dosimeters used over time (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003; Widner 2003, 2004).

Period	Type badge	Film or media used
1943–1944	PIC	Quartz fiber
1943–June 1946	Brass film badge	Eastman Kodak Lead Cross Type K Dental Film packet
July 1946–1948	Brass film badge–no windows or filters	Eastman Kodak Industrial Type K X-Ray Safety Film, DuPont D-2 Special Type X-Ray Film, and DuPont Adlux Film. After June 1947, only Eastman Kodak Type K was used routinely.
1949–1950	Brass "clip" badge–provided only partial shielding of film surface	Eastman Kodak Type K X-Ray Safety Film
1950–1951	Brass film badge–brass and lead filters plus unfiltered portion	Eastman Kodak Type K X-Ray Safety Film
1951–1962	Brass-cadmium badge–brass and cadmium filters plus open window	Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Kodak Type B (contained NTA fast neutron film and Fine Grain Positive)
1962–1978	Cycolac plastic badge–multielement filter, a second multielement filter with ^{6}Li, and an unfiltered area	Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Kodak Type B (contained NTA fast neutron film and Fine Grain Positive)
1978–March 1998	Model 7776 TLD badge (cadmium and non-cadmium versions)–copper, Cycolac plastic, and cadmium filters	Three TLD-700 chips (one covered with copper, one with plastic) and one TLD-600 chip (enriched in Li-6). In the cadmium badge the third TLD-700 chip and the TLD-600 chip were shielded by cadmium pockets; they were covered by plastic in the noncadmium badge.
April 1998–present	Model 8823 TLD badge	Two TLD cards hold eight TLD elements. One card has three TLD-700 elements and one TLD-400. Two elements are filtered with ABS plastic. Two have minimal filtration. The second card is in a cadmium box; two elements form a classic albedo detector with a TLD-600/-700 pair surrounded by cadmium except for an opening toward the body. Two positions are an incident thermal neutron detector ("an Anti-Albedo detector") with a TLD-600/-700 pair surrounded by cadmium except for an opening away from the body.

6.2.2.2 Neutron Dosimeters

LANL has used five general types of neutron dosimeters that differ dramatically in their response to neutron radiation. The following paragraphs describe the personnel neutron dosimeters used at LANL and their periods of use.

Pocket Ionization Chamber, Before 1949. Before 1949, some personnel who worked with the cyclotron and other neutron sources wore the Victoreen pencil PIC to determine their neutron doses [LASL 1969 (11/12/68 memorandum)]. The chamber consisted of a Bakelite cylinder with a clear Lucite top and an aluminum cap and ring on the bottom. The chambers were 5 in. long and 0.5 in. in diameter and had a pocket clip. The chambers were not self-reading. An internal electrode and the inner wall of the Bakelite chamber were coated with graphite. Doses received were recorded in n units. An n unit was defined as "the quantity of neutron radiation that will produce the same ionization in a 100-r Victoreen chamber (red Bakelite) as 1 R of gamma radiation." A 1968 study of the response of the Bakelite dosimeters indicated that 1 n unit corresponded to about 5.9 rad of neutron exposure (±25%) or 59 rem if a quality factor of 10 is applied [LASL 1969 (11/12/68 memorandum)]. A conclusion of that study was that the Bakelite dosimeters lacked adequate neutron sensitivity to be useful for the evaluation of neutron exposures. Dale Hankins of H-1 stated that "large errors can be made if the gamma-ray contribution to the response of the dosimeter was assumed to be neutron dose or that the neutron contribution to the dosimeter readings was assumed to be gamma-ray dose" [LASL 1969 (11/12/68 memorandum)].

Nuclear Track Plates. In late August 1949, the first NTPs were issued for the evaluation of fast neutrons. The first written report of fast neutron exposure was in May 1950. From 1943 to 1949, no monitoring for fast neutron doses was performed with the exception of activation analyses performed for several criticality accidents. As of October 4, 1956, NTPs with 1,000-µm emulsion on glass backing supplied by Ilford were used for fast neutron dose evaluation. They were thought to have been accurate to within a factor of 2 [3].

Nuclear Track Emulsion. In April 1951, changeover to a brass and cadmium film badge began. This badge incorporated an Eastman Kodak Type B packet that contained NTA fast neutron film and Fine Grain Positive film. In October 1962, the new multielement Cycolac film badge was first issued at the Laboratory. The Cycolac badge included an Eastman Kodak Type B packet that contained NTA fast neutron film and Fine Grain Positive film. It also contained indium, gold, and sulfur foils for accident neutron dosimetry. The main concerns with NTA film were that latent-image tracks faded rapidly when humidity was high and that the lowest energy neutrons detectable in routine evaluations were about 0.8 to 1 MeV (Hankins 1973). NTA film did provide useful information about doses from neutrons with energies above this threshold, particularly when used in conjunction with TLDs from about 1980 until 1995. After some study of fading issues at LANL, NTA film was sealed in plastic with a desiccant to minimize fading due to high humidity [LANL 1989 (6/22/89 memorandum)].

Thermoluminescent Dosimeters. LANL began issuing TLD badges to visitors in May 1978, and certain groups began to receive them in September. The Model 7776 TLD badge had cadmium and noncadmium versions. It incorporated copper, Cycolac plastic, and cadmium filters, and used three TLD-700 chips (one covered with copper, one with thin Cycolac plastic, and the third with thicker plastic) and one TLD-600 chip (enriched in ^{6}Li). In the cadmium badge, the third TLD-700 chip and the TLD-600 chip were shielded by cadmium pockets, as opposed to plastic covers in the noncadmium badge. TLD badges were used by a number of groups in 1978; the LANL Dosimetry section completed the changeover from film dosimetry badges to TLD badges on January 1, 1980.

The Model 7776 dosimeter relied heavily on the use of site- and operation-specific neutron correction factors (NCFs) for neutron dosimetry. The technique used an essentially bare TLD-600 and TLD-700 pair in a quasi-albedo arrangement (i.e., without a cadmium or other neutron-absorbing shield anterior to the TLD elements). The albedo dosimeters were sensitive to the intermediate and lower energy fast neutrons that other dosimetry methods could not detect, but their net neutron signal was highly energy-dependent and required the use of site-specific NCFs to convert the response to dose. NCFs could vary by more than an order of magnitude. As a consequence, they were assigned at very conservative values such that neutron doses were typically overestimated by a factor of 2 to 3 (Blackstock et al. 1978).

A detachable holder for NTA film was included in the Model 7776 TLD badge design to facilitate fast neutron measurement. This configuration was unacceptable, however, because it would invalidate the calibration of the badge and its DOELAP accreditation and it did not address fading problems (Mallett et al. 1990).

The Model 8823 TLD is a custom LANL design that contains two Harshaw/Bicron-NE TLD cards (Hoffman and Mallett 1999a,b). The holder also contains a 21-mil-thick cadmium box that holds the neutron TLD card. The cadmium box has an open window under positions 7 and 8 (next to the body of the wearer) and over positions 5 and 6 (toward the incident radiation) to facilitate the combined albedo and anti-albedo design.

In early 1996, LANL decided to issue the Model 8823 badge in conjunction with the LANL Model 7776 WB TLD before the acceptance of the Model 8823 as the dosimeter of record. During this interim period, the dedicated neutron portion of the Model 8823 was used to calculate employee-specific NCFs to be applied to the Model 7776 WB TLD net neutron reading [LANL 2001 (2/22/96 document)]. The Model 8823 dosimeter received its first DOELAP accreditation after it successfully passed performance testing in the spring of 1997 (Hoffman and Mallett 1999a,b). The Model 8823 became the dosimeter of record for LANL on April 1, 1998.

The LANL Model 8823 dosimeter is DOELAP-accredited in all applicable categories (no exceptions are required). The general beta category (VA), which includes ^{90}Sr/^{90}Y and ^{204}Tl, is selected over the special contact geometry uranium category (VB) and special beta category (VC), which include only ^{90}Sr/^{90}Y or ^{204}Tl.

Track-Etch Dosimeter. The LANL TED (or PN3) contains three dosimetry-grade CR-39 track-etch plastic foils (Hoffman and Mallett 1999a). The foils are placed in a hemispherically shaped ABS plastic case on the sides of a triangular polystyrene pyramid to minimize angular dependence of the TED. The LANL TED, which is sensitive only to neutron radiation, is used for special field conditions. When issued to personnel, it is used in combination with the Model 8823 dosimeter (Hoffman and Mallett 1999a). The LANL TED is entered in the DOELAP pure ^{252}Cf and moderated field category (Category VI).

These five general types of neutron dosimeters that have been most widely used at LANL, which are summarized in Table 6-7, differed significantly in their response to neutrons of different energies, as shown for NTA film and albedo TLD dosimeters in Figure 6-2 (IAEA 1990). While it should be noted that calibration factors were used to adjust the response curves for ^{6}LiF and NTA film upward to better align with *Hp(10)*, this did not remove the fundamental energy dependence of the two types of dosimeters.

Table 6-7. Neutron dosimeters used over time at LANL (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003; Widner 2003, 2004).

Period	Type badge	Film or media used
1943–1949	No monitoring of fast neutron exposure	None
1943–1953	No monitoring of thermal neutron exposure	None
1949–1951	Nuclear track plates	NTPs with 1,000-µm emulsion on glass backing supplied by Ilford
1951–1962	Brass-cadmium badge – brass and cadmium filters plus open window. (Thermal neutron monitoring stopped in 1955, restarted in 1956.)	Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Kodak Type B (contained NTA fast neutron film and Fine Grain Positive)
1962–1979	Cycolac plastic badge – multielement filter, a second multielement filter with ^{6}Li, and an unfiltered area.	Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Kodak Type B (contained NTA fast neutron film and Fine Grain Positive)
1980–1998	Model 7776 TLD badge (cadmium and non-cadmium versions) – used with NTA film in a piggyback holder for some (<40) workers 1981 – 1995 (measured thermal, intermediate, and fast neutrons, with no separation of fast neutrons)	Essentially bare TLD-600 and TLD-700 pair in a quasi-albedo arrangement (i.e., without a cadmium or other neutron-absorbing shield anterior to the TLD elements)
1995–present	TED	Plastic hemispherical case encompassing a polystyrene pyramidal detector holder. The holder supports three CR-39 detectors at 35° angles.
1998–present	Model 8823 TLD badge (used with the TED by those with potential high-energy neutron exposure) (measures thermal, intermediate, and fast neutrons, with no separation of fast neutrons)	Two elements form a classic albedo detector with a TLD-600/-700 pair in cadmium except for an opening toward the body. Two positions are an incident thermal neutron detector with a TLD-600/-700 pair in cadmium except for an opening away from the body.

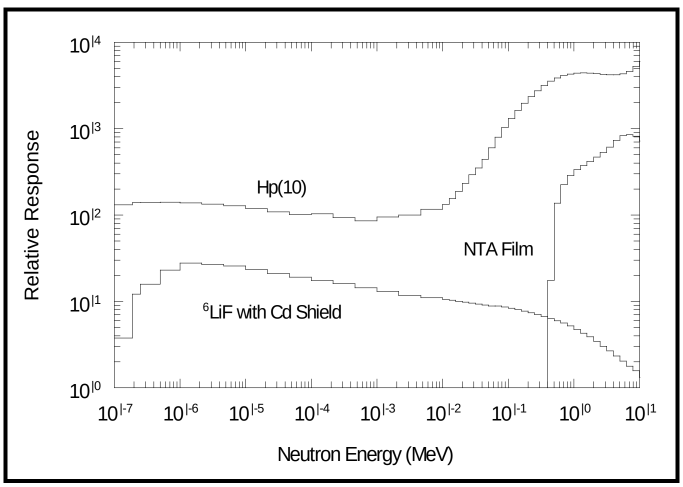


Figure 6-2. Comparison of *Hp(10)* for neutrons with energy responses of NTA film and neutron albedo dosimeter containing a thermoluminescent neutron dosimeter chip of ^{6}LiF and shielded by cadmium (IAEA 1990).

6.2.3 Calibration

Potential error in recorded dose is dependent on the characteristics of the dosimetry technology response 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 that in the workplace. The potential error is much greater for dosimeters with significant variations in response, such as film dosimeters with low-energy photons and NTA or Model 7776 TLDs with neutrons.

6.2.3.1 Beta/Photon Dosimeters

Brass Film Badge: Film badges used at LANL were initially calibrated with a radium source [LASL 1959 (8/4/47 memorandum)].

Brass-Cadmium Film Badge: In accordance with a 1956 procedure [LASL 1959 (2/16/1956 document)], calibrations were done with radium for gamma radiation and a sheet of depleted uranium for beta radiation. The optical density of the filtered area was subtracted from the optical density of the unfiltered area, a radium calibration curve was applied, and a factor of 5/3 was used to estimate beta exposure in rep [LASL 1959 (2/16/1956 document)]. For nonpenetrating dose in plutonium facilities, a 78-kVp X-ray calibration was used instead of the depleted uranium slab.

The standard method of film calibration as of April 1955 used a 195-mg radium source that was calibrated by the NBS. Overall error in the radium exposures delivered reportedly did not exceed 2%, including uncertainties in source strength, distance, and exposure time (Kalil 1955).

By 1960, film badges were calibrated to gamma radiation with a ^{60}Co source (Littlejohn 1961). The dose rate from the calibration source was measured with a Victoreen r-chamber calibrated by NBS. Calibrations were performed on a circular Masonite table in a relatively scatter-free room. Badges were calibrated with the front area of the badges toward the source, and workers were instructed to wear the badges in the same orientation.

Periodic calibrations were made to nickel-coated and uncoated plutonium. The uncoated plutonium was encased in 0.02-in. polyvinylchloride (PVC). Surface dose rates for both sources were determined by extrapolation chamber measurements. Films were calibrated in direct contact with the source and with various filtering materials between the source and the film to simulate dry-box conditions. Because the plutonium calibration curves were parallel to the ^{60}Co curve, open-window densities from plutonium exposures were evaluated from the ^{60}Co curve and then corrected by applying factors of 0.11 for coated plutonium and 0.065 for uncoated plutonium (Littlejohn 1961).

As of 1960, a 4-in.-square plate of depleted uranium was used to calibrate the film to beta radiation (Littlejohn 1961). The surface dose rate of the depleted uranium plate was measured with an extrapolation chamber. Films were normally placed in direct contact with the source or, when required, various filtering materials such as the PVC used in the wrist badge were inserted between the source and film.

An August 24, 1962, memorandum (LASL 1969) refers to the use of ^{60}Co calibration curves for evaluation of beta, gamma, and thermal neutron exposures. The ^{60}Co calibration curve was used to evaluate beta exposures with a relative sensitivity factor of 1/3 based on calibration with depleted uranium of a known surface dose rate. In addition, plutonium source calibrations were done to measure the response to the unfiltered area of the film. The use of nickel-coated plutonium as a calibration source was discontinued in January 1963 [LASL 1969 (3/20/63 memorandum)].

The brass-cadmium badges worn in plutonium areas at DP West were calibrated by placing the badge in contact with a 100-g piece of uncoated plutonium metal encased in PVC [LASL 1969 (3/5/63 memorandum)]. The surface dose rate from the encased metal was measured with an extrapolation ionization chamber. Exposures were evaluated by reading the net optical density from the unfiltered area of the film, reading the exposure from a ^{60}Co calibration curve, applying a correction factor of 0.08 to correct for unfiltered film sensitivity to the mixture, and dividing the result in roentgen by 2 to get rem, based on the assumption that only 50% of the X-ray dose penetrated to the depth of the gonads or 1 cm of tissue [LASL 1969 (3/5/63 memorandum)]. Beginning in January 1963, the factor of 2 for plutonium and soft X-ray evaluations was abandoned based on a 1962 study that indicated that results from the brass-cadmium badge underestimated expected (calculated) doses in DP West plutonium areas by a factor of 2 for fields unfiltered by glass or steel and by 3 for fields that were filtered by these materials [LASL 1969 (3/5/63 memorandum)].

Cycolac Film Badge: The Cycolac badge was calibrated to the 100-g piece of uncoated plutonium metal encased in PVC and to a fluorescent X-ray source that emitted 71% 20-keV, 22% 60-keV, 5% 100-keV, and 2% greater-than-200-keV X-rays, which simulated the radiations from plutonium at DP West [LASL 1969 (3/5/63 memorandum)].

For mixtures of higher and lower energy photons, the net optical density under a multielement filter was used with a ^{60}Co calibration curve to estimate penetrating photon dose. The nonpenetrating dose was calculated from the measured net optical density under the unfiltered window based on the ^{60}Co response, the penetrating dose was subtracted, and the remainder was multiplied by 0.07. This factor includes a correction for unfiltered film sensitivity (0.2) and conversion from roentgen to rem (0.35). The factor of 0.35 [which corresponded to the 1 rem = 0.5 R factor used with the brass-cadmium badge before January 1963 but was based on “better data” published by Watson (1959)] accounted for the fraction penetrating to the gonads based on Hanford Site research per a November 27, 1963, memorandum (LASL 1969). The DOELAP DCF for 17-keV photons is 0.38 rem/R (DOE 1986).

Around July 9, 1971, LANL started issuing film badges to selected individuals at DP Site that included an insert containing TLD ribbons [LASL 1977 (7/9/71 memorandum)]. The TLDs were calibrated on the P-6 gamma range [4] and with a plutonium fluoride neutron source. The purpose of these badges with TLD-600 and TLD-700 ribbons was to evaluate individual exposures between film development and evaluation.

Cycolac Film Badges and TLDs: As of 1977, LANL photon dosimeters were calibrated with three types of sources: (1) K fluorescent X-rays from 10 to 100 keV, (2) heavily filtered X-ray beams from 100 to 250 keV, and (3) gamma rays from isotopes above 250 to 1,000 keV (Storm, Cortez, and Littlejohn 1977). The K fluorescent X-rays were produced using a 300-kV constant potential X-ray unit to produce 10- to 100-keV X-rays emitted from the primary tungsten target that caused K-shell X-rays to be emitted from secondary targets that varied in atomic number from 29 to 92. The heavily filtered X-ray beams were obtained with the primary X-ray beam by varying the potential applied to the tube and using large amounts of tin filtration to obtain relatively narrow-spectrum X-rays. The gamma rays were primarily the 412-keV, 662-keV, and 1,170- and 1,330-keV photons from ^{198}Au, ^{137}Cs, and ^{60}Co, respectively.

For beta dose, personnel dosimeters were calibrated by exposure either in air to a high-dose-rate ^{90}Sr(^{90}Y) source or in contact with a low-dose-rate uranium source. Both emit beta rays with maximum energies of about 2.3 MeV. A comparison of dosimeter response with the two sources was conducted. In both cases, TLDs were given a total exposure of 100 mrad based on the dose rate from the strontium-yttrium source as measured by the ion chamber and the dose rate from the uranium measured by the extrapolation chamber. The TLDs were calibrated to gamma rays from a

^{60}Co source. TLDs mounted in Cycolac plastic yielded readings of 64 mrad when exposed in air to strontium-yttrium and 51 mrad in contact with uranium.

By 1977, calibrations were performed with dosimeters in air, on a phantom, and in a phantom (Storm, Cortez, and Littlejohn 1977). A free-air ionization chamber was the primary standard used in the measurement of photon radiation. Thimble-sized ionization chambers calibrated to the free-air chamber served as secondary standards. Electron radiation was measured with an end-window ionization chamber with a 7 mg/cm^2 Kodapak wall. The dosimeters were calibrated to determine penetrating doses by placement of the secondary chamber 1 cm deep in a phantom and the personnel dosimeter on the surface, with a filter over the TLD to simulate 1-cm depth (Storm, Cortez, and Littlejohn 1977). Nonpenetrating dose calibrations were measured by placement of the chamber and a “lightly filtered” dosimeter on the surface of the phantom.

Around 1977, the energy response of dosimeters to electrons was measured with beta-emitting isotopes that varied in maximum energy from 770 to 2,300 keV – ^{204}Tl, ^{32}P, and ^{90}Sr(^{90}Y) (Storm, Cortez, and Littlejohn 1977). The responses of the various dosimeters are listed in Table 6-8.

Table 6-8. TLD and film badge energy response to beta radiation, about 1977.

Dosimeter type	Maximum beta energy		
	0.77 MeV	**1.16 MeV**	**2.27 MeV**
Unfiltered TLD	0.43	0.53	0.64
TLD badge in 60 mg/cm^2 Cycolac plastic	0.07	0.14	0.42
Film badge (unfiltered)	0.06	0.18	0.59

In December 1984, LANL applied to participate in the DOELAP pilot program. LANL did not seek accreditation for category VB (beta, uranium) or for the low-energy component of category VA (beta). While local testing indicated that routine procedures would adequately evaluate beta doses from contact with a sheet of uranium, LANL believed that the calibration method was not consistent with the geometry under which most beta doses were received. “At Los Alamos we are aware of no persons working with and receiving beta exposures from ^{204}Tl” [LANL 1986 (12/14/84 memorandum)].

The LANL Model 7776 TLD badges in the pilot DOELAP test exhibited a positive bias, reportedly due to the results of backscatter from the Lucite calibration phantoms used in the DOELAP irradiations [LANL 1989 (2/14/86 memorandum)]. The phantom used by DOELAP personnel was reportedly much thicker than the one Storm used in developing the TLD calibration procedure, and the X-ray spectra used by DOELAP and Storm reportedly differed, even though both spectra had the same average energies (Widner 2003). The interplay of these two factors probably accounts for the "positive bias" in the LANL TLD badge response. LANL and all other participants in the pilot DOELAP test used the test results to modify their dose evaluation procedures to become compliant with DOELAP testing procedures (Widner 2003). Backscatter increases the badge response by about 10% for ^{137}Cs gammas and more than 10% in the photon energy range from 40 to 150 keV. Thus, for TLD badges calibrated in free air, the exposure evaluation for badges exposed on a Lucite phantom (i.e., according to DOELAP procedures) is high by at least 10%. Because LANL lacked the time and personnel resources to reevaluate the response of the LANL TLD badge over the full range of photon and beta energies and the total fading response, the interim correction in 1986 was to remove the 10% fading correction for photons and beta dose evaluations because the two effects compensate [LANL 1989 (2/14/86 memorandum)]. The 10% fading correction was retained for neutron exposure evaluation because the neutron calibration factors were established using a Lucite phantom. These changes were reportedly made operational for the January 1986 TLD badges.

Model 8823 TLD Badge: The general algorithm adopted for the Model 8823 was designed to determine the responses for each of the eight elements in the Model 8823 dosimeter through the use of a full set of DOELAP irradiation categories. At least 10 dosimeters were irradiated to each of the DOELAP techniques listed in Table 6-9 at Battelle, Pacific Northwest National Laboratory (PNNL) in late 1996. These irradiations included photons with effective energies ranging from 17 to 662 keV, betas with maximum energies of 760 and 2.27 MeV, and bare and moderated fission neutron sources.

Table 6-9. DOELAP irradiation techniques and effective energies.

Photons	Energy
K17	17 keV
M30	20 keV
S60	36 keV
K59	59 keV
Am-241	59 keV
M150	70 keV
H150	120 keV
Cs-137	662 keV
Betas	
Tl-204	760 keV
Sr/Y-90	2.27 MeV

The Model 8823 dosimeter is DOELAP-accredited in all applicable categories. The general beta category (VA), which includes both ^{90}Sr/^{90}Y and ^{204}Tl, is selected over the special contact geometry uranium category (VB) and special beta category (VC), which use only ^{90}Sr/^{90}Y or ^{204}Tl.

6.2.3.2 Neutron Dosimeters

Historical aspects of the calibration of LANL film, NTA, and TLD dosimeters are described in the *Photodosimetry Evaluation Book* (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003), technical basis documents, and LANL technical reports.

Film Badges: Thermal-neutron calibration data were obtained from film badges exposed in the south thermal column of the LANL homogeneous reactor (Kalil 1955; Littlejohn 1961). Thermal neutron fluxes for a given reactor level were known to within ±10%, and relative values were known even better (Kalil 1955). Gold foils were used to measure the thermal neutron flux, and a nomogram was employed in the evaluation of film exposed to thermal neutrons (Littlejohn 1961). The nomogram indicated thermal neutron exposure (rem) as a function of normalized cadmium minus brass film optical density. It also indicated gamma exposure and “open-window equivalent gamma exposure contributed by thermal neutrons and gamma rays,” a parameter that was used in the evaluation of beta exposures (the difference between this parameter and the open-window radium-equivalent gamma exposure was taken as an estimate of the beta exposure in rad) (Littlejohn 1961).

Nuclear Track Emulsion: The Kodak Type B film used for measuring fast neutron exposures as of August 1960 (Littlejohn 1961) was developed by J. S. Cheka of ORNL (Cheka 1954). LANL calibrated this film to neutron energies of 0.5, 0.6, 0.7, 0.8, 1, 1.5, 2.5, 4, 5, 8, 14, 17, and 20 MeV (Littlejohn 1961). The 2.5- and 14-MeV neutrons were obtained from a Cockcroft-Walton accelerator, and the others were from two Van de Graaff accelerators that the Laboratory had at the time. Data from these calibrations indicated that between the energies of 1 and 20 MeV, the film was energy-dependent within +100% or –50% of the stated exposure, and each proton recoil track that appeared in a 1 mm^2 portion of the cadmium-filtered area was assigned an average value of 0.008 rem (Littlejohn 1961). Fundamentally, the NTA dosimeter is capable of an accurate dose estimate only for neutron radiation greater than about 1 MeV because it has a lower energy threshold of about 700 keV.

As of October 16, 1987**,** NTA badges were calibrated with a ^{238}PuBe neutron dose of 500 mrem. A procedure was written for the processing of Kodak NTA film. Because TLDs are relatively insensitive to neutrons above about 3 MeV, the capability to process NTA films was retained. TLD badges with NTA film in piggyback holders were issued to Group HSE-11 at LAMPF. The combination badges were used with other detectors during neutron spectrum measurements in the ER-1 at LAMPF on July 22, 1987.

A 1990 report stated that NTA film was frequently calibrated at LANL using a ^{238}PuBe source or a bare ^{252}Cf source with an average neutron energy of 4.5 MeV or 2.3 MeV, respectively (Mallett et al. 1990). The film was irradiated in the Cycolac plastic holders through the use of an NBS slab phantom backing (40 by 40 by 15 cm methylmethacrylate slab). Based on neutron energy spectrum measurements performed at LAMPF in 1987 and the sensitive energy range of NTA film, it was concluded that the NTA dosimeter primarily measured exposure to neutrons in this facility from approximately 10 to 60 MeV; a response factor of 4 mrem/track/mm^2 was conservatively chosen (Mallett et al. 1990).

Earliest TLD Neutron Measurements: Around July 9, 1971, when LANL started issuing film badges at DP Site that contained TLD inserts, the TLDs were calibrated on the P-6 gamma range and with a PuF_4 neutron source [LASL 1977 (7/9/1971 memorandum)].

Model 7776 TLD Badge: A method for calibrating the albedo-neutron dosimeter was developed that did not require a detailed knowledge of the neutron energy spectrum (Hankins 1973). A BF_3 proportional counter, centered in separate measurements in 3-in. and 9-in. polyethylene spheres containing thin shells of cadmium, was used to measure neutrons from a variety of sources. The ratio of the 9- to 3-in. sphere counting rates was plotted against sensitivity (the ratio of the TLD-600 response less the TLD-700 response in units of ^{60}Co milliroentgen to the neutron millirem as measured on the 9-in. sphere). This yielded a linear relationship on a log-log plot. Under this method, the ratio of 9- to 3-in. sphere count rates was measured in each potential neutron exposure area. A neutron calibration factor (the inverse of the sensitivity factor) was obtained from a plot of the 9- to 3-in. count ratio to sensitivity generated for the albedo-neutron badge. The use of the 9- to 3-in. ratio technique allowed determination of an “average” neutron energy for a neutron source and an appropriate neutron calibration factor. In addition to using 9- to 3-in. sphere ratios for determination of NCFs, LANL compared responses of TLDs mounted on a phantom to responses from an adjacent 9-in., neutron rem detector-moderated, BF_3 tube-based, neutron survey instrument.

Model 8823 TLD Badge: The general algorithm technique adopted for the Model 8823 was designed to determine the responses for each of the eight elements in the Model 8823 dosimeter through the use of a full set of DOELAP irradiation categories. A minimum of 10 dosimeters was irradiated to each DOELAP category at PNNL in late 1996. These irradiations included bare and D_2O-moderated ^{252}Cf fission neutron sources 1997 (Hoffman and Mallett 1999a,b).

Model 8823 and Track-Etch Dosimeter: A March 9, 2000, report (LANL 2001) described the results of irradiation of LANL TLD and TED badges to monoenergetic, accelerator-produced neutrons from 0.144 to 19 MeV at *Physikalisch-Technische Bundesanstalt* (PTB), the national institute of natural and engineering sciences and technical authority for metrology and physical safety engineering of the Federal Republic of Germany. Neither the TLD nor the TED individually performed satisfactorily over the entire range of monoenergetic neutron energies. The TLD significantly under-responded to neutrons of 1.2 MeV and above; the monoenergetic PTB neutron fields were substantially different from bare and moderated fission sources for which the dosimeter algorithm was calibrated. The LANL TED (sometimes called the PN3) significantly under-responded below 1.2 MeV. By summing the results of the two dosimeter types, which was the practice at the time, these limitations are minimized. The combination results were within 40% of the delivered dose at 565 keV and above.

As of early 1998, LANL TEDs were calibrated with a bare fission source [LANL 2001 (3/30/98 memorandum)], apparently a ^{242}Cf fission source with no scattering material between the source and the dosimeter (Widner 2004).

Figure 6-3 shows a plot of the geometric mean of the neutron-to-photon ratio for each year from 1979 to 2008 based on LANL records that contain both deep dose and neutron dose of 50 mrem or greater. This is the period after the use of NTA film was phased out at LANL. Along the top of the graph, the dosimeters in use over time are identified.

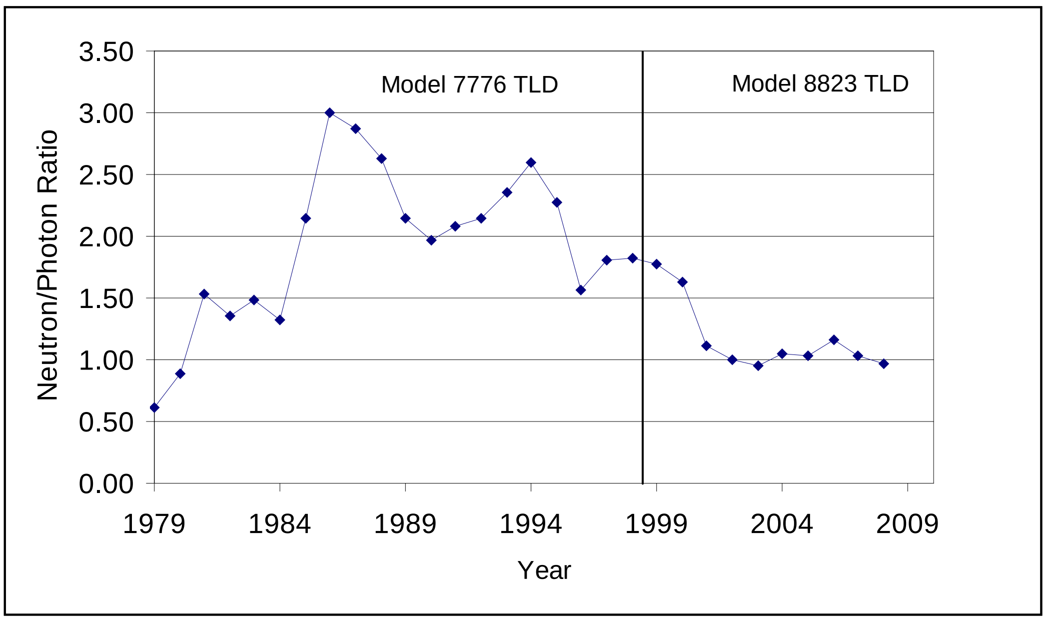


Figure 6-3. Geometric mean of neutron-to-photon ratios for records with both deep dose and neutron dose of 50 mrem or greater, 1979 to 2004 (LANL 2004, updated January 2009).

6.2.3.3 Workplace Radiation Fields

LANL operations have been characterized by significant complex beta, photon, and neutron radiation fields in reactor operations; criticality experimentation; handling of radioactive materials including plutonium, uranium, tritium, polonium, and barium/lanthanum; irradiated fuel processing; accelerator operations; X-ray facilities; and radioactive waste facilities.

6.2.3.4 Workplace Beta/Photon Dosimeter Response

The energy response of Eastman Kodak Type K film for an exposure of 0.1 R is shown in Figure 6-4.

In a March 5, 1963, memorandum, the primary radiation fields "in general" at DP West were described as listed in Table 6-10 (LASL 1969). More detailed photon energy breakdowns from the same report are listed in Table 6-11.

Based on film badge data from uranium processing areas from early 1953, a factor of 0.1 was selected to determine gamma exposure from measurements of gamma-plus-beta exposure in

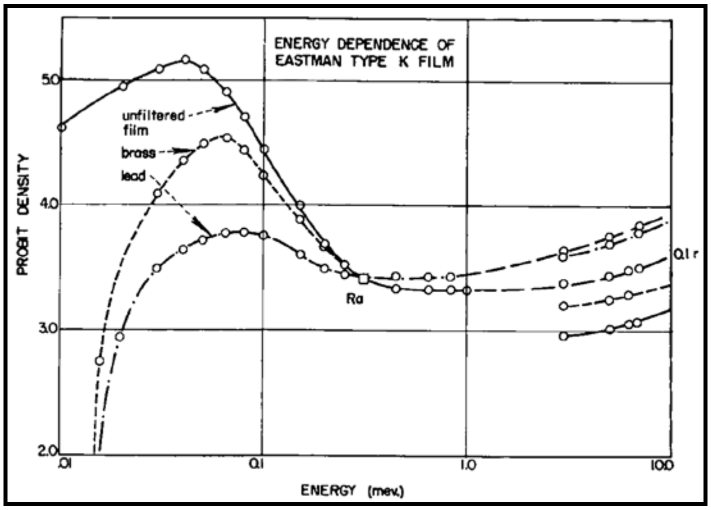


Figure 6-4. Energy dependence of Eastman Kodak Type K film for exposure of 0.1 R (Storm 1951).

Table 6-10. General energy distribution of photons in 1962 at DP West Site.

Percentage of dose	Photon energy
65 to 70	L X-rays (~17 keV and 26 keV)
10 to 20	60 keV
1 to 10	100 keV
0 to 7	Greater than 200 keV

Table 6-11. Estimated photon spectra for several plutonium sources in DP West Site.

Energy (keV)	Pu in glovebox	Pu with 20% Pu-240 in glovebox	Pu with 20% Pu-240, through glass	Pu with 20% Pu-240, through steel	Pu/Am electrorefining residues in milk carton and plastic
20	72	68	8.9	0	75
60	22	13	35	9.3	24
100	4.6	13	38	52	1.1
>200	2.1	6.4	19	38	0

preparing exposure records for computer entry [LASL 1959 (4/3/57 memorandum)]. The theoretical value for normal uranium was said to be about 1/17 gamma to beta-plus-gamma. The factor of 0.1 indicated that beta doses were about 9 times gamma doses in those uranium processing areas.

That 1963 memorandum described a study in which the brass-cadmium badge and the Cycolac badge were simultaneously exposed to three different plutonium sources at DP West that had known or calculable spectra (LASL 1969). With knowledge of the spectra and film sensitivities, expected results from each badge were calculated. The brass-cadmium badge underestimated the dose at DP

West by a factor of 2 when the radiation field was not filtered by glass or steel and a factor of 3 in the filtered cases. The Cycolac badge measured the dose within ±10% when the source was unfiltered. When the source was filtered by glass or steel, the hard component was measured correctly by the Cycolac badge but the soft component was overestimated, which caused the total dose to be in error (high) by as much as 60%.

Errors that were expected with the use of the Cycolac badge with low-energy photons (<45 keV) when a correction factor of 0.07 was used were as listed in Table 6-12, based on the 1962 study at DP West [LASL 1969 (3/5/63 memorandum)]. Guidance in that memorandum was that "when significant exposures to soft radiation (<45 keV) are measured or anticipated, a special evaluation will be made."

Table 6-12. Calculated errors from use of the Cycolac badge with low-energy photons and a correction factor of 0.07.

Energy (keV)	Dose (R) from lower energy photons	Reported dose (rem)	True dose (calculated)	Percent difference
10	0.3	0.02	0.01	50% high
20	2	0.14	0.50	360% low
30	10	0.7	0.75	7% low

A 1972 study at DP Site compared results from film badges and TLDs over a 6-month period [LANL 1996 (2/15/96 memorandum); Hankins 2007]. The study used data from 38 plutonium workers in these areas: ^{239}Pu recovery, ^{239}Pu areas only, ^{238}Pu areas, and the PuF_4 area. While the lowest dose was 294 mrem, most were around 1,000 mrem. Relevant results of the study, averaged over 6 months, are listed in Table 6-13. The film badge readings were about a factor of 3 higher than the TLDs. In his 1996 memorandum discussing the 1973 study [LANL 1996 (2/15/96 memorandum)], Hankins said that the method used to calibrate for plutonium did not consider the effect of the glovebox or buildup of ^{241}Am in the gloveboxes.

Table 6-13. Results of a 6-month comparison of film badges, NTA film, and TLDs at DP Site.

Area of DP site	Ratio of film dose to TLD gamma dose
Pu-239 recovery area	3.4 (range 2.4 to 4.2)
Pu-239 areas	1.9 (range 0.45 to 2.7)
PuF_4 areas	3.0 (range 2.7 to 3.4)
Pu-238 areas	1.5 (range 10 to 2.2)

In a study documented in 1975, D. E. Hankins showed that LiF TLDs exposed on a phantom (or a person) had an over response to gamma ray energies around the 60 keV characteristic of Am-241 (Hankins, 1975) as shown in Figure 6-5.

6.2.3.5 Uncertainty in Beta/Photon Recorded Dose

Table 6-14 lists LANL beta and photon energies and percentages.

Table 6-14. Selection of beta and photon radiation energies and percentages

Process/ Buildings	Description	Operations		Radiation type	Energy selection (keV)	Percentage
		Begin	End			
Reactors and reactor fuels	**During operation:** Dispersed fields of higher energy photons from fission, activation, and fission products. Narrow beams of higher energy neutrons from test ports, etc., into reactor core. Potential for significant airborne nuclides and significant higher energy beta radiation.			Beta[a] Photon	>15 30–250 >250	100 25 75
	Not in operation: Dispersed fields of higher energy photon radiation fields from activation and fission products. Insignificant neutrons. Possible higher energy beta radiation during maintenance work due to fission products.					
	LOPO Water Boiler (TA-2)	May 1944	Nov 1944			
	HYPO Water Boiler (TA-2)	Dec 1944	Feb 1951			
	SUPO Water Boiler (TA-2)	Mar 1951	Jun 1974			
	Plutonium Fast Reactor (Clementine, TA-2)	Dec 1946	Dec 1950			
	Omega West Reactor (TA-2)	Jul 1956	Dec 1992			
	LAPRE I (TA-35)	Feb 1956	Oct 1956			
	LAPRE II (TA-35)	Feb 1959	May 59			
	LAMPRE I (TA-35)	Early 1961	Mid-1963			
	UHTREX (TA-52)	Dec 1956	Feb 1970			
	Irradiated fuel work (including TA-21, TA-35, TA-48 in the 1960s and CMR Wing 9 in the 1960s through about 1986).					
Uranium production	**Processing and machining:** Depleted and enriched uranium.			Beta[a] Photon	>15 30–250	100 100
	TA-1 (Sigma, HT Buildings)	1943	1953			
	TA-3 (Sigma Complex, CMR Building)	1953	Present			
Plutonium processing	**Radiochemical operations:** Plutonium processed at LANL had largely been separated from fission products. Radiochemical operations were largely for recovery of fissionable material.			Beta[a] Photon	>15 <30 30–250	100 65[b] 35[b]
	TA-1, D Building	1943	1945			
	TA-21, DP West Site	Nov 1945	1978			
	TA-55, Plutonium Facility	1978	Present			
	TA-3 (including CMR Building)	1953	Present			
Plutonium production	**Plutonium component production:** Pu is machined into components using glovebox assembly process with mostly close anterior exposures. Radiation fields involve significant lower energy photons and neutron radiation.			Photon	<30 30–250	65[b] 35[b]
	TA-1 (D Building), TA-21 (DP Site), TA-55 (PF Site)					
	Plutonium storage: Radiation characteristics in this area generally involve dispersed lower energy neutron radiation and scattered photons, including 60-keV Am-241 gamma ray.					
	TA-1, D-5 Sigma Vault	1943	1945			
	TA-21, Building 21	Nov 1945	1978			
	TA-55 Vault	1978	Present			
Accelerator operations	**LAMPF** operations at TA-53: Primarily from residual activity induced in targets, accelerator structures and components, grease, oils, and soil.	1972	Present	Beta[a] Photon	>15 <30 30–50 >250	100[c] 1[c] 9 90
Calibrations	LANL site calibration of instruments and dosimeters	1943	Present	Beta[a] Photon	>15 30–250 >250	100 25 75
Waste handling	Radiation characteristics highly dependent on source of waste.			Beta[a] Photon	>15 30–250 >250	100 50 50
	Liquid waste: TA-45 and TA-50; Solid waste: Areas A, B, C, D, E, G, T, U, V	Various, 1944 on				
Radioactive lanthanum operations	**Preparation and use of radioactive lanthanum sources:**			Beta Photon	>15 30–250 >250	100 10 90
	TA-10 (Bayo Canyon)	1944	1950			
	TA-35, "Ten Site"	1951	1963			

Information sources: LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003.

a. Nonpenetrating dose was not measured by early LANL film badges that had no unfiltered areas. See Attachment A, Section A.5 for guidance on how to correct for that shortcoming by estimating nonpenetrating dose and attributing it to the beta radiation category.

b. Low-energy photons were not measured by early LANL film badges that had no unfiltered areas. See Attachment A, Section A.5 for guidance on how to correct for that shortcoming by estimating nonpenetrating dose and attributing it to the low-energy photon (<30 keV) category.

c. See Attachment A, Section A.5 for guidance on attribution of nonpenetrating doses at LAMPF/LANSCE to beta radiation and low energy photons.

6.2.3.6 Workplace Neutron Dosimeter Response

The AEC held a series of Personnel Neutron Dosimetry Workshops to address problems experienced by its sites concerning accurate measurement of neutron dose. The first workshop was held September 23 and 24, 1969 (Vallario, Hankins, and Unruh 1969) with the stated concern: "... for intermediate energy (i.e., > 0.4 eV to < 700 keV) ... neutron sources, NTA personnel neutron dosimeters cannot be effectively used. This leaves a gap in the personnel dosimetry program which at many installations may be quite serious." The significance of the underestimated neutron dose became evident with studies being conducted to implement TLDs. At LANL, studies of that type were conducted in the early 1970s [LANL 1996 (2/25/96 memorandum)].

In 1994, the neutron component of the collective person-rem for LANL was 75% of the total [LANL 2001 (2/22/96 memorandum)].

The main work areas at LANL where there has been a potential for neutron exposure include:

- D Building (TA-1)
- DP West (TA-21)
- DP East (TA-21)
- Current Plutonium Facility (TA-55)
- Omega Site (TA-2)
- LAMPF (TA-53)
- Criticality Lab (TA-2, TA-18)
- CMR Building (TA-3)

In 1989, the majority of workers who received neutron exposures worked at LAMPF (TA-53) and the Plutonium Facility (TA-55) [LANL 1996 (4/18/90 memorandum)].

Based on measurements with the Model 8823 dosimeter reported in a January 23, 2003, memorandum (LANL 2003):

- The vast majority (greater than 90%) of LANL employees, including those at TA-55, received WB neutron doses from "well moderated fields, akin to ~2.5-4" (or greater) polymoderated ^{252}Cf (fission spectrum)," and

- Less than 2% of LANL's positive neutron exposures were "in fields similar to bare Cf-252."

Based on neutron spectrum measurements performed by LANL personnel (Harvey and Hajnal 1993) and information from the *Photodosimetry Evaluation Book* [LANL 1996 (1/17/95 memorandum)], Table 6-15 lists the approximate correspondence between NCFs used by LANL and the dose fraction for the four bins of neutron energy used by NIOSH (2007c). The breakdowns by energy category are estimated based on the "H(%)" columns from the Harvey and Hajnal (1993) report. A lower NCF value indicates that the distribution of neutron energies has shifted to lower values; that is, it has moderated. As neutrons moderate, the dosimeter responds more per neutron, but the DE per neutron is lower.

Table 6-15. Approximate NCFs and dose fractions for neutron sources.

Type of source	NCF	Dose fraction by energy category			
		<10 keV	10–100 keV	0.1–2 MeV	2–20 MeV
Bare Pu-239	~1.0				
Bare Pu-Be	~1.5	1	1	33	65
Bare Cf-252	~1.3	0	0	42	58
Cf-252 through 10.2-cm Lucite	~0.15	5	1	33	61

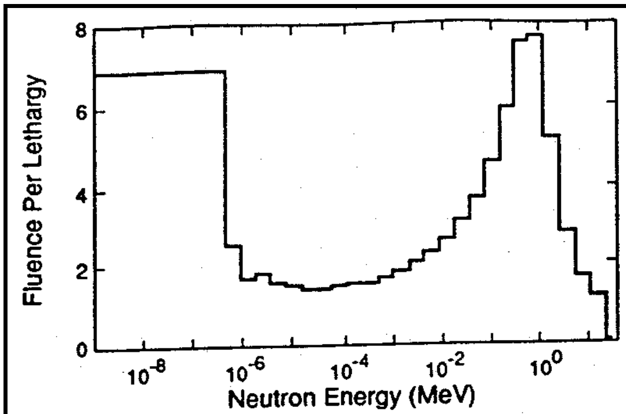
As described above, irradiation of LANL TLD and TED badges to monoenergetic, accelerator-produced neutrons from 0.144 to 19 MeV at PTB in Germany (LANL 2001) showed that the TLD significantly under-responded to neutrons of 1.2 MeV and above, the TED significantly under-responded below 1.2 MeV and, when results were combined (as was the practice at LANL), results were within 40% of the delivered dose at 565 keV and above.

6.2.3.6.1 Plutonium Processing Areas (TA-1, TA-21, TA-55)

6.2.3.6.1.1 Neutron Energy Spectrum

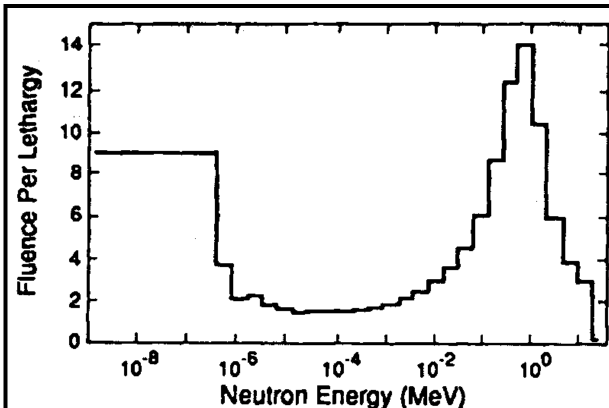
In a study released in 1978, 9-in. to 3-in. sphere ratio measurements at 13 locations at the TA-55 Plutonium Facility yielded ratios that indicated an average neutron energy of approximately 200 keV (Blackstock et al. 1978). The mean value of the ratio was 0.57, with a standard deviation of 35%. This result was thought to possibly explain why few neutron exposures had been observed using NTA film at this facility, because NTA film cannot detect neutrons with energies less than about 700 keV.

Multisphere neutron spectroscopy methods were applied to measure representative working fields in the LANL Plutonium Facility in 1993 (Harvey and Hajnal 1993). Work in this facility has involved ^{239}Pu and ^{238}Pu. Figure 6-5 shows the neutron spectrum measured during the hydrofluorination of $^{239}PuO_2$, Figure 6-6 shows the spectrum of the ball milling process with ^{238}Pu, and Figure 6-7 shows the spectrum of the Special Nuclear Material (SNM) storage vault.



Integral Values

Neutron Energy (MeV)	ϕ(%)	H(%)
7.04E-10 to 4.14E-07	53	6
4.14E-07 to 8.41E-03	16	2
8.41E-03 to 1.43E-01	9	5
1.43E-01 to 1.20E+00	14	47
1.20E+00 to 4.94E+00	6	28
4.94E+00 to 1.00E+01	1	6
1.00E+01 to 2.43E+01	1	6



Integral Values

Neutron Energy (MeV)	ϕ(%)	H(%)
7.04E-10 to 4.14E-07	51	4
4.14E-07 to 8.41E-03	13	2
8.41E-03 to 1.43E-01	8	3
1.43E-01 to 1.20E+00	17	44
1.20E+00 to 4.94E+00	8	31
4.94E+00 to 1.00E+01	2	8
1.00E+01 to 2.43E+01	1	8

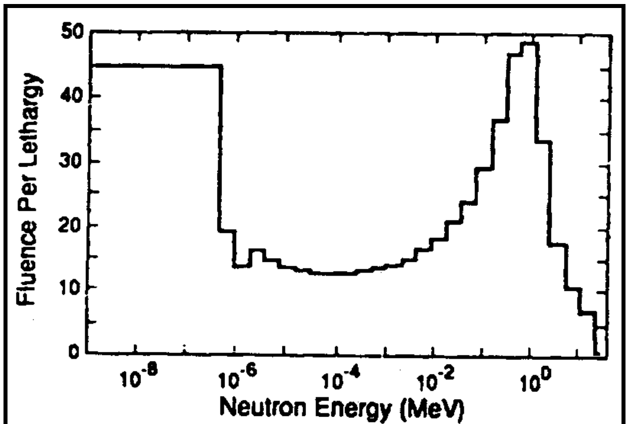
Figure 6-5. Neutron spectrum of hydrofluorination of $^{239}PuO_2$ at Plutonium Facility (Harvey and Hajnal 1993).

Figure 6-6. Neutron spectrum of ^{238}Pu ball milling process at Plutonium Facility (Harvey and Hajnal 1993).

6.2.3.6.1.2 Neutron-to-Photon Dose Ratio

The following data on neutron-to-photon ratios for LANL plutonium workers are available [LASL 1977 (11/9/72 memorandum)]:

- For ^{239}Pu workers not in fluoride areas, observed neutron-to-photon ratios ranged from 0.3 to 1.7 with an average of 0.7.



Integral Values

Neutron Energy (MeV)	ϕ(%)	H(%)
7.04E-10 to 4.14E-07	51	6
4.14E-07 to 8.41E-03	20	3
8.41E-03 to 1.43E-01	9	5
1.43E-01 to 1.20E+00	13	46
1.20E+00 to 4.94E+00	5	28
4.94E+00 to 1.00E+01	1	6
1.00E+01 to 2.43E+01	1	6

Figure 6-7. Neutron spectrum near door K in SNM Vault at Plutonium Facility (Harvey and Hajnal 1993).

- For ^{239}Pu-fluoride areas, a neutron-to-photon ratio of 2.8 was reported for a health physics technician, not a chemical operator.
- For ^{238}Pu workers, observed neutron-to-photon ratios ranged from 2.7 to 5.5 with an average of 3.9 (^{238}Pu exposures began in 1969).
- For health physics technicians in ^{238}Pu areas, observed neutron-to-photon ratios ranged from 1.9 to 4.6 with an average of 3.3.

The measured average quotient of neutron to gamma- and X-ray DE for the Plutonium Facility in 1993 was 2.5 (Harvey and Hajnal 1993).

The 1972 study at DP Site mentioned above [LANL 1996 (2/15/96 memorandum); Hankins 2007.] compared neutron dose results from NTA and TLDs and yielded neutron-to-photon ratios that varied from 1.33 to 2.30 for ^{239}Pu areas and averaged 3.98 for ^{238}Pu areas, as listed in Table 6-16.

Table 6-16. Results of 6-month comparison of film badges, NTA film, and TLDs at DP Site.

Area	Neutron component of total dose	Gamma-to-neutron ratio	Corresponding neutron-to-gamma ratio	Ratio of NTA dose to albedo TLD dose
Pu-239 recovery	39% to 80% (avg. 58%)	0.75	1.33	0.12
Pu-239 areas	50% to 84% (avg. 66%)	0.60	1.66	0.22
PuF_4 areas	60% to 78% (avg. 71%)	4.34	2.30	0.19
Pu-238 areas	69% to 90% (avg. 80%)	0.25	3.98	0.48

6.2.3.6.2 LAMPF (TA-53)

In 1987, neutron energy spectrum measurements were made at a potentially high neutron energy area at LAMPF (Mundis and Howe 1987). The resulting neutron spectrum is shown in Figure 6-8; associated data have been interpreted as follows in the Mundis and Howe memorandum and in a 1990 report on dosimetry at LAMPF (Mallett et al. 1990). When unfolding codes were applied to the measurement data, they revealed that more than 90% of the neutron DE was due to neutrons of energy greater than 1 MeV, and 70% was due to neutrons of energy greater than 10 MeV. The 1987 measurements showed that the LANL Model 7776 TLD badge under-responded by a factor of 5 to 7 for this particular neutron spectrum (Mallet et al. 1990) because the sensitivity of the albedo-type dosimeter falls off severely for neutrons with energies above a few MeV (Mundis and Howe 1987). NTA film also under-responded, but only by about 20%. The sum of the two dosimeters was reported to be in good agreement with the spectrum unfolding results.

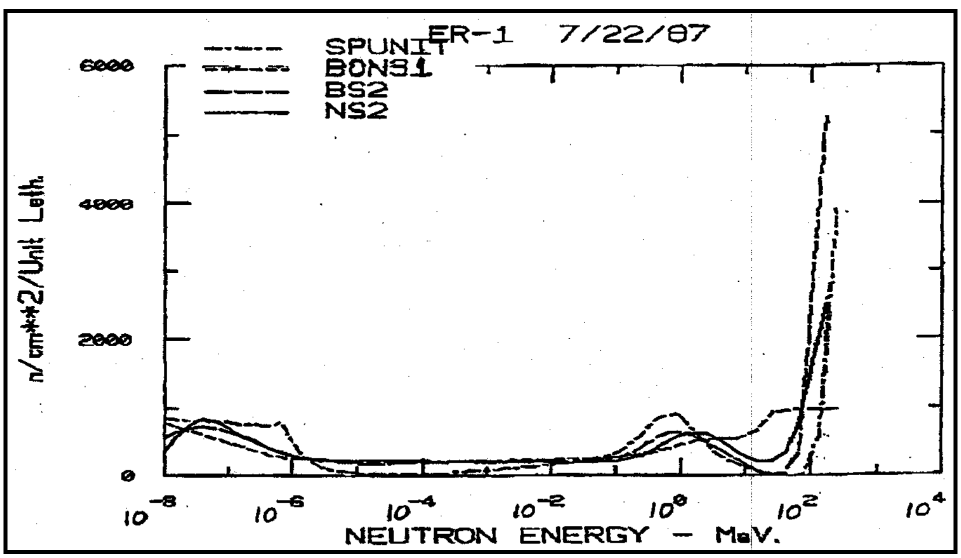


Figure 6-8. Neutron spectrum in ER-1 Area of LAMPF with proton beam stopped in the carbon beam block, as determined from unfolding codes (Mundis and Howe 1987).

In another study, however, 9-in. to 3-in. sphere ratio measurements at 18 locations at LAMPF (not just an area of potentially high neutron energy) yielded ratios that indicated an average neutron energy of <100 keV at LAMPF (Blackstock et al. 1978). The mean value of the ratio was 0.17, with a standard deviation of 30%. This result was thought to possibly explain why few neutron exposures had been observed with the use of NTA film at this facility, because NTA film cannot detect neutrons with energies less than about 700 keV.

6.2.3.6.3 Critical Assembly Testing (TA-18)

6.2.3.6.3.1 Neutron Energy Spectrum

Neutron spectral measurements were made in three areas at TA-18 in 1998 and 1999 to determine what NCFs should be used in conjunction with exposures from critical assembly testing [LANL 2001 (3/17/98 and 6/24/99 memoranda)]. As a result of this work, an NCF of 0.07 was recommended for areas surrounding TA-18. A plot of neutron spectra from several sources, including environmental monitoring TLD Station 6 in the parking lot for TA-18, is shown in Figure 6-9 [LANL 2001 (6/24/99 memorandum)].

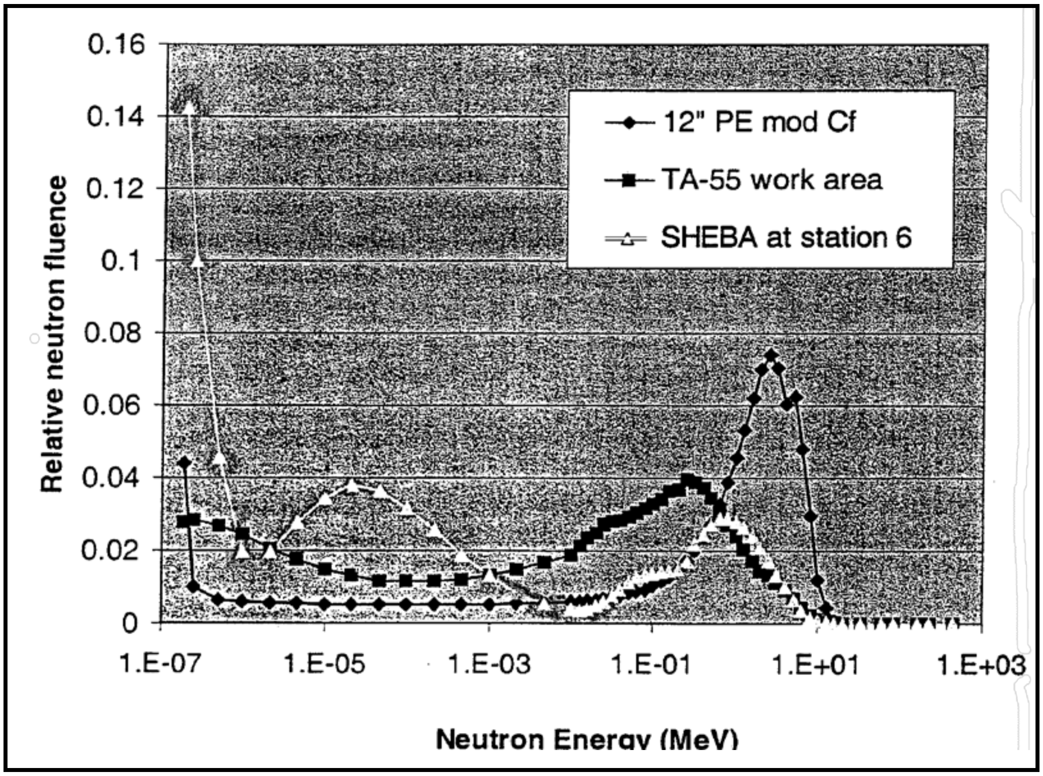


Figure 6-9. Neutron spectrum at Station 6 near TA-18 (white line).

A 1967 study of selected criticality dosimetry methods yielded neutron energy distributions for the key LANL critical assemblies (Hankins 1968). Table 6-17 lists the breakdown of total kerma by energy interval at a distance of 3 m (or 5.9 m for Hydro) from five critical assemblies when they were active. Spectral data taken at these distances will generally not be useful in the assessment of external doses to workers who were involved with criticality experimentation other than in the special cases of accidental exposures. Workers are normally at remote locations while the criticality experiments are in progress.

Table 6-17. Percent of total kerma by energy interval from critical assemblies during experiments (Hankins 1968).

Critical assembly	Distance from assembly (m)	Neutron energy			
		0.4–750 keV	0.75–1.5 MeV	1.5–2.9 MeV	>2.9 MeV
Jezebel (outside kiva)	3.0	14	23	21	42
Jezebel (inside kiva)	3.0	9	31	22	39
Hydro	5.9	27	36	3.4	34
Flattop	3.0	41	43	11	11

Parka	3.0	45	22	23	23
Godiva IV (burst mode)	3.0	18	37	24	24
Godiva IV (extended mode)	3.0	13	41	25	25

6.2.3.6.3.2 Gamma-to-Neutron Dose Ratio

The 1967 study of criticality dosimetry methods yielded estimates of gamma-to-neutron ratios for five critical assemblies at LANL based on measurements with TLDs and film badges placed in air, on the front of "plastic man" manikins filled with sodium solution, and on the back of plastic men (Hankins 1968). Table 6-18 lists the gamma-to-neutron and corresponding neutron-to-gamma ratios for the Hydro critical assembly based on measurements with TLDs on the front of plastic men at distances from 5.9 to 100 m. Hankins (1968) presents data for six distances from 5.9 to 19.8 m. A line was fit to these data for extrapolation of the ratios to greater distances.

Table 6-18. Gamma-to-neutron ratios measured with TLDs on the front of plastic man manikins at various distances from the Hydro critical assembly (Hankins 1968).

Distance from assembly (m)	Gamma-to-neutron ratio[a]	Corresponding neutron-to-gamma ratio[a]
5.9	1.5	0.67
6.0	1.0	1.0
8.7	1.2	0.83
12.3	1.1	0.91
16.2	1.1	0.91
19.8	0.84	1.2
25	0.83	1.2
35	0.71	1.4
50	0.58	1.7
70	0.46	2.2
90	0.39	2.6
100	0.36	2.8

a. Values beyond 20 meters are linearly extrapolated from data in Hankins (1968).

6.2.3.6.4 Reactor Areas (TA-2)

A March 4, 1982, document (in LANL 1986) describes a review of the NCFs in use for Omega West Reactor (CNC-5) personnel. Neutron measurements were made with a 9-in.-diameter polyethylene sphere, an RM-16 rate meter, and an Ortec scaler. TLD badges mounted on a 1.5-in. polyethylene slab were exposed beside the sphere. Measurements were made near the north face of the reactor, where significant personnel exposures were most likely to occur. Results indicated that a correction factor of 0.1 should be applied to the neutron dose rather than the 0.5 in current use. It is recommended that this change be made in the evaluation procedures. Data sheets attached to that March 4, 1982, document give penetrating radiation and neutron millirem values for five TLDs for each of the two runs.

Because neutron spectra have not been obtained for the LANL reactors, an assumption of 100% fission spectrum neutrons (0.1 to 1 MeV) is used.

6.2.3.6.5 CMR Building (TA-3)

Activities that involve plutonium at the CMR Building (also known as South Mesa Building 29, or SM-29) have included laboratory work on small quantities of uranium and plutonium (Widner et al.

2004). In addition, Wing 9 of that building contains hot cells that have handled irradiated uranium and sometimes plutonium.

Stack FE-19 of the CMR Building serves the glovebox processes and rooms on the south side of Wing 3. Since early 1974, FE-19 has been a major source of plutonium at LANL, up to 99% of the total released in 1980. Alpha-emitting radioactivity in liquids flowing into the TA-50 waste treatment plant rose sharply around 1973 because of increased use of ^{238}Pu in the CMR Building (Widner et al. 2004).

The neutron spectrum at the CMR Building is assumed to be similar to that of plutonium processing areas but with a slight increase in the fraction in the 2-to-20-MeV category due to the possibility that research activities involved sources that emitted more higher energy neutrons (such as PuBe or ^{252}Cf). The dose fraction in the 2-to-20-MeV category was raised from 33% to 40%, and dose fractions for the other categories evenly reduced accordingly.

6.2.3.7 Neutron Dose Fraction

The fraction of the total dose in each neutron energy group can be determined by dividing the neutron spectra into the four lower neutron energy groups discussed in NIOSH (2007c). The highest neutron energy group (>20 MeV) was not used because operations at LANL, other than in a particularly high-energy neutron area of LAMPF where worker exposures were probably uncommon, did not produce a significant component of neutrons of this energy. The dose for each neutron energy group was calculated by multiplying the neutron flux Ø (Roberson, Cummings, and Fix 1985; Brackenbush, Baumgartner, and Fix 1991) by the corresponding flux to DCFs in National Council on Radiation Protection and Measurements (NCRP) Report 38 (NCRP 1971). The neutron doses in each NCRP Report 38 energy interval are summed to develop the four neutron group doses. The dose fraction D_f for each neutron energy group n was calculated by dividing the neutron group dose by the total dose D_T:

$$D_f(E_n) = \frac{\sum_i \phi(E_i) DCF_i}{D_T} \tag{6-1}$$

where:

- $Ø(E_i)$ = neutron flux of the *i*-th energy bin
- DCF_i = NCRP Report 38 flux to dose-rate conversion factor for the *i*-th energy bin
- D_T = total dose

Table 6-19 lists the neutron dose fractions by energy group using data measured by Roberson, Cummings, and Fix (1985).

Table 6-19. Laboratory-measured dose fractions from PuF_4.

Neutron energy group	Shielding of PuF_4 source[a]		
	0 cm (bare)	**2.54 cm**	**5.08 cm**
<10 keV	0.00	0.00	0.01
10–100 keV	0.00	0.00	0.00
0.1–2 MeV	0.06	0.85	0.89
2–20 MeV	0.94	0.15	0.10
	Default dose fractions		
0.1–2 MeV	0.1	0.9	0.9
2–20 MeV	0.9	0.1	0.1

a. Thickness of acrylic shielding between source and detector.

6.2.3.8 Uncertainty in Neutron Dose

Measurement of neutron dose in the workplace is difficult (Brackenbush, Baumgartner, and Fix 1991). A significant under-response in recorded dose with NTA dosimeters became evident in the late 1960s at several sites that were preparing to implement the TLD neutron dosimeters.

6.3 ADJUSTMENTS TO RECORDED PHOTON DOSE

The following are instances for which corrections to recorded photon doses might be warranted:

- In a 1972 study with prototype albedo TLDs used alongside film badges in DP West plutonium areas, film badge readings were about a factor of 4 higher than TLD results for ^{239}Pu recovery areas and a factor of 2 higher in other DP West plutonium areas [LASL 1977 (1/23/74 memorandum)].

- In a 1963 study with the brass-cadmium film badge used alongside the Cycolac multi-element film badge, the brass-cadmium badge underestimated dose at DP West by a factor of 2 when the radiation was not filtered by glass or steel and a factor of 3 when photons were filtered [LASL 1969 (3/5/63 memorandum); average factor of 2.5].

- From September 1961 to October 1964, a software problem resulted in treatment of exposures to photons greater than 200 keV in energy from the brass-cadmium badge as soft gamma exposures, which caused doses higher than 100 mrem to be reported low by as much as a factor of 4 [LASL 1969 (10/13/64 memorandum)].

- The Cycolac film badge used from 1962 to 1978 over-responded to photons with energies below 100 keV, which resulted in overestimates of the dose by as much as a factor of 2 in the Plutonium Facility (Storm et al. 1981). This finding agreed with the results of Hankins' 6-month study from 1973 (Hankins 2007).

- From March 1963 to March 1973, penetrating photon doses (rem) from plutonium exposures were set equal to delivered exposures (roentgen) in error, which caused penetrating gamma doses to be reported high by about a factor of 2.9 [LASL 1977 (5/2/73 and 1/23/74 memoranda; the factor of 2.9 corrects for inappropriate reduction in the nonpenetrating component to 35% of actual in calibration)].

The information above has influenced recommendation of a series of nonoverlapping correction factors, given in Attachment A, Section A.3, for recommended application to photon doses reported by LANL. In several cases in which there is evidence that might support modification of reported doses, correction factors are not recommended because of the lack of incontrovertible evidence sufficient to justify adjustment of reported doses in manners that might not be favorable to claimants. The first, second, fourth, and fifth bullets above describe information that has not led to the recommendation of specific correction factors in Table A-3.

6.4 ADJUSTMENTS TO RECORDED NEUTRON DOSE

Adjustments to LANL recorded neutron doses are necessary to estimate doses because of the uncertainty associated with the recorded dose in the complex workplace radiation fields and the variability in exposure circumstances.

6.4.1 <u>Neutron Dose Adjustments</u>

LANL incorporated the energy variation of the DE in its calibration methodology. As a result, the recorded DE (DE_R) is a combination of all neutron energies. To calculate the probability of causation, the recorded neutron dose must be separated into neutron energy groups and later converted to International Commission on Radiological Protection (ICRP) Publication 60 methodology (ICRP 1991).

6.4.2 Neutron Weighting Factor

Adjustment to the neutron dose is necessary to account for the change in neutron quality factors between historical and current scientific guidance, as described in NIOSH (2007c). LANL neutron calibration factors determined from National Institute of Standards and Technology (NIST)-calibrated sources are used directly without modification for field conditions. 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 based on NCRP Report 38 (NCRP 1971), which lists flux-to-dose-rate conversion factors and associated quality factors that vary from 2 at energies less than 1 keV to 11 at 1 MeV. To convert from NCRP Report 38 quality factors to ICRP Publication 60 radiation weighting factors (ICRP 1991), a curve was fit that described the neutron quality factors as a function of neutron energy. The average quality factor for each neutron energy group was developed by integrating the area under the curve and dividing by the neutron energy range as shown in Equation 6-2:

$$\overline{Q}(E_{n,0.1-2.0MeV}) = \frac{\int_{0.1}^{2.0} Q_f(E)dE}{Range(2.0-0.1)} \qquad (6\text{-}2)$$

Table 6-20 summarizes changes in the quality factors and the average NCRP Report 38 quality factor for the neutron energy groups used in dose reconstruction (NCRP 1971).

6.4.3 Neutron Correction Factor

Table 6-21 lists the average quality factor for the four neutron energy groups that encompass LANL neutron exposures. The neutron DE correction factor can be calculated by dividing the dose fractions for each neutron energy group $D_f(E_n)$ by the corresponding energy-specific average NCRP Report 38 quality factor $Q(E_n)$ and then multiplying by the ICRP Publication 60 radiation weighting factor (w_R), as shown in Equation 6-3 (NCRP 1971; ICRP 1991).

$$C_f(E_n) = \frac{D_f(E_n)}{\overline{Q}(E_n)} \times w_R \qquad (6\text{-}3)$$

Table 6-21 summarizes default neutron dose fractions by energy for LANL work areas where field measurements of neutron spectra were performed through the use of the associated ICRP Publication 60 correction factors (ICRP 1991). For years after 1978, the neutron DE is calculated by multiplying the recorded neutron dose by the area-specific correction factors. For example, consider a 1,000-mrem recorded neutron dose to a worker at DP West; the corrected neutron dose is calculated as follows:

- 1,000 × 0.44 = 440 mrem from neutrons of 2 to 20 MeV estimated to represent 33% of the dose fraction
- 1,000 × 1.1 = 1,100 mrem from neutrons of 0.1 to 2 MeV estimated to represent 56% of the dose fraction

Table 6-20. Neutron quality or weighting factors

<table>
<tr><th>Neutron energy (MeV)</th><th>Historical dosimetry guideline[a]</th><th>NCRP 38 quality factors[b]</th><th>Average quality factor used at LANL</th><th>ICRP 60 neutron weighting factor (w_r)[c]</th></tr>
<tr><td>2.5E-8</td><td>3</td><td>2</td><td rowspan="6">2.35</td><td rowspan="6">5</td></tr>
<tr><td>1E-7</td><td rowspan="18">10</td><td>2</td></tr>
<tr><td>1E-6</td><td>2</td></tr>
<tr><td>1E-5</td><td>2</td></tr>
<tr><td>1E-4</td><td>2</td></tr>
<tr><td>1E-3</td><td>2</td></tr>
<tr><td>1E-2</td><td>2.5</td><td>5.38</td><td>10</td></tr>
<tr><td>1E-1</td><td>7.5</td><td rowspan="3">10.49</td><td rowspan="3">20</td></tr>
<tr><td>5E-1</td><td>11</td></tr>
<tr><td>1</td><td>11</td></tr>
<tr><td>2</td><td>10</td><td rowspan="6">7.56</td><td rowspan="6">10</td></tr>
<tr><td>2.5</td><td>9</td></tr>
<tr><td>5</td><td>8</td></tr>
<tr><td>7</td><td>7</td></tr>
<tr><td>10</td><td>6.5</td></tr>
<tr><td>14</td><td>7.5</td></tr>
<tr><td>20</td><td>8</td><td rowspan="3">Not applicable</td><td rowspan="3">5</td></tr>
<tr><td>40</td><td>7</td></tr>
<tr><td>60</td><td>5.5</td></tr>
</table>

a. Trilateral meeting in 1949 radiation protection guidelines (Fix, Wilson, and Baumgartner 1997).
b. Recommendations of NCRP Report 38 (NCRP 1971).
c. ICRP Publication 60 (ICRP 1991).

- 1,000 × 0.23 = 230 mrem from neutrons of <10 keV to 100 keV estimated to represent 11% of the dose fraction

Thus, the corrected neutron dose is a total of 1,770 mrem. These adjustments should be applied to measured dose, missed dose, and dose determined based on a neutron-to-photon ratio. For years before 1980 at LANL, multiply the annual photon dose (adjusted for any missed dose) by the neutron-to-photon dose factor from Section 6.4.4 and by the area-specific ICRP Publication 60 correction factor shown above to estimate neutron dose (ICRP 1991).

6.4.4 <u>Neutron-to-Gamma Dose Factors</u>

Essentially all LANL radiological work areas with significant neutron radiation also had significant photon radiation. For periods and workplace settings for which neutron dosimetry methods are thought to have been particularly unreliable or uncertain (for example, NTA film dosimetry for intermediate-energy neutron sources), it is sometimes possible and advisable to estimate neutron doses based on measured gamma doses through application of neutron-to-photon ratios. This is because of the documented under-estimating of doses by NTA dosimeters due to fading and significant effects of the NTA energy threshold in typical workplace neutron spectra. DOE personnel neutron dosimetry workshops stated strong concerns for the performance of the NTA dosimeters in typical plutonium facility neutron fields. A recent National Radiological Protection Board analysis of Monte Carlo N-Particle (MCNP) Transport Code calculations of NTA response in workplace neutron fields (NRPB 2001) reached the conclusion that there are few if any realistic parameters (such as calibration to a lower energy neutron spectra than the workplace spectra) that would result in an overestimate of the neutron dose using NTA dosimeters whereas there are numerous parameters that would result in a potential significant under-response.

Table 6-21. Facility dose fractions and associated ICRP Publication 60 correction factors (ICRP, 1991; LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003)

Process	Description/buildings	Operations		Neutron energy	Default dose fraction (%)	ICRP 60 correction factor
		Begin	End			
Plutonium production	Neutron dose was associated with overall LANL plutonium production process in which plutonium was purified, formed, machined, and recovered. Work was primarily conducted in gloveboxes with predominant close anterior exposure to workers.					
	Plutonium facilities (D Building at TA-1, DP West Site at TA-21, Plutonium Facility at TA-55)	1943	Present	<10–100 keV 0.1–2 MeV 2–20 MeV	11% 56% 33%	0.23 1.1 0.44
LAMPF	Neutrons of varying energies from high-energy proton linear accelerator studies.					
	LAMPF at TA-53	1972	Present	<10 keV 10–100 keV 0.1–-2 MeV 2–20 MeV	30% 30% 20% 20%	0.64 0.56 0.38 0.26
Reactor operations	Neutrons of varying energies from reactor operations.					
	Omega Site (TA-2) TA-35 TA-52	1944 1955 1969	1992 1963 1970	0.1–2 MeV	100%	1.9
Criticality experiments	Neutrons of varying energies from criticality testing and experimentation (in normally occupied areas, not including accidental exposures, which must be considered as special cases).					
	Omega Site (TA-2) TA-18	1943 Apr. 1946	Apr. 1946 Present	<10–100 keV 0.1–2 MeV 2–20 MeV	3.2% 59% 38%	0.060 1.1 0.50
Chemistry & metallurgy research	Neutrons of varying energies from actinide chemistry and metallurgy research.					
	TA-1 TA-3	1943 1952	1952 Present	<10–100 keV 0.1–2 MeV 2–20 MeV	10% 50% 40%	0.21 0.95 0.53

Section 6.2.3.6.1.2 contains reported neutron-to-photon ratios for LANL plutonium workers. Reported neutron-to-gamma ratios range from 0.3 to 5.5. Section 6.2.3.6.3.2 contains reported neutron-to-photon ratios for LANL critical assembly areas. Reported neutron-to-gamma ratios for the Hydro assembly range from 1.7 to 2.8 for working distances thought to be representative of normal testing procedures (50 to 100 m from the assembly). Based on these site-specific data, estimated median and 95th-percentile values of neutron-to-gamma ratio are recommended for plutonium facilities and criticality experiments in the first through third rows of data in Table 6-22. Values for other operations, based on analysis of annual deep and neutron doses reported by LANL for 1979 to 2004, are listed in the fourth row of data in Table 6-22. These values are based on post-NTA results in which the deep and neutron doses were 50 mrem or greater (LANL 2004).

Table 6-22. Recommended distributions for neutron-to-gamma ratio.

Neutron source type	Neutron-to-photon dose ratio	
	Median	95th percentile
Plutonium facilities (predominantly Pu-239)	0.7	2.8
Plutonium facilities (documented involvement with Pu-238 operations; applies only to 1969 or later; most likely at TA-21, TA-3-29 [CMR Building], or TA-55)	3.9	5.5
Criticality experiments (>50 m distant)	2.3	2.5
Other operations	1.6	6.4

6.5 MISSED DOSE

There are undoubtedly missed recorded doses for LANL workers. The analysis has been separated according to photon and neutron missed dose.

6.5.1 Photon Missed Dose

Missed photon dose for LANL workers would have occurred if doses received were below the limits of detection for the dosimeters provided and if they were based only on a recorded or assumed zero dosimeter result. Methods to be considered if there was a recorded or assumed zero dosimeter result for a period during a working career were examined by Watson et al. (1994). In general, estimates of missed dose can use dose results for coworkers or the recorded dose before and after the period of missed dose. However, these situations require careful examination. Missed dose for dosimeter results less than the MDL is particularly important for earlier years when MDLs were higher and dosimeter exchange was more frequent.

NIOSH (2007c) describes options to calculate missed dose. The typical method is to assign dose equal to the MDL divided by 2 for each dosimetry result that is either zero or some positive value less than the MDL/2.

Analysis of missed photon dose by period according to dosimeter type and exchange frequency is needed to evaluate claim information, particularly if only annual dose data are available. The normally cited MDLs for beta and photon dosimeters are based on laboratory irradiations. Actual MDLs are higher because of additional uncertainty in actual field use and the use of dose recording thresholds. Table 6-23 summarizes potential missed photon dose. Reasonable MDLs are listed in this table for most applications for film dosimeters based on LANL documentation and reports from other DOE facilities (Wilson 1960, 1987; NIOSH 1993; NRC 1989; Wilson et al. 1990) and for TLDs (Fix et al. 1982; Mallett, Hoffman, and Vasilik 1994; Hoffman and Mallett 1999a).

Table 6-23. Photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose.

Period of use[a]	Dosimeter	MDL[a] (mrem)	Exchange frequency	Mean annual missed dose[b] (mrem)
February 1945–September 1962[c]	Brass, brass clip, or brass-cadmium film	40	Monthly (n = 12)	240
			Biweekly (n =25)	500
			Weekly (n = 50)	1,000
			Daily (n = 250)	5,000
October 1962–December 1979	Cycolac multielement film	40	Monthly (n = 12)	240
			Biweekly (n =25)	500
			Weekly (n = 50)	1,000
			Daily (n = 250)	5,000
January 1, 1980–March 1998	Model 7776 TLD	10	Monthly (n = 12)	60
		10	Quarterly (n = 4)	20
April 1, 1998–2003 (ongoing)	Model 8823 TLD	10	Monthly (n = 12)	60
		10	Quarterly (n = 4)	20

a. Estimated MDLs for each dosimeter technology in the workplace. Dose values were recorded at levels less than the MDL.
b. Mean annual missed dose calculated using MDL/2 from NIOSH (2007c).
c. In accordance with the designation adding a class of LANL employees to the SEC, it is not feasible to reconstruct photon doses prior to 1946 (NIOSH 2007b).

6.5.2 Neutron Missed Dose

Neutron radiation was present around nine reactors at TA-2, -35, and -52; in the plutonium processing facilities at TA-1, -21, and -55; around LAMPF at TA-53; and at several other facilities. The approach recommended to calculate neutron missed dose can be divided into two periods. The first period is 1951 to 1978, when NTA film was primarily used; the second period is 1979 and after, when TLDs were primarily used. Table 6-24 summarizes the reported limits of detection or dose recording thresholds. Estimates of missing neutron doses before 1979 are based on reported photon doses, adjusted in accordance with Table A-3 in Attachment A, and use of the applicable neutron-to-photon ratio.

Table 6-24. Neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose.

Period of use	Dosimeter	MDL (mrem)	Exchange frequency	Mean annual missed dose (mrem)[a]
1951–1962	Brass-cadmium badge	<50	Monthly (n = 12)	<300[b]
April 1951–1978 (limited use with TLDs to 1995)	NTA film		Biweekly (n = 25) Weekly (n = 50)	<625[b] <1,250[b]
1962–1978	Cycolac multielement badge		Daily (n = 250)	<6,250[b]
1979–1998 (some quarterly exchange beginning in 1996)	Model 7776 TLD badge	10	Monthly (n = 12)	60
			Quarterly (n = 4)	20
1995–present	TED	20	Quarterly (n = 4)	40
1998–present (40% were exchanged quarterly by February 2002)	Model 8823 TLD badge	10	Monthly (n = 12)	60
			Quarterly (n = 4)	20

a. Mean annual missed neutron dose calculated using MDL/2 from NIOSH (2007c).
b. Neutron-to-photon ratio should be used to estimate missed doses during these periods.

6.6 ORGAN DOSE

Calculation of the POC requires an estimate of the organ dose because the claim is normally specific to disease in an organ. This is estimated from uncertainty distributions of various parameters related to dosimeter response, radiation type, energy, and worker orientation in the field.

Appendix A of NIOSH (2007c) discusses conversion of measured doses to organ DE, and Appendix B contains appropriate DCFs for each organ, radiation type, and energy range based on the type of monitoring performed. The selection of worker orientation is important to the calculation of organ dose. Examples of common exposure orientations are listed in NIOSH (2007c, Table 4.2); however, an assumption of 100% anterior-to-posterior (AP) geometry is typically the most representative, and is generally used for dose reconstruction. For exposures in which other geometries may result in a more accurate dose, the dose reconstructor is referred to the guidance in the reference.

6.7 ATTRIBUTIONS AND ANNOTATIONS

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

[1] Widner, Thomas E., Certified Health Physicist (CHP), Certified Industrial Hygienist (CIH). ChemRisk. Health Physicist. 2004.
The urchin initiator was a sphere that consisted of a hollow beryllium shell, with a solid spherical beryllium pellet nested inside. During implosion, violent turbulence quickly mixed the polonium and beryllium together and caused the emission of neutrons.

[2] Widner, Thomas E., CHP, CIH. ChemRisk. Health Physicist. 2007.
The numbers of workers at LANL each year were obtained from a number of LANL sources, and these values are quite uncertain for some years. For some years, the numbers of total workers supplied by LANL is smaller than the number of people who received dosimeters. Sources of workforce data for Table 6-2 included a LANL Human Resources – Workforce Data & Analysis and Los Alamos publication LASL-77-25 (LASL 1978). The major source of uncertainty appears to stem from variability in the worker types included in the worker count each year. Worker categories include full-time regular, part-time, limited-term, students, subcontractors, and visitors. More recent data have worker type information recorded, but historical data might not. For example, early military workers on the site were categorized as "visitors."

[3] Widner, Thomas E., CHP, CIH. ChemRisk. Health Physicist. 2005.
With NTA films used at LANL, the estimated standard error was probably larger than that for film badge measurement of photon doses, and varied significantly with the energy of the neutrons. Given the lack of specific technical information obtained in relation to dosimetry systems for early LANL history, measurement uncertainties have been estimated based on reported values for contemporary systems in use at other facilities. Based on the technical basis document for the Hanford Site (ORAUT 2004) and additional values for NTA film adapted from ORAUT (2006a), an overall bias factor for NTA film is estimated at 1.5 (range in bias 0.5 to 1.5) with a systematic uncertainty actor of 1.5.

[4] Widner, Thomas E., CHP, CIH. ChemRisk. Health Physicist. 2004.
The P-6 gamma range was in the Physics Building. It was normally used to calibrate instruments rather than dosimeter badges, with ^{60}Co and ^{137}Cs sources of different magnitudes and possibly a ^{226}Ra source for low-range calibrations. The sources were positioned in a concrete well and moved up and down to obtain different dose rates to the instruments at the surface. Dose rates were measured with Victoreen R-chambers because scattering contributed significantly to the radiations emerging from the well (Widner 2004).

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GLOSSARY

absorbed dose, *D*

Amount of energy imparted by radiation to unit mass of absorbing material (100 ergs per gram), including tissue. The unit used prior to the use of the International System of metric units (SI) is the rad; the SI unit is the gray.

accreditation

Recognition that a dosimeter system has passed the performance criteria of the DOE Laboratory Accreditation Program (DOELAP) standard in specified irradiation categories.

accuracy

If a series of measurements has small systematic errors, they are said to have high accuracy. The accuracy is represented by the bias.

albedo dosimeter

A TLD device that measures the thermal, intermediate, and fast neutrons that are scattered and moderated by the body from an incident fast neutron flux.

algorithm

A computational procedure.

BF_3 chamber or counter

Proportional counter using a gaseous BF_3 compound to detect slow neutrons through their interaction with boron.

backscatter

Deflection of radiation by scattering processes through angles greater than 90 degrees with respect to the original direction of motion.

beta particle

A charged particle of very small mass emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) direct fission products emit beta particles. Physically, the beta particle is identical with an electron moving at high velocity.

buildup

Increase in flux or dose due to scattering in the medium.

calibration blank

A dosimeter that has not been exposed to a radiation source. The results from this dosimeter establish the dosimetry system baseline or zero dose value.

collective dose equivalent

The sum of the dose equivalents of all individuals in an exposed population. Collective dose is expressed in units of person-rem (person-sievert).

control dosimeter

A dosimeter used to establish the dosimetry system response to radiation dose. The dosimeter is exposed to a known amount of radiation dose.

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

Cycolac
The commercial name for a plastic that was used in some LANL dosimeters, which informally took on that name. It contained styrene, butadiene, and acrylonitrile.

deep absorbed dose (D_d)
The absorbed dose at the depth of 1.0 cm in a material of specified geometry and composition.

deep dose equivalent (H_d)
The dose equivalent at the respective depth of 1.0 cm in tissue.

densitometer
Instrument that has a photocell to determine the degree of darkening of developed photographic film.

density reading
See *optical density*.

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

DOE Laboratory Accreditation Program (DOELAP)
Accredits DOE site dosimetry programs based on performance testing and onsite reviews performed on a 2-year cycle.

dose equivalent index
For many years the dose equivalent index was used to calibrate neutron sources that were used to calibrate neutron dosimeters. The index is based on summing the maximum dose equivalent delivered in the International Commission on Radiation Units and Measurements sphere at any depth for the respective neutron energies even though the maximum dose occurred at different depths.

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

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

DuPont 552
A film packet containing two pieces of film: A 502 sensitive film and a 510 insensitive film.

DuPont 558
A film packet containing a 508 film with one side having a sensitive emulsion and the other side an insensitive emulsion.

error
A term used to express the difference between the estimated and "true" value. *Error* can also be used to refer to the estimated uncertainty.

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

exposure
As used in the technical sense, a measure expressed in roentgens of the ionization produced by gamma (or X-) rays in air.

exposure-to-dose-equivalent conversion factor for photons (C_x)
The ratio of exposure in air to the dose equivalent at a specified depth in a material of specified geometry and composition. The C_x factors are a function of photon energy, material geometry (e.g., sphere, slab, or torso), and material composition (e.g., tissue-equivalent plastic, soft tissue ignoring trace elements, or soft tissue including trace elements).

extremity
That portion of the arm extending from and including the elbow through the fingertips, and that portion of the leg extending from and including the knee and patella through the tips of the toes.

fast neutron
Neutron of energy between 10 keV and 10 MeV.

film
Generally means a "film packet" that contains one or more pieces of film in a light-tight wrapping. The film when developed has an image caused by radiation that can be measured using an optical densitometer. (See *DuPont 552*, *DuPont 558*, *nuclear track emulsion, type A*.)

film density
See *optical density*.

film dosimeter
A small packet of film in a holder that attaches to a worker.

filter
Material used to adjust radiation response of a dosimeter to provide an improved tissue equivalent or dose response.

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

glovebox
A device used in handling quantities of radioactive isotopes to provide containment of the radioactivity and to avoid contamination of the hands.

gray (Gy)
The International System unit of absorbed dose (1 Gy = 100 rad).

intermediate-energy neutron
Neutron of energy between 0.5 eV (assumed to be 0.4 eV because of cadmium cutoff in neutron response) and 10 keV.

ionizing radiation
Electromagnetic radiation (consisting of photons) or particulate radiation (consisting of electrons, neutrons, protons, etc.) capable of producing charged particles through interactions with matter.

isotopes
Forms of the same element having identical chemical properties but differing in their atomic masses. Isotopes of a given element all have the same number or protons in the nucleus but different numbers of neutrons. Some isotopes of an element might be radioactive.

kerma
The sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a volume, divided by the mass of matter in that volume. Indirectly ionizing particles include X-rays and fast neutrons. Primary ionizing particles include photoelectrons, Compton electrons, and positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. The units are joules per kilogram (gray) or rad.

kiloelectron-volt (keV)
An amount of energy equal to 1,000 electron-volts.

kiva
A name given to the buildings used to house critical assemblies at LANL. From the Hopi word *kiva* for an underground or partly underground chamber in a Pueblo village, used by the men especially for ceremonies or councils.

luminescence
The emission of light from a material as a result of some excitation.

Manhattan Engineer District (MED)
U.S. agency designated to develop nuclear weapons; a predecessor to the U.S. Department of Energy.

minimum detection level (MDL)
Often confused because statistical parameters necessary to its calculation are not explicitly defined. Nonetheless, it is often assumed to be the level at which a dose is detected at the two-sigma level (i.e., 95% of the time). The MDL should not be confused with the minimum recorded dose.

megaelectron-volt (MeV)
An amount of energy equal to 1 million electron-volts.

multiple-collision neutron dose
Dose to flux through tissue based on the assumption that two or more interactions per neutron occur resulting in greater energy deposition.

nuclear emulsion
Generally refers to NTA film.

nuclear track emulsion, type A (NTA)
A film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using oil immersion and a 1,000-power microscope.

neutron
A basic particle that is electrically neutral weighing nearly the same as the hydrogen atom.

neutron, fast
Neutrons with energy equal to or greater than 10 keV.

neutron, intermediate
Neutrons with energy between 0.4 eV and 10 keV.

neutron, thermal
Strictly, neutrons in thermal equilibrium with surroundings. In general, neutrons with energy less than the cadmium cutoff at about 0.4 eV.

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

nonpenetrating dose
Designation (i.e., NP or NPen) on film dosimeter reports that implies a radiation dose, typically to the skin or whole body, from beta and lower energy photon radiation.

notional dose
An identified dose value assigned for lower dosed workers (at some facilities but not at LANL), often based on a small fraction of the regulatory limit.

open window
Common designation on film dosimeter reports that implies the use of little (i.e., only security credential) shielding. It commonly is used to label the film response corresponding to the open-window area.

optical density
The quantitative measurement of photographic blackening the density defined as $D = \log_{10} (I_o/I)$.

pencil dosimeters
A type of ionization chamber used by personnel to measure radiation dose. These results can be labeled as “pen” dose. Other names: pencil, pocket dosimeter, pocket pencil, pocket ionization chamber (PIC).

penetrating dose
Designation (i.e., P or Pen) on film dosimeter reports that implies a radiation dose, typically to the whole body, from higher energy photon radiation.

PuF_4 source
A neutron source with plutonium tetrafluoride activating material. The source was used to duplicate the neutron energies in plutonium facilities.

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

precision
If a series of measurements has small random errors, the measurements are said to have high precision. The precision is represented by the standard deviation.

quality factor (*Q*)
A modifying factor used to derive dose equivalent from absorbed dose.

rad
A unit of absorbed dose equal to the absorption of 100 ergs per gram of absorbing material, such as body tissue.

radiation
One or more of beta, neutron, and photon radiation.

radiation monitoring
Routine measurements and the estimation of the dose equivalent to determine and control the dose received by workers.

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

random errors
When a given measurement is repeated the resulting values, in general, do not agree exactly. The causes of the disagreement between the individual values must also be causes of their differing from the true value. Errors resulting from these causes are called random errors.

rem
A unit of dose equivalent, which is equal to the product of the number of rads absorbed and the quality factor.

rep
Historically the rep (roentgen-equivalent-physical) has been used extensively for the specification of permissible doses of ionizing radiations other than X-rays or gamma rays. Several definitions have appeared in the literature but in the sense most widely adopted, it is a unit of absorbed dose with a magnitude of 93 ergs per gram.

Roentgen (R or r)
A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kilogram of dry

air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue.

scattering
The diversion of radiation from its original path as a result of interactions with atoms between the source of the radiation and a point at some distance away. Scattered radiations are typically changed in direction and of lower energy than the original radiation.

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

shallow dose equivalent (Hs)
Dose equivalent at a depth of 0.07 mm in tissue.

shielding
Any material or obstruction that absorbs (or attenuates) radiation and thus tends to protect personnel or materials from radiation.

sievert (Sv)
The SI unit for dose equivalent. (1 Sv = 100 rem.)

skin dose
Absorbed dose at a tissue depth of 7 milligrams per square centimeter.

systematic errors
When a given measurement is repeated and the resulting values all differ from the true value by the same amount, the errors are called systematic.

thermal neutron
Strictly, neutrons in thermal equilibrium with surroundings. In general, neutrons of energy less than the cadmium cutoff of about 0.4 eV.

tissue equivalent
Used to imply that radiation response characteristics of the material being irradiated are equivalent to tissue. Achieving a tissue-equivalent response is an important consideration in the design and fabrication of radiation measuring instruments and dosimeters.

TLD chip
As used in this TBD, a small block or crystal made of LiF used in the TLD.
TLD-600 - A TLD chip made from ^{6}Li (greater than 95%) used to detect neutrons.
TLD-700 - A TLD chip made from ^{7}Li (greater than 99.9%) used to detect photon and beta radiation.

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

thermoluminescent dosimeter (TLD)
A holder containing solid chips of material that when heated will release the stored energy as light. The measurement of this light provides a measurement of absorbed dose. The solid chips are sometimes called crystals.

U.S. Atomic Energy Commission (AEC)

Original agency established for nuclear weapons and power production; a successor to the Manhattan Engineer District (MED) and a predecessor to the U.S. Department of Energy (DOE).

whole-body dose

Absorbed dose at a tissue depth of 1.0 centimeter (1,000 milligrams per square centimeter); also used to refer to the dose recorded.

X-ray

Ionizing electromagnetic radiation of extranuclear origin.

Zia

Refers to the Zia Company, a private firm that was created as the housekeeping contractor for LANL and its support community, facilities, and utilities.

ATTACHMENT A
GUIDANCE FOR DOSE RECONSTRUCTORS:
OCCUPATIONAL EXTERNAL DOSE FOR MONITORED WORKERS

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A.1 RECORDED DOSE PRACTICES AND INTERPRETATION OF REPORTED DOSES

Table A-1 summarizes LANL dose recording practices over the years.

Table A-1. Recorded dose practices over time (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003).[a]

Period	Values recorded in personnel exposure records	Compliance dose quantities	EEOICPA dose quantities
1943–1948	PIC reading Gamma exposure	Shallow DE = not measured Deep DE = gamma exposure	Electron dose = not measured Photon exposure = gamma exposure NADE = not measured
1949–1950	PIC reading Gamma exposure Beta exposure	Shallow DE = beta exposure + gamma exposure Deep DE = gamma exposure	Electron dose = beta exposure Photon exposure = gamma exposure NADE = not measured
1951–1959	PIC reading Gamma exposure Beta exposure Fast neutron dose	Shallow DE = beta exposure + gamma exposure + fast neutron dose Deep DE = gamma exposure + fast neutron dose	Electron dose = beta exposure Photon exposure = gamma exposure NADE = fast neutron dose
1960–1979	Gamma dose Beta dose Thermal neutron dose Fast neutron dose	Shallow DE = beta dose + gamma exposure + n_{th} dose + n_f dose Deep DE = gamma exposure + n_{th} dose + n_f dose	Electron dose = beta dose Photon exposure = gamma dose NADE = n_{th} + n_f doses
1980–1997	"Non-penetrating Rad" "Penetrating-rem" "Neutron-rem" "Total-rem"	Shallow DE = nonpen + pen + neutron Deep DE = pen + neutron	Electron dose = nonpen Photon deep dose = pen NADE = neutron
1998–present	Beta shallow DE Beta eye DE Gamma shallow DE Gamma deep DE Gamma eye DE Neutron deep DE Total shallow DE Total deep DE Total eye DE Total deep neutron DE	Shallow DE = total shallow DE Deep DE = total deep dose DE	Electron dose = beta shallow DE Photon deep dose = gamma deep DE NADE = neutron deep DE

a. DE = dose equivalent; NADE = neutron ambient dose equivalent; nonpen = nonpenetrating; pen = penetrating.

In reporting doses for LANL workers to NIOSH for the Dose Reconstruction Project, LANL personnel have used the following conventions (Widner 2005):

- Blank entries or "----" entries in tables of doses indicate a "null value" (i.e., no monitoring was performed for the individual for that period).

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- Dose entries that are all zeros (0.00 or 0.000) indicate that monitoring was performed for the individual during that period, but results were below the minimum detectable dose.

- The SHALLOW doses as reported by LANL are the shallow dose as measured by TLDs or film badges; they do not include neutron dose or tritium dose. This contrasts with those records reported as "SKIN" doses, which were reported in records submitted for dose reconstruction through late 2005.[4] To ensure that dose is appropriately attributed to the low-energy photon or electron categories for NIOSH dose reconstructions, nonpenetrating dose will be estimated as shallow dose – (deep dose).

- Early LANL case records contain a column labeled "SKIN." The SKIN doses reported are derived by LANL as shallow dose plus neutron dose plus tritium dose. To ensure that dose is appropriately attributed to the low-energy photon or electron categories for NIOSH dose reconstructions, nonpenetrating dose will be estimated as skin dose – (deep dose + neutron dose + tritium dose).

- When, for a given month, the dose report form identifies "Badge Type" as "Monthly," but there are up to five lines of data (see example below), multiple badges were worn during the month. The doses for the individual badges should be added to obtain the dose totals for the month.

External dose (rem)	Skin	Deep	Neutron	Tritium
June Monthly		0.000	0.000	
June Monthly		0.000	0.000	
June Monthly		0.010	0.010	
June Monthly		0.000	0.000	
June Monthly		0.040	0.020	

- Doses reported as follows reflect that the badge in use had two elements – dental X-ray film and NTA film. In the case below, the first line of data is from the NTA film and the second from the X-ray film. In these cases, the neutron dose entry on the second line is essentially a placeholder. This placeholder and the missing value for deep dose on the first line (which might be "----" in some reports) should not be corrected for unmonitored dose or missed dose.

External dose (rem)	Skin	Deep	Neutron	Tritium
April Monthly	0.010		0.010	
April Monthly	0.060	0.010	0.000	

A.2 UNMONITORED PHOTON DOSE

Table A-2 summarizes the lognormal probability statistical parameters for LANL dosimeter results that are equal to or exceed 50 mrem for all years of record. These data can be used to estimate unmonitored doses. They can also be used to estimate unrecorded doses for which no records exist.

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[4] When an automated tool is used for assigning doses to appropriate radiation types, the dose reconstructor must choose whether nonpenetrating doses were assigned as "SHALLOW" or "SKIN."

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It should be noted that the reported doses that are the basis of this table have not been corrected for potential missed doses.

It is recommended that dose reconstructors assign the median (that is, geometric mean) gamma dose from Table A-2 to an unmonitored worker for each year of employment.

Table A-2. Worker gamma dose statistics.[5]

Year	LANL recorded gamma dose data[a]			Lognormal fit		
	No. of workers reported gamma dose ≥ 50 mrem	Dose (mrem)		Dose (mrem)		
		Mean	Maximum	Median	95%	GSD
1946	245	3.52E+03	1.18E+05	5.07E+02	9.18E+03	5.82
1947	656	6.96E+02	1.65E+04	2.52E+02	1.85E+03	3.36
1948	683	4.82E+02	1.34E+04	1.99E+02	1.29E+03	3.13
1949	1,091	3.85E+02	1.07E+04	1.56E+02	8.82E+02	2.87
1950	1,364	3.17E+02	2.02E+04	1.40E+02	6.68E+02	2.58
1951	2,182	1.08E+03	1.36E+04	4.82E+02	4.46E+03	3.87
1955	823	8.81E+02	8.82E+03	3.98E+02	3.01E+03	3.43
1956	1,068	1.15E+03	1.86E+04	4.92E+02	4.47E+03	3.82
1957	780	6.46E+02	1.35E+04	2.88E+02	2.08E+03	3.33
1958	1,071	4.38E+03	3.50E+06	4.67E+02	4.26E+03	3.83
1959	740	5.11E+02	5.51E+03	2.37E+02	1.63E+03	3.23
1960	1,059	4.59E+02	5.00E+03	2.05E+02	1.33E+03	3.12
1961	749	3.82E+02	4.69E+03	1.94E+02	1.13E+03	2.92
1962	937	3.82E+02	5.65E+03	2.15E+02	1.14E+03	2.75
1963	640	3.24E+02	3.28E+03	1.84E+02	9.25E+02	2.67
1964	606	3.65E+02	4.10E+03	1.98E+02	1.09E+03	2.82
1965	635	5.13E+02	9.69E+03	2.38E+02	1.62E+03	3.20
1966	568	3.69E+02	4.67E+03	2.03E+02	1.09E+03	2.79
1967	551	4.06E+02	6.24E+03	2.08E+02	1.21E+03	2.92
1968	609	3.23E+02	4.03E+03	1.66E+02	9.30E+02	2.85
1969	798	3.58E+02	4.95E+03	1.55E+02	9.99E+02	3.11
1970	590	5.79E+02	4.78E+03	2.51E+02	1.95E+03	3.48
1971	531	5.52E+02	5.00E+03	2.44E+02	1.85E+03	3.43
1972	554	4.95E+02	5.73E+03	2.27E+02	1.52E+03	3.17
1973	553	5.84E+02	4.63E+03	3.11E+02	2.00E+03	3.10
1974	685	4.01E+02	2.77E+03	2.24E+02	1.28E+03	2.88
1975	944	3.82E+02	3.17E+03	2.04E+02	1.19E+03	2.91
1976	952	3.58E+02	3.29E+03	1.90E+02	1.11E+03	2.92
1977	921	4.22E+02	4.46E+03	2.01E+02	1.31E+03	3.13
1978	938	3.33E+02	3.68E+03	1.79E+02	9.83E+02	2.82
1979	779	2.70E+02	1.87E+03	1.69E+02	7.90E+02	2.56

5 In accordance with the addition of a class of LANL employees to the Special Exposure Cohort, it is infeasible to reconstruct gamma doses prior to the year 1946 (NIOSH 2007).

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Year	LANL recorded gamma dose data[a]			Lognormal fit		
	No. of workers reported gamma dose ≥ 50 mrem	Dose (mrem)		Dose (mrem)		GSD
		Mean	Maximum	Median	95%	
1980	666	2.69E+02	1.85E+03	1.73E+02	7.82E+02	2.50
1981	832	2.71E+02	2.40E+03	1.67E+02	7.87E+02	2.57
1982	821	3.25E+02	2.27E+03	1.84E+02	1.01E+03	2.82
1983	1,017	2.96E+02	2.16E+03	1.72E+02	8.68E+02	2.67
1984	1,513	2.32E+02	2.47E+03	1.37E+02	6.39E+02	2.55
1985	733	3.54E+02	1.88E+03	2.10E+02	1.12E+03	2.77
1986	527	3.21E+02	1.71E+03	2.03E+02	1.00E+03	2.64
1987	420	3.14E+02	2.74E+03	2.08E+02	9.26E+02	2.48
1988	428	2.97E+02	1.71E+03	1.96E+02	9.04E+02	2.54
1989	436	2.56E+02	1.47E+03	1.75E+02	7.34E+02	2.39
1990	340	2.41E+02	2.28E+03	1.62E+02	6.60E+02	2.35
1991	298	1.87E+02	1.86E+03	1.37E+02	4.63E+02	2.10
1992	221	1.38E+02	5.65E+02	1.15E+02	2.99E+02	1.79
1993	224	1.40E+02	9.46E+02	1.14E+02	3.11E+02	1.85
1994	215	1.47E+02	6.89E+02	1.20E+02	3.31E+02	1.86
1995	193	1.26E+02	2.85E+02	1.11E+02	2.55E+02	1.66
1996	267	1.74E+02	6.00E+02	1.40E+02	4.14E+02	1.93
1997	327	2.00E+02	1.21E+03	1.52E+02	4.93E+02	2.04
1998	313	1.92E+02	1.09E+03	1.41E+02	4.76E+02	2.09
1999	253	1.58E+02	6.41E+02	1.26E+02	3.67E+02	1.91
2000	215	1.20E+02	5.96E+02	1.01E+02	2.54E+02	1.75
2001	281	1.69E+02	2.13E+03	1.29E+02	3.93E+02	1.97
2002	380	1.86E+02	1.37E+03	1.42E+02	4.61E+02	2.05
2003	453	2.50E+02	2.35E+03	1.70E+02	6.39E+02	2.24
2004	282	1.55E+02	1.23+03	1.06E+02	4.06E+02	2.26
2005	339	1.57E+02	1.27E+03	1.16E+02	9.31E+02	3.55
2006	348	1.78E+02	1.33E+03	1.17E+02	4.59E+02	2.30
2007	284	1.94E+02	9.63E+02	1.33E+02	5.22E+02	2.30
2008	194	1.58E+02	1.06E+03	1.11E+02	4.42E+02	2.32

a. Individual dosimeter records analyzed only if gamma dose was equal to or greater than 50 mrem.

A.3 ADJUSTMENTS TO REPORTED PHOTON DOSES

Table A-3 lists adjustments to reported LANL photon doses.

Table A-3. Recommended adjustments to reported photon doses.

Period	Dosimeter	Facilities/operations	Adjustment to reported dose	References
1949	Brass clip film badge	Plutonium areas[a]	Multiply reported photon doses by 1.3.[b]	Traub, Sherpelz, and Taulbee 2005
Sep 1961–Oct 1964	Brass-cadmium badge	Photon exposures >200 keV (reactors, uranium production, accelerators, calibrations, waste handling, radioactive lanthanum, etc.)	Multiply reported photon doses that exceed 100 mrem by 4.	LASL 1969 (10/13/64 memorandum)

a. Plutonium areas have included TA-1, TA-21, TA-55, and some areas of TA-3.

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b. Based on calculated dose rate due to 30- to 250-keV photons, based on measured dose, (P2/C7) for a generic 6-kg pit (5 years), from Table A.3 of Traub, Sherpelz, and Taulbee (2005).

Based on site-specific documentation (LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003) and characterizations of similar dosimeters used at other sites, the standard error in recorded film badge doses from photons of any energy is estimated to have been ±30%. The estimated standard error for recorded doses from beta radiation was probably the same, but for unknown mixtures of beta and photon radiations the standard error was likely somewhat larger than 30%.

The standard error for neutron dose readings of approximately 100 mrem from NTA film is estimated to have been ±50%.

Based on these estimates and analysis of DOELAP testing result summaries for the LANL Model 7776 and Model 8823 dosimeters (Test Sessions 22 and 36, respectively), Table A-4 identifies recommended uncertainty factors to be applied to worker doses reported by LANL.

Table A-4. Recommended uncertainty factors for reported doses.

Radiation	Film badges	NTA film	Model 7776 dosimeter	Model 8823 dosimeter
Photon (deep)	±30%	Not applicable	±14%	±19%
Beta (shallow)	±30%	Not applicable	±16%	±14%
Neutrons (deep)	Not applicable	±50%	±8%	±8%

A.4 MISSED BETA/PHOTON DOSE

Missed dose is the dose that might not have been accounted for on an individual's records because the records might have indicated zero dose due to the detection limitations of the film or TLD.

Several exchange frequencies were in use at any one time, so the dose reconstructor needs to determine the exchange frequency that applies to a specific worker from individual records. The values in the last two columns of Table A-5 can be considered maximum annual missed doses for the purpose of dose reconstruction. Beginning with 1979, badge exchange frequencies should be assumed to be monthly if specific information to the contrary for the claimant is not available (ORAUT 2006b).

Table A-5. Beta/photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed doses.

Period of use	Dosimeter	Deep MDL[a] (mrem)	Nonpenetrating MDL[a] (mrad)	Exchange frequency	Geometric mean annual missed dose[b,c]	
					Deep dose (mrem)	Nonpenetrating dose (mrad)
July 1946–1948	Brass film badge	40	Nonpenetrating dose was not measured	Monthly (n = 12)	240	Unmonitored[d]
				Biweekly (n = 25)	500	
				Weekly (n = 50)	1,000	
				Daily (n = 250)	5,000	
1949–September 1962	Brass clip, brass-lead, brass-cadmium film badges	40	*40*	Monthly (n = 12)	240	240
				Biweekly (n = 25)	500	500

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October 1962–December 1979	Cycolac multi-element film badge			Weekly (n = 50)	1,000	1,000
				Daily (n = 250)	5,000	5,000
January 1, 1980–March 1998	Model 7776 TLD	10	*30*	Monthly (n = 12)	60	180
				Quarterly (n = 4)	20	60
April 1, 1998–2003 (ongoing)	Model 8823 TLD	10	*30*	Monthly (n = 12)	60	180
				Quarterly (n = 4)	20	60

a. Estimated MDLs for each dosimeter technology in the workplace.
b. See Table A-7 footnotes for guidance on calculation of unmonitored nonpenetrating dose.
c. Mean annual missed dose calculated using MDL/2 from NIOSH (2007c).
d. According to the designation adding a class of LANL employees to the Special Exposure Cohort, it is not feasible to reconstruct non-penetrating doses prior to 1949 (NIOSH 2007b).

Missed beta/photon dose is entered into the Interactive RadioEpidemiological Program as a lognormal distribution with a geometric mean consistent with Table A-5 and a geometric standard deviation (GSD) of 1.52.

A.5 ASSIGNMENT OF BETA/PHOTON DOSES TO ENERGY CATEGORIES

Tables A-6 and A-7 present the energy ranges for beta and photon exposures at LANL. LANL has possessed separated plutonium and sources of low-energy X-rays, so non-penetrating doses could have resulted from exposures to low-energy photons as well as beta particles.

Table A-6. Recommended beta and photon radiation energies and percentages for plutonium facilities.

Process/ buildings	Description	Operations		Radiation type	Energy selection (keV)	Percentage
		Begin	End			
Plutonium Processing	**Radiochemical Operations:** Plutonium processed at LANL had largely been separated from fission products. Radiochemical operations were largely for recovery of fissionable material.			Beta	>15	100%
	TA-1, D Building	1943	1945	Photon	<30 30–250	65%[a] 35%[a]
	TA-21, DP West Site	Nov 1945	1978			
	TA-55, Plutonium Facility	1978	Present			
	TA-3 (including CMR Building)	1953	Present			
Plutonium production	**Plutonium Component Production**: Plutonium is machined into weapon components using glovebox assembly process with predominant close anterior exposure to workers. Radiation characteristics in this area involve significant lower energy photons and neutron radiation.			Photon	<30 30–250	65%[a] 35%[a]
	TA-1 (D Building), TA-21 (DP Site), TA-55 (PF Site)					
	Plutonium Storage: Radiation characteristics in this area generally involve dispersed lower energy neutron radiation and scattered photons, including 60-keV Am-241 gamma ray.					
	TA-1, D-5 Sigma Vault	1943	1945			
	TA-21, Building 21	Nov 1945	1978			
	TA-55 Vault	1978	Present			

Information sources: LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003.
a. Low-energy photons were not measured by early LANL film badges that had no unfiltered areas. Photon exposure should be assessed as follows:
Before 1949: 100% of the measured photon dose should be attributed to the 30- to 250-keV category. An additional dose of 1.86 times the measured dose should be attributed to low-energy photon (<30-keV category).
1949 and after: Nonpenetrating dose should be estimated and attributed to the <30-keV category.
Nonpenetrating dose = skin dose – (deep dose + neutron dose + tritium dose).

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A.6 UNMONITORED NEUTRON DOSE

There should not, typically, be significant neutron exposure of unmonitored workers, with the exception of the years 1946 to 1949 (NIOSH 2007b). However, if there is an estimation of neutron dose, the recommended option is to apply the neutron-to-photon distribution data from Table A-8 to

Table A-7. Recommended beta and photon radiation energies and percentages for facilities other than plutonium facilities.

Process/ buildings	Description	Operations		Radiation type	Energy selection, keV	Percentage
		Begin	End			
Reactors (and criticality experiments)	**During operation:** Highly dispersed fields of higher energy photon radiation fields from fission process, activation, and fission product nuclides. Potentially narrow beams of higher energy neutron radiation from test ports, etc., into reactor core. Potential for significant airborne nuclides and significant higher energy beta radiation.			Beta[a] Photon[b]	>15 30–250 >250	100 25 75
	Not in operation: Highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides. No significant neutron radiation. There could be significant higher energy beta radiation during maintenance work resulting from fission products.					
	LOPO Water Boiler (TA-2)	May 1944	Nov 1944			
	HYPO Water Boiler (TA-2)	Dec 1944	Feb 1951			
	SUPO Water Boiler (TA-2)	Mar 1951	Jun 1974			
	Plutonium Fast Reactor (Clementine, TA-2)	Dec 1946	Dec 1950			
	Omega West Reactor (TA-2)	Jul 1956	Dec 1992			
	LAPRE I (TA-35)	Feb 1956	Oct 1956			
	LAPRE II (TA-35)	Feb 1959	May 1959			
	LAMPRE I (TA-35)	Early 1961	Mid-1963			
	UHTREX (TA-52)	Dec 1956	Feb 1970			
Uranium production	**Processing and machining:** Depleted and enriched uranium.			Beta[a] Photon[b]	>15 30–250	100 100
	TA-1 (Sigma, HT Buildings)	1943	1953			
	TA-3 (Sigma Complex)	1953	Present			
Accelerator operations	**LAMPF** operations at TA-53: Primarily from residual activity induced within targets, accelerator structures and components, grease, oils, and soil.	1972	Present	Beta Photon	>15 <30 30–250 >250	100[c] 1[c] 9[d] 90[d]
Calibrations	LANL site calibration of instruments and dosimeters	1943	Present	Beta[a] Photon[b]	>15 30–250 >250	100 25 75
Waste handling	Radiation characteristics highly dependent on source of waste.			Beta[a] Photon[b]	>15 30–250 >250	100 50 50
	Liquid waste: TA-45 and TA-50 Solid waste: Areas A, B, C, D, E, G, T, U, V	Various, 1944 on				
Radioactive lanthanum operations	**Preparation and use of radioactive lanthanum sources:**			Beta[a] Photon[b]	>15 30–250 >250	100 10 90
	TA-10 (Bayo Canyon)	1944	1950			
	TA-35, Ten Site	1951	1963			

Information sources: LASL 1959, 1969, 1977, 1979; LANL 1986, 1989, 1996, 2001, 2003.

a. For these operations 1949 to present: Nonpenetrating dose should be estimated and attributed to the beta radiation category. Nonpenetrating dose = skin dose – (deep dose + neutron dose + tritium dose).
b. The reported deep dose should be assigned to the photon dose categories in accordance with the fractions in this table.
c. Nonpenetrating dose to LAMPF/LANSCE workers should be estimated and attributed to beta radiation >15 keV (50%) and photon radiation <30 keV (50%). Nonpenetrating dose = skin dose – (deep dose + neutron dose + tritium dose).
d. The reported deep dose to LAMPF/LANSCE workers should be attributed to 30- to 250-keV (9%) and >250-keV photons (91%).

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measured or estimated missed or unmonitored photon doses. This process of calculation of a neutron dose is based on the expectation that the neutron dose to unmonitored workers is equivalent to the median neutron dose measured for monitored workers.

The application of the data from Table A-8 to measured or estimated photon doses can be accomplished through Monte Carlo simulation. As an alternative, to obtain an overestimate of

unmonitored neutron dose, the appropriate maximum value from Table A-8 can be applied to the measured or estimated photon dose for each period of interest.

Table A-8. Recommended distributions for neutron-to-photon ratio.

Neutron source type	Neutron-to-photon dose ratio	
	Median	**95th percentile**
Plutonium facilities (predominantly Pu-239)	0.7	2.8
Plutonium facilities (documented involvement with Pu-238 operations; applies only to 1969 or later; most likely at TA-21, TA-3-29 [CMR Building], TA-55)	3.9	5.5
Criticality experiments (>50 m distant)	2.3	2.5
Other operations	1.6	6.4

A.7 MISSED NEUTRON DOSE

Neutron radiation was present at LANL at D Building (TA-1), DP West (TA-21), DP East (TA-21), the current Plutonium Facility (TA-55), Omega Site (TA-2), LAMPF (TA-53), criticality laboratories (TA-2 and TA-18), and CMR Building (TA-3). For other locations, missed neutron dose is very unlikely because of the very low potential for neutron exposure. To calculate the missed neutron dose, the dose reconstructor must first determine if the person worked near neutrons and the category of neutrons. This can best be determined by examining the work location records and whether a worker or others in the badge reporting group were assigned any neutron DE. If no neutron dose was assigned to the worker or coworkers for several months, the dose reconstructor should assume that the person was not exposed to neutrons. Table A-9 lists the neutron missed dose for those exposed to neutrons.

Table A-9. Neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose.

Period of use	**Dosimeter**	**MDL (mrem)**	**Exchange frequency**	**Mean annual missed dose (mrem)[a]**
1951–1962	Brass-cadmium badge	<50	Monthly (n = 12)	<300[b]
Apr 1951–1978 (limited use with TLDs to 1995)	NTA film		Biweekly (n = 25) Weekly (n = 50)	<625[b] <1,250[b]
1962–1978	Cycolac multi-element badge		Daily (n = 250)	<6,250[b]
1978–1998 (some quarterly exchange beginning in 1996)	Model 7776 TLD badge	10	Monthly (n = 12)	60
			Quarterly (n = 4)	20
1995–present	Track-etch dosimeter	20	Quarterly (n = 4)	40
1998–present (40% were exchanged quarterly by Feb 2002)	Model 8823 TLD badge	10	Monthly (n = 12)	60
			Quarterly (n = 4)	20

a. Mean annual missed neutron dose calculated using MDL/2 from NIOSH (2007c).
b. Neutron-to-photon ratio should be used to estimate missed doses during these periods.

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A.8 ASSIGNMENT OF NEUTRON DOSES TO ENERGY CATEGORIES

Table A-10 lists default neutron dose fractions by energy categories for LANL work areas where field measurements of neutron spectra have been performed along with the associated ICRP Publication 60 correction factors (ICRP 1991). The neutron DE is calculated by multiplying the recorded neutron dose by the area-specific correction factors.

Table A-10. Recommended dose fractions and ICRP Publication 60 correction factors for neutron sources.

Process	Description/buildings	Operations Begin	Operations End	Neutron energy	Default dose fraction (%)	ICRP 60 correction factor
Plutonium production/ processing	Neutron dose was associated with overall LANL plutonium production process in which plutonium was purified, formed, machined, and recovered. Work was primarily conducted in gloveboxes with predominant close anterior exposure to workers. Neutron exposure also resulted from spontaneous fission neutrons from Cm-242 and Cm-244.					
	Plutonium facilities (D Building at TA-1, DP West Site at TA-21, Plutonium Facility at TA-55)	1943	Present	<10–100 keV 0.1–2 MeV 2–20 MeV	11 56 33	0.23 1.1 0.44
LAMPF	Neutrons of varying energies from high-energy proton linear accelerator studies.					
	LAMPF at TA-53	1972	Present	<10 keV 10–100 keV 0.1–2 MeV 2–20 MeV	30 30 20 20	0.64 0.56 0.38 0.26
Reactor operations	Neutrons of varying energies from reactor operations.					
	Omega Site (TA-2) TA-35 TA-52	1944 1955 1969	1992 1963 1970	0.1–2 MeV	100	1.9
Criticality experiments	Neutrons of varying energies from criticality testing and experimentation (in normally occupied areas, not including accidental exposures, which must be considered special cases).					
	Omega Site (TA-2) TA-18	1943 Apr 46	Apr 46 Present	<10–100 keV 0.1–2 MeV 2–20 MeV	3.2 59 38	0.06 1.1 0.5
Chemistry & metallurgy research	Neutrons of varying energies from actinide chemistry and metallurgy research.					
	TA-1 TA-3	1943 1952	1952 Present	<10–100 keV 0.1–2 MeV 2–20 MeV	10 50 40	0.21 0.95 0.53

A.9 RECOMMENDED DOSE CONVERSION FACTORS

DCFs should be selected from NIOSH (2007c) for the dose quantities specified in Table A-11 for the periods of interest.

Table A-11. Recommended DCFs for dose assessments.

Period	Recommended photon DCFs	Recommended neutron DCFs
1946–1984	Exposure (R) to organ DE (HT)	Deep DE [Hp,slab(10)] to organ DE (HT)
1985–present	Deep DE [Hp(10)] to organ DE (HT)	