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Project for NIOSH

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ACRONYMS AND ABBREVIATIONS

a.u.	arbitrary units
AEC	U.S. Atomic Energy Commission
AGHCF	Alpha Gamma Hot Cell Facility
AMFF	Advanced Materials Fabrication Facility
ANL-E	Argonne National Laboratory-East
ANL-W	Argonne National Laboratory-West
APS	Advanced Photon Source
ATLAS	Argonne Tandem Linear Accelerator System
ATSR	Argonne Thermal Source Reactor
amu	atomic mass unit
AWA	Argonne Wakefield Accelerator
C.F.R.	Code of Federal Regulations
Ci	curie
cm	centimeter
CP-1	Chicago Pile 1
CP-2	Chicago Pile 2
CP-3	Chicago Pile 3
CP-3´	Chicago Pile 3 Prime
CP-5	Chicago Pile 5
d	day
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
EBR-II	Experimental Breeder Reactor No. 2
EBWR	Experimental Boiling Water Reactor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
ERDA	Energy Research and Development Agency
ES&H	Environment, Safety, and Health
eV	electron volt
g	gram
GeV	giga electron volt, 1 billion electron volts
hr	hour
HVEM	High-Voltage Electron Microscope
ICRP	International Commission on Radiological Protection
in.	inch
IPNS	Intense Pulsed Neutron Source
IREP	Interactive RadioEpidemiological Program
keV	kilo electron volt, 1,000 electron volts
LAMPF	Los Alamos Meson Physics Facility
LANL	Los Alamos National Laboratory
LINAC	linear accelerator
LOD	limit of detection
mA	milliampere

MeV	mega electron volt, 1 million electron volts
mg	milligram
mm	millimeter
mo	month
mR	milliroentgen
mrad	millirad
mrem	millirem
mrep	millirep
MWSF	Mixed Waste Storage Facility
n	neutron
nC	nanocoulomb
NCRP	National Council on Radiological Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
NRTS	National Reactor Testing Station
NTA	nuclear track emulsion, type A
PIC	pocket ionization chamber
PNNL	Pacific Northwest National Laboratory
pps	pulses per second
QF	quality factor
qtr	quarter
R	roentgen
s	second
SSTR	solid-state track recorder
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
WBC	whole-body counter
wk	week
w_R	weighting factor
ZGS	Zero Gradient Synchrotron
ZPR-I	Zero Power Reactor No. 1
ZPR-II	Zero Power Reactor No. 2
ZPR-IV	Zero Power Reactor No. 4
ZPR-IV´	Zero Power Reactor No. 4 prime
ZPR-IX	Zero Power Reactor No. 9
ZPR-V	Zero Power Reactor No. 5
ZPR-VI	Zero Power Reactor No. 6
ZPR-VII	Zero Power Reactor No. 7
α	alpha particle
γ	gamma ray
§	section

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.

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

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

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

6.1.1 Purpose

Argonne National Laboratory was established on July 1, 1946 and this TBD is intended to cover since that date. The work was a continuation of that done by the Metallurgical Laboratory of the University of Chicago beginning in 1941 which is an Atomic Weapons Employer under EEOICPA. The job locations did not change until land and buildings were acquired for the laboratory.

The purpose of this TBD is to describe the external dosimetry systems and practices at Argonne National Laboratory-East (ANL-E). This document discusses historical and current practices in relation to the evaluation of external exposure data for monitored and unmonitored workers.

6.1.2 Scope

ANL-E, operated by the University of Chicago, has played an important role in the development of the U.S. nuclear program. ANL-E operations have involved research and development in the areas of nuclear reactors, high-energy physics, and nuclear materials. This TBD is part of the overall ANL-E Site Profile, which describes plant facilities and processes, historical information, and environmental data in relation to dose reconstruction for ANL-E workers. It contains supporting documentation to assist in the evaluation of occupational external doses from these processes in accordance with the *External Dose Reconstruction Implementation Guideline* (NIOSH 2002).

The methods and concepts of measuring occupational external doses to workers have evolved since the beginning of ANL-E operations. An objective of this document is to provide supporting technical data to evaluate the external ANL-E occupational doses that can reasonably be associated with worker radiation exposures under the EEOICPA legislation. These doses include occupational external exposures in ANL-E facilities and onsite exposures to ANL-E environmental releases. This document addresses the evaluation of unmonitored and monitored worker exposure and missed dose. Consistent with NIOSH guidelines, this document identifies how to adjust the historical occupational external recorded dose to account for current scientific methods and protection factors.

In addition, this document presents the technical basis of methods used to prepare ANL-E worker dose information for input to the NIOSH Interactive RadioEpidemiological Program (IREP). Information on measurement uncertainties is an integral component of the approach. This document describes the evaluation of uncertainty for ANL-E exposure and dose records.

6.2 EXTERNAL DOSIMETRY OVERVIEW

Over the years, ANL-E used dosimetry badge designs that were typical for other government contractors of the respective periods, but the Laboratory continued to use film dosimeters somewhat longer than at other sites. The initial design was a two-element badge incorporating a steel case, an open window, and a 1-mm cadmium filter. The same basic design was probably modified for wear on the wrist, head, or leg for extremity monitoring. No record of the type of beta-gamma film used initially in these badges was available, but DuPont films were in use by the late 1950s. The badges eventually included Kodak nuclear track emulsion, type A (NTA) films for locations where neutrons were of concern. The beginning of neutron monitoring is uncertain, but it appears to have been in use at other sites as early as 1951. Indirect references to it at ANL-E begin around 1953. By the mid-1950s some film badge rings (provided by a contactor) were in use on at least a trial basis to supplement wrist monitoring.

Before March 1954, ANL-E processed films for itself as well as several universities. ANL-E then contracted the service to three commercial laboratories before resuming in-house processing in 1965 (Strom 1982). Table 6-1 summarizes beta-gamma film-processing history. Even during the period of contracted film service, there is some indication that an in-house capability was maintained, probably for emergencies, special studies, etc. The Atomic Film Badge Corporation was the only contactor reported to process and read Kodak NTA film. Due to the labor needed to read NTA film, it appears that films were developed but not routinely read before 1960. Films were apparently not evaluated unless there had been a gamma dose measured for the same period (Dolecek 1981).

Table 6-1. Summary of beta-gamma film-processing history .

Film processor	Dates
ANL-E	1942–1954
Tracerlab	Mar 1954–Jun 1958
Landauer	Jul 1958–Jun 1960
Atomic Film Badge Corporation	Jul 1960–Dec 1964
Tracerlab	Jan 1965–Sep 1965
ANL-E	Oct 1965–1988

Around 1960, ANL-E transitioned to a four-filter film badge. It is uncertain whether the design was from its contactor, Atomic Film Badge Corporation, or was made to ANL-E specifications. The badge offered by the Atomic Film Badge Corporation had an open window backed by 0.060 in. of plastic, 0.008 in. of copper (front and back), 0.024 in. of copper (front and back), and 0.032 in. of lead (front and back). The whole-body and wrist versions were identical except for the means of securing the badge to the body. A ring badge was offered with a pair of 0.032-in. lead filters, suitable for X-ray, and gamma radiation only.

A new whole-body film badge design was put in place in 1962. The design was identical to the one used at the National Reactor Testing Station (NRTS) in Idaho and at Hanford in Washington State and was referred to as the ANL or NRTS type. This badge featured a holder constructed of Tenite II and a slide insert. The holder contained three filtered areas and an open window. The filters were 0.0191 in. of aluminum, 0.005 in. of silver, and 0.0395 in. (1 mm) of cadmium. The filters and an open window were on both sides of the film. Dose from photon energies greater than 150 keV, dose from photon energies less than 150 keV, and dose from beta radiation were interpreted by referring to various calibration curves (Strom 1982). The design was probably modified to be worn as an extremity monitor and incorporated Kodak NTA film when deemed necessary. Around 1970 Kodak films replaced DuPont films for beta-gamma monitoring. This badge design was used for whole-body dosimetry until being replaced by thermoluminescent dosimeters (TLDs) in 1988 to 1989.

Work on TLDs for monitoring dose to the fingers began around the mid-1960s, and these dosimeters were in use by 1967 in at least some facilities. This ring design differed from the current design. As at most sites, the limitations of NTA film were recognized and work was started on methods to replace or supplement the film. A solid-state track recorder (SSTR), incorporating ^{235}U foils and mica (to record track damage) was tested at the Zero Power Reactor (ZPR) facility. This method was used for the dose of record for a brief time, and was followed by two albedo neutron designs (Hankins and Hosger) using TLD-600 and TLD-700 chips. At least initially, NTA film was still added to the beta-gamma badges. The record is unclear exactly when NTA film was finally discontinued.

In 1984, ANL-E decided to change from film to an automated TLD system for beta-gamma dosimetry. The Panasonic system adopted by DOE-Idaho and used at ANL-West (ANL-W) was selected for all but the albedo neutron portion. The TLD portion consisted of three (natural abundance) lithium-borate elements and one calcium-sulfate element designated the Panasonic UD-814AS4. The system used the Panasonic UD-710A automatic dosimetry reader. Two of the lithium-borate elements under thin filters (16 mg/cm^2 and 58 mg/cm^2) are used to determine shallow dose equivalent. A lithium-borate element under a thicker filter (600 mg/cm^2 of plastic and aluminum) provides a flat energy response for deep dose equivalent. A calcium-sulfate element under the same thick filter provides an indication of low-energy photon radiation (ANL 1996). This dosimeter passed Department of Energy Laboratory Accreditation Program (DOELAP) testing in May 1988. Although the Panasonic UD-814AS4 dosimeter is not used for quantitative neutron dose determinations, the response to neutron radiation of the natural lithium borate versus the response of the calcium sulfate provides a flag that the wearer may have been exposed to neutrons. An albedo dosimeter containing Harshaw TLD-600 and TLD-

700 chips in a *polybox* is inserted into the ANL-E holder for workers with the potential for neutron exposure (ANL 1996). There is no evidence that the ANL-E albedo system has been accredited by DOELAP.

From the early days, Shonka-type pocket ionization chambers (PICs; both remote-reading and self-reading), often referred to in site documents as *dosimeters* or *pocket meters*, of various ranges were in use. Even though their readings were not considered as the official dose, the readings were recorded in the individual dosimetry records up to 1964. Film badges and PICs were stored at the entrances to the different facilities. The locations where the dosimeters were used are generally included in the dose record (exceptions are noted below). When workers entered facilities for which they did not have an assigned film badge, they were assigned a *rover* dosimeter (generally, if not always, a pocket chamber) (McDowell-Boyer 2005). The rover dosimeter's dose was then added to the film badge's penetrating reading for the same wear period.

Table 6-2 summarizes the ANL-E external dosimetry history. The years given are approximate. In some cases, changes probably were phased in over time or were implemented only in certain facilities or for certain groups. For example, TLD badges were already being used by security personnel by the summer of 1981 (Strom 1982).

6.3 INTERPRETING THE EXTERNAL DOSIMETRY RECORD

When the U.S. Department of Labor requests a worker's dosimetry records, the ANL-E Chemical Engineering Division searches for the relevant records. For external dosimetry, there are three records sources that might contain the needed information. The Worker Protection System is a database of employees between 1945 and the present. A second database (dBase III plus) contains the external dosimetry records for persons employed between 1989 and the present. Last, there are hard-copy records of the external doses for persons who were employed between 1942 and 1988. From these sources, an External Radiation Exposure Record (summary) is developed (Luck 2002). See Figure A-1 in Attachment A for an example. For early workers, only this summary report is initially provided. For workers with dose assigned in 1989 or later, a separate computer-generated summary is provided (Figure A-2) for those years. Requests for the detailed information have resulted in ANL-E providing records in the various formats from the hard-copy files. The records generally provide data for comparison to occupational exposure limits in effect at the time.

The pre-1989 record summaries report external dosimetry results as:

- Deep dose: Sum in millirem of penetrating photon plus neutron dose equivalent at a depth of 1.0 cm in a 30 cm sphere of soft tissue of density 1 g/cm^3.
- Shallow dose: Dose equivalent in millirem at a depth of 0.007 cm in a 30 cm sphere of soft tissue of density 1 g/cm^3.
- Code *M* for years in which the dose was less than the minimum sensitivity of the measuring device.
- Code - [hyphen] or *NM* for unmonitored periods; some records indicate unmonitored periods with a statement such as “Not monitored 1960-1962”.

- Code * (asterisk) after the dose when the only monitoring was by a direct reading dosimeter; additional codes used are explained on the report.

Table 6-2. ANL-E external dosimetry history.

Year	Holder	Beta/gamma				Neutron		Extremity	
		Detector	Filtration		Processor	Detector	Processor	Detector	Processor
			Deep	Shallow					
1945	University of Chicago (two filter)	Film, Type Unknown	1 mm Cd	Open (28 mg/cm^2 Wrapper)	ANL			Film	ANL
1946									
1947									
1948									
1949									
1952		"catastrophic" film added							
1953						Kodak NTA	ANL	Film rings Ring, wrist, & head films	R. C. Scientific & Others Wrist, head same as whole body
1954									
1955					Tracerlab, Inc.				
1956									
1957									
1958					Landauer, Inc.				
1959		DuPont 553							
1960	See text	DuPont 558	See text	See text	Atomic Film Badge Corp.	Kodak NTA	Atomic Film Badge Corp.		
1961									
1962	Hanford Type (four filter)	DuPont 558	0.0191" Al 0.005" Ag 0.0395" Cd	Open Window					
1963					ANL	Kodak NTA	ANL		
1964									
1965		DuPont 553							
1966		DuPont 558							
1970		Kodak Type 3						TLD ring	ANL
1971		Kodak Type 2							
1973						Kodak NTA & SSTR			
1974									
1975									
1976									
1977						Kodak NTA & Albedo TLD			
1978								Current TLD Ring	
1979-1987									
1988	INEEL design (beta & gamma only)	TLD Panasonic UD814AS4 (3 lithium borate & 1 calcium Sulfate)	$CaSO_4$ & $Li_2B_4O_7$ Under 600 mg/cm^2 Plastic & Al	$Li_2B_4O_7$ under 16 mg/cm^2 & 58 mg/cm^2 plastic	ANL	TLD Harshaw TLD 600/700			
1989									
1990									
1991									
1992									
1993									
1994									
2004									

The 1989 and later records summaries (Radiation Exposure Record) report external dosimetry results as:

- Deep dose equivalent (*DDE*), lens of eye dose equivalent (*LDE*), shallow dose equivalent (*SDE*, *WB*), shallow dose equivalent maximum extremity (*SDE*, *ME*)
- Code *NM* for not monitored
- Code *ND* for not detectable

The reported values for the early years when the dosimeters were calibrated to exposure assume that 1 mR is equal to 1 mrem. While this report (Figure A-2) is not directly useful for dose reconstruction, it provides a good cross check on the annual totals because it was compiled by someone familiar with the various records forms.

All dosimetry results for a worker are provided as a package. Gaps in results that are not the result of a break in employment should be interpreted as unmonitored periods. Breaks in employment can be determined by a standard request for dose history in the individual's file. For 1964 to 1975, only annual summary data for each individual are likely to be available (ANL 2005).

6.3.1 Dosimetry Records Systems

In the 1940s and 1950s, external dosimetry data were handwritten on preprinted forms. In 1961 the transition was made to a computer system, and printouts replaced hand-entered forms. From 1964 to 1975, a handwritten form was again used and only shows annual totals. Computer reports are provided from 1976 to the present. A separate neutron report and up to four reports on supplemental dosimeters issued could be included in some records.

An individual worker's records can contain one or more of the following depending on the years of employment. Dates given are approximate. Attachment A contains a redacted sample with personal identifiers removed from each record.

Individual Meter Record (1942 to mid-1953) – Hand Entered (Figure A-3)

- Each card covers 1 wk.
- The values are in roentgen rather than milliroentgen.
- Daily readings for PICs and a weekly total, number of times worn, and *Discg* (entry placed here for accidental discharge).
- Film meter exposure values for shield and window for the week.
- Location worn (e.g., Site A).

Cumulative Exposure Record (mid-1953 to 1961) – Hand Entered (Figure A-4)

- Results for each wear period.
- The values are in milliroentgens (γ) and arbitrary units (β).
- From mid-1953 (fiscal year 1954) to 1956, the forms are for one fiscal year. From 1956 to 1961 they are by calendar year.
- Two-column format so a year's results can fit on one form.
- Because dosimeters were stored at the entrances to facilities, the hard-copy records can contain multiple record sheets for the same period, each representing the dose accumulated at one facility or area. Locations are generally given as building numbers, sometimes preceded with a letter, e.g. *D* meaning a building on the D site. Sometimes doses from additional facilities are on the same form and footnoted as shown in Figure A-4.
- Zeroes represent a reading below the reporting threshold. Dashes mean that a badge was not read for that period.

- For betas, when the change from arbitrary units (*a.u.*; see Section 6.8.2.1) to beta dose occurred (1961), the a.u. column heading was lined through and *Beta* was written next to it.

- When a badge was not returned on time, an *N* was entered on the form. When the badge was read, the dose and a date (e.g., *R7/31*) were entered to the right of the *N* to indicate that the badge had been returned on July 31st and read late.

- The forms were divided into 4 qtr of 13 wk each. Each quarter was subtotaled.

- The forms only recorded beta-gamma PIC readings and film penetrating (*mr*) and nonpenetrating (*a.u.* or *beta*) doses. Neutron doses from NTA film were recorded on the Neutron Exposure Report, see below.

- Doses determined to be invalid or needing adjustment based on an investigation are footnoted and cross-referenced to a report explaining the change. In most cases, no administrative or notional doses were added for defective, fogged, or damaged film. However, in at least some cases, doses footnoted as invalid were added to the quarterly totals.

Accumulated Exposure Report (1961 to 1962) – Computer Printout (Figure A-5)

- Results for each biweekly wear period shown in a single line.

- Form includes entire calendar year

- Routine dosimeter (*ROUT DOS*), rover dosimeter (*ROV DOS*), and film (*BETA*, *GAMMA*, and *NEUT*) results are shown. Each of these results is totaled for the year.

- Biweekly total (*BIWK TOTAL*) and running totals for the calendar year (*CAL YR*) and last 14 weeks (*QTD TOTAL*) are given.

- The values are in milliroentgens (γ), mrad (β), and mrem (neutron).

- Section codes are used instead of building numbers (see Attachment B for a list of section codes). Up to three section codes can be displayed for each period.

- Less than the minimum reported values are shown as zeros.

- It could not be determined how unmonitored (by film badge) periods are shown, as every record appears to show 26 periods per year. Zeros in the section code column may indicate that the individual did not have a badge for that period.

Semi-Annual Accumulative External Exposure Report (1963 to 1964) – Computer Printout (Figure A-6)

- One form contains approximately 6 mo of data.

- The values are in milliroentgens (γ), mrad (β), and mrem (neutron).

- The location where the badge was worn is in the *LOC IDENT* column. This field is a combination of the location code (see Attachment B for a list of codes) and the employee's *IHS* number.

- For 1963, results for each biweekly film dosimeter are shown in a single line. There are two lines below the film badge for each weekly dosimeter (*WK DOS*, i.e., PIC) results. For 1964, the entries for the weekly dosimeters were eliminated.

- For 1963, routine dosimeter (*WK DOS*), rover dosimeter (*R DOS*), and film (*BETA*, *GAMMA*, and *NEUT*) results are shown. For 1964, there is no entry for routine dosimeters.

- Totals (penetrating) are shown for each period (*TOTAL*).

- Less than the minimum reported values are shown as zeros.

- Unmonitored (by film badge) periods are not shown on the form (i.e., a line of data is not created for the unmonitored period).

Whole-Body Radiation Exposure Summary (1964 to 1975) – Hand Entered (Figure A-7)

- Only annual totals are presented for *Rover Dosimeter*, *Film Badge* (beta, gamma, and neutron), and *Penetrating Total* (sum of rover, gamma, and neutron).

- The values are in mrem.

- PIC readings used routinely are not included.

- Section or building assignments are not included.

Master Radiation Exposure File (1976 to 1988) – Computer Printout (Figure A-8)

- For 1976 and 1977 only the right-hand side of the wide computer-paper form is copied for inclusion in the hard-copy records. The worker's name is cut off, but the social security number shows.

- Results for each monthly period are shown in a single line.

- Column headings are two-digit year and month (*YM*), location code (*OHS SEC*), count of rovers (*ROV CNT*), rover reading(s) (*ROV DOS*), film doses (*BETA*, *GAM*, *NEUT*), penetrating dose (*PEN*; sum of rover, gamma, and neutron), and Remarks (*RE*). A common remark was "99," indicating a dosimeter that was returned late.

- The values are in milliroentgens (γ), mrad (β), and mrem (neutron).

- Totals are provided for the calendar year and moving quarter. Because only the annual report is included in the record, the moving-quarter value will always be the forth quarter total.

Master External Radiation Exposure Report (1989 to 2002) – Computer Printout (Figure A-9)

- This report coincides with the start of TLD monitoring as the dose of record for the whole body and the first results from the DOELAP-accredited system.

- Results for each monthly period are shown in a single line.

- Column headings are location code (*SECTION*), *BADGE TYPE, ISSUE DATE, RETURN DATE, SHALLOW DOSE, DEEP DOSE, NEUTRON DOSE, PENETRATING TOTAL* (sum of deep and neutron), and *REMARKS*. Remarks include codes such as *99* (late), *NR* (not returned), and *IN* (investigate).

- For 1989 through 1991, the employee's name and dosimetry identification number (also ANL-E employee number) appear above the issue and return date. Starting in 1992, columns for each wear period were added for *LAST NAME* and *MASTERID*. The MASTERID is a combination of the wear period (*YYMM*), the location code, and the dosimetry identification number.

- The values are in mrem.

- Shallow dose is set to the higher of the measured value or deep value.

- Totals are provided for the calendar year.

- A note in a heading states that the zero in the neutron column should be ignored if the badge type is not *BGN* or *BGNC*. In other words, a zero does not imply that the worker was monitored for neutrons unless a neutron dosimeter was issued.

Neutron Exposure Report (1960 to 1961) – Hand Entered (Figure A-10)

- Multiple wear periods and results could be on one form.

- The values are in millirem.

- At times, the neutron dose equivalent appears not to have been carried over to be added to penetrating dose unless the limit of detection (LOD) was exceeded. In other cases, neutron dose equivalents as low as 5 mrem were added.

Special Exposure Records (1953 to 1960) – Hand Entered (Figure A-11)

- The records contain supplemental dosimeter readings, i.e., extra badge worn on wrist or body.

- The values are in milliroentgens and a.u.

- Multiple film badges and dosimeters and wear periods can be shown on one form.

- Information includes date, type (film badge or dosimeter), area, time (worn), position, mR under filter, a.u., and comments (might explain why worn).

Special Film Request (1958 to unknown) – Hand Entered (Figure A-12)

- This form recorded a request for special film badge and documents the results.

- It appears to overlap in time with the Special Exposure Records (Figure A-11), but is used for one badge only.

- Includes date(s) and time(s) worn, area (building), position worn, type of film (beta-gamma or neutron), and remarks. The remarks can indicate the reason for the badge.

- The results are in milliroentgens, a.u., and millirem (neutron).

Special Meter Assignment and Radiation Exposure Report (1961 to 1987) – Hand Entered (Figure A-13)

- The records contain supplemental dosimeter readings, i.e. beta-gamma badge worn on right wrist.
- This form probably replaced the Special Film Request (Figure A-12). At least four variations were noted corresponding to the dosimeters in use over the years: Two-element beta-gamma, four-element beta-gamma, NTA film, and albedo TLDs.
- The values are typically in milliroentgen, mrad, and millirem (neutron) and are listed on the forms.
- One form was created for each badge worn.
- Densities under filters and the open window as well as resultant exposures are documented.

Special TLD Finger Exposure Report (1978 to 1988) – Hand Entered (Figure A-14)

- This form appears to coincide with the start of the current finger dosimeter because it is designed for up to four readings.
- Multiple wear periods are on the same form.
- Fields shown are type of work, begin date, end date, TLD readings (1 to 4), and beta-gamma, gamma, and neutron exposures. The type of work was most frequently a location rather than a description. The gamma and neutron columns appear not to have been used.
- Either two or four TLD readings were shown. No notation is included to indicate that more than one ring was being worn in the case of four TLDs.
- Doses are in millirem or millirad (according to the column heading).

Personnel Dose Equivalent Evaluation – Level 1 (1960-unknown) – Hand Entered (Figure A-15)

- Reported exposures above certain thresholds were routinely investigated (Bleiler 1964).
- This record documents the results of investigations for the monthly wear period. All evaluations for a particular area were documented on one form.
- The primary purpose of the form was to bring abnormal doses to the attention of the individuals and the area health physicists and to encourage corrective measures.
- Contains the period worn, the level in millirem, the type, whether the dose is valid (yes/no), and whether it was anticipated (yes/no). There were four exposure types. Type A was a dose of greater than 300 mrem/mo to the whole body, head and trunk, gonads, active blood-forming organs, and lens of the eye. Type B was 900 mrem to the skin, other organs, tissues, and organ systems. Type C was 1,800 mrem/mo to the forearms and ankles. Type D was 4,500 mrem/mo to the hands and feet.

- Unanticipated and invalid doses required additional documentation.

- There also was a Level 2 evaluation, with four higher-level A, B, C, D types (900, 1,500, 3,000, 7,500 mrem/mo, respectively). No examples of the Level 2 evaluation were found.

Termination Occupational Exposure Report (1979 to unknown) – Hand Entered (Figure A-16)

- Form prepared when workers terminated employment during certain years.
- Provides the beginning and ending employment dates in blocks 8 and 9, respectively.
- The external dose in millirem is in block 11.

Explanations of invalid data were also sent to individual files. For example, the results for all but one group of badges worn between June 12 and July 9, 1964, were declared invalid due to exposure received in shipment. The individuals' detail cards were punched with code 89 and zero doses were recorded.

6.3.2 Observed Data Discrepancies

As can be seen from the descriptions in the previous section, some of the periods of use of the various forms overlap. Care should be taken to not double count the doses for these periods.

The claimant-favorable assumption is to include discrepant data in the annual total unless there is some explanation in the record as to why it should not be included.

6.4 HISTORICAL ADMINISTRATIVE PRACTICES

6.4.1 Badged Population

In 1956, the site *Radiation Safety Guide* (ANL 1956a) indicated that areas were posted and that individuals entering an active area were required to wear personnel monitoring devices found at the entrance. Areas spelled out as active included Building 330 (CP-5) and Building 211 (cyclotron and small Van de Graaff accelerator). Wing G of Building 203 (large Van de Graaff) was not an active area, but access was forbidden during operation and restricted at other times. In addition, permanent monitors for fast neutrons were installed. Wrist badges containing neutron film were required at CP-5 (ANL 1956a).

Information developed in a 1982 survey for a DOE health and mortality study (Strom 1982) indicates that early on everyone was badged. By 1965, nearly all employees were still badged. By the early 1970s, the site health physicists assigned badges based on the exposure potential. By 1982 it was noted that approximately one-third of the workers were badged.

In the 1973 to 1984 revisions of the site *Health and Safety Manual* (ANL 1973), a radiation area was defined as an area where the dose (equivalent) to an individual in any calendar quarter could exceed 300 mrem, where radioactive materials were stored in quantity, or where equipment producing ionizing radiation was operated. Each person entering a radiation area was required to wear a personal monitoring device. Assigned film badges and self-reading dosimeters were provided at the entrance to each area and were to be returned to the designated storage area at the end of the work shift (ANL 1973).

6.4.2 Badge Exchange Frequency

At first there were weekly film badge exchanges. On April 16, 1951, the badge exchange frequency was changed from weekly to biweekly for Site D and West Stands personnel. Although not stated, this change probably included Site A personnel. The only film badges still being developed weekly were for reclamation personnel (i.e., the site decontamination group) and twenty special cases at the new Chemistry Building at the University of Chicago (Rose 1951).

The 1961 specifications (scope of work) for film badge services indicated that the exchange frequency was to be biweekly (Strom 1982). During 1967 to 1974, badges were exchanged approximately biweekly (26 exchanges/yr) (Bleiler 1968a, 1968b, 1970, 1973a, 1974).

Due to a work force reduction in the Personal Monitoring Group biweekly exchanges were eliminated and all film badges were placed on a 4-wk exchange schedule as soon as possible (Bleiler 1973b). It appears that this change was made starting with the first exchange in 1974, which covered December 28, 1973, to January 24, 1974 (Bleiler 1975a). Starting in 1975, exchanges were monthly according to Bleiler (1975b). This does not agree with "Information concerning NIOSH Requests" (Luck 2002), which states that monthly exchanges started in October 1965. This may indicate that some groups were on a monthly exchange at least temporarily in the mid-1960s.

In 1981 and 1982, the exchange frequency was monthly (Strom 1982). A summer 1981 study done at ANL-E indicated that a quarterly TLD badge exchange was anticipated (Strom 1982). There is no evidence that this was implemented for the general population.

The *Advanced Photon Source* [APS] *Accelerator Systems Safety Assessment Document* states that personnel monitors are exchanged quarterly at that facility (ANL 1994).

Table 6-3 provides the claimant-favorable default dosimetry exchange frequencies to be used for dose reconstructions.

Table 6-3. Default dosimeter exchange frequencies.

Years	General population	Others
1945–1959	Weekly	
1960–1973	Biweekly	
1974	4-Week (13 periods/yr)	
1975–2005	Monthly (12 periods/yr)	1994 APS quarterly

6.4.3 Field-Specific Calibration Factors

No workplace-specific calibration factors have been found.

6.4.4 Minimum Reported Dose

The specifications for the multi-element film badge (Hanford type) indicated that the response range of the film badge was to be 0.025 R to 3,000 R (Strom 1982). In 1982, measured doses of less than 15 mR were reported as zero (Strom 1982).

The specifications for the Atomic Film Badge Corporation multi-element badge indicate that a lower limit of 25 mR was reported for X-ray, beta, and gamma. Amounts less than 25 mR were shown but not added to the cumulative total. Any neutron doses above zero were reported. Neutron tracks were counted in 25 random fields (Strom 1982). No information on minimum reported doses was recovered for the other early vendors.

A 1980 survey indicated that the lower dose thresholds below which results were considered background were 15 mrem for nonpenetrating and penetrating radiation and 50 mrem for neutrons (Neal 1980).

The algorithm for the Panasonic UD-814AS4 beta-gamma TLD (the current dosimeter) indicates that the minimum reported dose equivalents are 15 mrem deep (penetrating) and 30 mrem shallow (nonpenetrating). However, ANL (1996) also states that the reporting level is 10 mrem for deep dose equivalent, and this appears to be the current value. The minimum reporting level for neutrons is 10 mrem. However the dosimeter described is not the Panasonic UD-808AS tested by DOELAP in 1992, but a Hankins-type (one TLD-600 and one TLD-700 enclosed in a polybox) (ANL 1996).

6.5 COMMON ISSUES

6.5.1 Number of Zero Readings

The available dosimetry records do not provide individual dosimeter results from 1964 to 1975. As mentioned above, there is some overlap in the dose records for 1964; so 1964 detail might be available for some workers. In many cases it will therefore be necessary to estimate the dosimeter exchange frequency from 1964 to 1975. It appears that ANL-E did not generally use different exchange frequencies based on job categories, so assumption of a single frequency by time period is reasonable. Table 6-3 lists the default dosimeter exchange frequencies. For 1964 to 1973 the exchange frequency should be assumed to be biweekly (26 exchanges/yr). For 1974 the exchange frequency should be assumed to be every 4 wk (13 exchanges/yr). For 1975 the exchange frequency should be assumed to be monthly (12 exchanges/yr). For other years, determining the number of zero readings should be straightforward.

If the number of zero measurements cannot be determined, the missed dose evaluation becomes more complex. When only the annual dose is known, the number of zero doses should be estimated based on the dose level and the monthly, quarterly, or annual limits for that year and the number of possible zero monitoring intervals. This would be the situation, for example, if an individual received a cumulative dose of 2,000 mrem in a given year at a facility that had a monthly monitoring frequency and a maximum permissible exposure limit of 417 mrem/mo. The minimum number of months in which this dose could have been received is five. Therefore, the maximum number of missed dose months would be seven, and the minimum would be zero because the dose could have been received evenly throughout the year. The central estimated number of months should be the median (4), but the upper bound would be seven (NIOSH 2002). Table 6-4 lists historical dose limits.

Table 6-4. Historical dose limits.

Period	Daily or weekly limit	Quarterly or annual limits:
1945–1955	Beta & gamma, 100 mrem/d (Nickson 1946, Gilbreath undated)	Not applicable
1956–1972	Gamma 300 mrem/wk (AEC 1958) Beta & gamma (sum), 500 mrep/wk (ANL 1956a)	3 rem/qtr, 15 rem 5(N-18) rem accumulated (AEC 1958)
1973–1988	Not applicable	3 rem/qtr (ANL 1973) 5 rem/yr 5(N-18) (DOE 1981)
1989-1992	Not applicable	5 rem/yr annual effective dose equivalent (DOE 1988)
1993-2005	Not applicable	5 rem/yr total effective dose equivalent (DOE 1992)

Table 6-5 divides these dose limits into exchange frequencies. Using the methodology of NIOSH (2002), it is possible to develop a claimant-favorable estimate of the number of zeros for calculation of the missed dose.

6.5.2 Discrepancies

If the employee's record contains discrepancies, it is claimant-favorable to use the higher dose in the dose reconstruction. Care must be taken to interpret dose numbers properly if units were not specified. At first, ANL-E routinely reported exposures in roentgens. Since mid-1953 the laboratory has routinely used milliroentgens and millirem. It is highly unlikely that a record would show a dose greater than the quarterly or annual limit without an additional record indicating an overexposure.

Table 6-5. Dose limits (rem) based on exchange frequency.

Years	Limit (rem)	Period (yr)	52 Weekly	26 Biweekly	13 4-weekly	12 Monthly	4 Quarterly
1945–1955	0.1	~260	0.5	(a)	(a)	(a)	(a)
1956–1972	0.3	52	0.3	0.6	(a)	(a)	(a)
1973–1988	3	4	(a)	0.462	0.923	1.0	(a)
1989–2005	5	1	(a)	(a)	(a)	0.417	1.25

a. This exchange frequency was not routinely used in the given time period.

If no date is associated with a dose record or if it is illegible, it is claimant-favorable to use that dose in the dose reconstruction. The dose reconstructor should use his or her best judgment to credit the dose to the most likely year.

Corrections were noted in the dose record by lining through the incorrect information. If the record was updated and noted, the correction should not be applied again. If there is no obvious notation to indicate the incorporation of a correction, the claimant-favorable action is to incorporate the correction in the dose used for reconstruction.

6.5.3 Missing Entry

If the dosimetry history contains a missing entry, this probably indicates that the individual missed the dosimeter exchange and that the next dosimeter includes the dose from both exchange periods. A less likely but claimant-favorable assumption is that the badge was lost and no dose was assigned for that period. Dose should be assigned for that period using dosimetry data preceding and following that period in consideration of the approach of Watson et al. (1994).

6.5.4 Exposure Geometry

Because little information is available on the exposure geometry for an individual, the standard assumption is that all exposures are for anterior–posterior geometry.

6.6 PHOTON DOSE

6.6.1 Energy Groups

The NIOSH IREP probability of causation program contains three photon energy ranges: Below 30 keV, 30 to 250 keV, and above-250 keV (NIOSH 2002). Separation of the dose from each energy band is necessary.

Very little spectroscopy data to indicate gamma spectrum in ANL-E work areas have been found. To estimate the gamma spectrum to which workers were exposed, facilities were grouped into categories. From the information in Attachment B and the worker's external dosimetry records, the dose reconstructor can make a claimant-favorable estimate of the energy band. Plutonium facilities have mostly 17 keV photons with some 59 keV photons from ^{241}Am. ORAUT (2005b) suggests that a correction factor of 0.6 should be applied to the non-penetrating dose determined from early film dosimeters and that non-penetrating doses should be assigned as photons less than 30 keV if the employee worked with or around plutonium. Reactor facilities have dispersed fields of higher energy photons from fission as well as fission and activation products. Radioactive materials handling and processing facilities included a wide variety of activities. For the purpose of this analysis, the worst case was assumed to be handling of irradiated fuel. The gamma energy ranges were therefore taken to be the same as for reactors. For electron accelerator facilities (APS, electron LINACs), bremsstrahlung photons dominate the secondary radiation field. Thick shields of concrete or other materials will result in photons in the MeV energy range. For proton or positive ion accelerators (ZGS, IPNS, Van de Graaff) neutrons generally constitute the greatest hazard. Thick shields designed for the neutron hazard will eliminate all but the most energetic photons. With shielding and safety interlock systems, exposure to the direct beam of ANL-E accelerators was rare, and the personal exposure records should document them. However, maintenance personnel were exposed to activated accelerator components during repairs, target changes, etc. One reaction of particular importance is the thermal neutron capture of sodium in the concrete of the accelerator shielding (NCRP 2003). This reaction [$^{23}Na(n,\gamma)^{24}Na$] produces a radioactive isotope that decays with a 15-hr half-life by emitting gamma rays of 1.4 and 2.8 MeV. Therefore, the gamma energy band for accelerators was judged to consist primarily of photons with energies above 250 keV. Radiation from X-ray machines and some radioisotopes presented low-energy photon hazards, but these appear to have been generally used in conjunction with higher energy sources rather than in distinct facilities. Table 6-6 lists the photon energy range percentages.

Table 6-6. Selection of photon energies for IREP.

Facility type (see Attachment 6B)	Energy band (keV)	Percentage
Plutonium facilities[a]	<30	75
	30–250	25
	>250	0
Reactors	<30	0
	30–250	25
	>250	75
Radioactive materials	<30	0
	30–250	25
	>250	75
Accelerators	<30	0
	30–250	10
	>250	90

a. Shallow doses may be determined using open window readings for the early film badges and the methods in ORAUT (2005b)

6.6.2 Calibration Factor

6.6.2.1 Units for Dose Conversion Factors for Dose to Organ Dose

The early dosimeters were calibrated in roentgens (R) (Strom 1982). It is reasonable to assume that this continued until calibration of the Panasonic TLD dosimetry system with DOELAP sources at Pacific Northwest National Laboratory (PNNL). The personal dose equivalent *Hp(10)* is the appropriate unit to use for this period. Table 6-7 lists the dose units to use for organ dose conversion factors.

Table 6-7. Photon dose units for use with organ dose conversion factors.

Years	Dose unit
1945–1988	R
1989–2005	*Hp(10)*

6.6.3 Missed Dose

Section 2.1.2 of NIOSH (2002) recommends the use of the LOD/2 method for determining missed dose.

6.6.3.1 Limit of Detection

The film badge initially developed at the University of Chicago was used at other U.S. Atomic Energy Commission (AEC, a DOE predecessor agency) sites. All of these badges used X-ray film surrounded by a metal badge holder, and each had an open window and an area covered with 1 mm of silver, tin, or cadmium (ORAUT 2004a). Information found at ANL-E indicated that a cadmium filter was used. A PNNL study of this two-element dosimeter identified a detection level of about 40 mR at the upper 95% confidence level for radium gamma radiation (Wilson et al. 1990). An improved film implemented at Hanford in 1960 (Wilson et al. 1990) reduced this detection level to about 15 mR. Only limited information is available on the film types and when changes occurred. This information has been summarized in Table 6-2. In 1956, the two-element film badge was capable of measuring doses from 50 mR to 500 R (ANL 1956a). The specifications for the multi-element film badge (Hanford type) indicated that the low end of the exposure range was to be 0.025 R (Strom 1982). The LOD of the current Panasonic TLD system is 10 mR for photons. Table 6-8 lists the recommended photon dosimeter LODs for the ANL-E dosimeters.

Table 6-8. Photon dosimeter LODs.

Years	LOD
1945–1959	50 mrem
1960–1988	25 mrem
1989–2005	10 mrem

6.6.3.2 Determination of Missed Dose

Determination of missed dose is performed using LOD/2 times the number of zero readings (NIOSH 2002, Section 2.1.2.2). Except for the period from 1964 to 1975, the number of zero readings can be determined directly from the dosimetry data (Section 6.5.1). The missed dose is assumed to have a log normal distribution with central tendency *n*LOD/2, where *n* is the number of zero readings. The upper 95% dose is *n*LOD. If the number of zero readings cannot be determined, it must be estimated on the assumption that prorated dose limits were not exceeded. Section 6.5.1 and Section 2.1.2.3 of NIOSH (2002) discuss this estimate. In this case, the estimate is assumed to have a log normal distribution with central tendency *m*LOD/2, where *m* is the median of minimum and maximum possible number of zero readings. The upper 95% dose is *p*LOD, where *p* is the maximum possible number of zero readings.

6.6.3.3 Unmonitored Energy Range

The two-element film dosimeter used at ANL-E is similar to those used at other sites. The response of this dosimeter is addressed in the Savannah River TBD (ORAUT 2003). These documents address the significant over-response of film to low photon energies. Dosimeter calibration was performed on the open window using radium or ^{60}Co. Therefore, no missed photon dose correction factor is appropriate for this dosimetry system.

The multi-element film dosimeter at ANL-E provided better energy response to measure worker dose more accurately. Multiple calibration sources were used to characterize the energy response of the badge. A sophisticated procedure was developed to interpret the density readings under the open window and filters. It appears that corrections were incorporated to prevent missed photon dose. Therefore, no missed photon dose correction factor is appropriate for this dosimetry system.

With the implementation of the Panasonic TLD system, standard DOELAP sources have been used for the development of the algorithm and testing. Automated readout has eliminated many of the human variables associated with film development and interpretation. Modern data processing has allowed individual TLD element correction factors to be stored. Therefore, this system is unlikely to have missed photon dose in the energy range to which workers could be exposed. Therefore, no missed photon dose correction factor is appropriate for this dosimetry system.

6.6.4 Geometry - Angular Dependence

The film dosimeters used at ANL-E had various angular responses. Dosimeters were not always exposed normally, which resulted in variant responses in relation to actual worker exposure..

For a parallel beam of photons, the film dosimeters would have experienced an apparent decrease in dose with increasing angle from normal incidence due to the greater distance traveled in the filter. However at large angles, there would have been an increase in response because photons would be able to expose the film under the filter without passing through it. No data was found for the film dosimeters to quantify these effects.

Quantitative information is available for the Panasonic UD-814AS4 dosimeter (ANL 1996). For five DOELAP exposure categories, element responses generally decreased as the angle increased. This effect was more pronounced at lower photon energies. However, lower energies also caused an over-response at small angles. For angles of incidence up to 30°, the ratio of reported dose to delivered deep dose ranged from about 0.8 to 1.2 for photons.

There is insufficient data to identify an angular dependence correction to apply to any of the dosimeters. Dose reconstructors should follow current OCAS guidance.

6.6.5 Uncertainty

NIOSH (2002) describes methods for quantification of laboratory uncertainty associated with reading film and TLDs. These methods provide a statistical treatment of the variability associated with reading dosimeters in the laboratory.

6.6.5.1 Film

ANL-E used film to measure photons between 1945 and 1988. The DuPont 558 film packet (with the sensitive 508 film) was used in 1960. The 508 film was the successor to 502 film, and the National Research Council reports that both films have a useful range from 10 or 20 mR up to approximately 10 R (NRC 1989). It is not clear when ANL-E started using 502 film or when it changed to 508 film. Hanford changed to 508 film in 1960 (Wilson et al. 1990). Both film types have approximately the same reading uncertainty.

The method in NIOSH (2002) was used to determine the laboratory uncertainty (upper 95% confidence dose) for film readings. NRC detailed the method in *Film Badge Dosimetry in Atmospheric Nuclear Tests* (NRC 1989). The discussion of this method cites sensitivity parameters for 502 film. The spreadsheet developed for the Rocky Flats external dosimetry TBD (ORAUT 2004b) was modified with parameters specific to ANL-E. Review of dosimetry worksheets indicated that optical density readings were recorded to the nearest 0.01 density units (ANL 1966); therefore, the densitometer reading uncertainty is assumed to be ±0.005 density unit. Reviewing ANL-E optical density-to-dose conversion charts from 1962 (Strom 1982, four-element badge, reading under Cd for photons with energy above 150 keV), it was possible to determine film sensitivity (0.92 density units/R) for the four-element badge. However, the calibration curve did not extend past 200 mR. A curve for the two-element badge extended the range to 5 R (Strom 1982). The film sensitivity was estimated to be 0.71 density units/R for the two-element badge. Using these parameters, the upper 95% confidence doses for various dosimeter readings were calculated for each of the badge types.

Although the uncertainty is reduced at higher exposures, the NRC methodology recognizes that additional uncertainty contributed by variability in calibration, film processing, and reading the calibration curve prevents the upper 95% confidence dose from falling below 120% of the reported exposure. This limitation has been applied here and affects the estimate of the upper 95% confidence dose above 24 mR for the two-element badge and 18 mR for the four-element badge. Because of the 120% limit, the upper 95% confidence doses are the same above 24 mR. Table 6-9 lists the upper 95% confidence doses.

Table 6-9. Uncertainty for photon dose.

Dose (mR)	Upper 95% confidence photon dose (mR)		
	DuPont 508 film Two-element badge 1945-1959	**DuPont 508 film Four-element badge 1960-1988**	**DOELAP-accredited TLD 1989-2005**
10	15	14	20
20	25	24	31
50	60	60	64
100	120	120	120
200	240	240	240
500	600	600	600
1,000	1,200	1,200	1,200
2,000	2,400	2,400	2,400

6.6.5.2 Thermoluminescent Dosimeters

TLDs provided improved photon dosimetry. ANL-E replaced film whole-body dosimeters with TLDs in 1988 when DOELAP performance testing began. According to the ANL-E Technical Basis Document, the current beta-gamma TLD (Panasonic UD-814SA4) responds within 10% of the delivered dose equivalent for most single radiation fields and within 20% of the mixed radiation fields tested by DOELAP (ANL 1996). The largest positive deviations were for mixtures of X-rays and beta particles. The few negative deviations for mixed fields were less than 10% below the delivered dose. These data are for radiation normally incident to the badge (ANL 1996).

The standard deviation of the null readings associated with the DOELAP-accredited Panasonic dosimeter was not documented. Therefore, the analysis used the Simplified Dosimetry Uncertainty calculation recommended by NIOSH (2002, Section 2.1.1.3.3) where the critical level L_c is the LOD estimated in Section 6.6.3.1 of this document. The percent standard error at high air kermas was estimated to be 10%. This is a claimant-favorable assumption for this dosimetry system. Table 6-9 lists the upper 95% confidence doses.

6.7 NEUTRON DOSE

There were and are a number of facilities at ANL-E with the potential for neutron exposures. The record is not clear concerning early neutron monitoring at ANL-E, but boron-lined PICs were reported at most facilities before the early 1950s (NIOSH 2002). It is also unclear from the program documentation exactly when monitoring with Kodak NTA film began at ANL-E. Because the initial mission of the site was research on nuclear reactors where neutrons were a recognized hazard, it seems reasonable that ANL-E would have been one of the first sites to use NTA film. It was in use by 1956 and was referenced in the site *Radiation Safety Guide* (ANL 1956a). NTA film continued in general use until the late 1980s, when albedo TLD dosimeters replaced it (McDowell-Boyer 2005).

By 1972, Kodak Type 2 film was in use for beta-gamma determinations. According to Strom (1982), a procedure originated in 1967 and revised in August of 1972 (Procedure 120.0) provided a method to determine thermal neutron dose equivalent from the beta-gamma film by comparing the open window area and the area under the cadmium filter. Because thermal neutron exposures were normally only present in conjunction with high-energy gamma exposures, any extra darkening under the cadmium filter was assumed to be from neutron-gamma reactions in the filter. This method required some knowledge of the work being performed during the wear period (Strom 1982).

In 1972 and 1973, studies of the solid state track recorder (SSTR) neutron dosimeter were undertaken at the Zero Power Reactor (ZPR) VI facility where there was a concern that the moderated plutonium light element neutrons encountered during maintenance operations were not being detected by the NTA film dosimeters. It appears that, after a testing period, official doses were recorded from these dosimeters (Dolecek 1977).

ANL-E switched to TLDs for dose of record in 1989. However, some neutron doses were determined using TLD albedo dosimeters before this time. A Hankins albedo dosimeter was first employed at the ZPR facility around 1977. This dosimeter was followed by an in-house design termed the Hosger albedo dosimeter that contained two ^{6}Li (TLD-600) and two ^{7}Li (TLD-700) elements. It was noted that both of these types required knowledge of the neutron energy spectrum to accurately assess the dose equivalent. To avoid underestimating the dose equivalent, an overly conservative conversion factor was used (Strom 1982). It appears that ANL-E planned to implement a CR-39 track etch dosimeter in 1989, but there is no indication that this system was brought on line. Table 6-10 summarizes the methods employed by ANL-E to assess personnel neutron doses. The dates shown are approximate.

Table 6-10. Neutron dose assessment methods.

Type	Dates	Comment
NTA film	1953–1988	Only capable of reliably detecting neutrons of greater than approximately 800 keV
Kodak Type 2 beta-gamma film	1971–1988	Used to assign thermal neutron dose in the presence of high-energy gamma doses
SSTRs	1973–1975	Contained 0.5 g U-235, discontinued due to fissile material accountability and personnel dose concerns
Albedo dosimeters	1977–1982	Hankins type designed for use at the ZPR facility
	1982–1989	Hosger, a four-element ANL-E design (2 TLD-600 and 2 TLD-700), similar in appearance to a self-reading pocket chamber
	1988–2005	ANL-E design, TLD-600 and -700 in a polybox inserted in the Panasonic dosimeter, similar to a Hankins type

6.7.1 Energy Groups

The measured neutron dose must be divided into energy groups consistent with the dose conversion factors provided in Appendix B of NIOSH (2002). These energy groups and the associated radiation weighting factors (w_R) from International Commission on Radiological Protection (ICRP) Publication 60 (ICRP 1991) are:

Energy range (MeV)	w_R
< 0.01	5
0.01–0.1	10
>0.10–2	20
>2–20	10
>20	5

6.7.1.1 Neutron Energy Spectra

The research did not discover any comprehensive studies of the neutron energy spectra at ANL-E, but some facility-specific information was found. Most of this data was in the form of summary statements about the average, effective, or energy range of the neutrons. Some of the measurements were not appropriate for dose reconstruction because they were made under unusual operating conditions or in normally unoccupied areas. The ANL-E information was supplemented by other examples in the literature for similar facilities.

Neutrons are a significant concern at only a limited number of facilities at ANL-E. These include reactors, high-energy accelerators, and materials-handling areas where alpha emitters could interact with light elements. Facilities such as the 60-Inch Cyclotron, the Electron Linear Accelerator (LINAC), and other low-energy accelerators do not present a neutron hazard outside of their shielding under normal operating conditions (Coulson 1989). Neutrons rarely contribute more than 20% to the annual collective dose at accelerator facilities (Coulson 1989).

The Zero Gradient Synchrotron (ZGS) was a 12.5-GeV proton accelerator that operated between 1963 and 1979. No useful spectral information from ANL-E for potentially occupied areas was located. The LANL External Dosimetry TBD (ORAUT 2005a) Figure 6-8 provides neutron spectra unfolding results for the ER-1 target at the Los Alamos Meson Physics Facility (LAMPF) which uses an 800 MeV proton beam. The SPUNIT code result was chosen to simulate neutron spectra at the ZGS absent any better information. Using EXCEL a spectrum was generated to visually match that in Figure 6-8 of the LANL TBD. The Ing and Makra (1978) parameterization for the NCRP 38 flux to dose conversion factor was used to generate the energy spectrum of dose. The resulting neutron spectrum per unit lethargy (logarithm of energy) is shown in Figure 6-1 along with the integral spectrum of flux and dose equivalent. The fraction of dose equivalent in each of the IREP neutron energy intervals which is shown in Table 6-11 was determined from this spectrum.

The 500-MeV Intense Pulsed Neutron Source (IPNS) is capable of generating neutrons in the energy range from 0.025 eV to greater than 20 MeV. Outside of the biological shielding at the facility the energy levels of potential neutron exposures ranged from 0.1 to 1 MeV (Strom 1982). Low dose equivalent rates, on the order of 0.5 mrem/hr, were observed on the roof area due to suspected neutrons streaming through cracks. Spectral measurements made with Bonner spheres near the second-floor offices, and first-floor shops indicated average neutron energies of 0.1 to 0.5 MeV. Skyshine was a problem before 1989, but additional shielding was added above the enriched ^{235}U target (Coulson 1989). To establish the dose equivalent fractions in the IREP neutron energy intervals the spectrum from LAMPF was modified to eliminate neutrons above 30 MeV. At the IPNS, the proton beam bombards a thick (greater than the proton range) uranium target which through cascade and inelastic processes reduces the energy of the neutrons. At LAMPF and at the ZGS a thin target (less than the proton range) was used so that high energy particles emerged from the target. The resulting dose equivalent fraction estimates for the IPNS are also shown in Table 6-11.

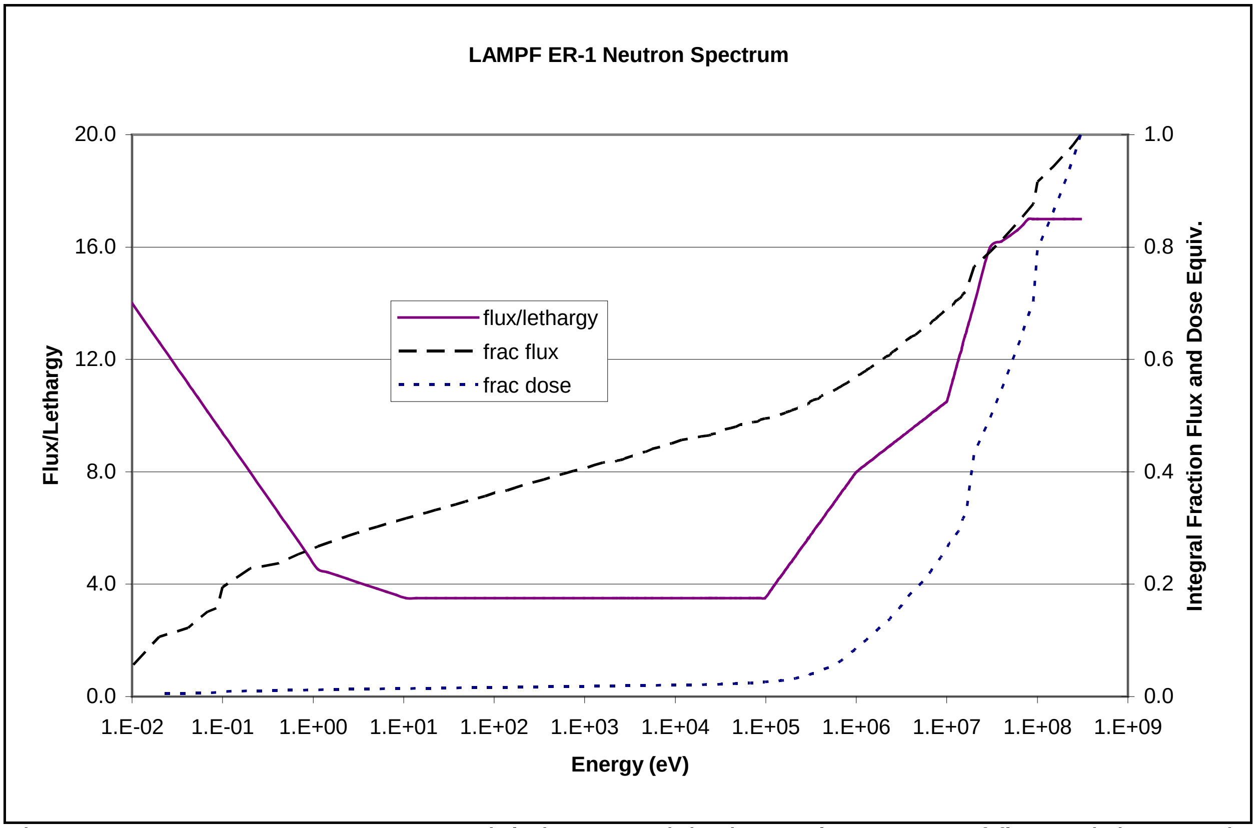

Figure 6-1. Neutron spectrum per unit lethargy and the integral spectrum of flux and dose equivalent for the LAMPF ER-1 spectrum.

Table 6-11. Percent of NCRP 38 dose equivalent in the IREP energy groups at ANL-E facilities.

Energy Group	Percent of Dose equivalent					
	Zero Power Reactors	CP-2, CP-3, CP-5, Janus, Argonaut, Juggernaut	ZGS	IPNS	Plutonium chemistry & metallurgy	No information available
< 0.01 MeV (w_R=5)	1	20	2	4	0	0
0.01–0.10 MeV (w_R=10)	8	5	2	3	10	0
>0.10–2.0 MeV (w_R=20)	65	50	9	19	50	100
>2.0–20 MeV (w_R=10)	26	25	30	61	40	0
> 20 MeV (w_R=5).	0	0	57	13	0	0

The Argonne Tandem-Linear Accelerator System (ATLAS) is a 17-MeV/amu heavy-ion accelerator. Direct neutron dose rates are low under normal experimental conditions. However, access is restricted when accelerating certain light ions. No skyshine has been observed (Coulson 1989). No spectral information was found.

At the 4.5-MeV Dynamitron, accelerating light ions produces neutrons in accessible areas. A rate of 0.2 mrem/hr/mA of deuterons outside of the experimental area was reported (Coulson 1989). No spectral information was located.

A 1966 shielding study at the 12-MeV Tandem Van de Graaff Accelerator used 6.5 MeV as the effective energy to determine the flux-to-dose equivalent conversion. However, the authors understood that this energy was an overestimate because the spectrum would have been degraded in the potentially occupied areas being measured (Dyer and Mundis 1966).

The Advanced Photon Source (APS) is an electron–positron accelerator that has been in full operation since 1995. Electrons are accelerated to an energy of 650 MeV in a LINAC and then raised to an energy of 7 GeV in a booster synchrotron. The electrons are then injected into a large-diameter storage ring. Calculations and measurements by ANL-E personnel indicate that dose rates are low and that there are no measurable neutron dose equivalents outside of shielded areas (DOE 2003, ANL 1994, Moe et al. undated).

Some of the highest neutron exposures probably occurred at the ZPR facilities (see Attachment B). The ZPRs were large critical assemblies fueled with uranium or plutonium. Spontaneous fission from ^{240}Pu and other isotopes and (α,n) reactions on light elements leads to significant doses near the reactors even when shutdown. The reactors were arranged in two halves that were split for loading and to set up experimental apparatus. Dose equivalent rates of 300 to 400 mrem/hr were seen between the halves. Even with temporary shielding in place, personnel working between the halves experienced significant dose equivalent rates, especially when working near a gap in the shielding, which was necessary to load fuel elements and perform other work. Although the fission spectrum was somewhat moderated by the components of the reactor, the flux of neutrons in the intermediate energy ranges was significant. There were many different configurations at ANL-E (and some at ANL-W). This analysis uses the ZPR-6 Assembly 7, but the energy spectra should not differ significantly among the ZPRs. A plot of the NCRP 38 dose equivalent rate for the measured spectrum from neutrons above a cutoff energy as a function of the cutoff energy was examined (Yule 1971), and the fraction of the dose equivalent in the IREP energy intervals was then estimated. The results obtained are in Table 6-11.

Some other reactors that have operated at ANL-E (CP-2, CP-3, CP-5, Janus, Argonaut, and Juggernaut) had similar neutron spectra to the Materials Test Reactor at INEEL (ANL 1956b, ANL 1961). Therefore, the recommendations in the TBD for INEEL are adopted for use here (ORAUT 2004c). Similarly the recommendations in the Los Alamos TBD are adopted for plutonium chemistry and metallurgy (ORAUT 2005a). Finally, if no information is available about where the exposure occurred, or if it occurred in multiple facilities, it is recommended that all of the dose equivalent be assigned to neutrons in the >0.10–2.0 MeV energy interval. Table 6-11 also presents these results.

6.7.1.2 Reported Dose to Energy Groups

NIOSH (2002) requires that the neutrons be apportioned into the energy groups used in ICRP Publication 60 (ICRP 1991). Because little neutron spectral information was available, the analysis assumed that the neutron doses reported were calculated using the quality factors (QFs) from NCRP Report 38 (NCRP 1971). The Report 38 QFs were averaged over the ICRP Publication 60 energy groups. A dose multiplier was then calculated for each energy group for conversion from the NCRP Report 38 dose equivalents to ICRP Publication 60 equivalent doses. Table 6-12 lists the dose multipliers for the energy ranges.

Table 6-12. ICRP Publication 60 dose multipliers (ICRP 1991).

ICRP 60 energy group (MeV)	Average NCRP 38 QF	ICRP 60 Dose multiplier
<0.01 (w_R=5)	2	2.5
0.01–0.1 (w_R=10)	5	2.0
>0.10–2 (w_R=20)	10	2.0
>2–20 (w_R=10)	7.5	1.3
>20 (w_R=5)	4.0	1.2

The ICRP 60 dose multipliers from Table 6-12 were used with the estimated neutron spectra in Table 6-11 to develop multipliers which can be used to determine the neutron equivalent dose for each IREP energy interval. The corrected neutron dose reported in the claimant's dose record is multiplied by these factors to determine the ICRP (1991) neutron dose for each neutron energy interval. Since 1960, when neutron doses began to be recorded routinely, the QFs for thermal and fast neutrons were usually 3 and 10, respectively (Dolecek 1981). Thermal neutron doses could have been measured by neutron PICs or beta-gamma film badges. In general, however, it is not possible to separate the thermal and higher-energy dose equivalents in the records. Energies above 800 keV were measured with NTA film. Corrections of the NTA film for neutrons between thermal and 800 keV are discussed separately. The current albedo dosimeters respond to all energies but are less sensitive to high energies. Table 6-13 lists the recommended multipliers to be applied to the reported neutron doses.

Table 6-13. Multipliers recommended to assign ICRP 60 equivalent dose to the IREP neutron energy intervals.

Energy Group	Multipliers used to assign to IREP neutron energy intervals					
	Zero Power Reactors	CP-2, CP-3, CP-5, Janus, Argonaut, Juggernaut	ZGS	IPNS	Plutonium chemistry & metallurgy	No information available
< 0.01 MeV (w_R=5)	0.025	0.5	0.05	0.1	0	0
0.01–0.10 MeV (w_R=10)	0.16	0.1	0.04	0.06	0.2	2
>0.10–2.0 MeV (w_R=20)	1.3	1.0	0.18	0.38	1.0	0
>2.0–20 MeV (w_R=10)	0.34	0.33	0.39	0.79	0.52	0
> 20 MeV (w_R=5).	0	0	0.68	0.16	0	0

6.7.2 Calibration Factor

6.7.2.1 Units for Dose Conversion Factors for Dose to Organ Dose

Early calibration information is limited, but ANL-E appears to have calibrated neutron film with unmoderated plutonium-beryllium (PuBe) neutron sources by 1958 (Strom 1982; Tedeschi 1958). A curve of neutron film correction factors versus effective neutron energy determined with a Dvorak-Dyer sphere was published in a 1965 study at the 50-MeV injector of the ZGS (Steele 1965). At an energy of 800 keV, the correction factor for a PuBe calibration was 1.6. At 2-MeV effective energy, the correction factor was about 1.2, which suggests that the neutron dose equivalent for fission spectrum and below should be multiplied by an average of 1.4 to account for the PuBe calibration.

This correction for the spectrum measured is accounted for as part of the unmonitored energy range correction discussed in Section 6.7.3.2.

The doses reported for the SSTRs and interim albedo dosimeters used before 1989 are assumed to represent ambient dose. During 1976 to 1977, SSTRs and Hankins albedo dosimeters compared favorably with time-motion studies at the ZPR facility (Dolecek 1977). In many cases, NTA film was worn in conjunction with these dosimeters.

ANL-E adopted the Panasonic TLD system in use at ANL-W for beta-gamma dosimetry in 1989. However, a different albedo neutron insert was used that was not based on the ANL-W Panasonic TLDs. This albedo design, using Harshaw TLD-600 and TLD-700 chips, has not been accredited by DOELAP. The ANL-E *Technical Basis Document for External Dosimetry* states that, "Calibration of the ANL-E albedo dosimeter has been conducted at various locations both on-site and off-site" (ANL 1996) and goes on to state the LOD for exposure to moderated ^{252}Cf. From these statements the albedo TLDs at ANL-E were apparently calibrated with DOELAP exposure standards in preparation for DOELAP performance testing. Therefore, the deep dose equivalent $H_{p,slab}(10)$ is appropriate for this dosimeter. Table 6-14 lists the dose units for use with organ dose conversion factors.

Table 6-14. Neutron dose units for use with organ dose conversion factors.

Years	Neutron dose unit
1945–1988	Ambient dose, $H^*(10)$
1989–2005	Deep dose equivalent, $H_{p,slab}(10)$

6.7.3 <u>Missed Dose</u>

6.7.3.1 Limit of Detection

The LOD for NTA film was not well documented, but most references are to 50 mrem (Steele 1965). It appears that, even when beta-gamma film processing and reading was contracted, ANL-E generally processed and read the neutron films (Strom 1982). An exception was between 1960 and 1964 when Atomic Film Badge Corporation processed the NTA films. There is some indication that this contractor reported all doses read for films with more tracks than the control films (Strom 1982). It is not clear what this minimum reporting level was, but it could have been below 50 mrem. When beta-gamma film was used to determine thermal neutron dose, the minimum reported was 50 mrem. Doses less than this value were interpreted as gamma exposures, which Procedure 120.0 claimed was conservative (Strom 1982). This also appears to have been the reporting threshold for neutron dose equivalent from Kodak NTA film from 1965 to 1972 (Strom 1982).

No LOD was reported for the SSTRs (Yule et al. 1972, Yule 1973). The LOD was probably less than 50 mrem, but is assumed to be the same as NTA film for dose reconstruction purposes.

Of the interim albedo dosimeters, only the Hosger dosimeter has a documented LOD, which was 20 mrem at an average energy of 2.4 MeV (Strom 1982). Because the LOD would be lower for the lower energy spectra likely to be encountered by most workers, this value is claimant-favorable for these dosimeters.

In 1989, ANL-E started using an albedo TLD inserted into the Panasonic holder for the dose of record. The stated LOD for this system is 10 mrem (Dolecek 1996). Table 6-15 lists the neutron dosimeter LODs. The dates given are approximate.

Table 6-15. Neutron dosimeter LODs.

Type	Dates	LOD
NTA film	1953–1988	50 mrem
Kodak Type 2 beta-gamma film	1971–1988	50 mrem (thermal neutron dose)
SSTRs	1973–1975	50 mrem
Albedo dosimeters	1977–1982 Hankins	20 mrem
	1982–1989 Hosger	20 mrem
	1988–2005	10 mrem

6.7.3.2 Unmonitored Energy Range

NTA film is a poor detector of neutron energies below 500 to 800 keV (Griffith et al. 1979; Wilson et al. 1990). In a 1965 study at the 50-MeV injector of the ZGS, ANL-E recognized that dosimetry results below an effective energy of 1 MeV (determined with a 12-in. Dvorak-Dyer paraffin sphere) should have a correction factor applied to the PuBe calibration. Below 300 keV, this correction factor was estimated to be so large that other methods of determining dose equivalent would be necessary. In addition, the author stated that chronic low-level exposures in areas where personnel are sometimes located are not recorded by the film (Steele 1965).

A 1966 investigation pointed out that the majority of neutrons in areas occupied by personnel at the 4.5-MeV and 2-MeV Van de Graaff accelerators had energies between 100 keV and 1 MeV. NTA film measurements in the facilities showed dose equivalents of less than 5% of the values from instrument measurements (Till 1966).

In 1973, a work force reduction in the Personal Monitoring Group led to a proposal to eliminate NTA film with the exception of the ZGS facility, which could indicate that NTA film deployed to other areas generally produced only background results. A response by site health physicists pointed to an example of a measurable neutron exposure at the Tandem Van de Graaff facility. In another example, SSTRs at the Building 316 ZPR facility detected neutrons where NTA film did not. The decision to discontinue NTA film was reversed at least partially due to accidental criticality considerations (Bleiler 1973 b).

In spite of the recognized shortcomings of NTA film, documentation was not found to indicate that any compensating measures were taken by the external dosimetry program. Before 1989, dose from neutrons below approximately 800 keV was not reliably detected. To determine the magnitude of potentially missed dose, the correction factors in Table 6-16 were estimated based on experience.

The ANL-E TLD albedo neutron dosimeter systems were calibrated using variously moderated spectra. These dosimeters over-respond to the lower (relative to the calibration spectrum) energy spectra most likely in operational areas. There is no need for a neutron dose correction for an unmonitored energy range for these dosimeters.

Table 6-16. NTA film unmonitored dose correction factors.

Facility	NTA film unmonitored dose correction factor
ZGS, IPNS	1.25
Other accelerators	1.5
CP-3, CP-3´, CP-5 reactors	1.5
ZPR Pu-fueled reactors	4
Pu-handling facilities	4

6.7.3.3 Neutron Dose Reconstruction Project

A 1982 survey (Strom 1982) indicated that, similar to Rocky Flats, not all neutron films that were developed were read. Before 1960, neutron films were apparently only read if the gamma dose was 100 mrem or more. This correction should be accounted for by adding missed dose for each zero reading where there is an indication that neutron monitoring occurred.

6.7.4 Geometry-Angular Dependence

A 1965 study of neutron field characteristics at the 50-MeV proton injector of the ZGS indicated that NTA film response decreased from 84% of the calculated dose equivalent when the film was perpendicular to the source to 57% when the film was at 90°. The effective energy of the neutrons was 1.18 MeV and the dose equivalent rates were high (174 rem/hr). The contribution of scattered neutrons to the dose equivalent at the point of measurement was determined to be 24% with an effective energy of 0.49 MeV (Steele 1965). The location of these measurements was not in an area occupied by personnel during operation of the accelerator. Due to multi-scattering, NTA film response in the normally occupied areas is likely to be less angular dependent. Therefore, with the possible exception of accidental exposures in high-dose areas, no correction for angular dependence is deemed necessary.

No information is available for the albedo TLDs used at ANL-E.

6.7.5 Uncertainty

6.7.5.1 Film

A 1962 review of commercial film badge services at ANL-E indicated that Atomic Film Badge Corporation was the only contractor to read neutron films. From February 27 to April 10, 1961, 418 control films exposed to 300 mrem from a Pu-Be source were processed. Of those, 199 films (47.6%) were not within ±25% of the expected value (Strom 1982). This same contractor's performance on gamma control films showed only 3.1% that were not within ±25% of the expected value.

Many authors have expressed concern over latent image fading for Kodak NTA film, especially in high-humidity environments. Some European manufacturers sealed their NTA-type film in aluminum or an aluminized plastic to reduce the effects of humidity (Hankins 1973). No NTA fading data was found for ANL-E. However, fading is not expected to be significant for a monthly exchange frequency.

In 1980, ANL-E participated in performance testing for the NTA film dosimeter conducted by the University of Michigan (Neal 1980). This data showed an average standard deviation of 10% for high doses (301-5000 mrem) of ^{252}Cf. However, for lower doses (100-300 mrem) the average standard deviation was 64%. The standard deviation of both ranges was 48%. Since this performance may not have been typical for earlier periods, a standard deviation of 50% was selected for this analysis. Again the simplified uncertainty analysis of NIOSH (2002) was used. The results are shown in Table 6-17.

6.7.5.2 Thermoluminescent Dosimeter

The LOD of Hosger albedo TLD was 20 ±10 mrem at the 95% confidence level with an average spectral energy of 2.4 MeV (Strom 1982). The standard deviation was therefore 26% (50% divided by 1.96). The simplified method was used to calculate the upper 95% confidence doses. No data were found for the other interim albedo dosimeters. Until such data is found the values for the Hosger albedo TLD should be used.

Table 6-17. Uncertainty for NTA film and TLD neutron dose .

Dose(mR)	Upper 95% confidence neutron dose (mrem)		
	NTA Film	Hosger & Other TLDs	Current TLD
5	55	25	15
10	61	31	21
20	74	42	34
50	120	82	77
100	210	160	150
200	400	300	300
500	990	800	760
1000	2,000	1,500	1,500
2000	4,000	3,000	3,000

The current albedo system did not undergo DOELAP testing in 1988 or 1991. The lower limit of detection for this badge is 10 mrem in normal personnel dosimetry practice (ANL 1996). Since this dosimeter involves reading individual TLD chips, like the Hosger dosimeter, the same standard deviation for high doses was assumed (26%). Again, the simplified method was used to calculate the upper 95% confidence doses. The results for both NTA film and TLDs are presented in Table 6-17.

6.7.6 Application of the Neutron Correction Factors

6.7.6.1 The sequence of application of the neutron correction factors for NTA film is:

- Calculate the missed dose (Section 6.7.3.1), if applicable
- Apply the correction factor for unmonitored energy range (Section 6.7.3.2)
- Apply the correction for the neutron quality factor for each IREP energy range (Table 6-13, Section 6.7.1.2)

6.7.6.2 Example

- An ANL-E worker in Bldg. 200 (plutonium chemistry facility) is monitored by NTA film for 6 months in 1960 and receives doses of 0 mrem, 0 mrem, 100 mrem, 300 mrem, 0 mrem, and 0 mrem.
- The missed dose is LOD/2 (25 mrem) X 4 = 100 mrem. The total for the period is 100 mrem (missed dose) + 100 mrem + 300 mrem = 500 mrem.
- Since the neutron film did not respond to energies below about 800 keV, the correction for the unmonitored energy range is 500 mrem X 4 (Table 6-16) = 2000 mrem.
- The doses for each IREP energy group from Table 6-13 for a plutonium chemistry and metallurgy facility are:
    - o < 0.01 MeV, 2000 mrem X 0 = 0 mrem

- 0.01 to 0.10 MeV, 2000 mrem X 0.2 = 400 mrem
- > 0.10 to 2 MeV, 2000 mrem X 1 = 2000 mrem
- > 2 to 20 MeV, 2000 mrem X 0.52 = 1040 mrem
- > 20 MeV, 2000 mrem X 0 = 0 mrem

6.8 ELECTRON DOSE

The earliest maximum permissible exposure limits published at ANL-E recognized the potential hazards of beta exposures of the skin (Nickson 1946). The pioneering work done there fabricating uranium fuel elements and processing irradiated fuel could have resulted in significant beta exposures. Work since the early days has involved a wide range of activities with different natural and man-made isotopes. Beta exposures, including exposures to high-energy (more than 1 MeV) betas, cannot be ruled out. The dose reconstructor should be aware that early results from ring and wrist dosimeters may have been reported on separate forms and may need to be considered for skin dose to the hands and forearms.

6.8.1 Energy Groups

Although documentation is lacking, it appears that for the two-element badge (1946 to approximately 1960) the open window doses are nearly always equal to or greater than the shielded window doses, indicating that the open window reading includes both penetrating and non-penetrating radiation. The exceptions are probably due to the reading uncertainty. The four-element badge (approximately 1960 to 1989) used an algorithm to determine beta dose. The algorithm also determined photon dose below 150 keV (termed "X-ray"). It appears that this dose was added to the photon dose above 150 keV (termed "gamma") to determine the penetrating dose. Thus penetrating and non-penetrating (beta only) radiations are reported separately after approximately 1960. No detail on the reporting of early film or TLD ring dosimeters was located. The current TLD system reports the shallow or skin dose as the sum of the penetrating and non-penetrating dose. ORAUT (2005b) suggests that a correction factor of 0.6 should be applied to the non-penetrating dose determined from early film dosimeters and that non-penetrating doses should be assigned as greater than 15 keV electrons or as photons less than 30 keV if the employee worked with or around plutonium.

All measured and missed non-penetrating doses that are considered electrons should be assigned to the > 15 keV IREP energy group.

6.8.2 Calibration Factor - Units for Dose Conversion Factors for Dose to Organ Dose

During the use of the two-element film badge, the term *arbitrary units* or *a.u.* was used to report the open window dose. This term was an acknowledgement that the open window reading could not be correctly interpreted without knowing the energy of the beta or soft X-ray that exposed it. The May 1958 specifications for film badge service defined arbitrary unit as a unit used to compare the density of a film in the badge window position caused by exposure to unknown beta-gamma and/or X-ray radiation to the equivalent density of a film in the badge window position caused by exposure to a known ^{60}Co or ^{226}Ra source in milliroentgens (Strom 1982). The arbitrary units were later correlated with an exposure to uranium. Although the open window in these dosimeters over responded to low energy photons, the records may underreport the doses from electrons (see 6.8.3.1).

By 1961 the practice of reporting in arbitrary units ended, and the specifications for the four-element film badge (Hanford type) indicated that the readings in the open window were to be reported in density units as well as beta units (Strom 1982). These later film dosimeters at ANL-E appear to have been calibrated with uranium starting at least in 1963 (Pingel and Gray 1963). The radiation weighting factor for electrons at all energies is 1 (ICRP 1991), thus, reported beta doses are equivalent to mrem.

ANL-E's current beta-gamma dosimeter, based on the Panasonic UD-814AS4, is accredited for the uranium slab geometry. However, the algorithm uses the ratio of the net beta response (after subtracting the contribution from photons) on elements 1 and 2 to determine beta energy. A calibration factor is estimated from the ratio (ANL 1996).

6.8.3 Missed Dose - Limit of Detection

In 1956, the two-element film badge was capable of measuring doses from 50 mR to 500 R (ANL 1956a). No separate LOD was given for beta radiation, so it is assumed to be the same. The specifications for the multi-element film badge (Hanford type) indicated that the low end of the exposure range was to be 25 mR and included beta radiation (Strom 1982). The LOD of the current Panasonic TLD system is 30 mrem for shallow dose equivalent (ANL 1996). Table 6-18 lists the beta LODs for the ANL-E dosimeters. Specialized extremity dosimetry used at ANL-E included film and at least two designs of TLD rings (see Section 6-10). No published LODs were found for the early dosimeters. The LOD for the current TLD ring is 10 mrem (ANL 1996).

Table 6-18. Beta dosimeter LODs.

Years	LOD
1945–1959	50 mrem
1960–1988	25 mrem
1989–2005	30 mrem whole body 10 mrem TLD ring

6.8.3.1 Under Reporting of Shallow Dose Equivalent

Due to the thickness of the covering material and the thickness of early beta detectors, early beta-monitoring systems under-reported the dose for a depth of 7 mg/cm^2. A general analysis of the under-response of beta dosimeters was done for INEEL (ORAUT 2004c). Since the dosimeters used at the two sites were similar and few details are available for ANL-E, the INEEL analysis is used in part here. Table 6-19 provides the fraction of beta dose recorded for the various dosimeters. To determine the corrected beta dose, the dose reconstructor should divide the non-penetrating results by the values in the last column of Table 6-19. This result will probably be an overestimate since the beta calibration involved but undoubtedly did not consider a similar correction. This value is used directly for the shallow dose equivalent [*Hp(0.07)*].

Table 6-19. Beta dosimeter thickness and associated underreporting.

Dosimeter System	Period	Cover (mg/cm^2)	Detector thickness (mg/cm^2)	Estimated fraction of dose reported
Two-filter film Early film ring	1945-1959	50	50	0.49
Multi-filter film	1960-1988	100	50	0.35
Old TLD ring	1970-1977	104	240	0.21
Current TLD ring	1978-2005	18	89	0.56
Panasonic TLD	1989-2005	16	15	0.78

6.8.4 Geometry

6.8.4.1 Angular Dependence

The sensitive dosimeter elements are mounted in a dosimetry badge. The assembled badge is expected to display a severe angular dependence to beta exposure, but in most cases a worker's normal movements tend to average out some of this dependence (DOE 2001).

The element responses of the Panasonic dosimeter were not specifically tested. For low-energy (K-17) X-rays, the element responses of the Panasonic dosimeter generally decreased as the angle between the incident radiation and the plane perpendicular to the TLD increased from 0°. Based on DOE (2001), no angular correction factor is proposed.

The current TLD ring dosimeter consists of two to four TLD-700 elements around the circumference of the ring. Exposures were made to X-rays of various energies to test the response of the elements to the direction of the radiation (ANL 1996). Because the angle of exposure is more or less random with this arrangement, no correction is possible.

6.8.4.2 Exposure Geometry

Due to exposure geometry, recorded beta doses may significantly overestimate or underestimate the dose to the skin at the cancer diagnosis location. Exposure geometry must be analyzed on a case-by-case basis. No site-wide correction is possible with the available information.

6.8.5 Uncertainty

The method in NIOSH (2002) was used to determine the uncertainty (upper 95% confidence dose) for film readings. This method is based on a statistical discussion in *Film Badge Dosimetry in Atmospheric Nuclear Tests* (NRC 1989).

6.8.5.1 Film

ANL-E used various films as described in Section 6.6 to measure beta dose with the whole-body dosimeter between 1945 and 1988. A similar uncertainty estimation methodology was used to develop a spreadsheet that matched the illustration given in NRC (1989). No beta calibration curves were found for the two-element badge. Beta dose was determined for the four-element badge by subtracting the density behind the aluminum filter from the density behind the open window and then correcting for possible X-ray exposure. Review of Kodak Type 2 calibration curve for uranium betas from 1981 determined film sensitivity (Strom 1982). A saturation density for 502 film was assumed. Using this approach, the upper 95% confidence doses for various beta doses were calculated. A limit of 120% was applied as discussed in Section 6.6.5.1. This limit affects the upper 95% confidence dose at 100 mrem and above. Table 6-20 lists these upper 95% confidence doses.

6.8.5.2 Thermoluminescent Dosimeter

TLDs provided improved beta dosimetry. ANL-E replaced film whole-body dosimeters with TLDs in 1988 when DOELAP performance testing began. According to the ANL-E Technical Basis Document, the current beta-gamma TLD (Panasonic UD-814SA4) responds within 20% of the mixed radiation fields tested by DOELAP. The largest positive deviations were for mixtures of X-rays and beta particles. The few negative deviations for mixed fields were less than 10% below the delivered dose. These data are for radiation normal to the badge (ANL 1996).

Table 6-20. Uncertainty for beta dosimeters.

Dose (mR)	Upper 95% confidence beta dose (mrem)	
	Kodak Type 2 film	DOELAP-accredited TLD
10	25	40
20	35	50
50	66	82
100	120	140
200	240	250
500	600	600
1,000	1,200	1,200
2,000	2,400	2,400

The standard deviation of the null readings associated with the DOELAP-accredited Panasonic dosimeter was not documented. The analysis therefore uses the simplified dosimetry uncertainty calculation from NIOSH (2002, Section 2.1.1.3.3), where the critical level L_c is the LOD estimated, as described in Section 6.6.3.1. The percent standard error at high air kermas was estimated to be 10%. This is a claimant-favorable assumption for this dosimetry system. Table 6-20 lists the upper 95% confidence doses.

6.8.6 Skin Contamination

Skin contamination incidents have occurred throughout the history of the site. Skin decontamination methods and procedures were generally well documented, but the specific forms used for reporting were not. These could have been covered in lower-level procedures that were not available. It can be assumed that the practices were consistent with other AEC, Energy Research and Development Agency (ERDA), and DOE sites where skin contaminations were documented in the health and/or dosimetry records. The *Environment, Safety & Health* [ES&H] *Manual* currently requires recording of the nonuniform shallow dose equivalent to the skin caused by contamination on the skin if the dose is equal to or greater than 2% of the limit specified for the skin in 10 C.F.R. 835.702(b) (ANL 2004).

By 1956, beta-gamma hand and foot monitoring was done with Geiger counters and alpha hand monitoring was done with a proportional counter. It appears that these were permanently installed devices used in addition to portable monitors (ANL 1956a).

Natural and depleted uranium was used and processed at ANL-E, and their progeny potentially contained in the material would result in beta exposures to the skin. Other high-energy beta emitters such as $^{90}Sr/^{90}Y$ were present at the ANL-E. In addition, beta-emitting fission products and accelerator-produced isotopes were widely used at the site.

The area of the contamination might not be available, and dose reconstructors should estimate it in accordance with Section 2.3.3 of NIOSH (2002). The contamination report will probably not indicate the length of time that the contamination was present on the skin. A reasonable claimant-favorable assumption is that the contamination was present for 4 hr because, for example, an individual could have received contamination at the beginning of the shift, not taken a midmorning break, and discovered the contamination upon monitoring when leaving the production area at lunch. Once the contamination was discovered, initial decontamination was performed locally, which normally resulted in removal of most of the contamination. If these initial efforts failed to remove enough of the contamination, the individual was taken to the occupational medicine group where further decontamination efforts were made under medical supervision (ANL 1956a; ANL 1973).

Dose reconstructors could use software such as VARSKIN (recommended in NIOSH 2002) or other appropriate means for this calculation.

6.9 UNMONITORED INDIVIDUALS

6.9.1 <u>In Radiologically Controlled Areas</u>

The available information indicates all workers at ANL-E were badged in the early years. By 1965, nearly every employee was still badged. By the early 1970s, ANL-E apparently had started to badge workers based on their exposure potentials (Section 6.4.1). The dosimeters used by workers assigned to a facility were stored at the entrance to that facility. Rover dosimeters were assigned to visiting radiological workers. Under this system, it seems unlikely that anyone would have routinely entered radiological facilities without a monitoring device. However, the following paragraph provides a claimant-favorable method of assigning dose to unmonitored individuals.

From 1973 to 1992, the radiation protection guideline was 3 rem/qtr (ANL 1973). Areas where personnel were required to wear monitoring devices were established at 10% of this value. Therefore, the missed dose estimate for unbadged individuals in radiologically controlled areas would be one-half of 10% of 3 rem/qtr, or 600 mrem/yr. A lognormal distribution with geometric mean of 600 mrem should be assumed, with the upper 95% dose estimate for these individuals of 10% of the guideline (1.2 rem/yr) (NIOSH 2002). After 1992, a monitoring threshold of 100 mrem/yr should be used.

6.9.2 <u>Outside of Radiologically Controlled Areas</u>

After the early 1970s, those who did not work in radiological areas would not have been badged. Visitor dosimeters were stored at the entrances to the various facilities for use by personnel who were not considered radiological workers.

For individuals working outside the radiologically controlled areas, environmental exposure would be a better estimate of their exposure (see ORAUT 2006).

6.10 EXTREMITY DOSIMETRY

Monitoring exposure to the skin was important very early in ANL-E's history and maximum permissible levels were established (Nickson 1946), but it is not clear what monitoring methods were in use in what periods. In the early years of the site, body badges were apparently fitted with alternate fastening devices and worn on the wrist, leg, or head.

Monthly radiation safety activity reports from the D-211 Cyclotron Facility indicated that commercial finger ring film service was initiated for a 13-wk trial basis in 1954 (Okolowitz and Jezik 1954). A nonmagnetic film badge holder from Tracerlab was issued to all cyclotron workers in November 1954 after testing in the magnetic field. Wrist and head monitors were worn for an evolution involving a ^{235}U target. The finger ring film service from R. C. Scientific Instrument Company expired in January 1955. It is not clear if this is the same ring referred to above (Okolowitz and Jezik 1955).

The 1956 Radiation Safety Guide indicates that wrist film badges were available (ANL 1956a). The badge was likely similar to the whole-body film badge (two-element design with an open window and a 1-mm cadmium filter). Wrist badges containing neutron film were available and were required at CP-5 (ANL 1956a).

TLD ring badges of an undetermined type were investigated for use in the Building 350 plutonium *hoodline* during all of 1967. The rings were calibrated with plutonium fuel using an extrapolation chamber. Depending on the type of work, either one or two rings (right and left) were worn. Workers continued to wear wrist dosimeters, and the results were to be compared (Steele and Allen 1967). The results and conclusions of the study have not been found.

The current extremity monitoring system consists of ring dosimeters. The dosimeters are issued to personnel who have the potential for significant hand exposure including those who work with X-ray diffraction equipment. However, this equipment is easily shielded and such exposures are assumed to have been rare. The TLD is a Harshaw TLD-700, and each chip measures 0.125 in. by 0.125 in. by 0.035 in. Each ring has four cavities spaced at 90° intervals around its circumference into which TLD chips can be placed. Normally two or four chips are used (ANL 1996). Curves of net counts versus exposure show that the difference in response of the four elements is greatest at the lower energies, as could be expected (ANL 1996). From the ANL-E technical basis document it is not clear how the dose of record is determined. However, a records review indicates that, if one chip reading is over 10 mrem, a non-zero dose is recorded in the record.

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GLOSSARY

Albedo dosimeter
A personnel dosimeter which measures the dose equivalent from neutrons incident on the body by detecting the moderated neutrons reflected from the body.

Atomic Energy Commission (AEC)
Original agency established for nuclear weapons and power production; a predecessor to the U.S. Department of Energy.

arbitrary unit
A unit used to compare the density of a film in the badge window position caused by exposure to unknown beta-gamma and/or x-radiation to the equivalent density of a film in the badge window position caused by exposure to a known ^{60}Co or ^{226}Ra source expressed in mR units.

beta dose
A designation (i.e., beta) on some external dose records referring to the dose from less energetic beta, X-ray, and/or gamma radiation (see *open window*, or *shallow dose*).

beta particle
An electron or positron emitted spontaneously at high velocity from the nuclei of certain radioactive elements. Most of the direct fission products are (negative) beta emitters.

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

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

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, the International System (SI) unit is the sievert (1 sievert = 100 rem).

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

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
The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external or internal sources of radiation.

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

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

exposure
As used in the technical sense, exposure refers to a measure expressed in roentgens (R) of the ionization produced by photons (i.e., gamma and X-rays) in air. In the generic sense, ionizing radiation applied to matter.

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.

field-specific calibration
Dosimeter calibration based on radiation types, intensities, and energies in the work environment.

film
In general, a "film packet" that contains one or more pieces of film in a light-tight wrapping. When developed, the film has an image caused by radiation that can be measured using an optical densitometer.

film density
See optical density.

film dosimeter
A small packet of film within a holder that attaches to a wearer. Also referred to in early site documents as a “badge” or “badge meter.”

fission
The splitting of a heavy atomic nucleus, accompanied by the release of energy.

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

ionizing radiation
Electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.

isotope
Elements having the same atomic number but different atomic weights; identical chemically but having different physical and nuclear properties.

minimum reporting level
Based on a policy decision, the minimum dose level that is routinely recorded.

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

neutron film dosimeter
A film dosimeter that contains a Kodak Nuclear Track Emulsion, Type A, film packet.

Nuclear Track Emulsion, Type A (NTA)
A film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using an appropriate imaging capability such as oil immersion and a 1000X-power microscope or a projection capability.

open window
Designation on film dosimeter reports that implies the use of little (i.e., only film wrapper) shielding. Commonly used to label the film response corresponding to the open-window area.

optical density
The quantitative measurement of photographic blackening; density defined as $D = Log_{10}(Io/I)$.

pencil dosimeter
A type of ionization chamber used by personnel to measure radiation dose. Often referred to in early site records as a "pocket meter" or simply "dosimeter" as opposed to the term "badge" used for film badges. Also pocket dosimeter, Shonka-type dosimeter, and pocket ionization chamber (PIC).

personal dose equivalent $H_p(d)$
Represents the dose equivalent in soft tissue below a specified point on the body at an appropriate depth (d). The depths selected for personnel dosimetry are 0.07 mm and 10 mm for the skin and body, respectively. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively.

personal dose equivalent, slab $H_{p,slab}(d)$
Represents the dose equivalent in a tissue-equivalent slab phantom at an appropriate depth (d). This quantity is used for the calibration of personnel dosimeters.

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

photon - X-ray
Electromagnetic radiation of energies between 10 keV and 100 keV whose source can be an X-ray machine or radioisotope.

quality factor, Q
A modifying factor used to derive dose equivalent from absorbed dose. Also appears as "QF" in some site documents.

radiation
Alpha, beta, neutron, and photon radiation.

radioactivity

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

radionuclide
A radioactive isotope of an element, distinguished by atomic number, atomic weight, and energy state.

rem
A unit of dose equivalent equal to the product of the number of rad absorbed and the quality factor.

Roentgen (R or r)
A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kg of dry air. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (~>100 keV) energy photons.

rover dosimeter or rover
A pencil dosimeter that was not permanently assigned. Worn by visitors or personnel not normally assigned to an area.

shallow dose equivalent (H_s)
Dose equivalent at a depth of 0.007 cm in tissue.

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

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

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

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

whole-body dose
Commonly defined as the absorbed dose at a tissue depth of 1.0 cm (1000 mg/cm^2); however, also used to refer to the recorded dose.

X-ray
Ionizing electromagnetic radiation of external nuclear origin. Photon generated from acceleration of electron or positron in x-ray generator or synchrotron radiation storage ring.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

REPORT DATE: 05/15/2002

EXTERNAL RADIATION
EXPOSURE RECORD FOR :

ID #: SSN#

Period of Coverage: 1948 - 1988

Year	Shallow (mrem)	Deep (mrem)	Neutron (mrem)
1948	M	M	NM
1949	M	M	NM
1950	M	M	NM
1951	930	540	NM
1952	845	280	NM
1953	460	340	NM
1954	810	610	NM
1955	1165	1020	NM
1956	3365	3100	NM
1957	20	20	NM
1958	450	450	NM
1959	1100	1100	NM
1960	193	167	NM
1961	86	86	10
1962	1451	1451	16
1963	25	25	5
1964	896	895	5
1965	1005	1005	M
1966	1085	2085	M
1967	450	450	M
1968	85	85	M
1969	205	206	M
1970	105	105	M
1971	980	955	M
1972	355	355	M
1973	100	100	M
1974	150	150	M
1975	180	180	M
1976	245	245	M
1977	130	130	M
1978	70	70	M
1979	45	45	M
1980	80	80	80
1981	M	M	10
1982	M	M	10
1983	M	M	10

PAGE 1

Figure A-1. External Radiation Exposure Record (page 1 of 2).

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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Year	Shallow (mrem)	Deep (mrem)	Neutron (mrem)
1984	M	M	35
1985	M	M	30
1986	130	130	M
1987	M	M	55
1988	90	90	90
Total	17276	15549	265

Other Monitoring:

1955 - Wrist 240 mrem gamma
1956 - Right Wrist 460 mrem gamma, 620 mrad beta
Left Wrist 1150 mrem gamma
1986 - Ring 35 mrem gamma
1988 - Ring 130 mrem gamma

Notes:

NM: Not monitored

Shallow and Deep Dose:
The dose equivalent at 0.007 centimeters (shallow) and 1.0 centimeter (deep) in a sphere of soft tissue of a density of 1 gram per cubic centimeter and a diameter of 30 cm., exclusive of neutron dose equivalent.

M :
The badge period reading(s) was (were) less than the minimum sensitivity level of the monitoring device.

PAGE 2

Figure A-1. External Radiation Exposure Record (page 2 of 2).

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 3 of 17

Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439

Radiation Exposure Record

for Doses Assigned in CY 1989 or later

Chemical Technology
Health Physics Instrumentation
And Dosimetry Group 630-252-3355

Last name First name M.I. Sex Employee # SSN Birth Date

Legend: NM - Not Monitored
ND - Not-Detectable
PSE - Planned Special Exposure

Monitoring period		External Dose (rem)				Internal Dose (rem) *		Total Dose (rem)		
		Deep Dose Equivalent	Eye Dose Equivalent	Shallow Dose Equivalent	Shallow Dose Equivalent Max Extremity	Committed Effective Dose Equivalent	Committed Dose Equivalent Max. Exposed Organ	Total Effective Dose Equivalent	Total Dose Equivalent Max. Organ	
Start	End	(DDE)	(LDE)	(SDE, WB)	(SDE, ME)	(CEDE)	(CDE)	(TEDE)	(TODE)	Comment
1/1/1989	12/31/1989	0.065	0.065	0.065	NM	ND	ND	0.065	0.065	
1/1/1990	12/31/1990	0.015	0.015	0.015	NM	ND	ND	0.015	0.015	
1/1/1991	12/31/1991	ND	ND	ND	NM	ND	ND	ND	ND	
1/1/1992	1/31/1992	ND	ND	ND	NM	NM	NM	ND	ND	
12/22/1993	12/22/1993	ND	ND	ND	NM	NM	NM	ND	ND	

* See attachment for non-zero values for CEDE or CDE

Signature: ______ Group Leader, Health Physics Instrumentation And Dosimetry

Thursday, August 08, 2002

THIS DOCUMENT CONTAINS INFORMATION COVERED BY THE PRIVACY ACT

Figure A-2. Radiation Exposure Record for Doses Assigned in CY 1989 or Later

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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Individual Meter Record

Name ____ Site A Supervisor ____

Film Meter No.__ ____
Issued ____
Withdrawn ____

Week Starting	Mon.	Tues.	Wed.	Thu.	Fri.	Sat.	Sun.	Cumulative Exposure: Pocket Meter: Total	Disc	Times Worn	Film Meter: Shield	Window
NOV 11 1946	01	01						.02		2	0	0
NOV 18 1946	0	02			01			.03		3	0	0
NOV 25 1946	16	0	0					.16		3		
DEC 2 1946			01	Dropped 18				.01+		2	LIGHT	STRUCK
DEC 9 1946	04	0	04	04				.12		4		
DEC 16 1946	0	01		03				.04		3		
Total NOV .. 19.. thru DEC 22 1946								.38+		17	0	0

Name No.

Figure A-3. Individual Meter Record.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

CUMULATIVE EXPOSURE RECORD

1958 N-Rd's 10/20/58

DATE	AREA	DOSIMETER mr	FILM mr	FILM e.u.	DATE	AREA	DOSIMETER mr	FILM mr	FILM e.u.
1-6					7-7	D200	0	0	0
1-13A	D200	5	0	0	7-14	"	0	0	0
1-20	"	5	0	0	7-21	"	0	0	0
1-27	"	25	30	20	7-28	"	50	0	0
2-3	"	5	0	0	8-4	"	0	0	0
2-10	"	5	0	0	8-11	"	0	0	0
2-17	"	15	0	0	8-18	"	0	0	0
2-24	"	60	50	40	8-25	"	0	0	0
3-3	"	0	50	40	9-1	"	0	0	0
3-10	"	40	0	0	9-8	"	50	0	0
3-17	"	5	0	20	9-15	"	5	120	95
3-24	"	0	0	0	9-22	"	90	0	0
3-31	"	15	0	0	9-29	"	0	0	0
TOTAL		~~166~~ 180	130	120	TOTAL		195	120	95
							*Special Assignment in Bldg. 40.		
4-7	"	0	0	0	10-6	"	0	* 8	* 8
4-14	"	0	N) 220 ([illegible])	240	10-13	"	0	N) 150* 0	195* 0
4-21	"	9	0	0	10-20	"	0	0* 0	*0 0
4-28	"	0	N 0 ([illegible])	0	10-27	"	15	0*	*0
5-5	"	0	N 0 ([illegible])	0	11-3	"	10	0 0*	0 0*
5-12	"	0	0	0	11-10	"	0	0 0	0 0
5-19	"	0	0	0	11-17	"	0	65* 0	490* 0
5-26	"	0	0	0	11-24	"	0	70* 0	65* 0
6-2	"	0	0	0	12-1	"	0	0	0
6-9	"	42	0	0	12-8	"	0	N 0 (12/26)	0
6-16	"	2	0	0	12-15	"	0	0	0
6-23	"	0	0	0	12-22	"	35	0	0
6-30	"	0	0	0	12-29	"	0	0	0
TOTAL		53	220	240	TOTAL		60	285	740

NAME

1958
YEAR

IHS #

IHF-26A (10-57)

Figure A-4. Cumulative Exposure Record.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 6 of 17

ACCUMULATED EXPOSURE REPORT 12-31-62

IHS NO.	NAME	SEX	CC	JC	BIRTHDATE	SER DATE	EFF DATE
		2	111	445			

IHS NO.	SUM CODE NO BW YR	ROUT DOS	ROV DOS	BETA	GAMMA	NUET	BIWK TOTAL	SECTION CODE	CAL YR TOTAL	QTD TOTAL	QUES RDGS
	00-01-62	005	000	0000	0000	0000	0000	YI SN	000000	0000	00
	00-02-62	010	000	0000	0000	0000	0000	YI SN	000000	0000	00
	00-03-62	015	000	0000	0000	0000	0000	YI SN	000000	0000	00
	00-04-62	005	000	0000	0000	0000	0000	YI SN	000000	0000	00
	00-05-62	000	000	0000	0000	0000	0000	YI SN	000000	0000	00
	00-06-62	005	000	0000	0061	0000	0061	YI SN	000061	0061	00
	00-07-62	005	000	0000	0000	0000	0000	SN	000061	0061	00
	00-08-62	005	000	0000	0000	0000	0000	SN	000061	0061	00
	00-09-62	005	000	0000	0000	0000	0000	SN	000061	0061	00
	00-10-62	000	000	0000	0029	0000	0029	SN	000090	0090	00
	00-11-62	020	000	0000	0000	0000	0000	SN	000090	0090	00
	00-12-62	010	000	0000	0000	0000	0000	SN	000090	0090	00
	00-13-62	005	000	0000	0000	0000	0000	SN	000090	0029	00
	00-14-62	010	000	0000	0000	0000	0000	SN	000090	0029	00
	00-15-62	010	000	0000	0000	0000	0000	SN	000090	0029	00
	00-16-62	005	000	0000	0000	0000	0000	SN	000090	0029	00
	00-17-62	005	000	0000	0000	0000	0000	SN	000090	0000	00
	00-18-62	010	000	0000	0000	0000	0000	SN	000090	0000	00
	00-19-62	005	000	0000	0000	0000	0000	SN	000090	0000	00
	00-20-62	005	000	0000	0000	0000	0000	SN	000090	0000	00
	00-21-62	000	000	0000	0000	0000	0000	SN	000090	0000	00
	00-22-62	005	000	0000	0000	0000	0000	SN	000090	0000	00
	00-23-62	005	000	0000	0000	0000	0000	SN	000090	0000	00
	00-24-62	055	000	0000	0034	0000	0034	SN	000124	0034	00
	00-25-62	020	000	0000	0000	0000	0000	SN	000124	0034	00
	00-26-62	000	000	0000	0000	0005	0005	SN	000129	0039	00
		0225	0000	00000	00124	00005	00129				

26

Figure A-5. Accumulated Exposure Report.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

SEMI-ANNUAL ACCUMULATIVE EXTERNAL EXPOSURE REPORT 02-28-64

IHS NO	EFF DATE	NAME	BIRTHDATE	SEX	SER DATE	JC	ORG
				M		445	116

IHS NO	EFF DATE	LOC	IDENT	WK DOS	R DOS	BETA	GAMMA	NEUT	TOTAL	RMKS	COND
	07-01-63	SN-				0000	0000	0000	0000		
	07-01-63			0005							
	07-08-63			0005							
	07-15-63	SN-				0000	0000	0000	0000		
	07-15-63			0000							
	07-22-63			0005							
	07-29-63	SN-				0000	0000	0000	0000		
	07-29-63			0005							
	08-05-63			0000							
	08-12-63	SN-				0000	0000	0000	0000		
	08-12-63			0000							
	08-19-63			0005							
	08-26-63	SN-				0000	0000	0000	0000		
	08-26-63			0005							
	09-02-63			0000							
	09-09-63	SN-				0000	0000	0000	0000		
	09-09-63			0005							
	09-16-63			0000							
	09-23-63	SN-				0000	0025	0000	0025		
	09-23-63			0005							
	09-30-63			0000							
	10-07-63	SN-				0000	0000	0000	0000		
	10-07-63			0010							
	10-14-63			0000							
	10-21-63	SN-				0000	0000	0000	0000		
	10-21-63			0005							
	10-28-63			0005							
	11-04-63	SN-				0000	0000	0000	0000		
	11-18-63	SN				0000	0000	0000	0000		
	12-02-63	SN-				0000	0000	0000	0000		
	12-16-63	SN-				0000	0000	0000	0000		
			TOTAL	00060		000000	000025	00000	000025		

Figure A-6. Semi-Annual Accumulative External Exposure Report.

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EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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WHOLE BODY EXTERNAL RADIATION EXPOSURE SUMMARY

for ____________ ______________ PR # ________

EXPOSURE in mrem

Year	Rover Dosimeter	Film Badge Beta	Film Badge Gamma	Film Badge Neutron	Penetrating Total
1964	0	0	340	16	356
1965	0	0	135	12	147
1966	0	0	0	0	0
1967	0	0	0	0	0
1968	23	0	0	0	23
1969	0	0	0	0	0
1970	0	0	0	0	0
1971	0	0	0	0	0
1972	0	0	15	15	30
1973	0	0	0	0	0
1974	0	0	140	35	175
1975	0	0	40	80	120

Figure A-7. Whole Body Radiation Exposure Summary.

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EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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REPORT: OHS-1 01/18/79 PAGE 234

MASTER RADIATION EXPOSURE FILE

PAYROLL NUMBER	NAME	COST CNTR	JOB CLASS	LAB LOCATION	SERVICE DATE	BIRTH DATE	SOCIAL SECURITY	S	PC	I	II
		235	00055	BLDG 0301 ROOM B101				M	11		Y

YM	OHS SEC	ROV CNT	ROV DOS	BETA	GAM	NEUT	PEN	RE
7801	AU	0	0	0	0	0	0	
7802	AU	0	0	0	20	0	20	05
7803	AU	0	0	0	35	0	35	
7804	AU	0	0	0	0	0	0	IN
7805	AU	0	0	0	0	0	0	
7806	AU	0	0	0	0	0	0	
7807	AU	0	0	0	0	0	0	99
7808	AU	0	0	0	0	0	0	
7808	JH	1	0	0	0	0	0	
7809	AU	0	0	0	15	0	15	99
7810	AU	0	0	0	0	0	0	
7811	AU	0	0	0	60	0	60	99
7812	AU	0	0	0	~~0~~ 25	0	0	~~01~~ 99
TOTAL CALENDAR YEAR:		1	0	0	~~130~~ 155	0	~~130~~ 155	
TOTAL MOVING QUARTER:			0	0	~~60~~ 85	0	~~60~~ 85	

Figure A-8. Master Radiation Exposure File

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

Page No. 443
05/16/95

MASTER EXTERNAL RADIATION EXPOSURE REPORT FOR PMG
JANUARY 1, 1993 THROUGH DECEMBER 31, 1993
(NOTE: IF BADGE TYPE NOT BGN OR BGNC,
PLEASE IGNORE 0 IN THE NEUTRON COLUMN)

SECTION	BADGE TYPE	ISSUE DATE	RETURN DATE	SHALLOW DOSE (MREM)	DEEP DOSE (MREM)	NEUTRON DOSE (MREM)	PENETRATING TOTAL (MREM)	REMARKS	LAST NAME	MASTERID
** PR#:										
SA	BGN	01/01/93	01/31/93	0	0	0	0			9301SA
SA	BGN	02/01/93	02/28/93	10	10	0	10			9302SA
SA	BGN	03/01/93	03/31/93	0	0	0	0			9303SA
SA	BGN	04/01/93	04/30/93	0	0	0	0			9304SA
SA	BGN	05/01/93	05/31/93	0	0	0	0			9305SA
SA	BGN	06/01/93	06/30/93	0	0	0	0			9306SA
SA	BGN	07/01/93	07/31/93	0	0	0	0			9307SA
SA	BGN	08/01/93	10/09/93	0	0	0	0	99-LATE		9308SA
SA	BGN	09/01/93	09/30/93	0	0	0	0			9309SA
SA	BGN	10/01/93	10/31/93	0	0	0	0			9310SA
SA	BGN	11/01/93	11/30/93	0	0	0	0			9311SA
SA	BGN	12/01/93	12/31/93	0	0	0	0			9312SA
** Subtotal **										
				10	10	0	10			

Figure A-9. Master External Radiation Exposure Report.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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NEUTRON EXPOSURE REPORT

PROCESSED
WEEK STARTING ______________________

FILM ID. NO.	IHS NO.	NAME	AREA WORN	POSITION WORN	DATE WORN	TIME WORN	READINGS: NO. ↑ ABOVE CONTROL	READINGS: n_f/cm^2 ($\times 10^6$)	READINGS: mrem	- COMMENTS
			D-200		1-30-61	2 weeks			10	
	"	" "	"		3/27/61	"			5	
	"	" "	"		4/24/61	"			10	
	"	" "	"		11-6-61	"			5	
	"	" "	"		12-18-61	"			5	

Figure A-10. Neutron Exposure Report.

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EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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SPECIAL EXPOSURE RECORDS

DATE	TYPE	AREA	TIME	POSITION	READING		COMMENTS
					[illegible]	[illegible]	
[illegible]	FB	A	[illegible]	B. Wright	0	0	Testing neutron chamber in CP 3' Thermal column beam.
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5		

NAME
YEAR
PR#

IHS-24B (4-54)

Figure A-11. Special Exposure Records.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 13 of 17

SPECIAL FILM REQUEST

DATE: 8/18/58

NAME:

IDS#:

DATE WORN: 8/12/58 - 8/15/58

TIME WORN: 4 - DAYS

AREA WORN: D-301

POSITION WORN:

BODY: ✓
HEAD:
RT. WRIST:
LT. WRIST:

OTHER:

TYPE OF FILM WORN:

✓ B-G FILM:

NTA FILM:

BE SURE TO MARK WINDOW AREA

REMARKS: TEMP. BADGE PRIOR TO ISSUE OF PERMANENT ASSIGNMENT
DOSIMETER READING TOTAL FOR 4 DAYS = 7 MR

RADIATION SAFETY
ORIGINATOR:

DO NOT WRITE BELOW THIS LINE

PROCESSED WEEK OF: AUG 18 1958

IDENTIFICATION: 25

REMARKS:

TECHNICIAN

	FILM	SHIELD (mr)	WINDOW (mr)
Beta-Gamma Film Readings	SENSITIVE FILM (502)	0	0
	INSENSITIVE FILM (510)		
Neutron Film Reading			

P.B. #4

Figure A-12. Special Film Request.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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SPECIAL METER ASSIGNMENT AND RADIATION EXPOSURE REPORT

ASSIGNMENT DATA

IHS NUMBER | NAME LAST FIRST M.I. | TYPE OF PERSONNEL: [X] ANL [ ] NON-ANL | OVERALL PERIOD OF COVERAGE: BEGINNING DATE: 9-27-65 ENDING DATE:

TYPE OF COVERAGE: [ ] 1-CHAMBER DOSIMETER [X] 2-BETA-GAMMA FILM [ ] 3-NEUTRON FILM

TYPE OF DOSIMETER (IF ANY): 200 mR

BLDG. LOC. OF ASSIGNMENT: D-306

RADIATION EXPOSURE DATA

ACTUAL PERIOD METER WORN: 1.5 [ ] WEEK(S) [ ] DAY(S) [X] HOUR(S)

TYPE OF RADIATION EXPOSURE: [X] 1-BETA [X] 2-GAMMA [ ] 3-X-RAY, ENERGY: [ ] 4-NEUTRON, ENERGY:

POSITION OF MONITORING METER DURING EXPOSURE: [ ] 1-TOTAL BODY [ ] 2-HEAD [ ] 3-L. WRIST [ ] 4-R. WRIST [X] 5-OTHER: Right Palm

TYPE OF WORK PERFORMED DURING EXPOSURE: Cleaning Thimble #3

BLDG. LOC. DURING EXPOSURE: D-306

WAS PERMANENT FILM BADGE WORN ALSO DURING EXPOSURE? [X] YES [ ] NO

CHAMBER DOSIMETER READING: 170 MR

IS SPECIAL FILM BEING SENT FOR PROCESSING? [X] YES [ ] NO

REMARKS:

22 R/2" H, 60 R/2" H&B

SPECIAL FILM FOR PROCESSING

ATTACH ENVELOPE CONTAINING SPECIAL FILM.

BY 9-27-65 DATE

NOTE: PLEASE INITIATE AN INDIVIDUAL REQUEST FOR EACH SPECIAL FILM TO BE PROCESSED. BE SURE TO COLLECT FILM AT END OF MONITORING WEEK AND ISSUE NEW FILM IF NECESSARY.

SPECIAL FILM RADIATION EXPOSURE REPORT

Date of Film Proc.	DENSITIES				
	Al(.0181)	Ag(.005)	O.W.	Ag or Cd (.0895)	Number of Tracks
10-1-65	.61	.58	.80	.48	

EFFECTIVE FILM DATE	FILM IDENT. NO.	EXPOSURES			
		Beta	Gamma	X-ray	Neutron
9-27-65	MJ-25	0 mrad	480 mr	80 mr	mrem

REMARKS:

Figure A-13. Special Meter Assignment and Radiation Exposure Report.

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EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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SPECIAL TLD FINGER EXPOSURE REPORT FOR BLDG. 212

OHS #	Name	Type of Work	Begin. Date	End. Date	TLD Readings 1	2	3	4	Exposure (mRem or mRad) βγ	γ	Neutron
		AGHCF	1/2/78	1/31/78	30	40			35		
		AGHCF	2/1/78	2/28/78	55	45			50		
		AGHCF	3/1/78	3/31/78	905	1170			1065		
		AGHCF	4/1/78	4/30/78	1150	680			1000		
		AGHCF	4/1/78	4/19/78	2670	4880			4440		
		AGHCF	5/1/78	5/15/78	780	1350	1085	665	1175		
		AGHCF	5/15/78	5/31/78	20	20	25	25	20		
		AGHCF	6/1/78	6/15/78	20	25	25	20	20		
		AGHCF	6/15/78	6/30/78	20	10	15	15	15		
		AGHCF	7/1/78	7/19/78	60	80	95	45	80		
		AGHCF	7/18/78	7/31/78	30	25	30	25	40		
		AGHCF	8/1/78	8/15/78	280	265	300	315	410		
		AGHCF	8/16/78	8/31/78	10	15	15	15	15		
		AGHCF	9/1/78	9/15/78	275	285	285	215	270		
		AGHCF	9/15/78	9/29/78	145	130	130	125	140		
		AGHCF	10/01/78	10/16/78	10	10	10	10	0		
		AGHCF	10/16/78	10/31/78	5	5	5	5	0		

BY ____________________ ________
Area Monitoring Section Date

BY ____________________ ________
Personal Monitoring Section Date

Figure A-14. Special TLD Finger Exposure Report.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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DATE 10-23-74

TO: ____________ Personal Monitoring Group

FROM: ____________ Health Physicist - OHS-RS

SUBJECT: Personnel Dose Equivalent Evaluation - Level 1
For Period 10-4-74 to 10-4-74

OHS NUMBER	NAME	LEVEL (mrem)	TYPE (A,B,C,D)	VALID? YES	VALID? NO	ANTICIPATED? YES	ANTICIPATED? NO
		5250	D	X		X	
	TLD - Right Forefinger						

HJH:mmb
4/12/74

Figure A-15. Personnel Dose Equivalent Evaluation – Level 1.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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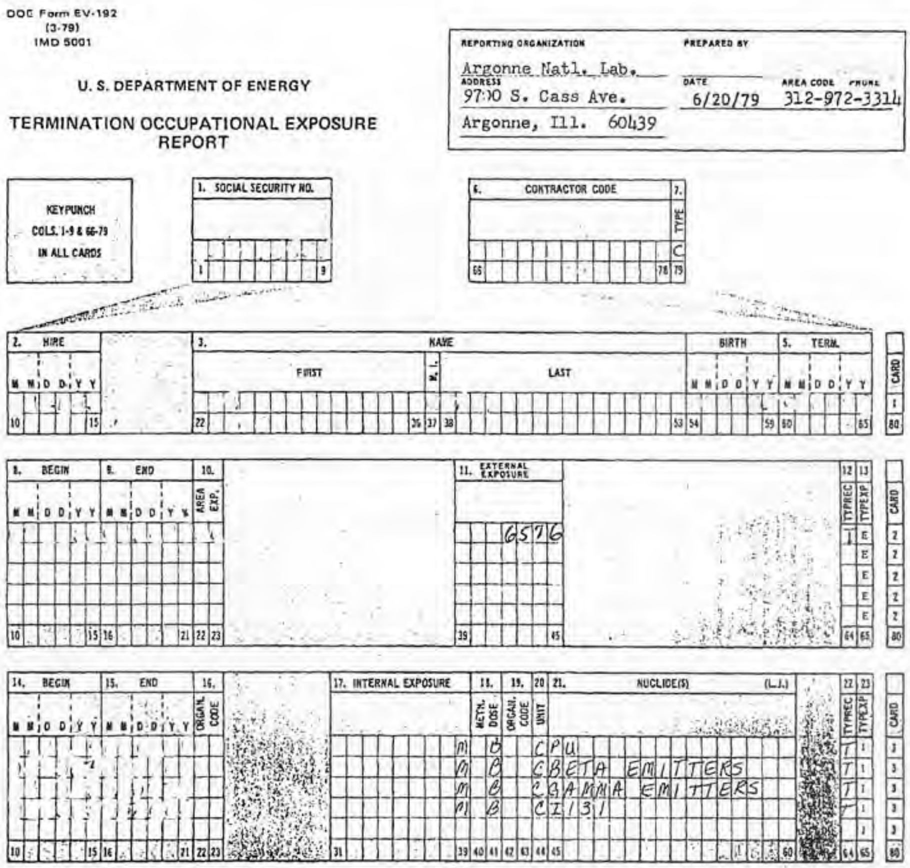
DOC Form EV-192
(3-79)
IMD 5001

U. S. DEPARTMENT OF ENERGY

TERMINATION OCCUPATIONAL EXPOSURE REPORT

REPORTING ORGANIZATION: Argonne Natl. Lab.
PREPARED BY:
ADDRESS: 9700 S. Cass Ave. Argonne, Ill. 60439
DATE: 6/20/79
AREA CODE PHONE: 312-972-3314

KEYPUNCH COLS. 1-9 & 66-79 IN ALL CARDS

1. SOCIAL SECURITY NO.
6. CONTRACTOR CODE
7. TYPE: C

2. HIRE (M M D D Y Y) | 3. NAME (FIRST, M.I., LAST) | 4. BIRTH (M M D D Y Y) | 5. TERM. (M M D D Y Y) | CARD 1

8. BEGIN | 9. END | 10. AREA EXP. | 11. EXTERNAL EXPOSURE: 6576 | 12. TYPEREC | 13. TYPEEXP: E | CARD 2

14. BEGIN | 15. END | 16. ORGAN. CODE | 17. INTERNAL EXPOSURE | 18. METH. DOSE | 19. ORGAN. CODE | 20. UNIT | 21. NUCLIDE(S) (L.J.) | 22. TYPEREC | 23. TYPEEXP | CARD 3

18. METH.	DOSE	20. UNIT	21. NUCLIDE(S)	22	23
M	B	C	PU	T	1
M	B	C	BETA EMITTERS	T	1
M	B	C	GAMMA EMITTERS	T	1
M	B	C	I131		1

Figure A-16. Termination Occupational Exposure Report.

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE
Page 1 of 3

Table B-1. Facilities by building number and section code[a].

Building	Section codes 1980	Section codes 2005	Facility name	Years of operation (approximate)	Additional information	Facility type
Site A			CP-2	1943–1954	CP-1 moved from West Stands and reassembled at Site A. Graphite moderated.	Reactor
Site A			CP-3, CP-3´	1944–1954	CP-3 was heavy-water moderated, natural uranium fuel. Natural U fuel replaced with enriched and renamed CP-3´ 1950.	Reactor
25	AA		Argonaut	1957–1980	University research reactor. Light-water moderated and cooled, graphite moderated. Enriched U-235 fuel (20%).	Reactor
40			Chemistry Hot Lab	1948–	Radioactive material stored there awaiting disposition (1994)	Radioactive Materials
200	JA, JG, JM, JR	JG, JM, VA	Chemistry Building	1951–	Characterization of isotopes and nuclides. High, moderate, and low-level cells. Only one wing (M Wing Addition) still used for studies of radioactive materials; designed to work with Pu safely.	Radioactive Materials
202	GE, GF, GJ	GE, GN, VE, VK	Biology Building Janus Reactor 1964-1992	1952–	Low and high gamma irradiation rooms. Neutron Irradiation Facility (1959). Radiation effects studies 1950s to 1970s.	Reactor (1964-1992) Radioactive Materials
203	ED, EF, EG, EL	ED, EF, EG, VH	Physics Building Initially housed Dynamitron and Van de Graaff accelerators	1952–	Many modifications to add new accelerator facilities, such as the Tandem Van de Graaff. ATLAS added to the north side of building in 1982. First ion beam accelerated 1985. 1 Ci PuBe source stored there (1994)	Accelerator
205	YI	VC	Chemical Technology	1951–	Nuclear fuel processing and fuel recovery studies. Proof-of-breeding experiments. G and K Wing Laboratories are current nuclear facilities.	Radioactive Materials
206	EA	EA, VF	Engineering Development Lab	1953–	Sodium studies. Half-scale mock up of EBR-II that was built at ANL-W. Temporary hot cell facility added 1955.	Radioactive Materials
208	EY	EY	Reactor Engineering Building	1952–	Mostly office space. A Van de Graaff (F Wing) added 1956.	Accelerator
211	JH, JK	JH, JK, JR, VB	Cyclotron Building or Low Energy Accelerator Facility	1951–	60-Inch Cyclotron. Caves to process irradiated materials. Major expansion 1962 adding a 3-MeV Van de Graaff and a 20-MeV high-current electron LINAC. 1992 characterization indicated Co-60 was most prevalent isotope.	Accelerator
212	GA, GB, GC, GD	GA, GB, GC, GD, VD	Fuel Technology Center AGHCF	1962–	HVEM formally dedicated 1981. AGHCF constructed in 1963 to contain Pu in N_2. HVEM removed 2001. AGHCF and the Advanced Materials Fabrication Facility (AMFF) are current nuclear facilities.	Radioactive Materials
223	GK, GL	GL	Material Science Division	1968–	Mainly used for the development of superconductors. 1,200 Ci Co-60 stored there in 1994.	Radioactive Materials

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE

Table B-1 (Continued). Facilities by building number and section code.

Building	Section codes 1980	Section codes 2005	Facility name	Years of operation	Additional information	Facility type
301			Physics and Metallurgy Hot Lab	1951–	Fuel analysis and processing activities. Five cave facilities. Principal hot lab for reactor development, reactor fuel studies, and handling of highly radioactive materials. In 1998, parts of building were not controlled areas, used as office space. The dominant floor contaminant was Cs-137.	Radioactive Materials
303			Mixed Waste Storage Facility (MWSF)	~1950–	Current nuclear facility. No history located on previous uses.	Radioactive Materials
306	MG, MJ	MH, MJ, VM	Waste Management Operations (Decontamination Shop)	1950–	Size nearly doubled in 1961. Two caves and six retention tanks. Size reduction and packaging for shipment. Laundry facilities. Current nuclear facility.	Radioactive Materials
308, 309	MA	MA	Energy Technology	1956–	High bay for EBR-II project (partial mock-up). Sodium loop tests for EBR-II and the Integral Fast Reactor.	Radioactive Materials
310	MK, MT		Experimental Waste Processing, Storage, and Shipping	1948–	Similar function to Build 306. Dry waste incineration. Retention tanks in basement. Gamma Irradiation Facility added in 1954. Spent fuel rods used in food irradiation experiments. Several additions in 1970s to support EBR-II fuel cycle facility at ANL-W	Radioactive Materials
314	ST	ST	ZPR Assembly	1968–	Fast Neutron Generator. Considered part of the ZPR complex.	Radioactive Materials
315, 316	SN, SP	SP, VP	ZPR Assembly	1950 (316)– 1962 (315)–1982	Additional cell added 1956. In all there were seven ZPRs and the ATSR in 316. 315 Constructed in 1962 to house two ZPRs. Part of a larger complex of buildings (314/315/316) used for storage of materials waiting disposal in 1994. Current nuclear facility.	1950-1982 Reactor 1983 to 2005 Radioactive Materials
317		MD	Above- and below-grade waste storage	Unknown–1994	The facilities in 317 Area included the southwest, south-middle, and southeast in-ground concrete vaults, the map tube facility, the deep vault, the north vault, a concrete storage pad, the waste baler building, and a graveled container storage area. 317B current nuclear facility (below-grade storage facility).	Radioactive Materials
329, 330	QM		CP-5 Reactor	1954–1979	Wing additions between 1958 and 1962. Reactor room, control room, laboratories, and fuel storage. Nuclear physics, materials research, and biological studies. Decontamination and decomissioning of reactor completed 2000.	Reactor
331	QW	QW	EBWR	1956–1967	Reactor removed from shell in 1995 during decontamination and decomissioning. Current nuclear facility, now used for storage of low-level and transuranic waste.	1956-1967 Reactor Radioactive Materials
335			Juggernaut Reactor	1962–unknown	Light-water moderated and cooled, graphite moderated. Highly enriched ^{235}U fuel (93%).	Reactor

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE

Table B-1 (Continued). Facilities by building number and section code.

Building	Section codes 1980	Section codes 2005	Facility name	Years of operation	Additional information	Facility type
340	MP		Experimental Animal Quarters	1950–	Housed animals irradiated in Bldg. 202. Bone cancer research 1963 to 1980.	Radioactive Materials
350	SH	SR, VN	Fuel Fabrication Facility (now New Brunswick Lab, a DOE facility)	1952–1979	1959 became the first large-scale plant for making fuel from Pu. Decommissioned in 1978-1979.	Radioactive materials
360-390	SA, SB, SC, SD, SE, SF, SG, SK, SM, SQ		ZGS	1963–1979	16 Buildings in the 360 area. Some of same facilities now used for the IPNS (see below). 2 Ci Pu–Be-239 stored in 360 in 1994	High-energy accelerator
366		SJ	AWA	2000–	Research facility for new accelerator design. The initial phase designed to provide short 100-nC bunches of electrons at 20 MeV. The facility is housed in a concrete bunker having 6- to 8-foot thickness. The designed safety operating envelope for the facility is 400 nC, 30 pps, at 20 MeV.	Accelerator
361, 391, 375		SA, SB, SC, SD, SE, SF, SG, SK, SQ, SS, SU, SV, SX, SZ, WC	IPNS	1981–	Uses some of the same equipment and facilities as the ZGS. A number of ^{239}PuBe sources stored in 375 in 1994	High-energy accelerator
400, 410, 411, 412, 415, 420		RA, RB, RD, RE, RF, RG, RH, RJ, RK, RL, RN, RP, RZ, RV	APS	1994–		Accelerator

a. blank = none.