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Subject Expert(s): Donald N. Stewart

Approval:	Signature on File Donald N. Stewart, Document Owner	Approval Date:	03/13/2013
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	03/12/2013
Concurrence:	Signature on File Edward F. Maher, Objective 3 Manager	Concurrence Date:	03/13/2013
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	02/12/2013
Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	03/21/2013

☐ 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.
03/21/2013	03	Revised to incorporate dose reconstruction limitations that relate to a class of LANL employees added to the SEC comprised of all workers from January 1, 1976, to December 31, 1995, SEC-00109 (NIOSH 2012). Attachment B has been added, which contains an analysis that evaluates the neutron-to-photon ratios promulgated in earlier revisions of the TBD. No changes were made to the neutron-to-photon ratios as a result. Incorporates formal internal and NIOSH review comments. For the years 1976-1980, NIOSH has agreed, in addressing comments on the TBD, to assign neutron dose using the 95^{th}-percentile value of the NP ratio to address uncertainties associated with the transition from film to TLD dosimeters in response to the LANL ABRWH Work Group. Constitutes a total rewrite of the document. 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
CFR	Code of Federal Regulations
CHP	Certified Health Physicist
Ci	curie
CIH	Certified Industrial Hygienist
cm	centimeter
CMR	Chemistry and Metallurgy Research (Building or Division)
d	day
DCF	dose conversion factor
DE	dose equivalent
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ERDA	U.S. Energy Research and Development Administration
eV	electron-volt
EVM	Evaluation Method
g	gram
GM	geometric mean
GSD	geometric standard deviation
H Division	Health Division
HT	Heat Treatment (building)
HYPO	Water Boiler Reactor in high-power configuration
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
kVp	peak kilovoltage
LAMPF	Los Alamos Meson Physics Facility
LAMPRE	Los Alamos Molten Plutonium Reactor Experiment
LANL	Los Alamos National Laboratory
LAPRE	Los Alamos Power Reactor Experiment
LANSCE	Los Alamos Neutron Science Center
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
mrad	millirad

mrem	millirem
mSv	millisievert
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
NP	neutron-to-photon
NTA	nuclear track emulsion, type A
NTP	nuclear track plate
PIC	pocket ionization chamber (i.e., pencil dosimeter)
PNL	Pacific Northwest Laboratory
PNNL	Pacific Northwest National 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
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
µC	microcurie
µm	micrometer
§	section or sections

6.1 INTRODUCTION

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

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

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation, 42 C.F.R. Pt. 82) restrict the "performance of duty" referred to in 42 U.S.C. § 7384n(b) to nuclear weapons work (NIOSH 2010).

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 2010):

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

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

6.1.1 Purpose

When the Los Alamos site 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 technical basis document (TBD) uses LANL for all periods. LANL assignments in the early 1940s included:

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

Processes 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 moved 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 the Hanford Site, 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 2007a) 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 on August 13, 1942. The primary challenges encountered by MED, and later U.S. Atomic Energy Commission (AEC, the MED 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 nine 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 2003 (Widner 2004). Table 6-1 lists the volumes that currently compose this resource.

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

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 measuring the dose from 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. Attachment B describes analyses performed to calculate the statistical parameters of lognormal distributions of neutron-to-photon (NP) dose ratios, and provides an annotated chronology of radiation-dosimetry related events at LANL.

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.

6.1.3 Special Exposure Cohort

The Secretary of the U.S. Department of Health and Human Services has designated three classes of LANL employees as additions to the SEC based on the findings and recommendations of NIOSH and the Advisory Board on Radiation and Worker Health Board:

- Employees of DOE predecessor agencies and their contractors or subcontractors who were monitored or should have been monitored for exposure to ionizing radiation during radioactive lanthanum (RaLa) operations at Technical Area (TA)-10 (Bayo Canyon Site), TA-35 (Ten Site), and Buildings H, Sigma, and U (in TA-1) for a number of workdays aggregating at least 250 workdays during the period from September 1, 1944, through July 18, 1963, or in combination with workdays within the parameters that have been established for one or more other classes of employees in the SEC (Leavitt 2006; NIOSH 2006).

Through the course of ongoing dose reconstruction and research, NIOSH determined that, due to undocumented worker movements across the site and limited claimant-specific information pertaining to work locations, it was unable to eliminate any specific worker from potential exposure scenarios based on assigned work location. NIOSH has found that a determination cannot always be made as to whether or not an employee worked in Technical Areas with a history of radioactive material use, or whether an employee should have been monitored for radiological exposures. Accordingly, NIOSH determined that it was necessary to remove the area-specific and monitoring criteria from the class description above, and to expand the SEC class definition to include all areas of LANL, and all employees of the DOE, its predecessor agencies, and their contractors and subcontractors who worked at LANL during the specified time period, regardless of monitoring. For this reason, the class of employees listed below was added.

- All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Los Alamos National Laboratory in Los Alamos, New Mexico from March 15, 1943 through December 31, 1975, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort (Sebelius 2010).

- Employees of DOE, its predecessor agencies, and DOE contractors or subcontractors who were monitored or should have been monitored for radiological exposures while working in operational TAs with a history of radioactive material use at LANL for an aggregate of at least 250 workdays during the period from March 15, 1943, through December 31, 1975, or in combination with workdays within the parameters that have been established for one or more other classes of employees in the SEC (Leavitt 2007; NIOSH 2007b).

- Employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at LANL from January 1, 1976, through December 31, 1995, for a number of workdays aggregating at least 250 workdays occurring either solely under this employment or in combination with workdays within the parameters established for one or more other classes of employees included in the SEC (Sebelius 2012; NIOSH 2012).

NIOSH has determined that it does not have access to sufficient information – including internal personnel dosimetry, workplace monitoring data, or sufficient process and radiological source information – that would allow it to estimate with sufficient accuracy the potential internal doses workers might have received. NIOSH has determined that there is insufficient information either to estimate the maximum radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the classes or to estimate the radiation doses of members of the classes more precisely than a maximum dose estimate.

From an occupational external dose reconstruction perspective, partial dose reconstructions can 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.

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 responses 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/d 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 with their alpha activity, and that film badges would be needed only 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 regulations 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 multielement 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 listed [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 are based have not been corrected for potential missed doses.

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 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.

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,b]
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,b]
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

Year	Total dose (person-rem)	No. of workers		Average total dose (rem)
		Monitored	Total	
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 before 1956; nonpenetrating doses cannot be reconstructed before 1949; and neutron doses can 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 2004 through 2007, an update to LANL (2004) was received during preparation of the Evaluation Report for SEC petition SEC-00109 (NIOSH 2012); for 2004 through 2007 (and part of 2008), only the numbers of employees monitored were available.

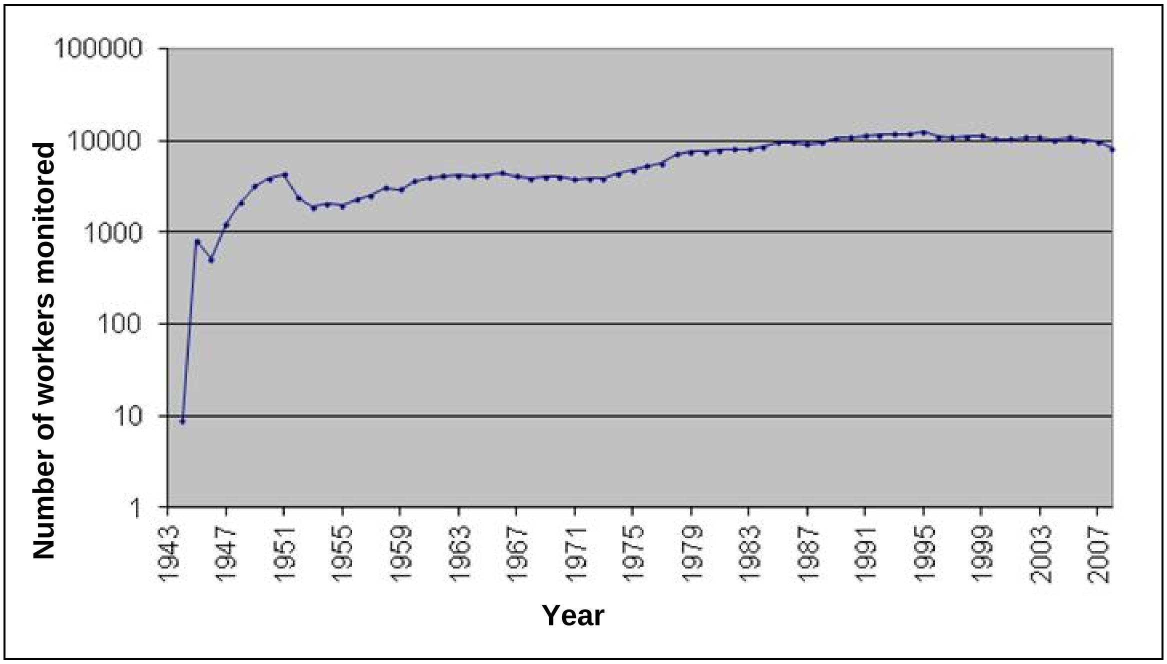

Figure 6-1. Number of workers monitored as a function of time (LANL 2004, updated January 2009).

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 before 1946, and infeasible to reconstruct nonpenetrating doses before 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 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:

  > *Control 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 with which LANL personnel were familiar from the early years of operations.

- A Los Alamos "Nuclear Track Plate Evaluation Procedure" dated February 27, 1956 (in LASL 1979), stated:

  > *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 1977) 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 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 never 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 1977 (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 [LANL 1986 (3/21/80 memorandum, p. 180 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. It was 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 (in millirem) have been evaluated and recorded (Hoffman and Mallett 1999a,b):

- 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 doses, which are reported to a tissue depth of 7 mg/cm^2 (H_p (0.07)), correspond to the old nonpenetrating doses. Doses to the lens of the eye are reported to a tissue depth of 300 mg/cm^2(H_p (3)). Deep doses, which are reported to a tissue depth of 1,000 mg/cm^2 (H_p (10)), 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.

Table 6-4. 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 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 results were below the minimum detectable dose.

  SHALLOW doses reported by LANL are the shallow doses as measured by TLDs or film badges; they do not include neutron dose or tritium dose. This contrasts with records reported as "SKIN" doses, which were reported in records submitted for dose reconstruction through late 2005.[2]

- 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.

- If, for a given month, the dose report form identifies "Badge Type" as "Monthly," but there are as many as 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.[3]

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		

- If the dose reported is as follows, 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

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[2] 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."

[3] For estimating missed dose, all zeroes should be included in the QC file for the multiple badges reported in one month to determine missed dose.

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 reporting to the primary employers 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; a DOE predecessor agency) 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, were 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 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 a 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	A new badge was 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	Changed 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 film.
1954	Thermal neutron measurements started.
1955	Routine measurement of thermal neutrons was discontinued.
1956	Routine evaluation of thermal neutron exposures restarted.
Oct 1962	Multielement Cycolac film badge was put into use. It included multielement filter, another multielement filter with Li-6, and unfiltered area. Two film packets: DuPont 543 (with DuPont 502 film) and Kodak Type B (with NTA fast film and Fine Grain Positive film).
31 Jan 1963	Practice of using wrist-to-finger ratios greater than 1 was discontinued.
Mar 1963	Comparison of Cycolac and brass-cadmium badges was conducted.
Aug 1968	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.

Period	Event
1971–1972	Prototype albedo-neutron TLD badge was studied at DP West and compared to Cycolac film badge data.
Jul–Dec 1972	Performance of film badges, NTA film, and prototype albedo-neutron-TLDs were 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 and 1979, as TLD cards and badges were acquired.
1978–1979	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 noncadmium versions. Cadmium version was initially used at LAMPF.
Late 1980	Changed to use of noncadmium 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	Applied to participate in pilot testing of DOELAP.
16 Jan 1985	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 were made at seven locations in TA-55 Room 209 using ESP-2 neutron instrument and TLD badges on Lucite phantom.
Jun 1991	Expressed interest in participating in some categories of DOELAP testing of extremity dosimeters (not the categories with low-energy beta emitters or neutrons).
Aug 1992	Comparison conducted of bubble dosimeters with Model 7776 TLDs.
1993	Purchased automated reader for use with chemically etched CR-39 detectors.
1995	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 dynamic determination of employee-specific NCFs.
Apr 1996	Began to phase in quarterly dosimeter exchange frequency for personnel who received “low” occupational radiation exposure.
1996	Submitted track-etch neutron dosimeters for irradiation at the Paul Scherrer Institute in Switzerland.
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	Participated in 4th Intercomparison of Personal Dosimeters Used in U.S. DOE Accelerator Facilities.
2000	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 (Chemistry and Metallurgical Research; also refers to a building)-12 Radiochemistry Group, and the GMX-1 Radiography Group. 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 Clinton Laboratories (which became Oak Ridge National Laboratory) 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 as much as 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 had 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.

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

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 film)
1962–1978	Cycolac plastic badge – multielement filter, a second multielement filter with Li-6, 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 film)
1978–March 1998	Model 7776 TLD badge (cadmium and noncadmium 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.

Period	Type badge	Film or media used
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.

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 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.

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.

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 film)
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 film)
1980–1998	Model 7776 TLD badge (cadmium and noncadmium 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	Two elements form a classic albedo detector with a

Period	Type badge	Film or media used
	TED by those with potential high-energy neutron exposure) (measures thermal, intermediate, and fast neutrons, with no separation of fast neutrons)	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.

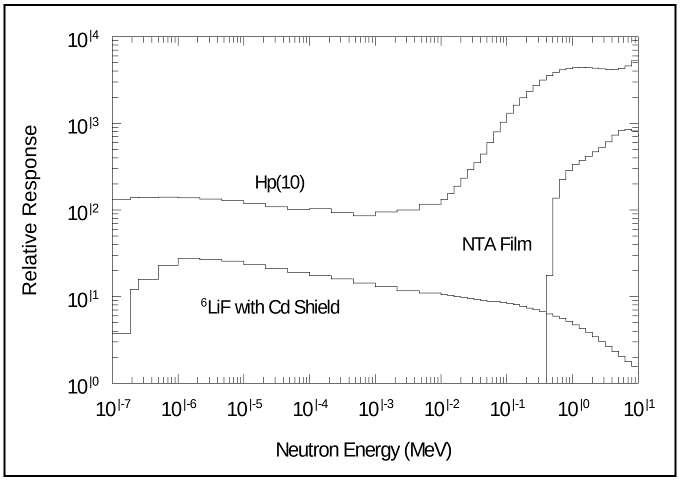


Figure 6-2. Comparison of *Hp(10)* for neutrons with energy responses of NTA film and neutron albedo dosimeter containing a thermoluminescent neutron dosimeter chip of ^{6}LiF and shielded by cadmium (IAEA 1990).

6.2.3.1 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 rather than the depleted uranium slab.

The standard method of film calibration as of April 1955 used a 195-mg radium source that was calibrated by 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, if required, 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.

DOELAP Irradiation Categories	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 thermoluminescent 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 Clinton Laboratories (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 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 in 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 NP ratio for each year from 1979 to 2008 based on LANL records that contain both deep dose and neutron doses 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.

6.2.3.3 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 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.

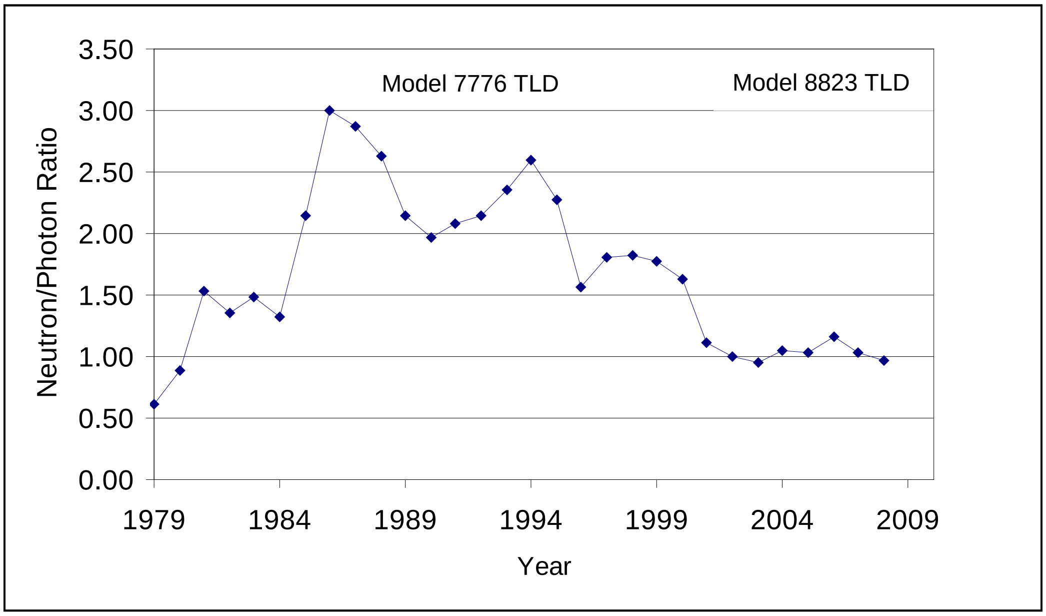


Figure 6-3. Geometric mean of neutron-to-photon ratios for records with both deep dose and neutron dose of 50 mrem or greater, 1979 to 2008 (LANL 2004, updated January 2009).

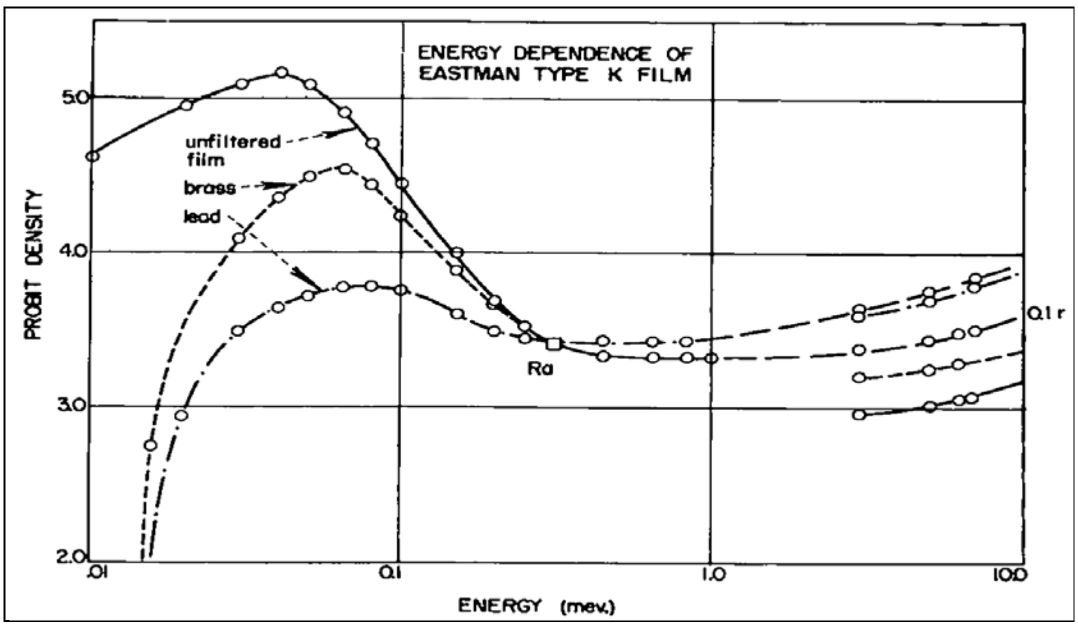


Figure 6-4. Energy dependence of Eastman Kodak Type K film for exposure of 0.1 R (Storm 1951).

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

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); Fix 2012]. 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 the method used to calibrate for plutonium did not consider the effect of the glovebox or buildup of ^{241}Am in the gloveboxes.

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 ^{241}Am (Hankins 1975).

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)

6.2.3.4 Workplace Radiation Fields

Table 6-14 lists LANL beta and photon energies and percentages. Table A-3 summarizes the recommended uncertainties to apply to the reported photon doses.

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

Process/ Buildings	Description	Operations Begin	Operations End	Radiation type	Energy selection (keV)	Percentage
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 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 1959			
	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 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 Photon	>15 <30 30–250	100 65 35
	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 35
	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. LANSCE	1972	Present	Non-Penetrating		
				Beta Photons	>15 > 30 keV photons	50 50
				Penetrating		
				Photon	<30 30–50 >250	1 9 90
Calibrations	LANL site calibration of instruments and dosimeters	1943	Present	Beta Photon	>15 30–250 >250	100 25 75
Waste	Radiation characteristics highly dependent on source of waste.			Beta	>15	100

Process/ Buildings	Description	Operations Begin	Operations End	Radiation type	Energy selection (keV)	Percentage
handling	Liquid waste: TA-45 and TA-50; Solid waste: Areas A, B, C, D, E, G, T, U, V	Various, 1944 on		Photon	30–250 >250	50 50
Radioactive lanthanum operations	**Preparation and use of radioactive lanthanum sources:**			Beta	>15	100
	TA-10 (Bayo Canyon)	1944	1950	Photon	30–250	10
	TA-35, “Ten Site”	1951	1963		>250	90

Sources: LASL (1959, 1969, 1977, 1979); LANL (1986, 1989, 1996, 2001, 2003).

6.2.3.5 Adjustments to Measured Dose Shallow Dose Components

Early LANL film badges had no unfiltered elements, and it has been determined that beta doses may only be estimated from 1949 onward. Shallow dose from photons in plutonium processing and production areas would have been unmonitored by the early dosimeters as well. For these cases, in the years prior to 1949, the recorded deep photon doses should be assigned in accordance with Table 6-14, and shallow dose should be assigned as low-energy photons (<30 keV), at 1.86 times the recorded photon dose.

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 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 Laboratory (TA-2, TA-18)
- CMR Building (TA-3)
- Reactor Operations (TA-35 and TA-52)

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 (more 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 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 (2007a). 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 PuBe	~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.

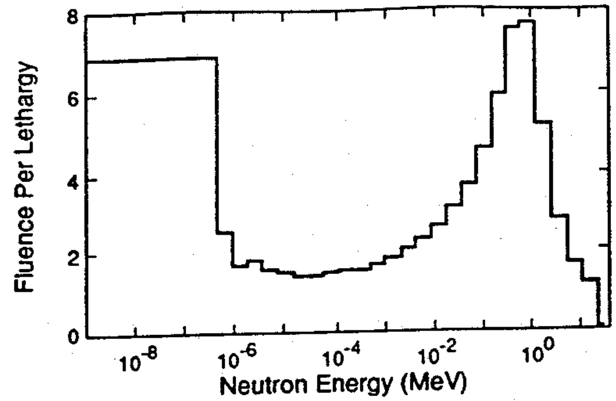
Multisphere neutron spectroscopy methods were applied to measure representative working fields in the LANL Plutonium Facility in 1993 (Harvey and Hajnal 1993). Work in this facility has involved ^{239}Pu and ^{238}Pu. Figure 6-5 shows the neutron spectrum measured during the hydrofluorination of $^{239}PuO_2$,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

6.2.3.6.1.2 Neutron-to-Photon Dose Ratio

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

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

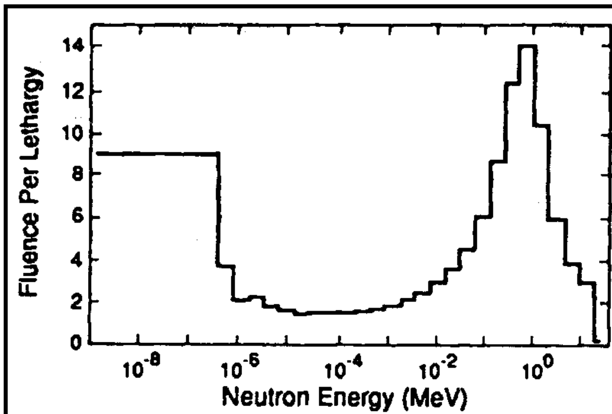
- For ^{239}Pu-fluoride areas, an NP ratio of 2.8 was reported for a health physics technician, not a chemical operator.



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

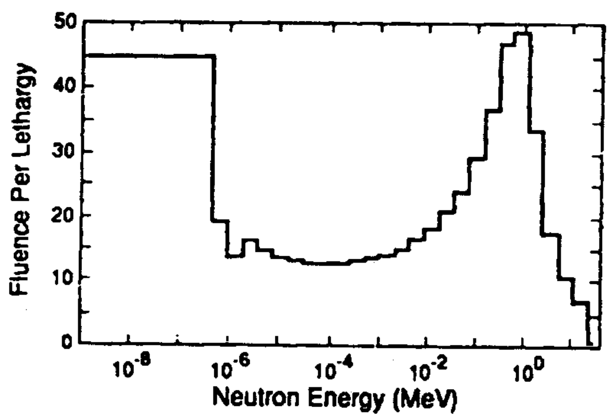
Figure 6-5. Neutron spectrum of hydrofluorination of $^{239}PuO_2$ at Plutonium Facility (Harvey and Hajnal 1993).



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



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 ^{238}Pu workers, observed NP 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 NP 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); Fix 2012] compared neutron dose results from NTA and TLDs and yielded NP 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.

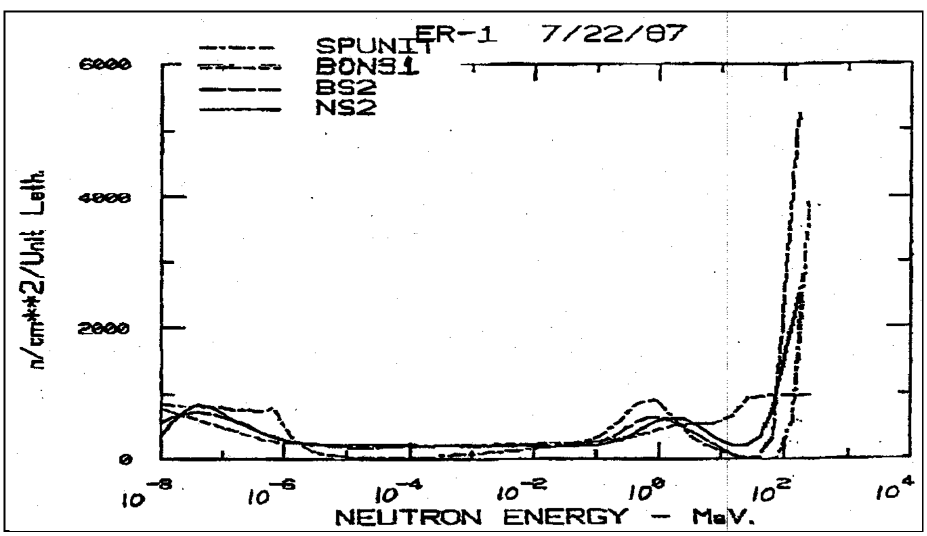


Figure 6-8. Neutron spectrum in ER-1 Area of LAMPF with proton beam stopped in the carbon beam block, as determined from unfolding codes (Mundis and Howe 1987).

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)].

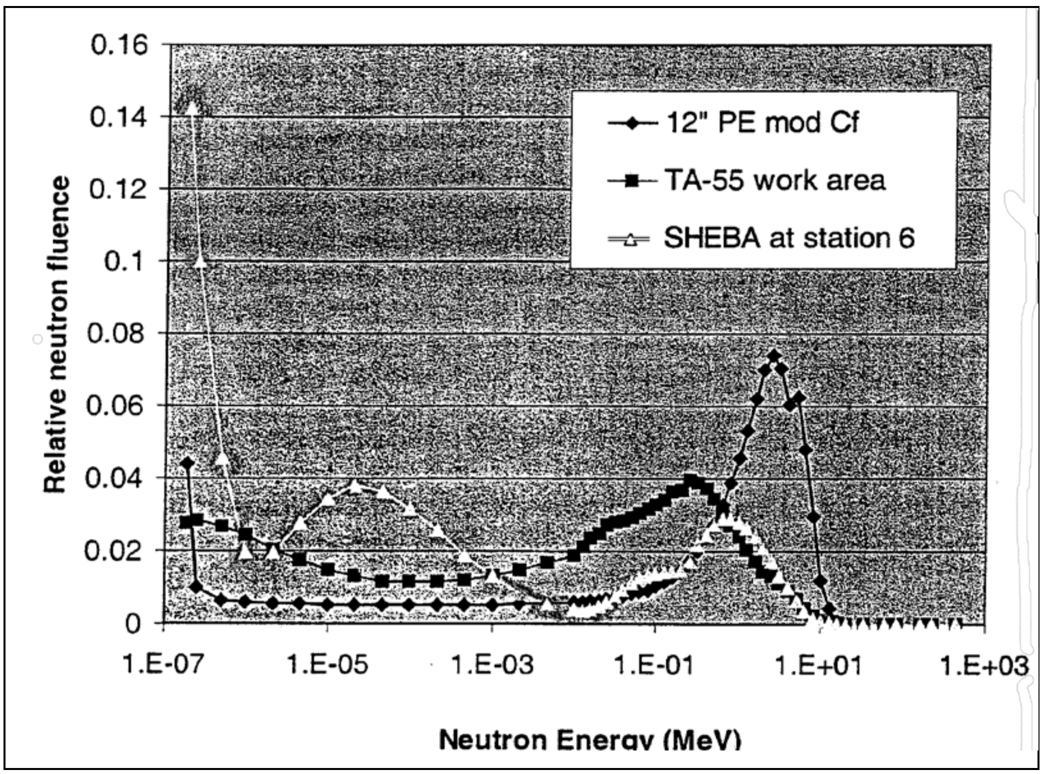


Figure 6-9. Neutron spectrum at Station 6 near TA-18 (white line).

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.

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

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

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 (2007a). 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:

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

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 TLD neutron dosimeters. Section 6.4 describes the neutron dose adjustments required, and Table A-3 summarizes the recommended uncertainties to apply to the recorded dose values.

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 multielement 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 the Hankins 6-month study from 1973 (Fix 2012).

- 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 (see 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-2.

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 Neutron Dose Adjustments

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 POC, 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 (2007a). 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).

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="13">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="4">7.56</td><td rowspan="4">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>
</table>

Neutron energy (MeV)	Historical dosimetry guideline[a]	NCRP 38 quality factors[b]	Average quality factor used at LANL	ICRP 60 neutron weighting factor (w_R)[c]
10		6.5		
14		7.5		
20		8	Not applicable	5
40		7		
60		5.5		

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).

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).

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

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: Begin	Operations: End	Neutron energy	Default dose fraction (%)	ICRP 60 correction factor
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. 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, LANSCE	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 April 1946	April 1946 Present	<10–100 keV 0.1–2 MeV 2–20 MeV	3.2 59 38	0.060 1.1 0.50
Chemistry and 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

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
- 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 an NP ratio. For years before 1979 at LANL, multiply the annual photon dose (adjusted for missed dose) by the NP dose factor from Section 6.4.4 and by the area-specific ICRP Publication 60 correction factor listed above to estimate neutron dose (ICRP 1991). For the years 1976-1980, NIOSH has agreed, in addressing comments on the TBD, to assign neutron dose using the 95^{th}-percentile value of the NP ratio to address uncertainties associated with the transition from film to TLD dosimeters.

6.4.4 Neutron-to-Gamma Dose Factors

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 NP ratios. This is because of the documented underestimating of doses by NTA dosimeters due to fading and significant effects of the NTA energy threshold in typical workplace neutron spectra. DOE 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.

Section 6.2.3.6.1.2 contains reported NP 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 NP 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). These values were reanalyzed for this revision of this TBD, and the results are included in Attachment B. The values were validated, though the 95th-percentile value was increased from 6.48 to 8.15. The calculated geometric standard deviations (GSDs) were included for all ratios in Table 6-22.

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

Neutron source type	Neutron-to-photon dose ratio		
	Median	GSD	95th percentile
Plutonium facilities (predominantly Pu-239)	0.7	2.3	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	1.23	5.5
Criticality experiments (>50 m distant)	2.3	1.05	2.5
Other operations	1.6	2.7	8.15

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 (2007a) 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 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. 1997; 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

Period of use[a]	Dosimeter	MDL[a] (mrem)	Exchange frequency	Mean annual missed dose[b] (mrem)
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 (2007a).
c. In accordance with the designation adding a class of LANL employees to the SEC, it is not feasible to reconstruct photon doses before 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-2 in Attachment A, and use of the applicable NP 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 (2007a).
b. NP 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 parameters related to dosimeter response, radiation type, energy, and worker orientation in the field.

Appendix A of NIOSH (2007a) 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 (2007a, Table 4.2); however, an assumption of 100% anterior-to-posterior geometry is typically the most representative, and is generally used for dose reconstruction. For exposures in which other geometries might result in a more accurate dose, the dose reconstructor is referred to the guidance in NIOSH (2007a).

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; 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 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 2010) 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 factor 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 (ergs or joules) deposited in a substance by ionizing radiation per unit mass (grams or kilograms) of the substance and measured in units of rads or grays. See *dose*.

accreditation
For external dosimetry, the assessment of whether or not a personnel dosimetry system meets specific criteria. The assessment includes dosimeter performance and the associated quality assurance and calibration programs.

accuracy
The characteristics of an analysis or determination that ensures that both the bias and precision of the resultant quantity will remain within the specified limits.

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

algorithm
Set of rules or steps for solving a problem, especially for calculating a value.

alpha radiation
Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2.

anterior-posterior
Physical orientation of the body relative to a penetrating directional radiation such that the radiation passes through the body from the front to the back.

attenuation
Process by which absorption and scattering reduces the number of particles or photons passing through a body of matter.

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

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

backscatter
Reflection or refraction of radiation at angles over 90 degrees from its original direction.

beta dose
Designation (i.e., beta) on some records for external dose from beta and less-energetic X-ray and gamma radiation, often for shallow dose or dose to the lens of the eye.

beta particle
See *beta radiation*.

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

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

calibration
Adjustment or determination of the response or reading of an instrument relative to a standard or a series of conventionally true values.

calibration blank
Dosimeter not exposed to radiation. This dosimeter establishes the dosimetry system base line or zero dose value.

collective dose equivalent
Sum of the dose equivalents of all individuals in an exposed population in units of person-rem or person-sievert. See *dose*.

confidence interval or level
The interval about an estimate of a stated quantity within which the value of the quantity is expected to be with a specified probability. See *uncertainty*.

control dosimeter
Dosimeter used to establish the background dose at one of several locations at Los Alamos. Control dosimeters were used to set the zero points for personnel dosimeter reading. Control dosimeters were also called “blanks” and “unirradiated dosimeters.”.

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

Cycolac
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)
Absorbed dose in units of rem or sievert at a depth of 1 centimeter (1,000 milligrams per square centimeter). See *dose*.

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

densitometer
Instrument that uses a photoelectric cell to measure the transition of light through developed X-ray film to determine the optical density.

density reading

See *optical density*.

DOE Laboratory Accreditation Program (DOELAP)

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

dose

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

dose conversion factor (DCF)

Multiplier for conversion of potential dose to the personal dose equivalent to the organ of interest (e.g., liver or colon). In relation to radiography, ratio of dose equivalent in tissue or organ to entrance kerma in air at the surface of the person being radiographed.

dose equivalent (DE or *H*)

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

dose equivalent index

Historical measure for neutron source calibration defined by the International Commission on Radiation Units and Measurements as the sum of the maximum dose equivalents delivered within a sphere at any depth for the respective neutron energies even though the maximum dose occurred at different depths and discounting the outer 0.07-millimeter-thick shell. Also called unrestricted dose equivalent index.

dosimeter

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

dosimetry system

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

DuPont 552 film packet

Film packet containing DuPont 502 sensitive film and DuPont 510 insensitive film.

DuPont 558 film packet

Film packet containing DuPont 508 film with sensitive and insensitive emulsions on either side.

error

Difference between the correct, true, or conventionally accepted value and the measured or estimated value. Sometimes used to mean estimated uncertainty. See *accuracy* and *uncertainty*.

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

exposure
(1) In general, the act of being exposed to ionizing radiation. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

exposure-to-dose-equivalent conversion factor for photons (C_x)
Ratio of exposure in air to the dose equivalent at a specified depth in a material of specified geometry and composition. 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 without trace elements, or soft tissue with trace elements).

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

extremities
The portion of the arm from and including the elbow through the fingertips and the portion of the leg from and including the knee and patella through the toes.

fast neutron
Neutron with energy equal to or greater than 10 kiloelectron-volts. This type of neutron causes fission in some isotopes (e.g., ^{238}U, ^{239}Pu). See *intermediate neutron* and *slow neutron*.

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

film density
See *optical density*.

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

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

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

gamma ray, particle, or photon (γ)
See *gamma radiation*.

geometric mean

The *n*th root of the product of all the members of a set of positive numbers, where *n* is the number of members. The sample geometric mean is designed for averaging ratio or proportion data. It is equivalent to taking logarithms of the sample values (i.e., transforming the sample), finding the arithmetic mean of the logs, and then retransforming back to the original scale (by taking antilogs). It can only be used when all the sample values are greater than zero.

geometric standard deviation (GSD)

In probability theory and statistics, the geometric standard deviation describes the spread of a set of numbers whose preferred average is the geometric mean

glovebox

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

gray (Gy)

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

intermediate neutron

Neutron with energy between 0.5 electron-volts and 10 kiloelectron-volts. See *fast neutron* and *slow neutron*.

ionizing radiation

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

isotope

One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U). Isotopes have very nearly the same chemical properties.

kerma

Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain. The word derives from kinetic energy released per unit mass.

kiloelectron-volt (keV)

Unit of particle energy equal to 1,000 (1×10^3) electron-volts.

kiva

One of the remotely controlled critical assembly buildings associated with the Critical Experiment Facility at LANL. From Hopi, *ki-* means house, but the meaning of *-va* is unknown.

luminescence

Emission of light from a material as a result of some excitation. See *thermoluminescence*.

Manhattan Engineer District (MED)

Subdivision of the U.S. Army Corps of Engineers that administered the World War II Manhattan Project to develop the first nuclear bomb. The word *Manhattan* was chosen to divert attention from the Project's real purpose. The U.S. Atomic Energy Commission assumed control of MED facilities and activities in 1946.

megaelectron-volt (MeV)

Unit of particle energy equal to 1 million (1×10^6) electron-volts.

minimum detectable activity

Smallest amount (activity or mass) of an analyte in a sample that can be detected with a probability β of nondetection (Type II error) while accepting a probability α of erroneously deciding that a positive (nonzero) quantity of analyte is present in an appropriate blank sample (Type I error).

minimum detectable level (MDL)

See *minimum detectable activity.*

missed dose

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

monitoring

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

multiple-collision neutron dose

Dose in relation to the neutron flux through tissue based on the assumption that two or more interactions per neutron occurs and results in greater energy deposition.

n, or n unit

Early unit of neutron dose used with pocket ionization chambers; the quantity of neutron radiation producing the same ionization in a 100-roentgen PIC as 1 roentgen of gamma radiation. See *pencil dosimeter*.

neutron

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

neutron film dosimeter

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

neutron radiation

Radiation that consists of free neutrons unattached to other subatomic particles emitted from a decaying radionuclide. Neutron radiation can cause further fission in fissionable material such as the chain reactions in nuclear reactors, and nonradioactive nuclides can become radioactive by absorbing free neutrons. See *neutron*.

nonpenetrating dose (NP, NPEN)

Dose from beta and lower energy photon (X-ray and gamma) radiation that does not penetrate the skin. It is often determined from the open window dose minus the shielded window dose. See *dose*.

notional dose

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

nuclear emulsion

Thick photographic coating in which the tracks of various fundamental particles show as black traces after development. The number of tracks in a given area is a measure of the dose from that radiation. See *nuclear track emulsion, type A*.

nuclear track emulsion, type A (NTA)

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

open window

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

optical density

Measure of the degree of opacity of photographic or radiographic film defined as $OD = \log_{10} (I_0/I)$, the base-10 logarithm of the ratio of the reference light intensity I_0 (without film) to the transmitted light intensity (through the film). Also called film density and density reading.

pencil dosimeter

See *pocket ionization chamber*.

penetrating dose (PEN)

Dose from moderate to higher energy photons and neutrons that penetrates the outer layers of the skin. See *dose*.

photon

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

photon radiation

Electromagnetic radiation that consists of quanta of energy (photons) from radiofrequency waves to gamma rays.

pit

Package at the center of an implosion weapon that contains the machined fissile material that begins the fission chain reaction. Also called primary.

pocket dosimeter
See *pocket ionization chamber*.

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

precision
Describes dispersion of measurements in relation to a measure of location or central tendency.

probability of causation (POC)
For purposes of dose reconstruction for the Energy Employees Occupational Illness Compensation Act, the percent likelihood, at the 99th percentile, that a worker incurred a particular cancer from occupational exposure to radiation.

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

quality factor (*Q*)
Principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose. The quality factor multiplied by the absorbed dose yields the dose equivalent.

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

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

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

random errors
When a given measurement is repeated and the values do not agree exactly. The causes of the disagreement between the values must also be the causes of their differences from the true value. See *systematic error*.

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

rep

Historical quantity of radiation (usually other than X-ray or gamma radiation) originally defined as 83 ergs absorbed per gram in the body and redefined in the 1940s or early 1950s as the amount that would liberate the same amount of energy (93 ergs per gram) as 1 roentgen of X- or gamma rays. Replaced by the gray in the International System of Units; 1 rep is approximately equal to 8.38 milligray. The word derives from roentgen equivalent physical.

roentgen (R)

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

scattering

Change in direction of radiation by refraction or reflection, often accompanied by a decrease in radiation due to absorption by the refracting or reflecting material.

shallow absorbed dose (Ds)

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

shallow dose equivalent (Hs)

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

shielding

Material or obstruction that absorbs ionizing radiation and tends to protect personnel or materials from its effects.

sievert (Sv)

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

skin dose

See *shallow dose equivalent*.

slow neutron

Neutron with energy less than 1 electron-volt. See *fast neutron* and *intermediate neutron*.

Special Nuclear Material (SNM)

Plutonium or uranium enriched to a higher-than-natural assay including ^{239}Pu, ^{233}U, uranium containing more than the natural abundance of ^{235}U, or any material artificially enriched in one of these isotopes.

systematic errors

When a given measurement is repeated and the values differ from the true value by the same amount. See *random error*.

Technical Area (TA)

Area of land at LANL for assigned operations.

thermal neutron

Neutron in thermal equilibrium with its surroundings having an average energy of 0.025 electron-volts.

thermoluminescence

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

thermoluminescent dosimeter (TLD)

Small block or crystal of lithium fluoride in a thermoluminescent dosimeter. A TLD-600 dosimeter contains a chip made from more than 95% ^{6}Li for neutron radiation detection, and a TLD-700 dosimeter contains a chip made from more than 99.9% ^{7}Li for photon and beta radiation detection. Also called crystals.

thermoluminescent dosimeter chip

Small block or crystal of lithium fluoride in a thermoluminescent dosimeter. A TLD-600 dosimeter contains a chip made from more than 95% ^{6}Li for neutron radiation detection, and a TLD-700 dosimeter contains a chip made from more than 99.9% ^{7}Li for photon and beta radiation detection. Also called crystals.

tissue equivalent

Substance with response to radiation equivalent to tissue. A tissue-equivalent response is an important consideration in the design and fabrication of radiation measuring instruments and dosimeters.

track-etch dosimeter (TED)

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

U.S. Atomic Energy Commission (AEC)

Federal agency created in 1946 to assume the responsibilities of the Manhattan Engineer District (nuclear weapons) and to manage the development, use, and control of nuclear energy for military and civilian applications. The U.S. Energy Research and Development Administration and the U.S. Nuclear Regulatory Commission assumed separate duties from the AEC in 1974. The U.S. Department of Energy succeeded the U.S. Energy Research and Development Administration in 1979.

uncertainty

Standard deviation of the mean of a set of measurements. The standard error reduces to the standard deviation of the measurement when there is only one determination. See *accuracy*, *confidence level*, and *error*. Also called standard error.

Van de Graaff accelerator

Direct current high-voltage accelerator in which a terminal in a pressurized tank accelerates the beam. The voltage is generated by charge carried on an insulating belt.

whole-body dose

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

X-ray radiation

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

Zia

Private firm created as the facilities contractor for LANL and its support community.

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A.1 UNMONITORED PHOTON DOSE

Table A-1 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. The reported doses that are the basis of this table have not been corrected for potential missed doses.

Table A-1. Worker gamma dose statistics.[a]

	LANL recorded gamma dose data[b]			Lognormal fit		
	No. of workers reported	Dose (mrem)		Dose (mrem)		
Year[a]	gamma dose ≥ 50 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
1952	936	7.12E+02	1.00E+04	3.10E+02	2.29E+03	3.37
1953	908	6.72E+02	1.07E+04	3.22E+02	2.28E+03	3.28
1954	1,007	8.61E+02	8.99E+03	4.04E+02	3.16E+03	3.49
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
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

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Year[a]	LANL recorded gamma dose data[b]			Lognormal fit		
	No. of workers reported gamma dose ≥ 50 mrem	Dose (mrem)		Dose (mrem)		GSD
		Mean	Maximum	Median	95%	
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. In accordance with the addition of a class of LANL employees to the Special Exposure Cohort, it is infeasible to reconstruct gamma doses before 1946 (NIOSH 2007b).
b. Individual dosimeter records analyzed only if gamma dose was equal to or greater than 50 mrem.

When necessary, it is recommended that dose reconstructors assign the median (that is, geometric mean) gamma dose from Table A-1 to an unmonitored worker for each year of employment; however, LANL had a strict policy for monitoring exposed employees, with some exceptions described above. Also, when unmonitored photon dose is assigned, the addition of missed dose is required as well. The dose reconstructor must make an assumption about the likely dosimeter exchange frequency, and assume all unmonitored dose occurred in one cycle, with missed dose for all other cycles.

A.2 ADJUSTMENTS TO REPORTED PHOTON DOSES

Table A-2 lists adjustments to reported LANL photon doses.

Table A-2. 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	Photon exposures >200 keV (reactors, uranium production,	Multiply reported photon doses that exceed	LASL 1969 (10/13/64 memorandum)

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	badge	accelerators, calibrations, waste handling, radioactive lanthanum, etc.)	100 mrem by 4.	

a. Plutonium areas have included TA-1, TA-21, TA-55, and some areas of TA-3.
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-3 lists recommended uncertainty factors to be applied to worker doses reported by LANL.

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

Radiation	Film badges (1946-1979)	NTA film (1951-1978)	Model 7776 dosimeter (1980-1998)	Model 8823 dosimeter (1999-Present)
Photon (deep)	±30%	Not applicable	±14%	±19%
Beta (shallow)	±30%	Not applicable	±16%	±14%
Neutron (deep)	Not applicable	±50%	±8%	±8%

A.3 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 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-4 can be considered maximum annual missed doses for 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).

Missed beta/photon dose is entered into the Interactive RadioEpidemiological Program (IREP) as a lognormal distribution with a geometric mean consistent with Table A-4 and a GSD of 1.52.

A.4 UNMONITORED NEUTRON DOSE

There should not, typically, be significant neutron exposure of unmonitored workers, with the exception of 1946 to 1949 (NIOSH 2007b). However, if there is an estimation of neutron dose, the recommended option is to apply the NP distribution data from Table 6-22 to 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

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measured for monitored workers. The application of the NP ratios is discussed in Section 6.4.3, and is facilitated with automated options in approved external dose spreadsheets.

Table A-4. 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
October 1962–December 1979	Cycolac multielement 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–present	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 6-14 footnotes for guidance on calculation of unmonitored nonpenetrating dose.
c. Mean annual missed dose calculated using MDL/2 from NIOSH (2007a).
d. According to the designation adding a class of LANL employees to the SEC, it is not feasible to reconstruct nonpenetrating doses before 1949 (NIOSH 2007b).

The application of the data from Table 6-22 to measured or estimated photon doses can be accomplished through Monte Carlo simulation.

A.5 RECOMMENDED DOSE CONVERSION FACTORS

DCFs should be selected from NIOSH (2007a) for the dose quantities specified in Table A-5 for the periods of interest.

Table A-5. Recommended DCFs for dose assessments.

Period	Recommended photon DCF	Recommended neutron DCF
1946–1984	Exposure (R) to organ DE (H_T)	Deep DE [$H_{p,slab}(10)$] to organ DE (H_T)
1985–present	Deep DE [$H_p(10)$] to organ DE (H_T)	

ATTACHMENT B
LANL NEUTRON-TO-PHOTON (NP) DOSE RATIO ANALYSIS

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B.1 INTRODUCTION

This attachment describes analyses performed to calculate the statistical parameters of lognormal distributions of NP dose ratios using recorded doses for LANL workers (LANL 2004) from 1944 through November 2008. This information extends the information in this TBD.

B.1.1 Purpose

The purpose of this attachment is to document the method of analysis and to present the calculated statistical lognormal distribution parameters [i.e., geometric mean (GM), GSD, and the 95th percentile] for each year and selected multiyear periods.

B.1.2 Method

The analysis of NP dose ratios used LANL recorded dose data in LANL (2004). Only annual neutron and photon doses that equal or exceed 50 mrem were used. The analysis results are in Fix (2011).

B.2 SUMMARY

The calculated NP dose ratio parameters for each year from 1944 through 2008 are listed in Table B-2 (Fix 2011). The pattern in the GM and 95th-percentile parameters are shown in Figure B-1 with significant events from the history of LANL dosimetry presented in this attachment. A documented personal communication with a LANL external dosimetry site and subject expert, who performed many workplace dose measurements and evaluations, was also done (Fix 2012).

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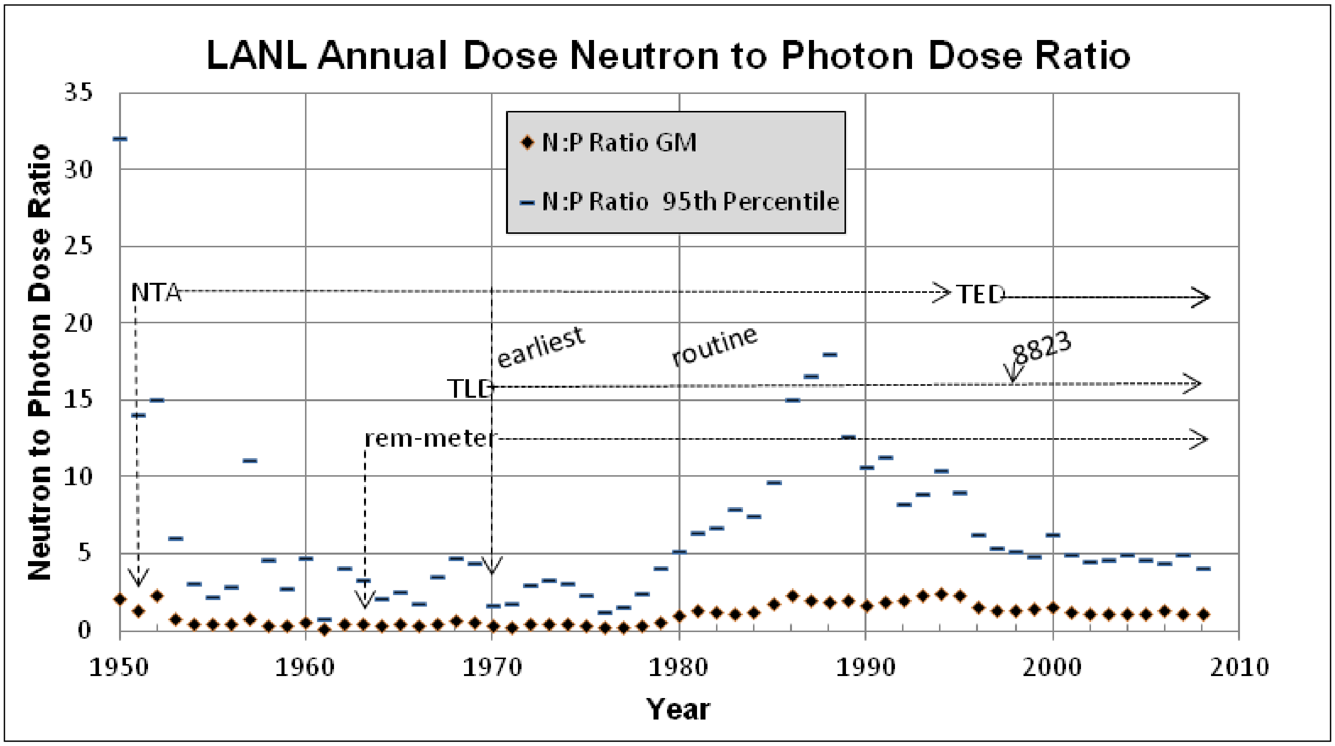

Figure B-1. LANL worker GM and 95th-percentile NP dose ratio, 1950 to 2008.

The statistical parameters in Table A-1 are based on 412,000 (1950–2008) measured annual dose results. Significant dosimetry-related events noted in Figure B-1 include:

- Implementation of the use of NTA film in 1951 (Littlejohn 1961). LANL had earlier used a similar nuclear track emulsion glass plate for routine dosimetry. The use of NTA to measure neutron dose continued until 1995 when the routine use of track-etch dosimetry was implemented.
- LANL had available an instrument capability to measure the neutron DE in rem that was used in 1963 (Hankins 1963). This capability provides a means to assess the performance of dosimeter-measured workplace doses with an accurate instrument measurement.
- LANL introduced thermoluminescent dosimetry capabilities over many years. The earliest noted studies occurred in 1970 (Hankins 1969), whereas regular assignment of TLDs to all workers was occurring in 1978 (Lawrence 1978).
- LANL participated in performance testing of the standard that eventually was issued as ANSI/HPS N13.11 in 1983 (HPS 1983). This standard formed the basis of the DOELAP for personnel dosimetry. LANL was DOELAP-accredited in 1985 for requested categories.
- LANL implemented updated TLD capabilities with the Bicron/Harshaw 8823 system in 1998, which uses TED capabilities for selected workers (Hoffman and Mallett 1999b).

The data in Figure B-1 can be summarized over selected periods based on the foregoing dosimetry operational considerations. Several options are listed in Table B-1.

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Table B-1. Statistical parameters for selected periods of LANL recorded doses.

Period	Description	NP dose ratio GM	GSD	95th percentile
1950–2008	All years of NTA, TLD, or TED dose data	1.04	3.06	6.43
1979–2004	ORAUT-TKBS-0010-6 (2009) period	1.55	2.73	8.27
1979–2008	ORAUT-TKBS-0010-6 (2009) plus 2005–2008	1.50	2.68	7.77
1980–2008	Era of dosimeter performance testing	1.53	2.66	7.90
1985–2008	DOELAP-accredited dosimetry systems	1.60	2.61	8.15

In the absence of a known or suspected neutron exposure, a reasonable assumption for neutron dose reconstruction is a GM of 1.6 and a GSD of 2.7.

ORAUT-TKBS-0010-6
Table 6-22 of this TBD summarizes recommended NP dose ratios for identified sources of neutron radiation. The analyses in this Attachment primarily pertain to Neutron Source Types A and D in Table 6-22. It is evident from the GM and 95th-percentile values that the results of the current analysis and those used in the development of recommendations in this TBD are equivalent. The values in Table 6-22 were updated to include the changed 95th-percentile value in the last row; all other values were verified.

B.3 CALCULATED NP DOSE RATIO STATISTICAL PARAMETERS, 1944–2008

Table B-2 summarizes the statistical analysis of recorded doses at LANL.

Table B-2. Statistical analysis of LANL recorded doses (Fix 2011).

Year	Number of workers: Total monitored	Positive recorded dose	Photon, neutron dose ≥50[a]	NP dose ratio: Mean	Max.	GM	GSD	95th percentile
1944	9	7	0					
1945[(b)]	812	413	2	139.32	275.00	31.62	1.47	261.43
1946[(b)]	508	391	7	14.02	16.94	13.93	1.12	16.53
1947	1,237	1,004	0					
1948	2,080	1,383	0					
1949	3,177	1,817	21	3.32	10.88	2.25	2.32	10.63
1950	3,895	1,981	75	4.86	24.00	2.12	2.64	14.78
1951	4,257	2,538	142	3.01	25.75	1.32	3.37	11.52
1952	2,366	1,262	97	3.81	39.94	2.31	2.08	9.40
1953	1,878	1,151	131	1.53	9.18	0.80	3.04	5.45
1954	2,068	1,166	99	0.85	5.14	0.48	2.77	2.92
1955	1,984	956	100	0.63	4.80	0.39	2.11	1.62
1956	2,287	1,189	112	0.84	8.75	0.49	2.60	2.28
1957	2,539	1,054	78	2.66	31.17	0.77	4.87	10.53
1958	3,032	1,378	133	1.01	8.27	0.36	4.43	4.29
1959	2,930	1,552	186	0.75	11.57	0.37	3.16	2.30
1960	3,622	1,718	179	1.04	6.80	0.58	2.44	2.88
1961	3,973	1,395	24	0.24	0.83	0.16	2.10	0.63
1962	4,119	2,101	45	1.02	4.42	0.49	3.63	3.93
1963	4,176	1,702	71	1.01	8.40	0.40	5.36	5.46
1964	4,103	1,580	89	0.60	3.38	0.35	2.90	2.02
1965	4,222	1,352	101	0.75	10.00	0.40	2.71	2.14

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Year	Number of workers			NP dose ratio				
	Total monitored	Positive recorded dose	Photon, neutron dose ≥50[a]	Mean	Max.	GM	GSD	95th percentile
1966	4,446	1,514	98	0.53	4.14	0.29	3.41	1.89
1967	4,072	1,493	84	0.95	9.60	0.44	3.22	3.42
1968	3,861	2,044	114	1.26	9.00	0.62	3.59	4.79
1969	3,980	2,679	159	1.18	9.29	0.59	3.17	3.87
1970	4,031	1,018	150	0.49	6.80	0.28	2.59	1.48
1971	3,775	806	85	0.48	2.45	0.25	3.24	1.69
1972	3,877	938	127	0.78	5.40	0.39	3.48	2.86
1973	3,866	924	202	0.91	10.20	0.48	2.71	2.67
1974	4,337	1,392	250	0.92	18.07	0.42	3.46	3.17
1975	4,716	1,874	229	0.67	10.20	0.38	2.91	2.23
1976	5,254	2,165	136	0.37	2.80	0.20	3.39	1.42
1977	5,624	1,851	130	0.47	8.67	0.22	3.47	1.69
1978	7,045	2,070	135	0.64	6.50	0.29	3.92	2.44
1979	7,549	2,511	288	1.14	11.33	0.59	3.33	4.15
1980	7,638	3,443	340	1.63	12.80	1.00	2.82	5.51
1981	7,966	5,034	463	1.96	14.50	1.30	2.14	5.35
1982	7,997	4,297	456	1.89	15.30	1.21	2.19	5.07
1983	8,144	4,419	445	1.85	11.57	1.13	2.08	5.00
1984	8,622	6,069	535	1.94	11.57	1.26	2.05	5.29
1985	9,487	4,921	434	2.63	21.40	1.76	1.94	6.36
1986	9,612	2,262	324	3.72	21.40	2.27	2.24	11.59
1987	9,202	1,621	253	3.54	17.71	1.99	2.27	10.75
1988	9,469	1,548	271	3.68	25.80	1.85	2.58	12.59
1989	10,605	1,616	244	3.24	14.33	1.93	2.43	9.58
1990	10,796	1,538	207	2.69	14.71	1.64	2.40	8.80
1991	11,284	2,356	156	3.05	19.90	1.85	2.28	8.73
1992	11,560	1,687	131	2.85	17.24	2.00	2.11	7.29
1993	11,772	1,948	132	3.23	15.03	2.34	2.29	9.18
1994	11,783	3,145	170	3.38	15.88	2.41	2.19	9.37
1995	12,448	3,219	188	3.21	20.92	2.27	2.18	8.21
1996	10,959	2,358	197	2.14	11.69	1.57	1.91	5.09
1997	10,860	2,992	215	1.86	10.78	1.31	2.50	5.61
1998	11,168	2,201	171	1.78	9.16	1.40	2.21	4.50
1999	11,212	1,720	158	1.85	8.34	1.40	2.25	4.94
2000	10,456	1,485	122	2.10	7.03	1.52	2.07	5.22
2001	10,443	1,435	156	1.74	6.91	1.22	2.61	5.39
2002	10,931	1,760	199	1.55	6.91	1.07	2.39	4.22
2003	10,752	2,101	239	1.57	7.91	1.25	2.66	4.77
2004	10,192	1,731	156	1.64	9.86	1.13	2.52	4.79
2005	10,826	2,176	193	1.71	7.47	1.29	2.24	4.42
2006	10,104	2,021	215	1.93	9.24	1.51	2.21	4.70
2007	9,745	1,525	203	1.79	8.01	1.34	2.36	4.73
2008[c]	8,148	941	106	1.48	5.91	1.05	2.52	4.42

a. Number of workers with recorded neutron and deep photon doses, respectively, ≥ 50 mrem.
b. Doses anticipated to have been estimated following accidents and not routinely measured.
c. Anticipated to represent <1 year of dose data (i.e., November 2008 last noted dose entry).