## TABLE OF CONTENTS


Section Page

6.1 Introduction ..... 8

6.2 Dose Reconstruction Parameters ..... 10
6.2.1 LANL Administrative Practices ..... 11
6.2.1.1 Assignment of Dosimeters to Workers ..... 11
6.2.1.2 Dosimeter Exchange Frequencies ..... 12
6.2.1.3 Use of Control Dosimeters ..... 15
6.2.1.4 Reporting Conventions ..... 16
6.2.1.5 Recordkeeping ..... 19
6.2.1.6 Quality of LANL External Dosimetry Data ..... 20
6.2.2 Dosimetry Technology ..... 21
6.2.2.1 Beta/Photon Dosimeters ..... 22
6.2.2.2 Neutron Dosimeters ..... 25
6.2.3 Calibration ..... 28
6.2.3.1 LANL Beta/Photon Dosimeters ..... 28
6.2.3.2 LANL Neutron Dosimeters ..... 32
6.2.3.3 LANL Workplace Radiation Fields ..... 34
6.2.3.4 LANL Workplace Beta/Photon Dosimeter Response ..... 34
6.2.3.5 Uncertainty in Beta/Photon Recorded Dose ..... 36
6.2.3.6 Workplace Neutron Dosimeter Response ..... 36
6.2.3.6.1 Plutonium Processing Areas (TA-1, TA-21, TA-55) ..... 38
6.2.3.6.1.1 Neutron Energy Spectrum ..... 38
6.2.3.6.1.2 Neutron-to-Photon Dose Ratio ..... 39
6.2.3.6.2 LAMPF (TA-53) ..... 39
6.2.3.6.3 Critical Assembly Testing (TA-18) ..... 41
6.2.3.6.3.1 Neutron Energy Spectrum ..... 41
6.2.3.6.3.2 Neutron-to-Photon Dose Ratio ..... 42

6.2.3.6.4 Reactor Areas (TA-2) ... 43
6.2.3.6.5 CMR Building (TA-3) ... 43
6.2.3.7 Neutron Dose Fraction ... 44
6.2.3.8 Uncertainty in Neutron Dose ... 44

6.3 Adjustments to Recorded Photon Dose ... 44

6.4 Adjustments to Recorded Neutron Dose ... 45
6.4.1 Neutron Dose Adjustments ... 45
6.4.2 Neutron Weighting Factor ... 45
6.4.3 Neutron Correction Factor ... 46
6.4.4 Neutron-to-Photon Dose Factors ... 47

6.5 Missed Dose ... 48
6.5.1 Photon Missed Dose ... 48
6.5.2 Neutron Missed Dose ... 49

6.6 Organ Dose ... 49

References ... 50

Glossary ... 55

Attachment 6E GUIDANCE FOR DOSE RECONSTRUCTORS—OCCUPATIONAL EXTERNAL DOSE FOR MONITORED WORKERS ... 63

6E.1 Recorded Dose Practices And Interpretation Of Reported Doses ... 64

6E.2 Unmonitored Photon Dose ... 65

6E.3 Adjustments To Reported Photon Doses ... 67

6E.4 Missed Beta/Photon Dose ... 68

6E.5 Attribution Of Beta/Photon Doses To Energy Categories ... 69

6E.6 Unmonitored Neutron Dose ... 71

6E.7 Missed Neutron Dose ... 71

6E.8 Attribution Of Neutron Doses To Energy Categories ... 72

6E.9 Recommended Dose Conversion Factors ... 72

## LIST OF TABLES

| Table | | Page |
|---|---|---|
| 6-1 | Volumes of LANL Photodosimetry Evaluation Book | 10 |
| 6-2 | Annual external radiation doses, 1944–2003 | 13 |
| 6-3 | Summary of typical exchange frequencies for LANL dosimeters primarily in use during different periods of time | 15 |
| 6-4 | Quantities recorded in Los Alamos exposure records over time | 18 |
| 6-5 | LANL external dosimetry events | 21 |
| 6-6 | Photon and beta dosimeters used over time at Los Alamos | 25 |
| 6-7 | Neutron dosimeters used over time at Los Alamos | 28 |
| 6-8 | TLD and film badge energy response to beta radiation, ca 1977 | 30 |
| 6-9 | DOELAP irradiation techniques and effective energies | 31 |
| 6-10 | General energy distribution of photons in 1962 at DP West Site | 35 |
| 6-11 | Estimated photon spectra for several plutonium sources in DP West facility | 35 |
| 6-12 | Calculated errors from use of the Cycolac badge with low energy photons and a correction factor of 0.07 | 35 |
| 6-13 | Results of a 6-month comparison of film badges, NTA film, and TLDs at DP Site | 36 |
| 6-14 | Selection of beta and photon radiation energies and percentages for LANL facilities | 37 |
| 6-15 | Approximate NCFs and dose fractions for neutron sources at LANL | 38 |
| 6-16 | Results of six-month comparison of film badges, NTA film, and TLDs at DP site | 39 |
| 6-17 | Percent of total kerma by energy interval from LANL critical assemblies | 42 |
| 6-18 | Gamma-to-neutron ratios measured with TLDs on the front of “plastic man” manikins near LANL critical assemblies | 43 |
| 6-19 | Laboratory-measured dose fractions from $PuF_4$ | 44 |
| 6-20 | Neutron quality or weighting factors | 46 |
| 6-21 | LANL facility dose fractions and associated ICRP 60 correction factors | 47 |
| 6-22 | Recommended distribution for neutron-to-gamma ratio for Los Alamos | 48 |
| 6-23 | LANL photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose | 49 |
| 6-24 | LANL neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose | 50 |
| 6E-1 | Recorded dose practices over time at Los Alamos | 64 |
| 6E-2 | LANL worker gamma dose statistics | 65 |
| 6E-3 | Recommended adjustments to reported LANL photon doses | 67 |
| 6E-4 | Recommended uncertainty factors for reported LANL doses. | 67 |
| 6E-5 | LANL beta/photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed doses | 68 |
| 6E-6 | Recommended beta and photon radiation energies and percentages for LANL plutonium facilities | 69 |
| 6E-7 | Recommended beta and photon radiation energies and percentages for LANL facilities *other than* plutonium facilities | 70 |
| 6E-8 | LANL neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose | 71 |
| 6E-9 | Recommended distributions for neutron-to-gamma ratio for Los Alamos | 71 |
| 6E-10 | Recommended dose fractions and ICRP 60 correction factors for LANL neutron sources | 72 |
| 6E-11 | Recommended dose conversion factors for LANL dose assessments | 72 |

## LIST OF FIGURES

Figure Page

6-1 Number of workers monitored at LANL as a function of time ..... 14
6-2 Comparison of Hp(10) for neutrons with energy responses of NTA film and neutron albedo dosimeter containing a TLND chip made of $^{6}$lithium fluoride and shielded by cadmium ..... 27
6-3 Geometric mean of neutron-to-photon doses from LANL for 1940-2004 for records with both deep dose and neutron dose 50 mrem or greater ..... 34
6-4 Energy dependence of Eastman Kodak Type K Film for exposure of 0.10 R ..... 35
6-5 Neutron spectrum of hydrofluorination of $^{239}PuO_2$ at LANL Plutonium Facility ..... 40
6-6 Neutron spectrum of $^{238}$Pu Ball Milling Process at LANL Plutonium Facility ..... 40
6-7 Neutron spectrum near door K in SNM Vault at LANL Plutonium Facility ..... 40
6-8 Neutron spectrum in ER-1 Area of LAMPF with proton beam stopped in the carbon beam block, as determined from unfolding codes ..... 41
6-9 Neutron spectrum at "Station 6" near TA-18 ..... 42

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AEC | U.S. Atomic Energy Commission (DOE predecessor agency) |
| ABS | acrylonitrile-butadiene-styrene, a plastic used in some dosimeter badges |
| AP | anterior-posterior |
| CMR | Chemistry and Metallurgy Research (building or Division) |
| CMR-12 | The Radiochemistry Group at early LANL |
| CR-39 | Columbia Resin Number 39, a material used in track etch neutron dosimeters |
| DCF | dose conversion factor |
| DE | dose equivalent |
| DOE | U.S. Department of Energy |
| DOELAP | DOE Laboratory Accreditation Program |
| DP | DP Site[1], or TA-21. The site of plutonium processing at LANL from 1945 until 1978. Also housed polonium processing. |
| EDBS | External Dosimetry Badge System |
| ERDA | Energy Research and Development Administration (DOE predecessor agency) |
| GMX-1 | The Radiography Group at early LANL |
| H | H Division or Health Division at LANL |
| Hp(d) | Personal Dose Equivalent at depth d in tissue |
| HRL | Health Research Laboratory (located at TA-43) |
| HT | Heat Treatment Building at TA-1 |
| HYPO | Water Boiler Reactor in high-power configuration |
| IARC | International Agency for Research on Cancer |
| ICRP | International Committee for Radiological Protection |
| ICRU | International Commission on Radiation Units and Measurements |
| LAMPF | Los Alamos Meson Physics Facility |
| LAMPRE | Los Alamos Molten Plutonium Reactor Experiment |
| LANL | Los Alamos National Laboratory (January 1981 to present) |
| LAPRE I | First Los Alamos Power Reactor Experiment |
| LAPRE II | Second Los Alamos Power Reactor Experiment |
| LASL | Los Alamos Scientific Laboratory (January 1947 to December 1980; name changed to Los Alamos National Laboratory in January 1981) |
| LOPO | Water Boiler Reactor in low-power configuration |
| MED | Manhattan Engineer District |
| MeV | million electron volts |
| MDL | Minimum Detection Level |
| mm | millimeter |

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

| | |
|---|---|
| NBS | National Bureau of Standards (predecessor to NIST) |
| NCF | neutron correction factor |
| NCRP | National Council on Radiation Protection and Measurements |
| NIOSH | National Institute for Occupational Safety and Health |
| NRC | U.S. Nuclear Regulatory Commission |
| NRD | "neutron rem detector," a neutron survey instrument using a moderated $BF_3$ detector |
| NIST | National Institute of Standards and Technology |
| NTA | Eastman-Kodak Nuclear Track, Type A emulsion |
| NTP | nuclear track plate |
| ORNL | Oak Ridge National Laboratory |
| PIC | pocket ionization chamber (i.e., "Pencil" dosimeter) |
| PN3 | a name for LANL's track-etch neutron dosimeter |
| PNNL | Pacific Northwest National Laboratory |
| PVC | polyvinylchloride |
| R | roentgen |
| rem | roentgen equivalent man |
| rep | roentgen equivalent physical |
| SUPO | Water Boiler Reactor in highest (Super) power configuration |
| TA | Technical Area; a section of land at Los Alamos, with TA number from 0 to 74, that has been the site of identified operations or activities |
| TBD | technical basis document |
| TED | track-etch dosimetry or dosimeter |
| TLD | thermoluminescent dosimeter |
| UC | University of California, operator of the Los Alamos facility since its founding |
| UHTREX | Ultra High-Temperature Reactor Experiment |
| WB | whole body |
| Y | Site Y, the code name for Los Alamos Laboratory under the MED from April 1943 to December 1946. |

## 6.1 INTRODUCTION

Technical Basis Documents (TBDs) and Site Profile Documents are general working documents that provide guidance concerning 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 the National Institute for Occupational Safety and Health (NIOSH) in the completion of the individual work required for each dose reconstruction. This TBD section provides information to support reconstruction of external radiation doses to a variety of body organs in individuals who have worked at Los Alamos National Laboratory. This document does not currently address reconstruction of skin dose.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy facility” as defined in the Energy Employee Occupational Illness Compensation Program Act of 2000 [42 U.S.C. Sections 7384l (5) and (12)].

When the Los Alamos Laboratory 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) (LANL 2001a); for simplicity, except in reference citations, this TBD uses LANL for all time periods. LANL assignments in the early 1940s included:

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

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

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

Operations, facilities, and capabilities that were needed to support development and production of the various types of nuclear devices expanded in many cases to support other missions after World War II (ChemRisk 2004). Programs in chemistry, metallurgy, and low-temperature physics expanded into nonmilitary development and fundamental research. The Health Division grew significantly and expanded into many areas of health physics, industrial hygiene, medicine, safety, and biomedical

research regarding people and radiation. Early reactors built to confirm critical masses for fissionable materials and to study properties of fission and the behavior of 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 the modern decades, LANL has been a large multidisciplined 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 radiations. 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 (Hoffman and Mallett 1999a). Neutron radiation exposures at LANL originate from isotopic 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 staff for compliance with radiation control limits. The National Institute for Occupational Safety and Health (NIOSH) *External Dose Reconstruction Implementation Guidelines* (NIOSH 2002) has identified these as the highest quality records for retrospective dose assessments. The information in this TBD pertains to analyzing 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, about 1940. The primary challenges encountered by MED, and later 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 concerning policies, procedures, practices, and issues dealing with external radiation monitoring at LANL are documented in a compilation of correspondence and reports called the *Photodosimetry Evaluation Book*. Informally, this compilation, which has eight volumes, has been referred to as "the Bible" of external radiation dosimetry at LANL. The "Bible" was assembled by James N.P. Lawrence in 1956, expanded by Lawrence until around 1970, when Joe Cortez assumed responsibility (Widner 2004). Table 6-1 lists the volumes that currently comprise this resource.

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

| Volume | Approximate date range | Reference |
|---|---|---|
| Ia | 1/19/44 to 1/12/59 | LASL 1959 |
| Ib | 10/10/56 to 7/28/58 | LASL 1958 |
| II | 1/2/60 to 12/23/69 | LASL 1969 |
| IIIa | 2/18/70 to 12/20/74 | LASL 1974 |
| IIIb | 1/19/75 to 7/26/77 | LASL 1977 |
| IVa | 1/27/78 to 12/3/80 | LASL 1980 |
| IVb | 6/2/81 to 10/21/86 | LANL 1986 |
| V | Misc. docs. - 6/5/45 to 2/8/79 | LASL 1979 |
| VI | 4/8/85 to 12/15/89 | LANL 1989 |
| VII | 2/2/90 to 2/15/96 | LANL 1996 |
| VIII | 02/08/96 to 12/5/01 | LANL 2001b |
| IX (active) | 2/14/02 to 5/28/03 | LANL 2003 |

## 6.2 DOSE RECONSTRUCTION PARAMETERS

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

Overall, accuracy and precision of the original recorded individual worker doses and their comparability to be considered in using NIOSH (2002) guidelines depend on (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 LANL Administrative Practices

Historically, LANL had an extensive radiation safety monitoring program using portable radiation instruments, contamination surveys, zone controls, and personnel dosimeters to measure exposure in the workplace (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; 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 whole-body (WB) beta/photon dosimeters
- Pocket ionization chamber (PIC) dosimeters
- Personnel extremity dosimeters
    - Personnel whole-body neutron dosimeters

Shortly after operations began in 1943, some workers were monitored with PICs alone. In 1943, photon film dosimetry methods were first used by a LANL group. Other 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 dependence of film response. LANL officially switched to the use of thermoluminescent dosimeters (TLDs) in 1980, and is currently using its second generation of TLD badge. Prior to 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 were first used, and badges incorporated Nuclear Track, Type A (NTA) emulsion film 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 have been used for evaluation of fast neutron doses since 1995.

Parameters concerning 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)]. 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. 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 consideration 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 compared to their alpha activity, and that film badges would only be needed for those who worked in and around the storage vault if it were to contain about 2,000 Ci or more. For “urchin”-type initiators, 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 curie-minutes at 1 cm, and it was recommended that studies involving use of impressions of the ridges on the finger tips as indicators of radiation exposure be continued [LASL 1959 (June 7 and 8 memoranda)]. For preparation of polonium-beryllium (PoBe) neutron sources, fast neutron exposure was limiting. Around October 1948, the need for film monitoring at the DP West plutonium facilities was recognized because of low-level gamma exposure from spontaneous fission in plutonium and the possibility of a criticality accident. It was emphasized at the time that AEC Safety Regulation 3 required that film badges be worn in any area where radioactive materials were handled.

As of April 1960, the brass-cadmium film badge was being worn by about half of University of California (UC) 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 was starting (Widner 2003). Between 1943 and late 1981, the number of persons monitored for external exposures increased from less than 100 to more than 5,000 per year, 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 to workers at LAMPF for high-energy dosimetry during accelerator operations (about 7 months per year) (LANL 1996).

Table 6-2 presents a listing of the reported numbers of workers monitored by LANL from 1944 to 2003 along with total doses and average doses calculated from those data (LANL 2004). Figure 6-1 shows the number of workers monitored each year over the same period (LANL 2004). The data upon which Table 6-2 and Figure 6-1 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. When 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 had been issued to all Sigma and HT (Heat Treatment 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

Table 6-2. Annual external radiation doses, 1944–2003 (LANL 2004).

| Year | Total dose (person-rem) | No. of workers monitored | Average total dose (rem) |
|---|---|---|---|
| 1944 | 7.89 | 9 | 0.88 |
| 1945 | 2,153.37 | 812 | 2.65 ** |
| 1946 | 3,819.95 | 508 | 7.52 ** |
| 1947 | 464.62 | 1,237 | 0.38 |
| 1948 | 343.05 | 2,080 | 0.16 |
| 1949 | 466.42 | 3,177 | 0.15 |
| 1950 | 552.49 | 3,895 | 0.14 |
| 1951 | 2,503.80 | 4,257 | 0.59 |
| 1952 | 812.72 | 2,366 | 0.34 |
| 1953 | 717.16 | 1,878 | 0.38 |
| 1954 | 920.18 | 2,068 | 0.44 |
| 1955 | 763.25 | 1,984 | 0.38 |
| 1956 | 1,280.80 | 2,287 | 0.56 |
| 1957 | 585.75 | 2,539 | 0.23 |
| 1958 | 5,704.65 | 3,032 | 1.88 ** |
| 1959 | 447.09 | 2,930 | 0.15 |
| 1960 | 541.02 | 3,622 | 0.15 |
| 1961 | 299.22 | 3,973 | 0.08 |
| 1962 | 386.62 | 4,119 | 0.09 |
| 1963 | 251.83 | 4,176 | 0.06 |
| 1964 | 250.63 | 4,103 | 0.06 |
| 1965 | 364.67 | 4,222 | 0.09 |
| 1966 | 241.24 | 4,446 | 0.05 |
| 1967 | 268.31 | 4,072 | 0.07 |
| 1968 | 285.12 | 3,861 | 0.07 |
| 1969 | 388.69 | 3,980 | 0.10 |
| 1970 | 408.92 | 4,031 | 0.10 |
| 1971 | 341.21 | 3,775 | 0.09 |
| 1972 | 338.66 | 3,877 | 0.09 |
| 1973 | 436.00 | 3,866 | 0.11 |
| 1974 | 409.64 | 4,337 | 0.09 |
| 1975 | 452.67 | 4,716 | 0.10 |
| 1976 | 393.26 | 5,254 | 0.07 |
| 1977 | 432.81 | 5,624 | 0.08 |
| 1978 | 364.53 | 7,045 | 0.05 |
| 1979 | 320.88 | 7,549 | 0.04 |
| 1980 | 375.54 | 7,638 | 0.05 |
| 1981 | 588.55 | 7,966 | 0.07 |
| 1982 | 672.83 | 7,997 | 0.08 |
| 1983 | 673.33 | 8,144 | 0.08 |
| 1984 | 798.77 | 8,622 | 0.09 |
| 1985 | 715.19 | 9,487 | 0.08 |
| 1986 | 531.67 | 9,612 | 0.06 |
| 1987 | 400.48 | 9,202 | 0.04 |
| 1988 | 391.98 | 9,469 | 0.04 |
| 1989 | 326.93 | 10,605 | 0.03 |
| 1990 | 228.85 | 10,796 | 0.02 |
| 1991 | 163.25 | 11,284 | 0.01 |
| 1992 | 132.49 | 11,560 | 0.01 |
| 1993 | 141.81 | 11,772 | 0.01 |
| 1994 | 178.44 | 11,783 | 0.02 |
| 1995 | 234.93 | 12,448 | 0.02 |
| 1996 | 188.70 | 10,958 | 0.02 |
| 1997 | 182.02 | 10,860 | 0.02 |
| 1998 | 158.21 | 11,167 | 0.01 |
| 1999 | 128.89 | 11,212 | 0.01 |
| 2000 | 87.45 | 10,456 | 0.01 |
| 2001 | 114.28 | 10,443 | 0.01 |
| 2002 | 160.06 | 10,871 | 0.01 |
| 2003 | 218.83 | 10,660 | 0.02 |

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

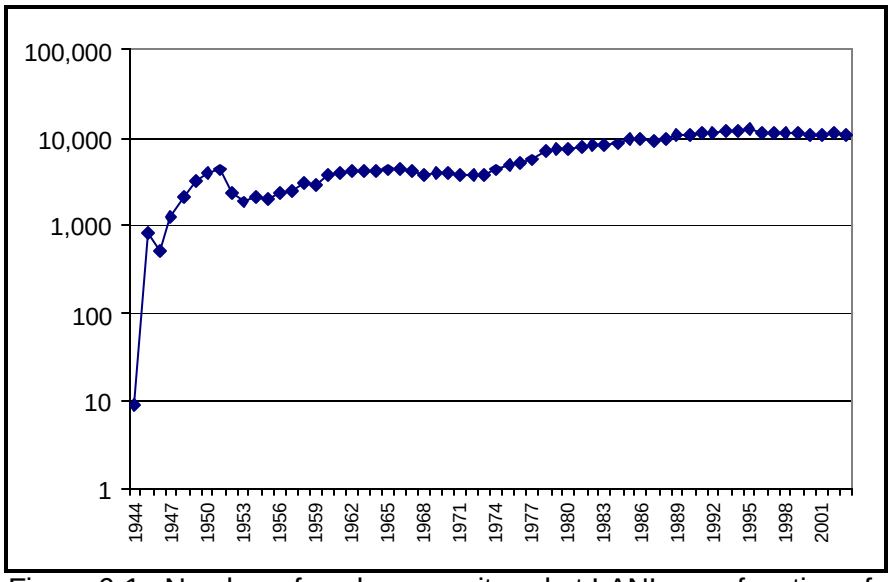



Figure 6-1. Number of workers monitored at LANL as a function of time (LANL 2004).

Group personnel were then considering exchanging 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)]. Nuclear track plates (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 manpower considerations. At that time, only half the plates issued were read [LASL 1959 (10/4/56 memorandum)].

In September 1988, LANL evaluated changing from monthly to monthly/quarterly badge issue (LANL 1989). The HSE-1 section leader recommended against changing to monthly/quarterly issuance, stating that problems with fading supported continuation of monthly exchange. Monthly exchange continued to be the most common.

In February 1992, LANL temporarily switched to quarterly badge exchange due to installation startup problems with a new data management system, with the exception of 22 employees who were involved in a special project that required weekly exchange. Monthly exchange was reinstated in April 1992. LANL began phasing in a quarterly dosimeter exchange frequency for personnel who received low occupational radiation exposure beginning in April 1996 (LANL 2001b). The cutoff was <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. Summary of typical exchange frequencies for LANL dosimeters primarily in use during different periods of time.

| Dosimeter type | Date range | Exchange frequency |
|---|---|---|
| PICs | Prior to 1945 | Daily |
| Film Badges | 1943 – 1979 | Monthly for some, biweekly for some, up to daily for some operations |
| TLDs | 1980 –1995 | Monthly |
| TLDs | 1996 – present | Monthly for most, Quarterly for some |
| NTPs | 1949 – approx. 1951 | 4-week interval |
| NTA Film | 1951 – 1995 | 4-week interval |
| TEDs | 1995 – present | Quarterly |

#### 6.2.1.3 Use of Control Dosimeters

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

- An October 1944 report (in LASL 1959) received at LANL from the MED about the use of lead cross dental film packets to monitor gamma, X, and beta exposure mentions 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 a unidentified MED warehouse says that "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 that LANL personnel were familiar with from the early years of operations.

- A Los Alamos "Nuclear Track Plate Evaluation Procedure" dated 2/27/56 (in LASL 1979) states that: "It has been found that NTPs which are not worn, but are processed and 'read,' will indicate some exposure. This exposure varies somewhat with the seasons, etc., and is attributed to cosmic radiation. Therefore, whenever a group of NTPs are packaged for issue, a "blank" NTP is also packaged and immediately sent to P-10 for processing and reading. Then the blank's exposure will be subtracted from the personnel's neutron exposure during the process of evaluating the NTPs."

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

- A July 23, 1991 memo from to the Dosimetry Evaluation Book (in LANL 1996) indicates that, in response to a finding from a DOELAP on-site audit, "several 'unirradiated dosimeters' have been added to the blind audit program since January, 1991."

- An April 29, 2003 memo from Jeffrey Hoffman to Michael McNaughton (in LANL 2003) discusses 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), indicates that the blind-testing protocol at that time included 19 whole-body TLDs, 13 extremity TLDs, 13 track-etch dosimeters 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 whenever 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 all photographically developed at the same time. These badge racks, which were for storage of dosimeter badges when the badges were not being worn by the persons to whom they were issued (e.g., overnight or over weekends), were in areas where only background radiation was expected under normal circumstances, and “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 vs. the exposure given to the calibration film were plotted 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 some rare occasions when the “personnel control film” showed some exposure due to fallout from Nevada test 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 reading the other personnel films (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 (likely 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, when PICs were used. Gamma exposures were recorded in units of roentgen (R). Prior to 1949, some Laboratory personnel who worked with the cyclotron and other neutron sources wore Victoreen pencil PICs to determine 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 (Widner 2004). See Section 6.2.2.2 for more details about the n unit.

When brass film badges came into use by more and more LANL groups between 1943 and 1945, only gamma exposure was evaluated, in roentgens.

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

- Pocket ionization chamber readings (R)
- Gamma exposure (R)
    - Beta exposure in roentgens equivalent physical (rep)

Beta exposures were 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 R 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)).

Also starting in 1949, NTPs came into use. As of February 1956, NTPs were evaluated by assuming all 10-100 micron 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 $cm^{-2}$ $sec^{-1}$ in the early years, neutron doses were reported in terms of rem in 1953 and possibly earlier [LASL 1959 (Jan. 1953 document)].

Prior to April 1957, exposures for HT shop and Sigma areas (where uranium was handled) were recorded as pure beta exposures, while 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 1/10 was used in converting radiation exposure records for IBM entry to retrospectively calculate 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.

The Roentgen-to-rem dose conversion factor 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 1960):

- 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 handling $^{238}Pu$ [LASL 1974 (12/3/71 memorandum)]. This appears to have been a special study for a relatively small group of workers, possibly using hand-fabricated badges with loose chips, because TLDs were in relatively short supply at that time (Widner 2003).

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

- "Non-penetrating Rad" – represented the total skin dose from external ionizing radiation; was equal to old beta-rad + gamma-rem or old gamma-R.
- "Penetrating-rem" – represented the total whole-body dose from external ionizing radiation; was equal to old gamma-rem dose. Evaluated based on the copper-filtered TLD chip.

- "Neutron-rem" – was typically equal to the albedo (body-scattered) neutron dose from the TLD badge; when "piggyback" NTA film was used, the fast neutron dose from NTA film was added to the albedo neutron dose, and "NTA" was entered in the Remarks field.
- "Total-rem" – was equal to penetrating-rem + neutron-rem + tritium-rem (where "tritium-rem" was calculated from tritium urine assays).

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

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

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

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

Table 6-4. Quantities recorded in Los Alamos exposure records over time
(LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003).

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

In 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., that no monitoring was performed for the subject individual for that period, and no dose records are available.
- 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.
- The SKIN doses reported are derived by LANL as shallow dose + neutron dose + tritium dose.
- When for a given month, the dose report form identifies "Badge Type" as "Monthly," but there are up to five lines of data (see example below), that indicates that multiple badges were worn during the month. The doses for the individual badges should be added to obtain the dose totals for the month.

| EXTERNAL DOSE (rem) | | SKIN | DEEP | NEUTRON | TRITIUM |
|---|---|---|---|---|---|
| June | Monthly | 0.000 | 0.000 | | |
| June | Monthly | 0.000 | 0.000 | | |
| June | Monthly | 0.010 | 0.010 | | |
| June | Monthly | 0.000 | 0.000 | | |
| June | Monthly | 0.040 | 0.020 | | |

- When doses are reported as follows, it reflects that the badge in use had two elements– dental x-ray film and NTA film. In the case below, the first line of data is from the NTA film, and the second is from the dental x-ray film. In these cases, the neutron dose entry on the second line for the month is essentially a place holder, 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 file [LASL 1959 (1/20/51 document)]. December 9, 1946, was the first date for which a record of visitor badge issuance has been found in LA notebooks, and the use of the notebooks for visitor badge data ended in January 1951 [LASL 1980 (10/30/79 memorandum)].

In August 1950, H Division started supplying PICs and film badges for use by GMX-1 group in "extraordinary work" [LASL 1959 (February1956 memorandum)]. Prior to that time, dosimetry for the GMX-1 group was reportedly handled by GMX-1 personnel at GT Site, and apparently no long-term records of these early measurements were retained.

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

In 1957, a computerized "IBM" 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 1960). 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 [LASL 1980 (9/28/78 document)]. For purposes of reporting to the primary employer of visitors, non-zero exposures recorded by the LANL Cycolac film badge were defined to be total-rem 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 for <0.04 rem was not required, which would have been an enormous undertaking due to the need to track down each visitor to obtain employer name and address for reporting purposes. On January 1, 1976, LANL had to start reporting zero exposures for all Energy Research and Development Administration (ERDA) visitors, because ERDA had just established a radiation exposure record system for all its employees [LASL 1980 (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. Pending implementation of the new external dosimetry data management system, NTA neutron doses were entered using the same guidelines as those for TLD neutron doses: doses ≤ 4 mrem were entered as 0 rem, 5-14 mrem were entered as 0.01 rem, 15-24 were entered as 0.02 rem, 25-34 were entered as 0.03 rem, 35-44 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 (EDBS).

#### 6.2.1.6 Quality of LANL External Dosimetry Data

At LANL, dosimeters were selected, issued to workers, and processed, with resulting measurements 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 1958, 1959, 1969, 1974, 1977, 1979, 1980; 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 recorded dose of record.

### 6.2.2 Dosimetry Technology

LANL health physicists learned from experiences at other MED sites following the general evolution in dosimeter technology, using PICs in addition to one- or two-element dosimeters in the 1940s and early 1950s, followed by multielement film dosimeters in the latter 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, generally corresponding to the period of regulatory dose controls (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003). At the beginning of Laboratory operations, a dose control of 1 mSv per day (100 millirem/day) was in effect. This was changed to 3 mSv per week (300 millirem/week) and later to 50 mSv per year (5,000 millirem) in the late 1950s. These changes were in accord with AEC regulations at the time and with the appropriate National Bureau of Standards handbooks (Widner 2003). Table 6-5 summarizes major events in the LANL personnel dosimetry program.

Table 6-5. LANL external dosimetry events (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003).

| Period | Event |
|---|---|
| 1943 | Monitoring for external radiation exposures began, using PICs. |
| 1943 | Film badges first used at Los Alamos, by the GMX-1 Radiography Group. These badges apparently used Lead Cross Type K dental film in a brass holder. |
| Early 1944 | LANL H-Division health physicists gathered information about film monitoring practices from other MED sites. |
| May 1944 | Film badges, made at LANL, distributed to various workers by H Division on a trial basis. |
| February 1945 | System of monitoring exposure of personnel with photographic film was established by the H Division, with badges exchanged monthly. Continued to use PICs. |
| Late 1945 | After Omega Site criticality accident, "catastrophe badges" were developed and assigned to workers who could be involved in criticality accident. |
| Aug 1947 | “Brass Film Badge” in use included three types of film in a brass container with no windows or filters of other metals. |
| Sep 48 - Mar 49 | New badge phased in. Brass clip provided only partial shielding of film surface. |
| 29-Aug-49 | First NTPs issued for evaluation of fast neutrons. |
| 20-Apr-50 | Started changeover to new badge that used brass and lead filters plus unfiltered area. |
| 7-Mar-51 | Studied ring badges and wrist badges, and variability of ratios between them. |
| 24-Mar-51 | New finger film badge developed. Used Eastman Kodak Type K or DuPont sensitive Type 552, brass and cadmium filters. |
| April 1951 | Change to brass and cadmium badge. Brass and cadmium filters, plus open window. Used DuPont 502 dental film and Eastman Kodak Type B packet that contained NTA fast neutron film and Fine Grain Positive. |
| 1954 | Thermal neutron measurements started. |
| 1955 | Routine measurement of thermal neutrons was discontinued. |
| 1956 | Routine evaluation of thermal neutron exposures reinstituted. |
| October 1962 | Multielement Cycolac film badge put into use. It included multielement filter, another multielement filter with $^{6}$Li, and unfiltered area. Two film packets: DuPont 543 (with DuPont 502 film), Kodak Type B (with NTA fast neutron film and Fine Grain Positive). |
| 31-Jan-63 | Practice of using wrist-to-finger ratios greater than 1 discontinued. |
| March 1963 | Comparison of Cycolac and brass-cadmium badges conducted. |
| August 1968 | LANL tried to duplicate Battelle PNL badge performance study of 1966, in which it did not participate. |
| September 1970 | Started issuing film badges with TLD-ribbon containing plastic insert to selected individuals at DP Site. Purpose of these badges with TLD-600 and TLD-700 ribbons was to evaluate individual exposures between film development and evaluation. |
| 1971 -1972 | Prototype albedo-neutron TLD badge studied at DP West, compared to Cycolac film badge data. |
| Jul.- Dec. 1972 | Performance of film badges, NTA film, and prototype albedo-neutron-TLDs compared at DP West plutonium facilities over a 6-month period. |

Table 6-5 (Continued). LANL external dosimetry events (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003).

| Period | Event |
|---|---|
| May 1978 | Began issuing Model 7776 TLD badges to visitors. Certain LANL groups got them starting in September. Additional LANL groups changed from film to TLD throughout 1978-1979, as TLD cards and badges were acquired. |
| 1978-1979 | LANL participated in NRC/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-80 | Dosimetry section completed changeover from film dosimetry badges to TLD badges as dosimeter of record. Model 7776 badge had cadmium and non-cadmium versions. Cadmium version was initially used at LAMPF. |
| Late 1980 | Changed to use of non-cadmium badge at LAMPF to gain sensitivity. |
| June 1981 | Concurrent monitoring with NTA film and TLDs was conducted. |
| June 1981 | Discontinued routine issue of NTA film for LAMPF personnel. |
| December 1984 | LANL applied to participate in pilot testing of DOELAP. |
| 1/16/85 | LANL selected for participation in pilot testing of DOELAP. |
| July 1987 | TLD plus NTA badges used with other detectors during special neutron spectral measurements at LAMPF. |
| May 1988 | Neutron measurements made at seven locations in TA-55 Room 209 using ESP-2 neutron instrument and TLD badges on Lucite phantom. |
| June 1991 | LANL expressed interest in participating in some categories of DOELAP testing of extremity dosimeters (not the categories with low-energy beta emitters or neutrons). |
| August 1992 | Comparison conducted of bubble dosimeters with Model 7776 TLDs. |
| 1993 | LANL purchased automated reader for use with chemically etched CR-39 detectors. |
| 1995 | LANL introduced track-etch dosimeter (TED) in 1995 as replacement for NTA film as high-energy neutron dosimeter at LAMPF. |
| 22-Feb-96 | Moved up deployment of new eight-element TLD (worn with 7776 TLD badge) for use in dynamically determining employee-specific neutron correction factors. |
| April 1996 | Began to phase in quarterly dosimeter exchange frequency for personnel who received "low" occupational radiation exposure. |
| 1996 | LANL submitted track-etch neutron dosimeters for irradiation at PSI in Europe. |
| February 1998 | Review of Model 8823 TLD as neutron dosimeter issued. |
| 1-Apr-98 | Model 8823 became dosimeter of record. Eight-element TLD (called Model 8823 by manufacturer Harshaw/Bicron) uses Model 7774 TLD cards. |
| October 1998 | Began using wrist dosimeter for routine monitoring in October 1998. |
| 1999 | LANL track-etch dosimeter passed DOELAP performance testing for neutrons. |
| 1999 | LANL participated in 4th Intercomparison of Personal Dosimeters Used in U.S. DOE Accelerator Facilities. |
| 2000 | LANL submitted TLDs and track-etch badges for irradiation by monoenergetic, accelerator produced neutrons from 0.144 MeV to 19.0 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, 1943-1948.** Prior to 1951, external dosimetry was provided by three different organizations within LANL; H Division, the CMR-12 Radiochemistry Group, and the GMX-1 Radiography Group. The first use of film badges at Los Alamos was apparently in 1943 by the GMX-1 Radiography Group (Widner 2004).

On January 19, 1944, H-Division personnel inquired with Col. Stafford Warren at Oak Ridge National Laboratory about using strips of film to check exposures to radiation. They requested film and instructions for its use, for use in checking their Victoreen pocket ionization chambers. By May 18, 1944, LANL had started to distribute film monitors to various people (LASL 1959 (5/18/44 memorandum)]. On June 14, 1944, Stafford Warren of MED gave authorization to order Lead Cross Type K Dental Film from Eastman Kodak Co. In February 1945, the H Division instituted a system of monitoring 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 placed over one face (and 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 0.5 mm-thick lead cross folded over the edge of the packet; the combined thickness of the lead and the 0.033 inch thick brass holder served to absorb 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, 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 - 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 1500 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 concerning the point in time when the film badge in use at LANL switched from the version 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. When a breakpoint is needed to provide guidance for dose reconstruction, it is assumed that the Lead Cross film was used through June 1946.

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

**Brass Clip Badge, 1949-1950.** 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. 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, 1950-1951.** 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, 1951-1962.** 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, 1962-1978.** 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 sulphur foils for accident dosimetry. The Cycolac badge was seen to have the advantages of relative gamma and X-ray energy independence (within 30%) from about 30 keV to 1400 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, 1978-1998.** 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 receiving 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 having plastic covers in the "noncadmium badge." The Dosimetry section completed the changeover from film dosimetry badges to TLD badges as 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 thermoluminescent dosimeter 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-colored 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, into 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 for determining photon deep dose. Positions 2 and 3 are beta windows that are covered with one and two layers of aluminized Mylar, respectively. The aluminized Mylar is coated with black paint on the back to maximize light attenuation.

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

Table 6-6. Photon and beta dosimeters used over time at Los Alamos (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003; Widner 2003, 2004).

| Period | Type badge | Film or media used |
|---|---|---|
| 1943-1944 | Pocket Ionization Chambers | Quartz fiber |
| 1943 to June 1946 | Brass Film Badge | Eastman Kodak Lead Cross Type K Dental Film packet |
| July 1946 to 1948 | Brass Film Badge– no windows or filters of any sort | 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 |
| 1950-1951 | Brass Film Badge– brass and lead filters plus unfiltered portion | Eastman Kodak Type K |
| 1951-1962 | Brass-Cadmium Badge– brass and cadmium filters, plus open window | Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Type B (contained NTA fast neutron film and Fine Grain Positive) |
| 1962-1979 | "Cycolac" Plastic Badge– multielement filter, a second multi-element filter with $^{6}$Li, and an unfiltered area | Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Type B (contained NTA fast neutron film and Fine Grain Positive) |
| 1980-March 1998 | Model 7776 TLD Badge (Cadmium and non-cadmium versions)- copper, Cycolac plastic, and cadmium filters | 3 TLD 700 chips (one covered with Cu, one with plastic) and one TLD 600 chip (enriched in 6Li). In the "cadmium badge," the 3rd TLD 700 chip and the TLD 600 chip are shielded by cadmium pockets; they are covered by plastic in the "noncadmium badge." |
| April 1998 -present | Model 8823 TLD Badge | Two TLD cards hold a total of 8 TLD elements. One card has 3 TLD-700 elements and one TLD-400. Two elements are filtered with ABS plastic. Two have minimal filtration. The 2nd card is in a Cd box; two elements form a classic Albedo detector with a TLD-600/-700 pair surrounded by Cd 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 Cd except for an opening away from the body. |

#### 6.2.2.2 Neutron Dosimeters

LANL has used five general types of neutron dosimeters, which 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, Prior to 1949.** Prior to 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 inches long and 0.5 inch 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 one n unit corresponded to about 5.9 rad of neutron exposure ($\pm$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 evaluating 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 prepared 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-micron emulsion on glass backing supplied by Ilford were used for fast neutron dose evaluation. They were thought to have been accurate to within factor of 2.

**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 sulphur foils for accident neutron dosimetry. The main concerns with NTA film were that latent-image tracks faded rapidly when humidity was high, and the lowest energy neutrons detectable in routine evaluations were about 0.8 to 1.0 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 dessicant to minimize fading due to high humidity [LANL 1989 (6/22/89 memorandum)].

**Thermoluminescent Dosimeters.** LANL began issuing TLD badges to visitors beginning 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 having 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 certification, 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 whole-body TLD before the Model 8823 was accepted as the dosimeter of record. During this interim period, the dedicated neutron portion of the Model 8823 was used to calculate employee-specific neutron correction factors to be applied to the Model 7776 whole-body TLD net-neutron reading (LANL 2001b [2/22/96 document]). The Model 8823 dosimeter received its first DOELAP accreditation after successfully passing 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 Track-Etch Dosimeter (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 to only 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).

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

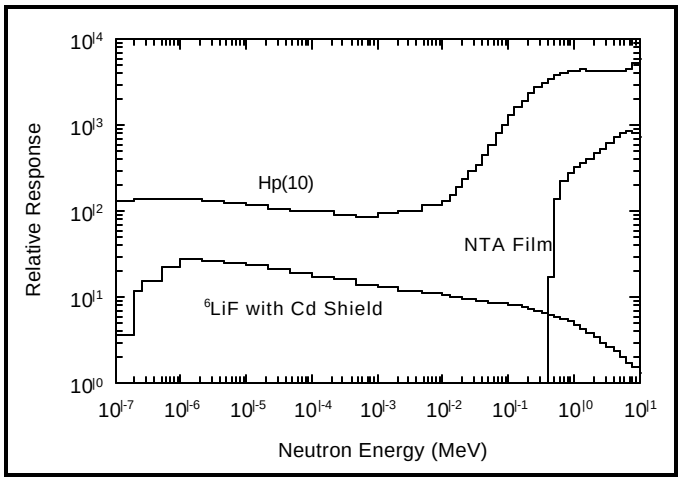



Figure 6-2. Comparison of Hp(10) for neutrons with energy responses of NTA film and neutron albedo dosimeter containing a TLND chip made of $^{6}$lithium fluoride and shielded by cadmium (IAEA 1990).

Table 6-7. Neutron dosimeters used over time at Los Alamos (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; 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 to1951 | Nuclear Track Plates | NTPs with 1000 micron emulsion on glass backing supplied by Ilford |
| 1951-1962 | Brass-Cadmium Badge- brass & 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 Type B (contained NTA fast neutron film and Fine Grain Positive) |
| 1962-1979 | "Cycolac" Plastic Badge- multielement filter, a second multielement filter with $^{6}$Li, and an unfiltered area. | Two film packets: DuPont 543 (contained DuPont 502 dental film), Eastman Type B (contained NTA fast neutron film and Fine Grain Positive) |
| 1980-1998 | Model 7776 TLD Badge (Cadmium & Noncadmium versions)- (used with NTA film in a "piggy back" 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 to present | Track-Etch Dosimeter | 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 track-etch dosimeter by those with potential high energy neutron exposure) [measures thermal, intermediate, and fast neutrons, with no separation of fast neutrons] | Two elements form a classic Albedo detector with a TLD-600/-700 pair in Cd except for an opening toward the body. Two positions are an incident thermal neutron detector, with a TLD-600/-700 pair in Cd except for an opening away from the body. |

### 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 dosimeter response to low-energy photon radiation and NTA and Model 7776 TLD response to neutron radiation.

#### 6.2.3.1 LANL 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:** Per a 2/16/56 memorandum (LASL 1959), calibrations were done with radium for gamma and a sheet of depleted uranium for beta. 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. For non-penetrating dose in plutonium facilities a 78-kVP x-ray calibration was used instead of the depleted uranium slab.

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

By 1960, film badges were calibrated to gamma radiation with a $^{60}$Co source (Littlejohn 1960). The dose rate from the calibration source was measured with a Victoreen r-chamber calibrated by the National Bureau of Standards. 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 also made to nickel-coated and uncoated plutonium. The uncoated plutonium was encased in 0.020-inch 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 drybox conditions. Because the plutonium calibration curves were parallel to the $^{60}$Co curve, open-window densities resulting 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 1960).

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

An 8/24/62 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 known surface dose rate. Plutonium source calibrations were also done to measure the response to 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-gram 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 R 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 centimeter 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-gram piece of uncoated plutonium metal encased in PVC and to a fluorescent X-ray source emitting 71% 20-keV, 22% 60-keV, 5% 100-keV, and 2% >200-keV X-rays, simulating 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 non-penetrating 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 roentgen factor used with the brass-cadmium badge prior to January 1963 but was based on “better data” published by Watson (1959)] accounted for the fraction penetrating to the gonads based on Hanford research per a November 27, 1963, memorandum (LASL 1969). The DOELAP dose conversion factor for 17 keV photons is 0.38 rem/roentgen (DOE 1986).

Around July 9, 1971, LANL started issuing film badges to selected individuals at DP Site that also included an insert containing TLD ribbons [LASL 1974 (7/9/71 memorandum)]. The TLDs were calibrated on the P-6 gamma range[1] 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 1000 keV (Storm et al. 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 varying 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 1170- and 1330-keV photons from $^{198}$Au, $^{137}$Cs, and $^{60}$Co, respectively.

For beta dose, personnel dosimeters were calibrated by exposing them 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 Sr/Y 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 Sr/Y and 51 mrad in contact with uranium.

By 1977, calibrations were performed with dosimeters in air, on a phantom, and in a phantom (Storm et al. 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 placing 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 et al. 1977). Non-penetrating dose calibrations were measured by placing 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 varying in maximum energy from 770 to 2,300 keV; $^{204}$Tl, $^{32}$P, and $^{90}$Sr($^{90}$Y) (Storm et al. 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, ca 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 |

[1] The P-6 gamma range was located in the Physics Building. It was normally used for calibrating instruments, not 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, since scattering contributed significantly to the radiations emerging from the well (Widner 2004).

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) will be high by at least 10%. Lacking the time and manpower 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 is designed to determine the responses for each of the eight elements in the Model 8823 dosimeter using 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 PNNL in late 1996. These irradiations included photons with effective energy ranging from 17 to 662 keV, betas with maximum energies of 760 to 2.27 MeV, and bare and moderated fission neutron sources.

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

| **Photons** | |
|---|---|
| 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 LANL Neutron Dosimeters

Historical aspects of the calibration of LANL film, NTA, and TLD dosimeters are described in the *Photodosimetry Evaluation Book* (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; 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 1960). 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 1960). 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 evaluating 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 1960).

**Nuclear Track Emulsion:** The Kodak Type B film used for measuring fast-neutron exposures as of August 1960 (Littlejohn 1960) was developed by J. S. Cheka of Oak Ridge National Laboratory (ORNL) (Cheka 1954). LANL calibrated this film to neutron energies of 0.5, 0.6, 0.7, 0.8, 1.0, 1.5, 2.5, 4.0, 5.0, 8.0, 14.0, 17.0, and 20.0 MeV (Littlejohn 1960). The 2.5- and 14.0-MeV neutrons were obtained from a Cockcroft-Walton accelerator, and the others were from two Van de Graff accelerators that the Laboratory had at the time. Data from these calibrations indicated that between the energies of 1.0 and 20 MeV, the film was energy-dependent within +100% or -50% of the stated exposure, and each proton recoil track appearing in a 1-$mm^2$ portion of the cadmium-filtered area was assigned an average value of 0.008 rem (Littlejohn 1960). Fundamentally, the NTA dosimeter is capable of an accurate dose estimate only for higher energy 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 using a National Bureau of Standards (NBS) slab phantom backing (40 x 40 x 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 also contained TLD inserts, the TLDs were calibrated on the P-6 gamma range and with a $PuF_4$ neutron source.

**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 3-inch polyethylene spheres containing thin shells of cadmium was used to measure neutrons from a variety of sources. The ratio of the 9-inch to 3-inch sphere counting rates was plotted against sensitivity (the ratio of the TLD-600 response less the TLD-700 response in units of $^{60}$Co mR to the neutron mrem as measured on the 9-inch sphere). This yielded a linear relationship on a log-log plot. Under this method, the ratio of 9-inch to 3-inch 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-inch:3-inch count ratio to sensitivity generated for the albedo-neutron badge. The use of the 9-inch:3-inch ratio technique allowed determination of an "average" neutron energy for a neutron source and an appropriate neutron calibration factor. In addition to using 9-inch:3-inch sphere ratios for determination of NCFs, LANL compared responses of TLDs mounted on a phantom to responses from an adjacent 9-inch "NRD" moderated $BF_3$ tube-based neutron survey instrument.

**Model 8823 TLD Badge:** The general algorithm technique adopted for the Model 8823 is designed to determine the responses for each of the eight elements in the Model 8823 dosimeter using 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.

**Model 8823 and Track-Etch Dosimeter:** A March 9, 2000, report (LANL 2001b) described the results of irradiation of LANL TLD and track-edge dosimeter (TED) badges to monoenergetic, accelerator-produced neutrons from 0.144 to 19.0 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 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's track-etch dosimeters were calibrated with a bare fission source [LANL 2001b (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 neutron-to-photon ratio for each year 1979 to 2004 (partial year) based on LANL records that have both deep dose and neutron dose 50 mrem or greater. This is the period after use of NTA film was phased out from use at LANL. Along the top of the graph, the types of monitoring in use over time are identified.

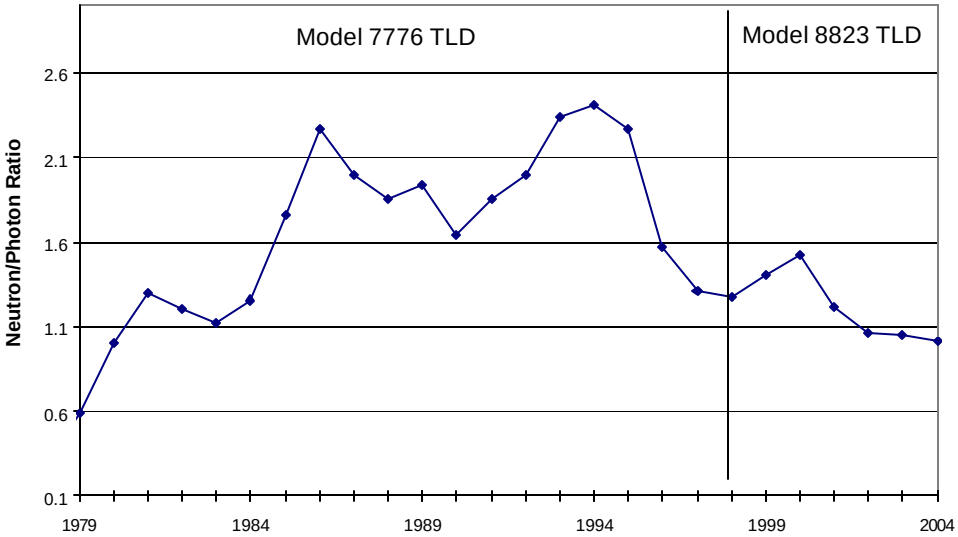



Figure 6-3. Geometric mean of neutron-to-photon doses from LANL for 1979-2004 for records with both deep dose and neutron dose 50 mrem or greater (LANL 2004).

#### 6.2.3.3 LANL Workplace Radiation Fields

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

#### 6.2.3.4 LANL Workplace Beta/Photon Dosimeter Response

The energy response of Eastman Kodak Type K film for an exposure of 0.10 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 breakdown from the same report are presented in Table 6-11.

Based on film badge data from uranium processing areas from early 1953, a factor of 1/10 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 1/10 indicated that beta doses were about 9 times gamma doses in those uranium processing areas.

That 1963 memorandum described a study in which the brass-cadmium badge and the Cycolac badge were simultaneously exposed to three different plutonium sources at DP West that had known or calculable spectra; 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 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, causing the total dose to be in error (high) by as much as 60%.

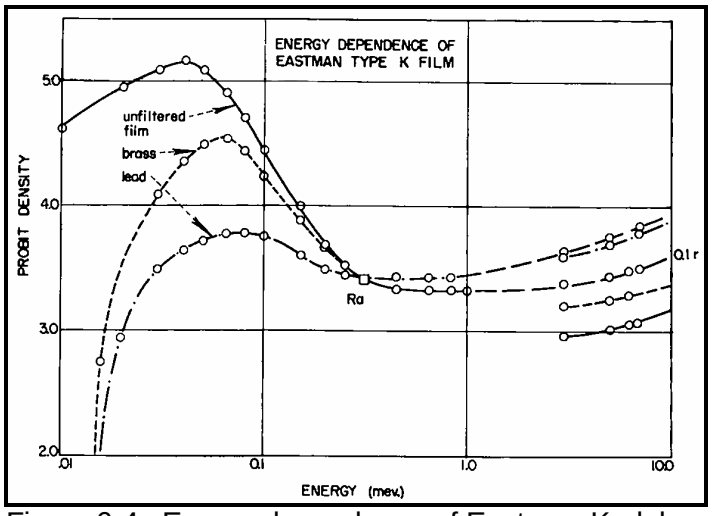



Figure 6-4. Energy dependence of Eastman Kodak Type K Film for exposure of 0.10 R (Storm 1951)

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 facility.

| Energy (keV) | Pu in Glovebox | Pu with 20% $^{240}$Pu in glovebox | Pu with 20% $^{240}$Pu, thru glass | Pu with 20% $^{240}$Pu, thru 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 |

Errors that were expected when using the Cycolac badge with low energy photons (<45 keV) when the correction factor of 0.07 was used were as shown in Table 6-12, based on the 1962 study at DP West [LASL 1969 (3/5/63 memorandum)]. Guidance given 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)]. The study used data from 38 plutonium workers in these areas: $^{239}$Pu recovery, $^{239}$Pu areas only, $^{238}$Pu areas, and the $PuF_4$ area. While the lowest dose was 294 mrem, most were around 1,000 mrem. Relevant results of the study, averaged over 6 months, are listed in Table 6-13. The film badge readings were about a factor of 3 higher than the TLDs. In his 1996 memorandum discussing the 1973 study [LANL 1996 (2/15/96 memorandum)], Hankins said that the method used to calibrate for plutonium did not consider the effect of the glovebox or buildup of $^{241}$Am in the gloveboxes.

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

| Area of DP Site | Ratio of film dose to TLD gamma dose |
|---|---|
| Pu-239 Recovery | 2.3 |
| Pu-239 Areas | 3.0 |
| $PuF_4$ Areas | 3.4 |
| Pu-238 Areas | 1.6 (range 1.1-2.2) |

### 6.2.3.5 Uncertainty in Beta/Photon Recorded Dose

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

### 6.2.3.6 Workplace Neutron Dosimeter Response

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

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

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

- D Building (TA-1)
- DP West (TA-21)
- DP East (TA-21)
- Current Plutonium Facility (TA-55)
- Omega Site (TA-2)
- LAMPF (TA-53)
- Criticality Lab (TA-2, TA18)
- CMR Building (TA-3)

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

| Process/ Buildings | Description | Operations Begin | Operations End | Radiation type | Energy selection, keV | Percentage |
|---|---|---|---|---|---|---|
| Reactors | **During Operation:** Highly dispersed fields of higher energy photon radiation fields from fission process, activation and fission product nuclides. Potentially narrow beams of higher energy neutron radiation from test ports, etc., into reactor core. Potential for significant airborne nuclides and there could be significant higher energy beta radiation. | | | Beta [a] | > 15 | 100% |
| | **Not in Operation:** Highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides. No significant neutron radiation. There could be significant higher energy beta radiation during maintenance work resulting from fission products. | | | | | |
| | LOPO Water Boiler (TA-2) | May 44 | Nov. '44 | Photon | 30-250<br>>250 | 25%<br>75% |
| | HYPO Water Boiler (TA-2) | Dec. '44 | Feb. '51 | | | |
| | SUPO Water Boiler (TA-2) | Mar. '51 | Jun. '74 | | | |
| | Plutonium Fast Reactor (Clementine, TA-2) | Dec. '46 | Dec. '50 | | | |
| | Omega West Reactor (TA-2) | Jul. '56 | Dec. '92 | | | |
| | LAPRE I (TA-35) | Feb. '56 | Oct. '56 | | | |
| | LAPRE II (TA-35) | Feb. '59 | May '59 | | | |
| | LAMPRE I (TA-35) | Early '61 | Mid-63 | | | |
| | UHTREX (TA-52) | Dec. '56 | Feb. '70 | | | |
| Uranium Production | **Processing and machining:** depleted and enriched uranium. | | | Beta [a] | >15 | 100% |
| | TA-1 (Sigma, HT Buildings) | 1943 | 1953 | Photon | 30-250 | 100% |
| | TA-3 (Sigma Complex, CMR Bldg.) | 1953 | Present | | | |
| Plutonium Processing | **Radiochemical Operations:** Plutonium processed at LANL had largely been separated from fission products. Radiochemical operations were largely for recovery of fissionable material. | | | Beta [a] | > 15 | 100% |
| | TA-1, D Building | 1943 | 1945 | Photon | <30<br>30-250 | 65% [b]<br>35% [b] |
| | TA-21, "DP Site, West" | Nov. '45 | 1978 | | | |
| | TA-55, Plutonium Facility | 1978 | Present | | | |
| | TA-3 (including CMR Bldg.) | 1953 | Present | | | |
| Plutonium production | **Plutonium Component Production**: Plutonium is machined into weapon components using glovebox assembly process with predominant close anterior exposure to workers. Radiation characteristics in this area involve significant lower energy photons and neutron radiation. | | | Photon | < 30<br>30 – 250 | 65% [b]<br>35% [b] |
| | TA-1 (D Building), TA-21 (DP Site), TA-55 (PF Site) | | | | | |
| | **Plutonium Storage:** Radiation characteristics in this area generally involve dispersed lower energy neutron radiation and scattered photons, including 60-keV Am-241 gamma ray. | | | | | |
| | TA-1, D-5 Sigma Vault | 1943 | 1945 | | | |
| | TA-21, Building 21 | Nov. '45 | 1978 | | | |
| | TA-55 Vault | 1978 | present | | | |
| Accelerator operations | **LAMPF** operations at TA-53: Primarily from residual activity induced within targets, accelerator structures and components, grease, oils, and soil. | 1972 | present | Beta [a]<br>Photon | > 15<br>< 30<br>30 – 250<br>> 250 | 100%<br>5%<br>5%<br>90% |
| Calibrations | LANL site calibration of instruments and dosimeters | 1943 | present | Beta [a]<br>Photon | > 15<br>30 – 250<br>> 250 | 100%<br>25%<br>75% |
| Waste handling | Radiation characteristics highly dependent on source of waste. | | | Beta [a] | > 15 | 100% |
| | Liquid waste: TA-45 and TA-50;<br>Solid waste: Areas A,B, C, D, E, G, T, U, V | Various,<br>1944 on | | Photon | 30 – 250<br>> 250 | 50%<br>50% |
| Radioactive Lanthanum Operations | **Preparation and Use of Radioactive Lanthanum Sources:** | | | Beta [a] | > 15 | 100% |
| | TA-10 (Bayo Canyon) | 1944 | 1950 | Photon | 30 – 250<br>> 250 | 10%<br>90% |
| | TA-35, "Ten Site" | 1951 | 1963 | | | |

Information sources: LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003.

[a] Nonpenetrating dose was not measured by early LANL film badges that had no unfiltered areas. See Section 6E.5 for guidance regarding how to correct for that shortcoming by estimating nonpenetrating dose and attributing it to the beta radiation category.

[b] Low energy photons were not measured by early LANL film badges that had no unfiltered areas. See Section 6E.5 for guidance regarding how to correct for that shortcoming by estimating nonpenetrating dose and attributing it to the low energy photon (<30 keV) category.

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

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

- The vast majority (greater than 90%) of LANL employees, including those at TA-55, received whole-body neutron doses from "well moderated fields, akin to ~2.5-4" (or greater) poly-moderated Cf-252 (fission spectrum)," and
- Less than 2% of LANL's positive neutron exposures were "in fields similar to bare Cf-252."

Based on neutron spectrum measurements performed by LANL personnel (Harvey and Hajnal 1993) and information from the *Photodosimetry Evaluation Book* [LANL 1996 (1/17/95 memorandum)], Table 6-15 lists the approximate correspondence between NCFs used by LANL and the dose fraction for the four bins of neutron energy used by NIOSH. 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 dose equivalent per neutron is lower.

As described earlier, irradiation of LANL TLD and TED badges to monoenergetic, accelerator-produced neutrons from 0.144 MeV to 19.0 MeV at PTB in Germany (LANL 2001b) showed that the TLD significantly under-responded to neutrons 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.

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

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

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

#### 6.2.3.6.1.1 Neutron Energy Spectrum

In study released in 1978, 9-inch to 3-inch sphere ratio measurements at 13 locations at the TA-55 Plutonium Facility yielded ratios that indicate 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 SNM storage vault.

#### 6.2.3.6.1.2 Neutron-to-Photon Dose Ratio

The following data concerning neutron-to-photon ratios for LANL plutonium workers are available [LASL 1974 (11/9/72 memorandum)]:

- For $^{239}$Pu workers not in fluoride areas, observed neutron-to-photon ratios ranged from 0.3 to 1.7, with an average of 0.7.
- For $^{239}$Pu-fluoride areas, a neutron-to-photon ratio of 2.8 was reported for a health physics technician, not a chemical operator.
- For $^{238}$Pu workers, observed neutron-to-photon ratios ranged from 2.7 to 5.5, with an average of 3.9 ($^{238}$Pu exposures began in 1969).
- For health physics technicians in $^{238}$Pu areas, observed neutron-to-photon ratios ranged from 1.9 to 4.6, with an average of 3.3.

The measured average quotient of neutron to gamma- and X-ray dose equivalent for the plutonium facility in 1993 was 2.5 [Harvey and Hajnal 1993 (LA-12538-MS)].

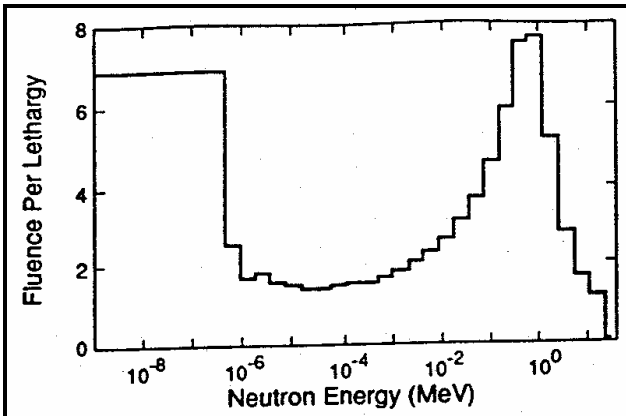
The 1972 study at DP Site mentioned earlier [LANL 1996 (2/15/96 memorandum)] compared neutron dose results from NTA and TLDs, and yielded neutron-to-photon ratios that varied from 1.4 to 1.8 for $^{239}$Pu areas and averaged 1.3 for $^{238}$Pu areas, as shown in Table 6-16.

Table 6-16. Results of six-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 78% | 0.56 | 1.8 | 0.10 |
| Pu-239 areas | | 0.66 | 1.5 | 0.17 |
| $PuF_4$ areas | | 0.71 | 1.4 | 0.23 |
| Pu-238 areas | 69% to 90% | 0.80 | 1.3 | 0.57 (0.05 to 1.13) |

#### 6.2.3.6.2 LAMPF (TA-53)

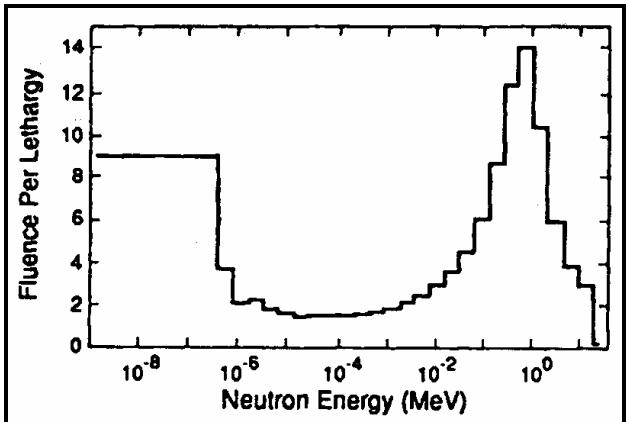
In 1987, neutron energy spectrum measurements were made at a potentially high neutron energy area at LAMPF (Mundis and Howe 1987). The resulting neutron spectrum is shown in Figure 6-8, and associated data have been interpreted as follows in the Mundis and Howe (1987) memorandum and in a 1990 report 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 dose equivalent 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 said to be in good agreement with the spectrum unfolding results.




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 |

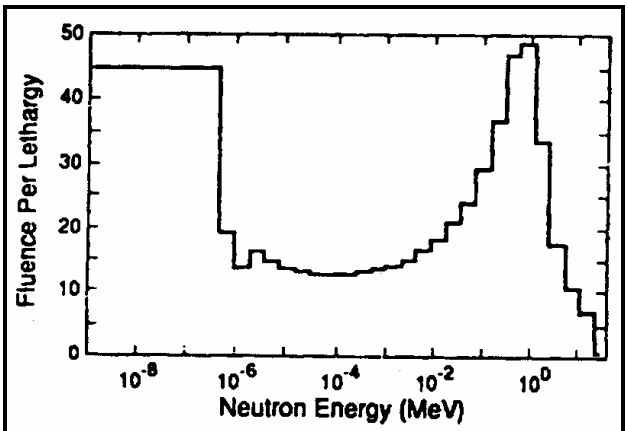
Figure 6-5. Neutron spectrum of hydrofluorination of $^{239}PuO_2$ at LANL Plutonium Facility (Harvey and Hajnal 1993).




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 LANL 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 LANL Plutonium Facility (Harvey and Hajnal 1993).

In another study, however, 9-inch to 3-inch sphere ratio measurements at 18 locations at LAMPF (not just an area of potentially high neutron energy) yielded ratios that indicate 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.

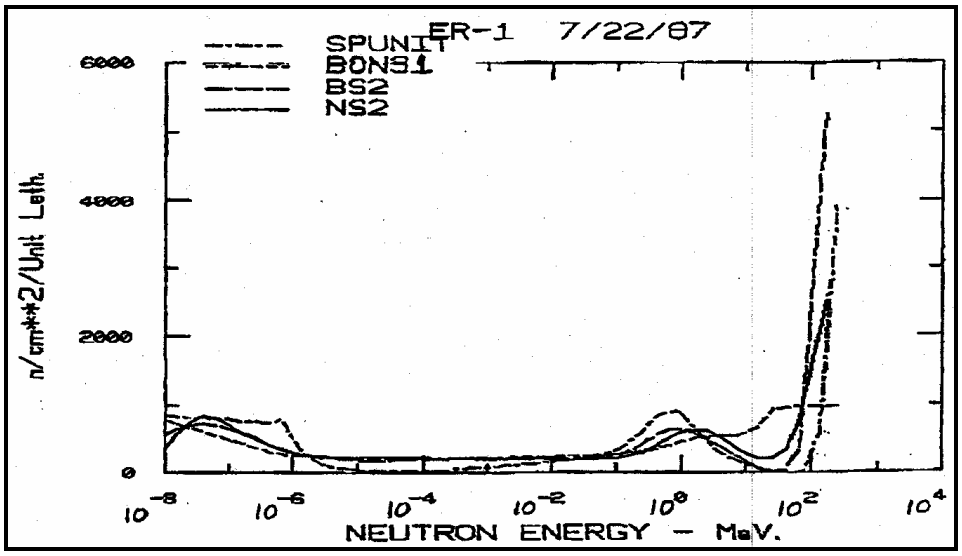



Figure 6-8. Neutron spectrum in ER-1 Area of LAMPF with proton beam stopped in the carbon beam block, as determined from unfolding codes (Mundis and Howe 1987).

### 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 2001b (3/17/98 and 6/24/99 memoranda)]. As a result of this work, a 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)].

A study of selected criticality dosimetry methods that was conducted in 1967 yielded neutron energy distributions for the key LANL critical assemblies (Hankins 1968). Table 6-17 presents the breakdown of total kerma by energy interval at a distance of 3 meters (or 5.9 meters for Hydro) from five critical assemblies when they were active. Spectral data taken at these distances will generally not be useful in assessing 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.

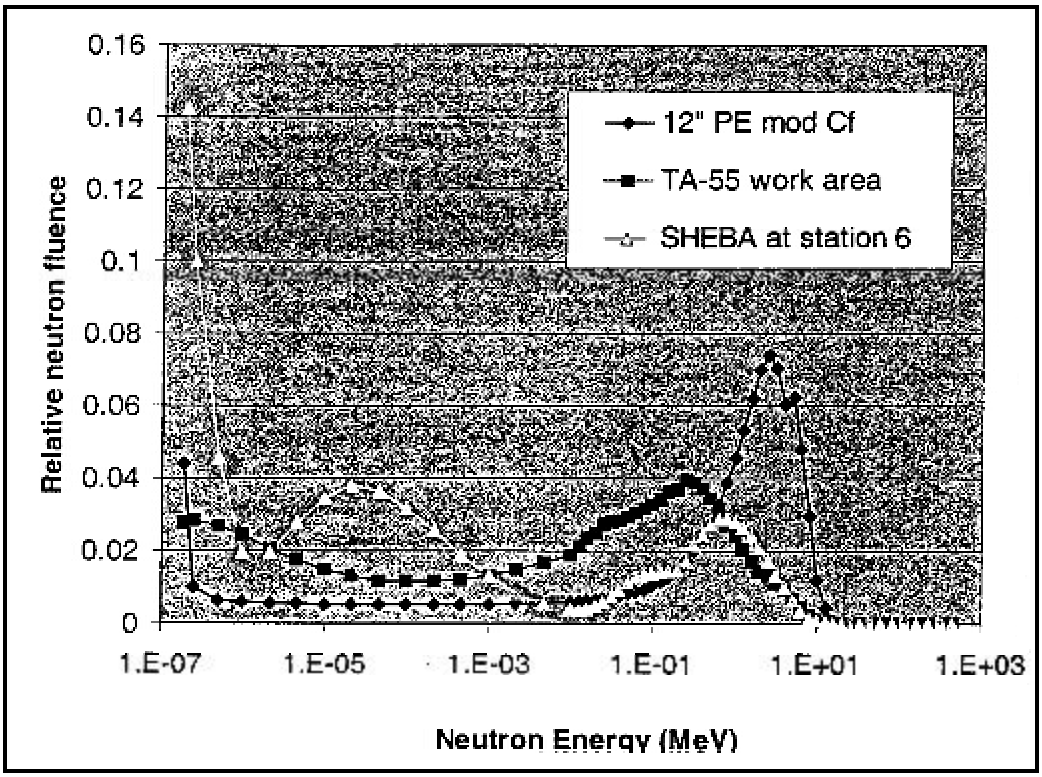



Figure 6-9. Neutron spectrum at "Station 6" near TA-18 (white line).

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

| Critical assembly | Distance from assembly (m) | Neutron energy | | | |
|---|---|---|---|---|---|
| | | 0.4–750 keV | 0.75–1.5 MeV | 1.5–2.9 MeV | > 2.9 MeV |
| Jezebel (outside kiva) | 3.0 | 14 | 23 | 21 | 42 |
| Jezebel (inside kiva) | 3.0 | 9 | 31 | 22 | 39 |
| Hydro | 5.9 | 27 | 36 | 3.4 | 34 |
| Flattop | 3.0 | 41 | 43 | 11 | 11 |
| Parka | 3.0 | 45 | 22 | 23 | 23 |
| Godiva IV (burst mode) | 3.0 | 18 | 37 | 24 | 24 |
| Godiva IV (extended mode) | 3.0 | 13 | 41 | 25 | 25 |

#### 6.2.3.6.3.2 Neutron-to-Photon Dose Ratio

The study of criticality dosimetry methods that was conducted in 1967 also yielded estimates of gamma-to-neutron ratios for five critical assemblies at LANL based on measurements with TLDs and film badges placed in air, on the front of “plastic man” manikins filled with sodium solution, and on the back of plastic men (Hankins 1968). Table 6-18 presents 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 meters. Hankins (1968) presents data for six distances from 5.9 to 19.8 meters. 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* | Corresponding neutron-to-gamma ratio* |
|---|---|---|
| 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 |

* 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 neutron correction factors in use for Omega West Reactor (CNC-5) personnel. Neutron measurements were made with a 9-inch diameter polyethylene sphere, an RM-16 rate meter, and an Ortec scaler. TLD badges mounted on a 1.5-inch 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 indicate 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 mrem values for 5 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 involving plutonium at the Chemical and Metallurgical Research building (also known as "South Mesa" Building 29, or SM-29) have included laboratory work on small quantities of uranium and plutonium (ChemRisk 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 glove box processes and rooms on the south side of Wing 3. Since early 1974, FE-19 has been 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 (ChemRisk 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 Pu-Be or $^{252}$Cf). The dose fraction in the 2 to 20 MeV category was raised from 33% to 40%, with 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 subdividing the neutron spectra into the four lower neutron energy groups discussed in NIOSH (2002). 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 likely 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 dose-rate conversion factors (DCFs) found in National Council on Radiation Protection and Measurements (NCRP) Report 38 (NCRP 1971). The neutron doses in each NCRP 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 ($D_T$).

$$D_f(E_n) = \frac{\sum_i f(E_i) DCF_i}{D_T} \tag{6.1}$$

where:

$Ø(E_i)$ = Neutron flux of the ith energy bin
$DCF_i$ = NCRP 38 (1971) flux to dose-rate conversion factor for the ith 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 1980). A significant under-response in recorded dose with NTA dosimeters became evident in the late 1960s at several sites preparing to implement the TLD neutron dosimeters.

## 6.3 ADJUSTMENTS TO RECORDED PHOTON DOSE

Following are instances for which corrections to recorded photon doses appear to 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 four higher than TLD results for $^{239}Pu$ recovery areas and a factor of two higher in other DP West plutonium areas [LASL 1974 (1/23/74 memorandum); average factor = 3].

- 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 two 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 = 2.5].

- From September 1961 to October 1964, a software glitch resulted in exposures to photons over 200 keV in energy from the brass-cadmium badge being treated as soft gamma exposures, causing doses over 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 1962 to 1978 over responded to photons with energies below 100 keV, resulting in overestimates of the dose by as much as a factor of 2 in the plutonium facility (Storm et al. 1981).

- From March 1963 to March 1973, penetrating photon doses (rem) from plutonium exposures were set equal to delivered exposures (R) in error, causing penetrating gamma doses to reported high by about a factor of 2.9 [LASL 1974 (5/2/73 and 1/23/74 memoranda; the factor of 2.9 corrects for inappropriate reduction in nonpenetrating component to 35% of actual in calibration)].

These situations have been translated into a series of non-overlapping correction factors, given in Section 6E.3, for recommended application to photon doses reported by LANL. In several cases where there is some evidence that might support reduction of reported doses, correction factors are not recommended because of the lack of incontrovertible evidence sufficient to justify adjustment of reported doses in a manner that would not be favorable to claimants.

## 6.4 ADJUSTMENTS TO RECORDED NEUTRON DOSE

Adjustments to LANL recorded neutron doses are necessary to estimate doses, considering 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 dose equivalent in its calibration methodology. As a result, the recorded dose equivalent ($DE_R$) is a combination of all neutron energies. To calculate the probability of causation, the recorded neutron dose must be separated into neutron energy groups and later converted to International Committee for Radiological Protection (ICRP) Publication 60 methodology (ICRP 1990).

### 6.4.2 Neutron Weighting Factor

Adjustment to the neutron dose is necessary to account for the change in neutron quality factors between historic and current scientific guidance, as described in NIOSH (2002). 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 38 quality factors to ICRP Publication 60 radiation weighting factors (ICRP 1990), a curve was fit describing 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.

$$\overline{Q}(E_{n,0.1-2.0MeV}) = \frac{\int_{0.1}^{2.0} Q_f(E)dE}{Range(2.0-0.1)} \tag{6.2}$$

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

Table 6-20. Neutron quality or weighting factors

| 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] |
|---|---|---|---|---|
| $2.5 \times 10^{-8}$ | 3 | 2 | 2.35 | 5 |
| $1 \times 10^{-7}$ | 10 | 2 | | |
| $1 \times 10^{-6}$ | | 2 | | |
| $1 \times 10^{-5}$ | | 2 | | |
| $1 \times 10^{-4}$ | | 2 | | |
| $1 \times 10^{-3}$ | | 2 | | |
| $1 \times 10^{-2}$ | | 2.5 | 5.38 | 10 |
| $1 \times 10^{-1}$ | | 7.5 | 10.49 | 20 |
| $5 \times 10^{-1}$ | | 11 | | |
| 1 | | 11 | | |
| 2 | | 10 | 7.56 | 10 |
| 2.5 | | 9 | | |
| 5 | | 8 | | |
| 7 | | 7 | | |
| 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 (ICRP1990).

### 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 dose equivalent 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 1990).

$$C_f(E_n) = \frac{D_f(E_n)}{\overline{Q}(E_n)} \times w_R \tag{6.3}$$

Table 6-21 summarizes default neutron dose fractions by energy for LANL work areas where field measurements of neutron spectra were performed, using the associated ICRP 60 correction factors

(ICRP 1990). For years after 1978, the neutron dose equivalent is calculated by multiplying the recorded neutron dose by the area-specific correction factors. For example, consider a 1,000-millirem recorded neutron dose by a worker at DP West; the corrected neutron dose is calculated as follows:

Table 6-21. LANL facility dose fractions and associated ICRP 60 correction factors.

| Process | Description/buildings | Operations | | Neutron energy | Default dose fraction (%) | ICRP 60 correction factor |
|---|---|---|---|---|---|---|
| | | Begin | End | | | |
| Plutonium production | Neutron dose was associated with overall LANL plutonium production process in which plutonium was purified, formed, machined, and recovered. Work was primarily conducted in gloveboxes with predominant close anterior exposure to workers. | | | | | |
| | Plutonium facilities (D Building at TA-1, DP West Site at TA-21, Plutonium Facility at TA-55) | 1943 | Present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 11%<br>56%<br>33% | 0.23<br>1.1<br>0.44 |
| LAMPF | Neutrons of varying energies from high energy proton linear accelerator studies. | | | | | |
| | LAMPF at TA-53 | 1972 | Present | <10 keV<br>10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 30%<br>30%<br>20%<br>20% | 0.64<br>0.56<br>0.38<br>0.26 |
| Reactor operations | Neutrons of varying energies from reactor operations. | | | | | |
| | Omega Site (TA-2)<br>TA-35<br>TA-52 | 1944<br>1955<br>1969 | 1992<br>1963<br>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)<br>TA-18 | 1943<br>Apr. '46 | Apr. '46<br>present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 3.2%<br>59%<br>38% | 0.060<br>1.1<br>0.50 |
| Chemistry & Metallurgy Research | Neutrons of varying energies from actinide chemistry and metallurgy research. | | | | | |
| | TA-1<br>TA-3 | 1943<br>1952 | 1952<br>present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 10%<br>50%<br>40% | 0.21<br>0.95<br>0.53 |

- 1,000 x 1.323 x 0.33 = 437 millirem from neutrons 2–20 MeV estimated to represent 33% of the dose fraction

- 1,000 x 1.907 x 0.56 = 1068 millirem from neutrons 0.1–2 MeV estimated to represent 56% of the dose fraction

- 1,000 x 2.055 x 0.11 = 226 millirem from neutrons <10 keV–100 keV estimated to represent 11% of the dose fraction

Thus, the corrected neutron dose is a total of 1731 millirem. These adjustments should be applied to measured dose, missed dose, and dose determined based on a neutron-to-photon ratio. For years before 1980 at LANL, multiply annual photon dose (adjusted for any missed dose) times the neutron-to-photon dose factor from Section 6.4.4 and by the area-specific ICRP 60 correction factor shown above to estimate neutron dose.

### 6.4.4 Neutron-to-Photon Dose Factors

Essentially all LANL radiological work areas with significant neutron radiation also had significant photon radiation. For time periods and workplace settings for which neutron dosimetry methods are thought to have been particularly unreliable or uncertain (for example, NTA film dosimetry for

intermediate energy neutron sources), it is sometimes possible and advisable to estimate neutron doses based on measured gamma doses through application of neutron-to-photon ratios.

Section 6.2.3.6.1.2 contains reported neutron-to-photon ratios for Los Alamos plutonium workers. Reported neutron-to-gamma ratios range from 0.3 to 5.5 for Los Alamos plutonium workers. Section 6.2.3.6.3.2 contains reported neutron-to-photon ratios for Los Alamos 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 meters from the assembly). Based on these site-specific data, uniform distributions of neutron-to-gamma ratio are recommended for plutonium facilities and criticality experiments in the first and second lines of data in Table 6-22. A general distribution (also uniform) for application to other operations, based on analysis of annual deep and neutron doses reported by LANL for 1979-2004, is shown on the third line of data in Table 6-22. Dose data used for this general factor included post-NTA results where the deep and neutron doses were 50 mrem or greater.

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

| Neutron source type | Neutron-to-photon dose ratio (uniform distribution) | |
|---|---|---|
| | **Minimum** | **Maximum** |
| Plutonium facilities | 0.30 | 5.5 |
| Criticality experiments (> 50 m distant) | 1.7 | 2.8 |
| Other operations | 0.59 | 2.4 |

## 6.5 MISSED DOSE

There is undoubtedly missed recorded dose 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 occur if there is no recorded dose because workers were not monitored or the dose is otherwise unavailable. Methods to be considered if there is no recorded dose for a period during a working career have been 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 (2002) describes options to calculate missed dose. One option is to estimate a mean missed dose where MDL/2 is multiplied by the number of zero dose results. The following sections describe potential missed photon dose adjustments according to year, facility/location, dosimeter type, and energy range.

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

Table 6-23. LANL 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) |
|---|---|---|---|---|
| Prior to February 1945 | PIC | 5 | Daily (n=250) | 625 |
| February 1945 through September 1962 | Brass, brass clip, or brass-cadmium film | 40 | Monthly (n=12) | 240 |
| | | | Biweekly (n=25) | 500 |
| | | | Weekly (n=50) | 1000 |
| | | | Daily (n = 250) | 5000 |
| October 1962 through December 1979 | Cycolac multielement film | 40 | Monthly (n=12) | 240 |
| | | | Biweekly (n=25) | 500 |
| | | | Weekly (n=50) | 1000 |
| | | | Daily (n = 250) | 5000 |
| January 1, 1980, through March 1998 | 7776 TLD | 10 | Monthly (n=12) | 60 |
| | | 10 | Quarterly (n=4) | 20 |
| April 1, 1998, to 2003 (ongoing) | 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 (2002).

### 6.5.2 Neutron Missed Dose

Neutron radiation was present around nine reactors at TAs 2, 35, and 52; in the plutonium processing facilities at TAs 1, 21, and 55; around LAMPF at TA 53; and at several other facilities. The approach recommended for use to calculate neutron missed dose can be divided into two periods. The first period is 1951 to 1978, when primarily NTA film was 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 prior to 1979 are based on reported photon doses, adjusted per Table 6E-3, and use of the applicable neutron-to-photon ratio.

## 6.6 ORGAN DOSE

The process to calculate the probability of causation requires an estimate of the organ dose, because the claim is normally specific to disease in an organ. This is estimated from uncertainty distributions of various parameters regarding dosimeter response, radiation type, energy, and worker orientation in the field. Appendix A of NIOSH (2002) discusses conversion of measured doses to organ dose equivalent, and Appendix B contains appropriate dose conversion factors 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 (2002, Table 4.2). Unfortunately, there is no definitive process to determine the exposure geometry for each LANL worker. Through discussions with Task 5 personnel, a simple 100% AP geometry will be assumed for all workers, even likely compensable workers.

Table 6-24. LANL 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 to 1962 | Brass-cadmium badge | < 50 | Monthly (n=12) | < 300 [b] |
| April 1951 through 1978 (limited use with TLDs to 1995) | NTA film | | Biweekly (n=25) | < 625 [b] |
| | | | Weekly (n=50) | < 1250 [b] |
| 1962 to 1978 | Cycolac multielement badge | | Daily (n=250) | < 6250 [b] |
| 1979 to 1998 (some quarterly exchange beginning in 1996) | Model 7776 TLD badge | 10 | Monthly (n=12) | 60 |
| | | | Quarterly (n = 4) | 20 |
| 1995 to present | Track-etch dosimeter | 20 | Quarterly (n = 4) | 40 |
| 1998 to present (40% were exchanged quarterly by Feb. 2002) | Model 8823 TLD badge | 10 | Monthly (n=12) | 60 |
| | | | Quarterly (n = 4) | 20 |

a. Mean annual missed neutron dose calculated using MDL/2 from NIOSH (2002).

b. Neutron-to-photon ratio should be used to estimate missed doses during these periods.

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## GLOSSARY

**absorbed dose, D**

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

**accreditation**

Recognition that a dosimeter system has passed the performance criteria of the DOE Laboratory Accreditation Program (DOELAP) standard (DOE 1986) in specified irradiation categories.

**accuracy**

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

**albedo dosimeter**

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

**algorithm**

A computational procedure.

**Atomic Energy Commission**

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

**$BF_3$ chamber or counter**

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

**backscatter**

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

**beta particle**

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

**buildup**

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

**calibration blank**

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

**collective dose equivalent**

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

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

**curie**
A special unit of activity. One curie exactly equals $3.7 \times 10^{10}$ nuclear transitions per second.

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

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

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

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

**density reading**
See optical density.

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

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

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

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

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

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

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

**Eastman Kodak Nuclear Track Emulsion, Type A (NTA)**
A film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using oil immersion and 1000X power microscope.

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

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

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

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

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

**fast neutron**
Neutron of energy between 10 keV and 10 MeV (NBS 1957).

**film**
Generally means a "film packet" that contains one or more pieces of film in a light-tight wrapping. The film when developed has an image caused by radiation that can be measured using an optical densitometer. (See *Dupont 552*, *Dupont 558*, *Eastman Kodak, Nuclear Emulsions*.)

**film density**
See optical density.

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

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

**gamma rays**

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

**glovebox**

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

**gray (Gy)**

The SI unit of absorbed dose (1 Gy = 100 rad).

**intermediate energy neutron**

Neutron of energy between 0.5 ev (assumed to be 0.4 ev because of cadmium cutoff in neutron response) and 10 keV (NBS 1957).

**ionizing radiation**

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

**isotopes**

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

**kerma**

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

**kilo-electron volt (keV)**

An amount of energy equal to 1,000 electron volts.

**kiva**

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

**luminescence**

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

**Manhattan Engineer District (MED)**

U.S. agency designated to develop nuclear weapons; a predecessor to the U.S. Department of Energy (DOE).

**Minimum Detection Level, MDL**

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

**million-electron volt (MeV)**

An amount of energy equal to 1,000,000 electron volts.

**Multiple-Collision Neutron Dose**

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

**nuclear emulsion**

Generally refers to NTA film.

**neutron**

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

**neutron, fast**

Neutrons with energy equal or greater than 10 keV.

**neutron, intermediate**

Neutrons with energy between 0.4 eV and 10 keV.

**neutron, thermal**

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

**neutron film dosimeter**

A film dosimeter that contains an Eastman-Kodak Neutron Track Emulsion, type A, film packet.

**nonpenetrating dose**

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

**open window**

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

**optical density**

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

**pencil dosimeters**

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

**penetrating dose**

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

**$PuF_4$ source**

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

**Personal Dose Equivalent, $H_p(d)$**

Radiation quantity recommended for use as the operational quantity to be recorded for radiological protection purposes by the International Commission on Radiological Units and Measurements. Represented by $H_p(d)$, where d identifies the depth (in mm) and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 mm and is noted as $H_p(0.07)$. For penetrating radiation of significance to “whole-body” dose, d = 10 mm and is noted as $H_p(10)$.

**photon**

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

**precision**

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

**quality factor, Q**

A modifying factor used to derive dose equivalent from absorbed dose.

**rad**

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

**radiation**

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

**radiation monitoring**

Routine measurements and the estimation of the dose equivalent for the purpose of determining and controlling the dose received by workers.

**radioactivity**

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

**random errors**

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

**RBE**

A ratio of the absorbed dose of a reference radiation to the absorbed dose of a test radiation producing the same biological effects, other conditions being equal.

**rem**

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

**rep**

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

**roentgen**

A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of $2.58 \times 10^{-4}$ coulomb in 1 kg of dry air. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue.

**scattering**

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

**shallow absorbed dose (Ds)**

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

**shallow dose equivalent (Hs)**

Dose equivalent at a depth of 0.07 mm in tissue.

**shielding**

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

**sievert (Sv)**

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

**sigma pile**

A device used to obtain thermal neutrons for calibration purposes.

**skin dose**

Absorbed dose at a tissue depth of 7 $mg/cm^2$.

**systematic errors**

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

**thermal neutron**

Strictly, neutrons in thermal equilibrium with surroundings. Generally, refers to neutrons of energy less-than the cadmium cutoff of about 0.4 ev.

**tissue equivalent**

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

**TLD chip**

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

**thermoluminescent**

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

**thermoluminescent dosimeter (TLD)**

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

**whole-body dose**

Absorbed dose at a tissue depth of 1.0 cm (1,000 mg/cm2); however, also used to refer to the dose recorded.

**X-ray**

Ionizing electromagnetic radiation of extranuclear origin.

**Zia**

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

# ATTACHMENT E
# GUIDANCE FOR DOSE RECONSTRUCTORS
# OCCUPATIONAL EXTERNAL DOSE FOR MONITORED WORKERS

## TABLE OF CONTENTS

Section Page

6E.1 RECORDED DOSE PRACTICES AND INTERPRETATION OF REPORTED DOSES ..... 64
6E.2 UNMONITORED PHOTON DOSE ..... 65
6E.3 ADJUSTMENTS TO REPORTED PHOTON DOSES ..... 67
6E.4 MISSED BETA/PHOTON DOSE ..... 68
6E.5 ATTRIBUTION OF BETA/PHOTON DOSES TO ENERGY CATEGORIES ..... 69
6E.6 UNMONITORED NEUTRON DOSE ..... 71
6E.7 MISSED NEUTRON DOSE ..... 71
6E.8 ATTRIBUTION OF NEUTRON DOSES TO ENERGY CATEGORIES ..... 72
6E.9 RECOMMENDED DOSE CONVERSION FACTORS ..... 72

## LIST OF TABLES

Table Page

6E-1 Recorded dose practices over time at Los Alamos ..... 64
6E-2 LANL worker gamma dose statistics ..... 65
6E-3 Recommended adjustments to reported LANL photon doses ..... 67
6E-4 Recommended uncertainty factors for reported LANL doses. ..... 67
6E-5 LANL beta/photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed doses ..... 68
6E-6 Recommended beta and photon radiation energies and percentages for LANL plutonium facilities ..... 69
6E-7 Recommended beta and photon radiation energies and percentages for LANL facilities *other than* plutonium facilities ..... 70
6E-8 LANL neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose ..... 71
6E-9 Recommended distributions for neutron-to-gamma ratio for Los Alamos ..... 71
6E-10 Recommended dose fractions and ICRP 60 correction factors for LANL neutron sources ..... 72
6E-11 Recommended dose conversion factors for LANL dose assessments ..... 72

## 6E.1 RECORDED DOSE PRACTICES AND INTERPRETATION OF REPORTED DOSES

Table 6E-1 summarizes LANL dose recording practices over the years.

Table 6E-1. Recorded dose practices over time at Los Alamos (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003).[a]

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

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

In 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., that no monitoring was performed for the subject individual for that period, and no dose records are available.
- 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.
- The "SKIN" doses reported are derived as shallow dose + neutron dose + tritium dose. To ensure that dose is appropriately attributed to the low energy photon or electron categories for NIOSH dose reconstructions, nonpenetrating dose will be estimated as skin dose – (deep dose + neutron dose + tritium dose).
- When for a given month, the dose report form identifies "Badge Type" as "Monthly," but there are up to five lines of data (see example below), that indicates that multiple badges were worn during the month. The doses for the individual badges should be added to obtain the dose totals for the month.

| EXTERNAL DOSE (rem) | | SKIN | DEEP | NEUTRON | TRITIUM |
|---|---|---|---|---|---|
| June | Monthly | | 0.000 | 0.000 | |
| June | Monthly | | 0.000 | 0.000 | |
| June | Monthly | | 0.010 | 0.010 | |
| June | Monthly | | 0.000 | 0.000 | |
| June | Monthly | | 0.040 | 0.020 | |

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

| EXTERNAL DOSE (rem) | | SKIN | DEEP | NEUTRON | TRITIUM |
|---|---|---|---|---|---|
| April | Monthly | 0.010 | | 0.010 | |
| April | Monthly | 0.060 | 0.010 | 0.000 | |

## 6E.2 UNMONITORED PHOTON DOSE

Table 6E-2 summarizes the respective 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. It should be noted that the reported doses that are the basis of this table have not been corrected for potential missed doses.

Table 6E-2. LANL worker gamma dose statistics.

| Year | LANL recorded gamma dose data[a] | | | Lognormal fit | | |
|---|---|---|---|---|---|---|
| | No. of workers reported gamma dose ≥ 50 mrem | Dose (mrem) | | Dose (mrem) | | GSD |
| | | Mean | Maximum | Median | 95% | |
| 1944 | 6 | 1.31E+03 | 5.21E+03 | 6.36E+02 | 4.86E+03 | 3.44 |
| 1945 | 407 | 4.21E+03 | 1.32E+05 | 9.65E+02 | 1.19E+04 | 4.61 |
| 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 |

Table 6E-2 (Continued). LANL worker gamma dose statistics.

| Year | LANL recorded gamma dose data[a] | | | Lognormal fit | | |
|---|---|---|---|---|---|---|
| | No. of workers reported gamma dose ≥ 50 mrem | Dose (mrem) | | Dose (mrem) | | GSD |
| | | Mean | Maximum | Median | 95% | |
| 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 | 1017 | 2.96E+02 | 2.16E+03 | 1.72E+02 | 8.68E+02 | 2.67 |
| 1984 | 1513 | 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 (partial) | 209 | 1.38E+02 | 6.38E+02 | 1.11E+02 | 3.02E+02 | 1.84 |

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

It is recommended that dose reconstructors assign the median (that is, geometric mean) gamma dose from Table 6E-2 to an unmonitored worker for each year of employment.

## 6E.3 ADJUSTMENTS TO REPORTED PHOTON DOSES

Table 6E-3. Recommended adjustments to reported LANL 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.[a] | LASL 1959 (2/16/56 memorandum) |
| 1950 thru 1962 | Brass and Brass-Cadmium film badges | Plutonium areas [a] | Divide reported photon doses by 1.2. [3 ÷ 2.5 = 1.2; see Section 6.3] | LASL 1974 (1/23/74 memorandum); LASL 1969 (3/5/63 memorandum) |
| Apr. 1973 to Dec. 1979 | Cycolac film badge | Plutonium areas [a] | Multiply reported photon doses by 2. | LASL 1969 (3/5/63 memorandum); Storm et al. 1981 |
| Sep. 1961 – Oct. 1964 | Brass-Cadmium badge | Photon exposures >200 keV (reactors, uranium production, accelerators, calibrations, waste handling, RaLa, etc.) | Multiply reported photon doses that exceed 100 mrem by 4. | LASL 1969 (10/13/64 memorandum) |

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

[b] Based on calculated dose rate due to 30-2560 keV photons, based on measured dose, (P2/C7) for a generic 6-kg pit (5 y), from Table A.3 of Traub et al. 2005.

Based on site-specific documentation (LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; 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 likely 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 results summaries for LANL's Model 7776 and Model 8823 dosimeters (Test Sessions 22 and 36, respectively), Table 6E-4 identifies recommended uncertainty factors to be applied to worker doses reported by LANL.

Table 6E-4. Recommended uncertainty factors for reported LANL doses

| | Film Badges | NTA Film | Model 7776 Dosimeter | Model 8823 Dosimeter |
|---|---|---|---|---|
| **Photon (deep)** | ± 30% | Not applicable | ± 14% | ± 19% |
| **Beta (shallow)** | ± 30% | Not applicable | ± 16% | ± 14% |
| **Neutrons (deep)** | Not applicable | ± 50% | ± 8% | ± 8% |

## 6E.4 MISSED BETA/PHOTON DOSE

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

Several exchange frequencies were in use at any one time, so the dose reconstructor needs to determine from individual records which exchange frequency applies to a specific worker. The values in the last two columns of Table 6E-5 can be considered maximum annual missed doses for the purpose of dose reconstructions. Beginning with 1979, badge exchange frequencies are assumed to be monthly if specific information to the contrary for the claimant is not available (NIOSH 2003).

Missed beta/photon dose is entered into IREP as a lognormal distribution with a geometric mean consistent with Table 6E-5 and a GSD of 1.52.

Table 6E-5. LANL 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) | Geometric mean annual missed dose[b,c]; Nonpenetrating dose (mrad) |
|---|---|---|---|---|---|---|
| 1943 – 1944 | PIC | 5 | Nonpenetrating dose was not measured | Daily (n=250) | 625 | Unmonitored |
| 1943 thru June 1946 | Brass badge with lead-cross film | 40 | Nonpenetrating dose was not measured | Monthly (n=12) | 240 | Unmonitored |
| July 1946 through 1948 | Brass film badge | | | Biweekly (n=25) | 500 | Unmonitored |
| | | | | Weekly (n=50) | 1000 | Unmonitored |
| | | | | Daily (n=250) | 5000 | Unmonitored |
| 1949 thru Sept. 1962 | Brass clip, brass-lead, brass-cadmium film badges | 40 | *40* | Monthly (n=12) | 240 | 240 |
| | | | | Biweekly (n=25) | 500 | 500 |
| October 1962 through December 1979 | Cycolac multi-element film badge | | | Weekly (n=50) | 1000 | 1000 |
| | | | | Daily (n=250) | 5000 | 5000 |
| January 1, 1980, through March 1998 | 7776 TLD | 10 | *30* | Monthly (n=12) | 60 | 180 |
| | | | | Quarterly (n=4) | 20 | 60 |
| April 1, 1998, to 2003 (ongoing) | 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 6E-7 footnotes for guidance regarding calculation of unmonitored nonpenetrating dose.
c. Mean annual missed dose calculated using MDL/2 from NIOSH (2002).

## 6E.5 ATTRIBUTION OF BETA/PHOTON DOSES TO ENERGY CATEGORIES

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

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

| Process/ Buildings | Description | Operations | | Radiation type | Energy selection, keV | Percentage |
|---|---|---|---|---|---|---|
| | | Begin | End | | | |
| Plutonium Processing | **Radiochemical Operations:** Plutonium processed at LANL had largely been separated from fission products. Radiochemical operations were largely for recovery of fissionable material. | | | Beta | > 15 | 100% |
| | TA-1, D Building | 1943 | 1945 | Photon | <30<br>30-250 | 65% [a]<br>35% [a] |
| | TA-21, "DP Site, West" | Nov. '45 | 1978 | | | |
| | TA-55, Plutonium Facility | 1978 | Present | | | |
| | TA-3 (including CMR Bldg.) | 1953 | Present | | | |
| Plutonium production | **Plutonium Component Production**: Plutonium is machined into weapon components using glovebox assembly process with predominant close anterior exposure to workers. Radiation characteristics in this area involve significant lower energy photons and neutron radiation. | | | Photon | < 30<br>30 – 250 | 65% [a]<br>35% [a] |
| | TA-1 (D Building), TA-21 (DP Site), TA-55 (PF Site) | | | | | |
| | **Plutonium Storage:** Radiation characteristics in this area generally involve dispersed lower energy neutron radiation and scattered photons, including 60-keV Am-241 gamma ray. | | | | | |
| | TA-1, D-5 Sigma Vault | 1943 | 1945 | | | |
| | TA-21, Building 21 | Nov. '45 | 1978 | | | |
| | TA-55 Vault | 1978 | present | | | |

Information sources: LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003.

a. Low energy photons were not measured by early LANL film badges that had no unfiltered areas. Photon exposure should be assessed as follows:

Before 1949: 100% of the measured photon dose should be attributed to the 30-250 keV category. An additional dose of 1.86 times the measured dose should be attributed to low energy photon (<30 keV category).

1949 and after: Nonpenetrating dose should be estimated and attributed to the <30 keV category.
Nonpenetrating dose = skin dose – (deep dose + neutron dose + tritium dose).

Table 6E-7. Recommended beta and photon radiation energies and percentages for LANL facilities *other than* plutonium facilities.

| Process/ Buildings | Description | Operations Begin | Operations End | Radiation type | Energy selection, keV | Percentage |
|---|---|---|---|---|---|---|
| Reactors | **During Operation:** Highly dispersed fields of higher energy photon radiation fields from fission process, activation and fission product nuclides. Potentially narrow beams of higher energy neutron radiation from test ports, etc., into reactor core. Potential for significant airborne nuclides and there could be significant higher energy beta radiation. | | | Beta [a] | > 15 | 100% |
| | **Not in Operation:** Highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides. No significant neutron radiation. There could be significant higher energy beta radiation during maintenance work resulting from fission products. | | | Photon [b] | 30-250<br>>250 | 25%<br>75% |
| | LOPO Water Boiler (TA-2) | May 44 | Nov. '44 | | | |
| | HYPO Water Boiler (TA-2) | Dec. '44 | Feb. '51 | | | |
| | SUPO Water Boiler (TA-2) | Mar. '51 | Jun. '74 | | | |
| | Plutonium Fast Reactor (Clementine, TA-2) | Dec. '46 | Dec. '50 | | | |
| | Omega West Reactor (TA-2) | Jul. '56 | Dec. '92 | | | |
| | LAPRE I (TA-35) | Feb. '56 | Oct. '56 | | | |
| | LAPRE II (TA-35) | Feb. '59 | May '59 | | | |
| | LAMPRE I (TA-35) | Early '61 | Mid-63 | | | |
| | UHTREX (TA-52) | Dec. '56 | Feb. '70 | | | |
| Uranium Production | **Processing and machining:** depleted and enriched uranium. | | | Beta [a] | >15 | 100% |
| | TA-1 (Sigma, HT Buildings) | 1943 | 1953 | | | |
| | TA-3 (Sigma Complex) | 1953 | Present | Photon [b] | 30-250 | 100% |
| Accelerator operations | **LAMPF** operations at TA-53: Primarily from residual activity induced within targets, accelerator structures and components, grease, oils, and soil. | 1972 | Present | Beta [a] | > 15 | 100% |
| | | | | Photon [b,c] | 30 – 250<br>> 250 | 5%<br>95% |
| Calibrations | LANL site calibration of instruments and dosimeters | 1943 | present | Beta [a] | > 15 | 100% |
| | | | | Photon [b] | 30 – 250<br>> 250 | 25%<br>75% |
| Waste handling | Radiation characteristics highly dependent on source of waste. | | | Beta [a] | > 15 | 100% |
| | Liquid waste: TA-45 and TA-50;<br>Solid waste: Areas A,B, C, D, E, G, T, U, V | Various, 1944 on | | Photon [b] | 30 – 250<br>> 250 | 50%<br>50% |
| Radioactive Lanthanum Operations | **Preparation and Use of Radioactive Lanthanum Sources:** | | | Beta [a] | > 15 | 100% |
| | TA-10 (Bayo Canyon) | 1944 | 1950 | | | |
| | TA-35, "Ten Site" | 1951 | 1963 | Photon [b] | 30 – 250<br>> 250 | 10%<br>90% |

Information sources: LASL 1958, 1959, 1969, 1974, 1977, 1979, 1980; LANL 1986, 1989, 1996, 2001, 2003.

a. For these operations 1949 to present: nonpenetrating dose should be estimated and attributed to the beta radiation category. Nonpenetrating dose = skin dose – (deep dose + neutron dose + tritium dose).

For these operations before 1949: a dose equal to 1.008 times the reported deep dose should be attributed to the beta radiation category. This factor is based on the median shallow-to-deep dose ratio calculated from median annual shallow and deep doses to LANL workers over a ten-year period from 1949 through 1958 (LANL 2004). Only dose records for individuals with $\geq$50 mrem gamma dose were included in this analysis.

b. The reported deep dose should be assigned to the photon dose categories in accordance with the fractions given in this table.

c. The fractions assigned to the 30-250 keV and >250 keV photon energy groups for accelerator operations have been adjusted slightly from those in Table 6-14 so that 100% of the reported deep dose is attributed to these energy groupings, and nonpenetrating dose is attributed to the beta radiation category.

## 6E.6 UNMONITORED NEUTRON DOSE

There should not, typically, be significant neutron exposure of unmonitored workers. However, if there is an estimation of neutron dose, the recommended option is to apply the neutron-to-photon distribution data from Table 6E-9 to measured or estimated missed or unmonitored photon doses. This process of calculating a neutron dose is based on the expectation that the neutron dose to unmonitored workers is equivalent to the median neutron dose measured for monitored workers.

The application of the data from Table 6E-9 to measured or estimated photon doses can be accomplished through Monte Carlo simulation. Alternatively, to obtain an overestimate of unmonitored neutron dose, the appropriate maximum value from Table 6E-9 can be applied to the measured or estimated photon dose for each period of interest.

## 6E.7 MISSED NEUTRON DOSE

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

Table 6E-8 lists the neutron missed dose for those exposed to neutrons.

Table 6E-8. LANL 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 to 1962 | Brass-cadmium badge | < 50 | Monthly (n=12) | < 300 [b] |
| April 1951 through 1978 (limited use with TLDs to 1995) | NTA film | | Biweekly (n=25) | < 625 [b] |
| | | | Weekly (n=50) | < 1250 [b] |
| 1962 to 1978 | Cycolac multielement badge | | Daily (n=250) | < 6250 [b] |
| 1978 to 1998 (some quarterly exchange beginning in 1996) | Model 7776 TLD badge | 10 | Monthly (n=12) | 60 |
| | | | Quarterly (n = 4) | 20 |
| 1995 to present | Track-etch dosimeter | 20 | Quarterly (n = 4) | 40 |
| 1998 to present (40% were exchanged quarterly by Feb. 2002) | Model 8823 TLD badge | 10 | Monthly (n=12) | 60 |
| | | | Quarterly (n = 4) | 20 |

a. Mean annual missed neutron dose calculated using MDL/2 from NIOSH (2002)

b. Neutron-to-photon ratio should be used to estimate missed doses during these periods.

Table 6E-9. Recommended distributions for neutron-to-photon ratio for Los Alamos.

| Neutron source type | Neutron-to-photon dose ratio (uniform distribution) | |
|---|---|---|
| | Minimum | Maximum |
| Plutonium facilities | 0.30 | 5.5 |
| Criticality experiments (> 50 m distant) | 1.7 | 2.8 |
| Other operations | 0.59 | 2.4 |

## 6E.8 ATTRIBUTION OF NEUTRON DOSES TO ENERGY CATEGORIES

Table 6E-10 presents default neutron dose fractions by energy for LANL work areas where field measurements of neutron spectra have been performed, along with the associated ICRP 60 correction factors (ICRP 1990). The neutron dose equivalent is calculated by multiplying the recorded neutron dose by the area-specific correction factors.

Table 6E-10. Recommended dose fractions and ICRP 60 correction factors for LANL neutron sources.

| Process | Description/buildings | Operations | | Neutron energy | Default dose fraction (%) | ICRP 60 correction factor |
|---|---|---|---|---|---|---|
| | | Begin | End | | | |
| Plutonium production | Neutron dose was associated with overall LANL plutonium production process in which plutonium was purified, formed, machined, and recovered. Work was primarily conducted in gloveboxes with predominant close anterior exposure to workers. | | | | | |
| | Plutonium facilities<br>(D Building at TA-1, DP West Site at TA-21, Plutonium Facility at TA-55) | 1943 | Present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 11%<br>56%<br>33% | 0.23<br>1.1<br>0.44 |
| LAMPF | Neutrons of varying energies from high energy proton linear accelerator studies. | | | | | |
| | LAMPF at TA-53 | 1972 | Present | <10 keV<br>10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 30%<br>30%<br>20%<br>20% | 0.64<br>0.56<br>0.38<br>0.26 |
| Reactor operations | Neutrons of varying energies from reactor operations. | | | | | |
| | Omega Site (TA-2)<br>TA-35<br>TA-52 | 1944<br>1955<br>1969 | 1992<br>1963<br>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)<br>TA-18 | 1943<br>Apr. '46 | Apr. '46<br>present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 3.2%<br>59%<br>38% | 0.060<br>1.1<br>0.50 |
| Chemistry & Metallurgy Research | Neutrons of varying energies from actinide chemistry and metallurgy research. | | | | | |
| | TA-1<br>TA-3 | 1943<br>1952 | 1952<br>present | <10-100 keV<br>0.1-2 MeV<br>2-20 MeV | 10%<br>50%<br>40% | 0.21<br>0.95<br>0.53 |

## 6E.9 RECOMMENDED DOSE CONVERSION FACTORS

Dose conversion factors (DCFs) should be selected from NIOSH (2002) for the dose quantities specified in Table 6E-11 for the periods of interest.

Table 6E-11. Recommended dose conversion factors for LANL dose assessments.

| Time Period | Recommended Photon DCFs | Recommended Neutron DCFs |
|---|---|---|
| 1943-1984 | Exposure *(R)* to Organ Dose Equiv. *($H_T$)* | Deep Dose Equiv. *($H_{p,slab}(10)$)* to Organ Dose Equiv. *($H_T$)* |
| 1985 to present | Deep Dose Equiv. *($H_p(10)$)* to Organ Dose Equiv. *($H_T$)* | |