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ACRONYMS AND ABBREVIATIONS

a.u.	arbitrary units
AGHCF	Alpha Gamma Hot Cell 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
CFR	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
DOL	U.S. Department of Labor
EBR-II	Experimental Breeder Reactor No. 2
EBWR	Experimental Boiling Water Reactor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
eV	electron-volt
g	gram
GeV	gigaelectron-volt, 1 billion electron-volts
hr	hour
HVEM	High-Voltage Electron Microscope
in.	inch
INEEL	Idaho National Engineering and Environmental Laboratory
IPNS	Intense Pulsed Neutron Source
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
LAMPF	Los Alamos Meson Physics Facility
LINAC	linear accelerator
LOD	limit of detection
mA	milliampere
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mm	millimeter
mo	month
mR	milliroentgen

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
ORAU	Oak Ridge Associated Universities
PIC	pocket ionization chamber
PNNL	Pacific Northwest National Laboratory
POC	probability of causation
QF	quality factor
qtr	quarter
R	roentgen
SRDB Ref ID	Site Research Database Reference Identification (number)
SSTR	solid-state track recorder
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
wk	week
w_R	radiation weighting factor
yr	year
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, particle, or photon
§	section or sections

6.1 INTRODUCTION

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

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

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

The statute also includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2010):

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

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

6.1.1 Purpose

Argonne National Laboratory-East (ANL-E) was established on July 1, 1946; this technical basis document (TBD) covers the period from that date to the present. The work at the site has been a continuation of that done by the Metallurgical Laboratory of the University of Chicago beginning in 1941, which was 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 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 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. This document contains supporting documentation to assist in the evaluation of occupational external doses from these processes in accordance with OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007).

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 EEOICPA. 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 for preparing 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 ANL-E initially used in these badges is 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 contractor) 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 reported contractor that processed and read Kodak NTA film. Due to the labor necessary 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 measured gamma dose for the same period (Dolecek 1981).

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

Film processor	Dates
Onsite	1942[a]–1954
Tracerlab	Mar 1954–Jun 1958
Landauer	Jul 1958–Jun 1960
Atomic Film Badge Corporation	Jul 1960–Dec 1964
Tracerlab	Jan 1965–Sep 1965
Onsite	Oct 1965–1988

a. Film processing was in existence before the establishment of ANL-E in 1946.

Around 1960, ANL-E transitioned to a four-filter film badge. It is uncertain whether the design was from its contractor, 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 that at the National Reactor Testing Station (NRTS) in Idaho and at the Hanford Site; it 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 reference 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 the Hankins and Hosger albedo neutron designs using TLD-600 and TLD-700 chips. At least initially, NTA film was still added to the beta-gamma badges. The record is unclear about exactly when NTA film was 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 in 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 (Dolacek 1996). This dosimeter passed DOE 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 with 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 (Dolacek 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 to be the official dose, the readings were recorded in the individual dosimetry records through 1964. Film badges and PICs were stored at the entrances to the different facilities which were controlled for radiological purposes (Novak 1956 and ANL 1973-1984). 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 PIC) (ORAUT 2005a). 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 periods of use are approximate. In some cases, changes were probably 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 DOL requests a worker's dosimetry records, the ANL-E Chemical Engineering Division searches for the relevant records. For external dosimetry, there are three record sources that might contain the needed information (ANL-E records can also include those of the predecessor facility employees who became employees of ANL-E upon its establishment in 1946). The Worker Protection System is a database of employees between 1945 and the present. A second database (created in dBase III plus) contains the external dosimetry records for workers between 1989 and the present. Last, there are hard-copy records of the external doses for workers between 1942 and 1988. From these sources, a two-page 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 provided initially. For workers with assigned dose in 1989 or later, a separate computer-generated summary is provided (Figure A-2) for those years. In response to requests for more detailed information, ANL-E has provided 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.

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

Year	Holder	Beta/gamma				Neutron		Extremity	
			Filtration						
		Detector	Deep	Shallow	Processor	Detector	Processor	Detector	Processor
1945[a]	University of Chicago (two filter)	Film, type Unknown	1 mm Cd	Open (28 mg/cm^2 Wrapper)	ANL-E			Film	ANL-E
1946									
1947									
1948									
1949									
1952		“catastrophic” film added							
1953						Kodak NTA	ANL-E	Film rings Ring, wrist, & head films	R.C. Scientific & others Wrist, head same as whole body
1954									
1955					Tracerlab				
1956									
1957									
1958					Landauer				
1959		DuPont 553							
1960	Four filter	DuPont 558	0.008 in. Cu, 0.024 in. Cu, 0.032 in Pb, front and back	Open Window (0.060 in. plastic backing)	Atomic Film Badge Corporation	Kodak NTA	Atomic Film Badge Corporation		
1961									
1962	Hanford Type (four filter)	DuPont 558	0.0191-in. Al 0.005-in. Ag 0.0395-in. Cd	Open Window					
1963					ANL-E	Kodak NTA	ANL-E		
1964									
1965		DuPont 553							
1966		DuPont 558							
1970		Kodak Type 3						TLD ring	ANL-E
1971		Kodak Type 2							
1973						Kodak NTA & SSTR			
1974									
1975									
1976									
1977						Kodak NTA & albedo TLD			
1978								Current TLD Ring	
1979–1987									

Year	Holder	Beta/gamma				Neutron		Extremity	
			Filtration						Processor
		Detector	Deep	Shallow	Processor	Detector	Processor	Detector	
1988 – present	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-E	TLD Harshaw TLD 600/700			

a. Film processing was in existence before the establishment of ANL-E in 1946.

The pre-1989 record summaries (Figure A-1, two pages) 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 with density of 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 with density of 1 g/cm^3.
- An "M" for years in which the dose was less than the minimum sensitivity of the measuring device.
- A hyphen ("-") or "NM" for unmonitored periods; some records indicate unmonitored periods with a statement such as "Not monitored 1960-1962."
- An asterisk ("*") after the dose when the only monitoring was by a direct reading dosimeter; additional codes used are explained on the report.

The 1989 and later records summaries (Radiation Exposure Record; Figure A-2) report external dosimetry results as:

- Deep dose equivalent (DDE), lens of eye dose equivalent (LDE), shallow dose equivalent (SDE, WB), and shallow dose equivalent maximum extremity (SDE, ME).
- "NM" meant not monitored.
- "ND" meant not detectable.

The reported values for the early years when the dosimeters were calibrated to exposure assumed 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 2005a).

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 the forms. From 1964 to 1975, a handwritten form was again used and shows only 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 forms and reports depending on the years of employment. The dates of use given here are approximate. Attachment A contains redacted samples; personal identifiers have been removed from each sample.

Individual Meter Record (1946 to mid-1953) – Hand Entered (Figure A-3)

- Each card covers 1 week.
- The units are roentgen rather milliroentgen.

- Daily readings and Total (weekly) from PICs, Times Worn, and a Discg column for entry of accidental discharge.

- Film meter exposure values for shield and window for each day of the week.

- Location of use (e.g., "Site A").

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

- Results for each wear period.

- The gamma units are milliroentgen (mr on the form), and the beta units are "arbitrary units" (a.u.; see Section 6.8.2).

- From mid-1953 (fiscal year 1954) to 1956, the forms cover the fiscal year. From 1956 to 1961, they cover the 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 accumulated dose 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 a.u. 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 31 and read late.

- The forms were divided into 4 quarters of 13 weeks each. Each quarter was subtotaled.

- The forms only recorded beta-gamma PIC readings, film penetrating dose (mr), and film nonpenetrating dose (a.u. or beta). 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 that were 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 gamma units are milliroentgen, the beta units are millirad, and the neutron units are millirem.

- 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 might 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 months of data.

- The gamma units are milliroentgen, the beta units are millirad, and the neutron units are millirem.

- 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 (i.e., PIC) result (WK DOS). 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 was 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 Dosimeter, Gamma, and Neutron).

- The units are millirem.

- 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 form was 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 ROV DOS, GAM, and NEUT), and Remarks (RE). A common remark was "99," indicating a dosimeter that was returned late.

- The gamma units are milliroentgen, the beta units are millirad, and the neutron units are millirem.

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

Master External Radiation Exposure Report (1989 to present) – 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 DOSE and NEUTRON DOSE), 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 (which was also the 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 units are millirem.

- 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 a 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 units are 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 (e.g., an extra badge worn on wrist or body).

- The units are milliroentgen and a.u.

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

- Information includes DATE, TYPE (film badge or dosimeter), AREA, TIME (worn), POSITION, READING (including mR under filter and 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 was used for one badge only.

- Includes DATE, TIME WORN, AREA WORN (building), POSITIONS WORN, TYPE OF FILM WORN (beta-gamma or neutron), and remarks. The remarks can indicate the reason for the badge.

- The units are milliroentgen and a.u. for beta-gamma, and millirem for neutron.

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

- The records contain supplemental dosimeter readings (e.g., a beta-gamma badge worn on the right wrist).

- This form probably replaced the Special Film Request (Figure A-12). At least four variations were noted that corresponded to the dosimeters in use over the years, which were the two-element beta-gamma film, four-element beta-gamma film, NTA film, and albedo TLDs.

- The units are typically millirad for beta, milliroentgen for gamma, and millirem for neutron as 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 for BLDG. [number] (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 Exposure βλ, λ, and Neutron. 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 was included to indicate that more than one ring was being worn in the case of four TLDs.

- The units are 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, LEVEL in millirem, TYPE, Valid (yes or no), and ANTICIPATED (yes or 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 a worker's employment ended 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 during 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 not to count the doses for these periods twice.

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

6.4 HISTORICAL ADMINISTRATIVE PRACTICES

6.4.1 Badged Population

In 1956, the site *Radiation Safety Guide* (Novak 1956) indicated that areas were posted and that individuals entering an active area (i.e., a radiologically controlled area) were required to wear personnel monitoring devices that were provided at the entrance. Areas that were spelled out as active included Building 330 (Chicago Pile 5; 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 with neutron film were required at CP-5 (Novak 1956).

In the 1973 to 1984 revisions of the site *Health and Safety Manual* (ANL 1973–1984), 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 that

produced ionizing radiation was operated. Consistent with the earlier Radiation Protection Guide, each person who entered 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 1973–1984).

6.4.2 Badge Exchange Frequency

At first there were weekly film badge exchanges. On April 16, 1951, the badge exchange frequency 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 20 special cases at the new Chemistry Building at the University of Chicago (Mendelstein 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 per year) (Bleiler 1968a, 1968b, 1970, 1973a, 1974).

Due to a work force reduction in the dosimetry group, biweekly exchanges were eliminated and all film badges were placed on a 4-week 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 discrepancy could 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 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 were exchanged quarterly at that facility (ANL 1994).

Dose reconstructors should use dosimeter exchange frequencies reflected in the record when available. In the absence of such records, Table 6-3 provides default dosimeter exchange frequencies that are favorable to claimants to be used for dose reconstructions.

Table 6-3. Default dosimeter exchange frequencies.

Years	General population	Others
1946–1959	Weekly	Site D and West Stands (and likely Site A) personnel switched to biweekly in 1951
1960–1973	Biweekly	
1974	4-Week (13 periods/yr)	
1975–present	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 multielement 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 multielement 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. All 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 described dosimeter is not the Panasonic UD-808AS that was tested by DOELAP in 1992, but rather a Hankins-type (one TLD-600 and one TLD-700 in a polybox) (Dolacek 1996).

6.5 COMMON ISSUES

6.5.1 Interpretation of Blanks and Gaps in Monitoring Records

Prior to 1964

Records of individual dosimeter results before 1964 might include blanks rather than recorded zeros for some periods. Because all workers entering radiologically controlled areas are assumed to have been badged, intermittent blanks on such records should be interpreted as zeros values, and missed dose should be assessed using the frequencies established in Table 6-3. The exchange frequency should be assumed to be weekly (52 exchanges per year) before 1960 and biweekly (26 exchanges per year) from 1960 through 1963. This is not applicable to workers whose occupations did not require entry to radiologically controlled areas and for whom dose records do not exist (see Section 6.9).

Gaps in records (such as a missing year of records for an otherwise monitored worker) may also exist in some cases. Dose should be assigned for such periods using dosimetry data before and after that period in consideration of the approach of Watson et al. (1994). This method applies to otherwise monitored individuals whose occupations were not likely to have changed during the period.

1964 through 1975

The available dosimetry records do not provide individual dosimeter results from 1964 to 1975, but instead provide only annual dose summaries (see Figure A-7; as mentioned above, there is some overlap in the dose records for 1964; therefore, some detail for 1964 might be available for some workers). For these cases, it is necessary to estimate the dosimeter exchange frequency from 1964 to 1975 for years in which positive or zero doses are recorded. Blank values for a year on this summary form indicate no monitoring was performed for that year. It appears that ANL-E did not generally use different exchange frequencies in relation to job categories, so assumption of a single

frequency by 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 per year). For 1974 the exchange frequency should be assumed to be every 4 weeks (13 exchanges per year). For 1975 the exchange frequency should be assumed to be monthly (12 exchanges per year).

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 5,000 mrem/yr. The minimum number of months in which this dose could have been received is 5. Therefore, the maximum number of missed dose months would be 7, and the minimum would be 0 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 7 (NIOSH 2007). Table 6-4 lists historical dose limits.

Table 6-4. Historical dose limits.

Period	Daily or weekly limit	Quarterly or annual limits:
1946–1955	Beta & gamma, 100 mrem/d (Nickson 1946; Gilbreath ca. 1946)	Not applicable
1956–1972	Gamma 300 mrem/wk (AEC 1958) Beta & gamma (sum), 500 mrep/wk (Novak 1956)	3 rem/qtr, 15 rem 5(N-18) rem accumulated (AEC 1958)
1973–1988	Not applicable	3 rem/qtr (ANL 1973–1984) 5 rem/yr 5(N-18) (DOE 1981)
1989–1992	Not applicable	5 rem/yr annual effective dose equivalent (DOE 1988)
1993–present	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 (2007), it is possible to develop an estimate of the number of zeros for calculation of the missed dose that is favorable to claimants.

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
1946–1955	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–present	5	1	(a)	(a)	(a)	0.417	1.25

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

After 1975

Determining the number of zero readings should be straightforward beginning in 1976 since records are of better quality and individual cycle monitoring results are included in the record.

As with the period before 1964, if there are gaps in records (which is less likely to occur for the more recent period), dose should be assigned using dosimetry data before and after that period in consideration of the approach of Watson et al. (1994). This method applies to otherwise monitored individuals whose occupations were not likely to have changed during the period.

6.5.2 Discrepancies

If the employee's record contains discrepancies, it is favorable to claimants 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, but since mid-1953 the laboratory has routinely used milliroentgen and millirem. It is highly unlikely that a record would show a dose greater than the quarterly or annual limit without an additional record that indicates an overexposure.

If no date is associated with a dose record or if it is illegible, it is favorable to claimants to use that dose in the dose reconstruction. The dose reconstructor should use 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 action most favorable to claimants is to incorporate the correction in the dose to be used for reconstruction.

6.5.3 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, which is favorable to the claimant for most organs. In accordance with the NIOSH External Dose Reconstruction Implementation Guideline (NIOSH 2007), rotational and isotropic geometries must also be evaluated in accordance with that document for bone surface, red bone marrow, esophagus, or lung exposures. The favorable to claimant geometry from this comparison should be used for these organs unless workplace information indicates that anterior-posterior geometry is applicable for a specific exposure situation.

6.6 PHOTON DOSE

6.6.1 Energy Groups

The NIOSH IREP POC program contains three photon energy ranges: below 30 keV, 30 to 250 keV, and above 250 keV (NIOSH 2007). Separation of the dose from each energy band is necessary.

Very little spectroscopy data have been found to indicate gamma spectrum in ANL-E work areas. 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 an estimate of the energy band that is favorable to the claimant. Plutonium facilities have mostly 17-keV photons with some 59-keV photons from ^{241}Am. ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (ORAUT 2005b), suggests that a correction factor of 0.6 should be applied to the nonpenetrating dose that is determined from early film dosimeters and that nonpenetrating 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 linear accelerator (LINAC)], bremsstrahlung photons dominate the secondary radiation field. Thick shields of concrete or other materials result in photons in the MeV energy range. For proton or positive ion accelerators [Zero Gradient Synchrotron (ZGS), Intense Pulsed Neutron Source (IPNS), and Van de Graaff], neutrons generally constitute the greatest

hazard. Thick shields that are designed for the neutron hazard 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, and so forth. One reaction of particular importance is the thermal neutron capture of sodium in the concrete of the accelerator shielding as discussed in National Council on Radiation Protection and Measurements (NCRP) Report 144 (NCRP 2003). This reaction [$^{23}Na(n,\gamma)^{24}Na$] produces a radioactive isotope that decays with a 15-hour 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 used generally 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 can be determined using open window readings for the early film badges and the methods in ORAUT (2005b).

6.6.2 Calibration Factor and Units for Dose Conversion Factors

The early dosimeters were calibrated in roentgens (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
1946–1988	R
1989–present	*Hp(10)*

6.6.3 Missed Dose

Section 2.1.2 of NIOSH (2007) recommends the use of the LOD/2 method for determining missed dose.

6.6.3.1 Limit of Detection

The film badge that was initially developed at the University of Chicago was used at other DOE sites. All of these badges used X-ray film in a metal badge holder, and each had an open window and an area covered with 1 mm of silver, tin, or cadmium (ORAUT 2006). Information from 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. 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 (Novak 1956). The specifications for the multielement 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
1946–1959	50 mrem
1960–1988	25 mrem
1989–present	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 2007, 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 lognormal 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 of this document and Section 2.1.2.3 of NIOSH (2007) discuss this estimate. In this case, the estimate is assumed to have a lognormal 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 ANL-E used was similar to those at other sites. The response of this dosimeter is addressed in ORAUT-TKBS-0003, *Savannah River Site* (ORAUT 2005c), which addresses the significant over-response of film to photons of low energy. 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 multielement 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 Angular Dependence

The film dosimeters 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 of travel 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 (Dolacek 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 NIOSH guidance.

6.6.5 Uncertainty

NIOSH (2007) 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 1946 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 (NRC) reported that both films had 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 (2007) 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 ORAUT-TKBS-0011-6, *Rocky Flats Plant – Occupational External Dose* (ORAUT 2010), 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 was 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 cadmium 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 smaller at higher exposures, the NRC methodology recognizes that additional uncertainty from 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 was 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 1946–1959	DuPont 508 film four-element badge 1960–1988	DOELAP-accredited TLD 1989–present
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 for External Dosimetry* (Dolacek 1996), the current beta-gamma TLD (Panasonic UD-814SA4) responds within 10% of the delivered dose equivalent for most single radiation fields and within 20% for the mixed radiation fields that were DOELAP-tested. 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 (Dolacek 1996).

The standard deviation of the null readings for the DOELAP-accredited Panasonic dosimeter was not documented. Therefore, the analysis used the Simplified Dosimetry Uncertainty calculation recommended by NIOSH (2007, 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 kerma was estimated to be 10%. This assumption is favorable to claimants 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 2007). 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* (Novak 1956). NTA film continued in general use until the late 1980s when albedo TLD dosimeters replaced it (ORAUT 2005a).

By 1972, Kodak Type 2 film was in use for beta-gamma determinations. According to Strom (1982), a procedure that was first written 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 SSTR neutron dosimeter were undertaken at ZPR-VI where there was a concern that the moderated plutonium light element neutrons that were being 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, but 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 this occurred. Table 6-10 summarizes the methods ANL-E used to assess personnel neutron doses. The dates 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–present	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 in Appendix B of NIOSH (2007). These energy groups and the associated radiation weighting factors (w_R) from International Commission on Radiological Protection 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 energy, effective energy, 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 few 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 LINAC, and other low-energy accelerators do not present a neutron hazard outside of their shielding under normal operating conditions (Coulson, Elwin, and Freeman 1989). Neutrons rarely contribute more than 20% to the annual collective dose at accelerator facilities (Coulson, Elwin, and Freeman 1989).

The ZGS was a 12.5-GeV proton accelerator that operated between 1963 and 1979. No useful information about spectra from ANL-E for potentially occupied areas was found. Figure 6-8 in ORAUT-TKBS-0010-6, *Los Alamos National Laboratory – Occupational External Dose* (ORAUT 2013), 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. Given the lack of better information, the SPUNIT program result was chosen to simulate neutron spectra at the ZGS. A spectrum was generated to visually match that in Figure 6-8 of ORAUT (2013). The Ing and Makra (1978) parameterization for the NCRP Report 38 (NCRP 1971) 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 (Table 6-11) was determined from this spectrum.

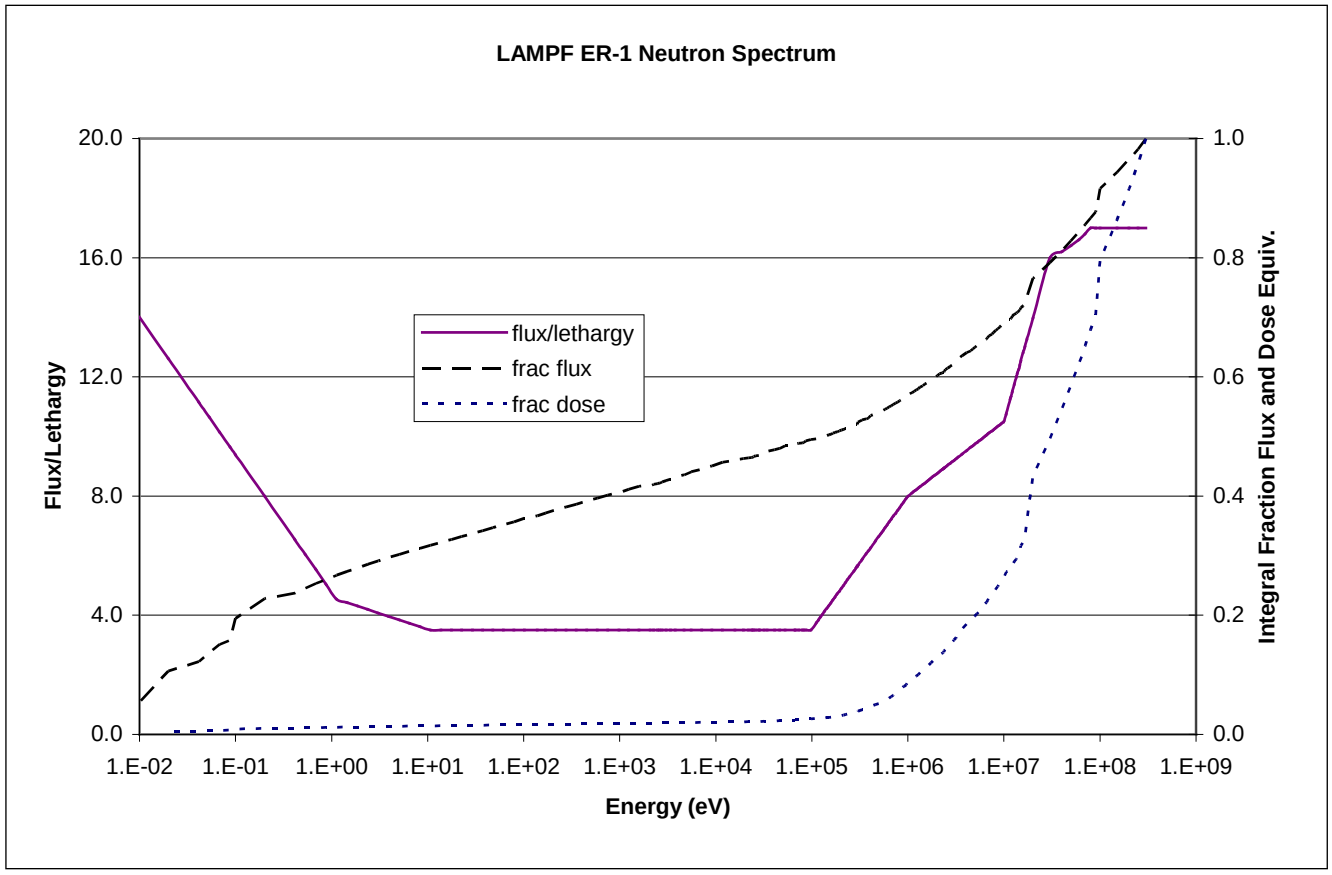

Figure 6-1. Neutron spectrum per unit lethargy and the integral spectrum of flux and dose equivalent for the LAMPF ER-1 spectrum.

The 500-MeV IPNS is capable of generating neutrons in the energy range from 0.025 eV to greater than 20 MeV. In 1982, outside 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 when additional shielding was added above the enriched ^{235}U target (Coulson, Elwin, and Freeman 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.

Table 6-11. Percent of NCRP Report 38 (NCRP 1971) dose equivalent in the IREP energy groups at ANL-E facilities.

	Percent of dose equivalent					
Energy Group	**ZPRs**	**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, Elwin, and Freeman 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, Elwin, and Freeman 1989). No spectral information was found.

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 that were being measured (Dyer and Mundis 1966).

The 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 the shielded areas (DOE 2003; ANL 1994; Moe et al. ca. 1994).

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, other isotopes, and (α,n) reactions in light elements led to significant doses near the reactors even when shut down. 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 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 ZPR 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 Report 38 (NCRP 1971) 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 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 the Idaho National Engineering and Environmental Laboratory (INEEL) (Lennox and Kelber 1956; Folkrod, Moon, and Saluja 1961). Therefore, the recommendations in ORAUT-TKBS-0007-6, *Idaho National Laboratory and Argonne National Laboratory-West – Occupational External Dosimetry* (ORAUT 2011), are adopted for use here. Similarly, the recommendations in the Los Alamos TBD (ORAUT 2013) are adopted for plutonium chemistry and metallurgy. 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- to 2.0-MeV energy interval. Table 6-11 presents these results.

6.7.1.2 Reported Dose to Energy Groups

NIOSH (2007) requires that the neutrons be apportioned into the energy groups in ICRP Publication 60 (ICRP 1991). Because little neutron spectra information was available, the analysis assumed that the reported neutron doses 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 Report 38 dose equivalents to 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 Publication 60 dose multipliers from Table 6-12 were used with the estimated neutron spectra in Table 6-11 to develop multipliers that can be used to determine the neutron equivalent dose for each IREP energy interval. The corrected neutron dose that is reported in the claimant's dose record should be 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 Publication 60 equivalent dose to the IREP neutron energy intervals.

	Multipliers used to assign to IREP neutron energy intervals					
Energy Group	**ZPRs**	**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	0
>0.10–2.0 MeV (w_R=20)	1.3	1.0	0.18	0.38	1.0	1.91
>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 and Units for Dose Conversion Factors

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

The reported doses for the SSTRs and interim albedo dosimeters that were 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 site's TBD for external dosimetry (Dolacek 1996) states, "Calibration of the ANL-E albedo dosimeter has been conducted at various locations both on-site and off-site," and goes on to state the LOD for exposure to moderated ^{252}Cf. These statements appear to indicate the albedo TLDs at ANL-E were 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
1946–1988	Ambient dose, $H^*(10)$
1989–present	Deep dose equivalent, $H_{p,slab}(10)$

6.7.3 Missed Dose

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 read doses 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 reported minimum 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, Armani, and Gold 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 favorable to claimants 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 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–present	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 Steele (1965) stated that chronic low-level exposures in areas where personnel were sometimes located were not recorded by the film.

A 1966 investigation pointed out that the majority of neutrons in areas that were 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 workforce reduction in the dosimetry group led to a proposal to eliminate NTA film with the exception of the ZGS facility, which could indicate that NTA film that had been 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 1973b).

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. Factors for the ZPR and plutonium facilities should only be applied when the record indicates work was performed in those facilities. If the exact work location is unknown, but the record indicates that no work was performed with plutonium (e.g., participation in bioassay monitoring for radionuclides other than plutonium or americium), a factor of 1.5 would be favorable to claimants for other facilities.

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

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.

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 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 was 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 ANL-E used.

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 that were exposed to 300 mrem from a PuBe 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 (AEC 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 by the University of Michigan of the NTA film dosimeter (Neal 1980). This data showed an average standard deviation of 10% for high doses (301 to 5,000 mrem) of ^{252}Cf. However, for lower doses (100 to 300 mrem) the average standard deviation was 64%. The standard deviation of both ranges was 48%. Because this performance might not have been typical for earlier periods, a standard deviation of 50% was selected for this analysis. Again the simplified uncertainty analysis of NIOSH (2007) was used. The results are shown in Table 6-17.

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

6.7.5.2 Thermoluminescent Dosimeter

The LOD of the 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 are found, the values for the Hosger albedo TLD should be used.

The current albedo system did not undergo DOELAP testing in 1988 or 1991. The lower LOD for this badge is 10 mrem in normal personnel dosimetry practice (Dolacek 1996). Because this dosimeter involves the reading of 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

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

1. Calculate the missed dose (Section 6.7.3.1), if applicable;

2. Apply the correction factor for unmonitored energy range (Section 6.7.3.2); and

3. Apply the correction for the neutron quality factor for each IREP energy range (Table 6-13, Section 6.7.1.2).

Example
An ANL-E worker in Building 200 (plutonium chemistry facility) is monitored by NTA film for 6 months in 1960 and receives doses of 0, 0, 100, 300, 0, and 0 mrem.

1. The missed dose is LOD/2 (25 mrem) × 4 = 100 mrem. The total for the period is 100 (missed dose) + 100 + 300 = 500 mrem.

2. Because the neutron film did not respond to energies below about 800 keV, the correction for the unmonitored energy range is 500 × 4 (Table 6-16) = 2,000 mrem.

3. The doses for each IREP energy group from Table 6-13 for a plutonium chemistry and metallurgy facility are:

   - <0.01 MeV, 2,000 × 0 = 0 mrem,
   - 0.01 to 0.10 MeV, 2,000 × 0.2 = 400 mrem,
   - >0.10 to 2 MeV, 2,000 × 1 = 2000 mrem,
   - >2 to 20 MeV, 2,000 × 0.52 = 1040 mrem, and
   - >20 MeV, 2,000 × 0 = 0 mrem.

6.8 ELECTRON DOSE

The earliest published maximum permissible exposure limits at ANL-E recognized the potential hazards of beta exposures of the skin (Nickson 1946). The pioneering work there in 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 betas (more than 1 MeV), cannot be ruled out. The dose reconstructor should be aware that early results from ring and wrist dosimeters might have been reported on separate forms and might 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 were nearly always equal to or greater than the shielded window doses, indicating that the open window reading included both penetrating and nonpenetrating 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. Therefore, penetrating and nonpenetrating (beta only) radiations are reported separately after approximately 1960. No detail on the reporting of early film or TLD ring dosimeters was found. The current TLD system reports the shallow or skin dose as the sum of the penetrating and nonpenetrating doses. ORAUT (2005b) suggests that a correction factor of 0.6 should be applied to the nonpenetrating dose from early film dosimeters and that nonpenetrating 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 nonpenetrating doses that are considered electrons should be assigned to the >15 keV IREP energy group.

6.8.2 Calibration Factor and Units for Dose Conversion Factors

During the use of the two-element film badge, the term “arbitrary units” (a.u.) (or sometimes “other”) was used to report the open window dose through 1960. 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 that was caused by exposure to unknown beta-gamma or X-ray radiation, or both, to the equivalent density of a film in the badge window position that would be caused by exposure to a known ^{60}Co or ^{226}Ra source in milliroentgen (Strom 1982). The arbitrary units were later correlated with an exposure to uranium by applying a factor of 1.6 based on information from Landauer (ca. 1951). Although the open window in these dosimeters over-responded to low-energy photons, the records might underreport the doses from electrons (see Section 6.8.3.1). Therefore, open window readings that were reported as arbitrary units through 1960 should be multiplied by 1.6 to obtain beta doses in millirem, or by the factor applicable to a specific exposure situation as indicated in an individual dose record (typically hand written). Beta doses reported in units of millirem or millirep do not need to be adjusted.

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 w_R for electrons at all energies is 1 (ICRP 1991). Therefore, reported beta doses are equivalent to millirem.

The current ANL-E beta-gamma dosimeter, which is 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 (Dolacek 1996).

6.8.3 Missed Dose and Limit of Detection

In 1956, the two-element film badge was capable of measuring doses from 50 mR to 500 R (Novak 1956). No separate LOD was given for beta radiation, so it was assumed to be the same. The specifications for the multielement 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 (Dolacek 1996). Table 6-18 lists the beta LODs for the ANL-E dosimeters. Specialized extremity dosimetry 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 (Dolacek 1996).

Table 6-18. Beta dosimeter LODs.

Years	LOD
1946–1959	50 mrem
1960–1988	25 mrem
1989–present	30 mrem whole body 10 mrem TLD ring

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 2011). Because the dosimeters at the two sites were similar and few details are available for ANL-E, the INEEL analysis was used in part here. Table 6-19 provides the fraction of recorded beta dose for the various dosimeters. To determine the corrected beta dose, the dose reconstructor should divide the nonpenetrating results by

the values in the last column of Table 6-19. This result will probably be an overestimate because 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 under-reporting.

Dosimeter system	Period	Cover (mg/cm^2)	Detector thickness (mg/cm^2)	Estimated fraction of dose reported
Two-filter film Early film ring	1946–1959	50	50	0.49
Multifilter film	1960–1988	100	50	0.35
Old TLD ring	1970–1977	104	240	0.21
Current TLD ring	1978–present	18	89	0.56
Panasonic TLD	1989–present	16	15	0.78

6.8.4 Angular Dependence and Exposure Geometry

The sensitive dosimeter elements were 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 (Dolacek 1996). Because the angle of exposure is more or less random with this arrangement, no correction is possible.

Due to exposure geometry, recorded beta doses might 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 (2007) 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 1946 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 the 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.

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

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 site's TBD (Dolacek 1996), the current beta-gamma TLD (Panasonic UD-814SA4) responds within 20% of the mixed radiation fields that were 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 (Dolacek 1996).

The standard deviation of the null readings of the DOELAP-accredited Panasonic dosimeter was not documented. The analysis therefore used the simplified dosimetry uncertainty calculation from NIOSH (2007, Section 2.1.1.3.3), where the critical level L_c is the estimated LOD, as described in Section 6.6.3.1. The percent standard error at high air kerma was estimated to be 10%. This assumption is favorable to claimants 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 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 DOE sites where skin contaminations were documented in the records. The *Environment, Safety and Health Manual* currently requires recording of the nonuniform shallow dose equivalent to the skin from contamination on the skin if the dose is equal to or greater than 2% of the specified limit for the skin in 10 CFR 835.702(b) (ANL 2005b).

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 in addition to portable monitors (Novak 1956).

Natural and depleted uranium were used and processed at ANL-E, and their progeny was potentially contained in the material and would result in beta exposures to the skin. Other high-energy beta emitters such as $^{90}Sr/^{90}Y$ were present at 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, in which case dose reconstructors should estimate it in accordance with Section 2.3.3 of NIOSH (2007). The contamination report will probably not indicate the length of time that the contamination was present on the skin. A reasonable assumption that is favorable to claimants is that the contamination was present for 4 hours 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 (Novak 1956; ANL 1973–1984).

Dose reconstructors could use software such as VARSKIN (recommended in NIOSH 2007) or other appropriate means for this calculation.

6.9 EXPOSURES OUTSIDE RADIOLOGICALLY CONTROLLED AREAS

For individuals who worked outside the radiologically controlled areas, ambient on-site external exposure is an appropriate estimate of exposure, and dose should be assessed in accordance with ORAUT-TKBS-0036-4 (ORAUT 2006) rather than this document. Available information should be evaluated (such as job titles, work locations, presence or absence of dose records, etc.) to determine an individual's likelihood of having worked in a radiologically controlled area. For workers who would not have been required to enter radiologically controlled areas based on such information (for example, clerks, typists, janitors, cafeteria workers, etc.), ambient external dose should be applied. If records are inadequate to determine whether an individual's occupation would have involved work in a radiologically controlled area, or if monitoring records exist for an individual, they should be assumed to have been radiological workers, and dose should be assigned in accordance with the guidance of this document.

6.10 EXTREMITY DOSIMETRY

Monitoring exposure to the skin was important very early in ANL-E's history and, while maximum permissible levels were established (Nickson 1946) it is not clear what monitoring methods were in use during what periods. In the early years of the site, body badges were apparently fitted with alternative 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-week 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 (Novak 1956). 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 with neutron film were available and were required at CP-5 (Novak 1956).

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 by 0.125 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 (Dolacek 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 (Dolacek 1996). Dolacek (1996) is not clear about 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.

6.11 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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GLOSSARY

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

arbitrary unit (a.u.)
Unit for comparing the density of a film in the badge window position from exposure to unknown beta-gamma radiation or x-rays, or both, to the equivalent density of a film in the badge window position from exposure to a known ^{60}Co or ^{226}Ra source in milliroentgen units.

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

beta particle (β)
See *beta radiation*.

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

deep absorbed dose (D_d)
Absorbed dose in units of rem or sievert at a depth of 1 centimeter (1,000 milligrams per square centimeter).

deep dose equivalent [*Hd*, *Hp(10)*]
Dose equivalent in units of rem or sievert for a 1-centimeter depth in tissue (1,000 milligrams per square centimeter). See *dose*.

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

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

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

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

dosimetry
Measurement and calculation of internal and external radiation doses.

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

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

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

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

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

film
(1) In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*. (2) X-ray film.

film density
See *optical density*.

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

fission
Splitting of the nucleus of an atom (usually of a heavy element) into at least two other nuclei and the release of a relatively large amount of energy. This transformation usually releases two or three neutrons.

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

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

ionizing radiation

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

isotope

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

minimum reporting level

Level below which an analytical dose is not recorded in the worker's dose record, usually based on a site-specific policy decision. The recording level is not necessarily the same as the minimum detectable amount or activity for that measurement. Also called less-than value, minimum reportable dose, minimum recordable or recording dose, recording level, and reporting level.

neutron (n)

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

neutron film dosimeter

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

nuclear track emulsion, type A (NTA)

Film sensitive to fast neutrons made by the Eastman Kodak Company. The developed image has tracks caused by neutrons that become visible under oil immersion with about 1,000-power magnification. The number of tracks in a given area is a measure of the dose from that radiation.

nuclide

Stable or unstable isotope of any element. Nuclide relates to the atomic mass, which is the sum of the number of protons and neutrons in the nucleus of an atom. A radionuclide is an unstable nuclide.

open window

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

optical density

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

pencil dosimeter

See *pocket ionization chamber*.

personal dose equivalent [*Hp(d)*]

Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square

centimeter), respectively, for the skin (shallow) and whole-body (deep) doses. These are noted as *Hp(0.07)* and *Hp(10)*, respectively. The International Commission on Radiological Measurement and Units recommended *Hp(d)* in 1993 as dose quantity for radiological protection.

personal dose equivalent, slab phantom [*Hp,slab(d)*]

Personal dose equivalent in relation to a slab phantom. See *phantom* and *slab phantom*.

phantom

Any structure that contains one or more tissue substitutes (any material that simulates a body of tissue in its interaction with ionizing radiation) and is used to simulate radiation interactions in the human body. Phantoms are primarily used in the calibration of in vivo counters and dosimeters. See *slab phantom*.

photon

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

photon X-ray

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

pocket ionization chamber (PIC)

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

quality factor, Q

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

radiation

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

radioactive

Of, caused by, or exhibiting radioactivity.

radioactivity

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

radionuclide

Radioactive nuclide. See *radioactive* and *nuclide*.

rem

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

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

rover dosimeter or rover
Pencil dosimeter that was not permanently assigned. Typically worn by visitors or personnel who were not normally assigned to an area.

shallow dose equivalent [*Hs, Hp(0.07)*]
Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

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

slab phantom
Phantom in the form of a slab of plastic typically about 30 or 40 centimeters square by 15 centimeters deep. See *phantom*.

skin dose
See *shallow dose equivalent*.

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

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

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

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

X-ray
See *X-ray radiation*.

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

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

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ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

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	3355	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	895	895	6
1965	1005	1005	M
1966	1085	2085	M
1967	450	450	M
1968	85	85	M
1969	205	205	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 (continued)

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 (continued)

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: __
Thursday, August 08, 2002

_____, Group Leader, Health Physics Instrumentation And Dosimetry

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 (continued)

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	Pocket Meter Disc	Pocket Meter Times Worn	Film Meter Shield	Film Meter 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				.014		2	LIGHT	STRUCK
DEC 9 1946	04	0	04	04				.12		4		
DEC 16 1946	0	01		03				.04		3		
Total NOV. 1946 thru DEC 22 1946								.384		17	0	0

Name _____ No. _____

Figure A-3. Individual Meter Record.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

CUMULATIVE EXPOSURE RECORD

1958

DATE	AREA	DOSIMETER mr	FILM mr	FILM n.u.	DATE	AREA	DOSIMETER mr	FILM mr	FILM n.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		~~60~~ 180	130	120	TOTAL		195	120	95
4-7	"	0	0	0	10-6	"	0	* 0	* 0
4-14	"	0	N) 220 (2nd run)	240	10-13	"	0	N) 150* 0	135* 0
4-21	"	0	0	0	10-20	"	0	0	* 0
4-28	"	0	N 0 (2nd run)	0	10-27	"	15	0	* 0
5-5	"	0	N 0 (2nd run)	0	11-3	"	10	0	0
5-12	"	0	0	0	11-10	"	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 (2nd run)	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

*Special Assignment in Bldg. 40.

NAME _____ 1958 YEAR _____ IHS # _____

(HS-38A (10-59))

Figure A-4. Cumulative Exposure Record.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

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 (continued)

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.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

WHOLE BODY EXTERNAL RADIATION EXPOSURE SUMMARY

for _____ _____ PR # _____

EXPOSURE in mrem

Year	Rover Dosimeter	Film Badge			Penetrating Total
		Beta	Gamma	Neutron	
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.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

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	SEC	OHS CNT	ROV DOS	ROV 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	~~825~~	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 (continued)

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 (continued)

NEUTRON EXPOSURE REPORT

PROCESSED
WEEK STARTING _____

FILM ID. NO.	BHS NO.	NAME	AREA WORN	POSITION WORN	DATE WORN	TIME WORN	READINGS			COMMENTS
							NO. ↑ ABOVE CONTROL	n/cm² (x 10⁶)	mrem	
			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.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

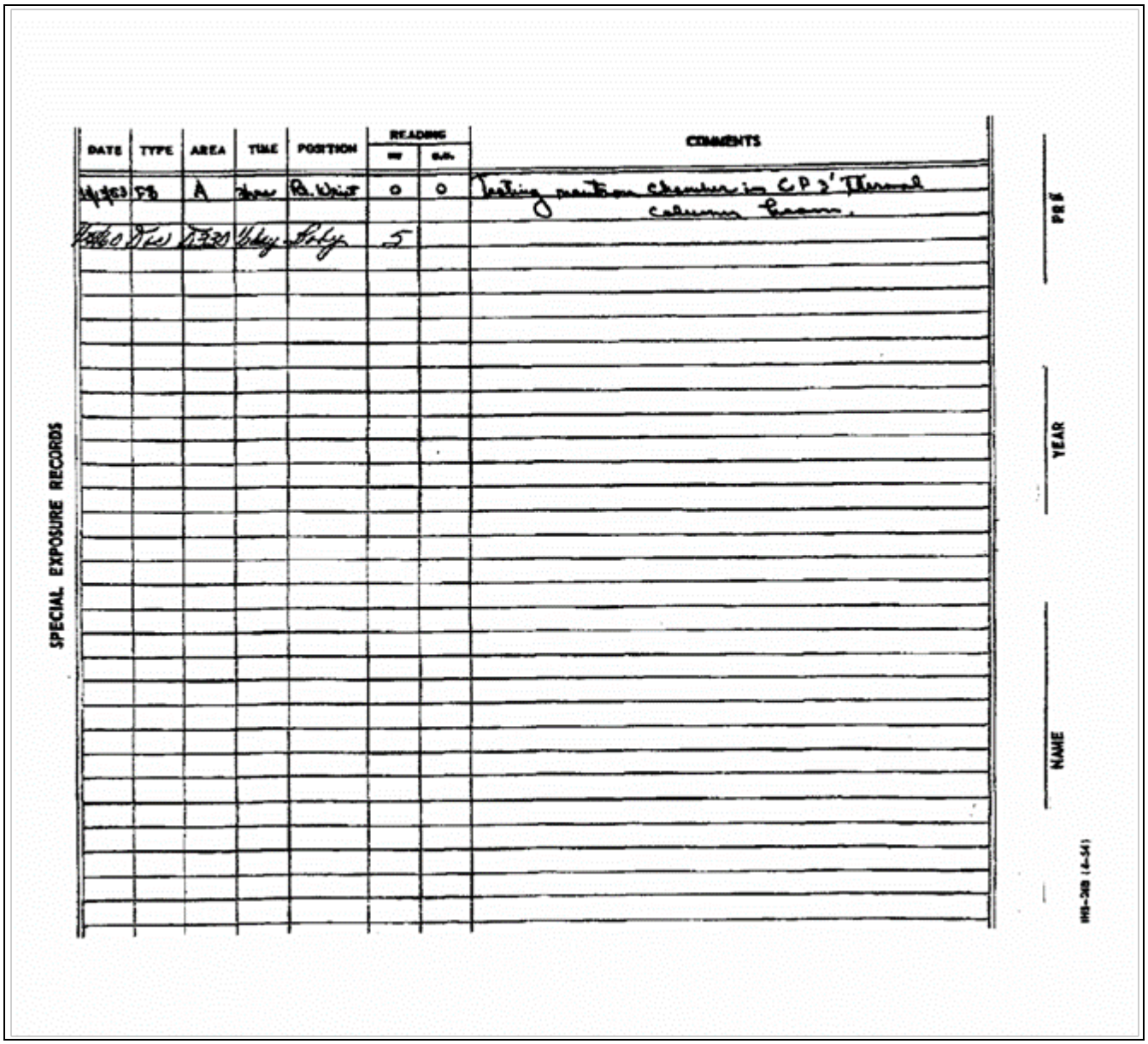
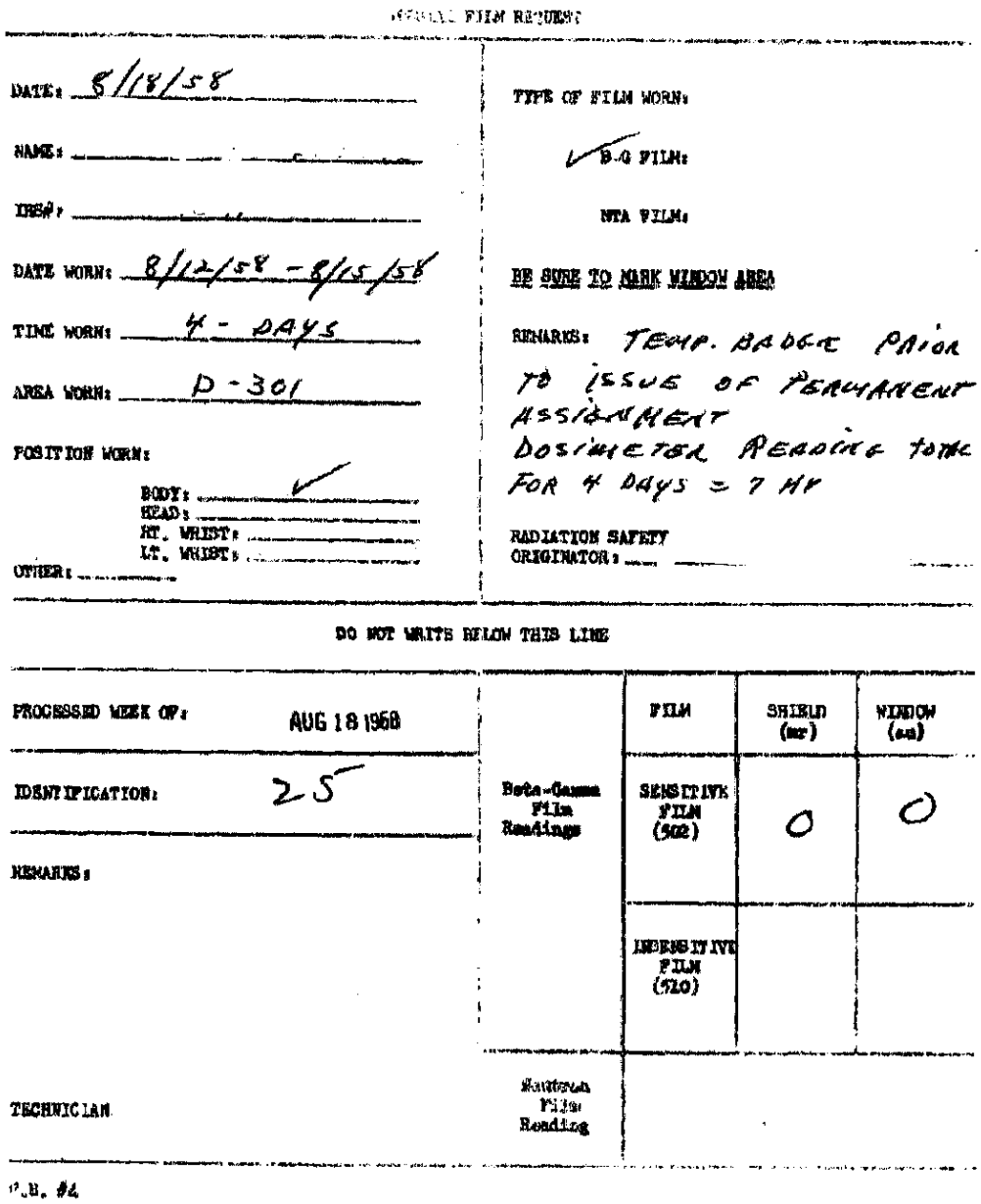


Figure A-11. Special Exposure Records.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)



SPECIAL FILM REQUEST

DATE: 8/18/58

NAME: _____

IDENT: _____

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.H. #4

Figure A-12. Special Film Request.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

SPECIAL METER ASSIGNMENT AND RADIATION EXPOSURE REPORT

ASSIGNMENT DATA

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

TYPE OF COVERAGE	TYPE OF DOSIMETER (IF ANY)	BLDG. LOC. OF ASSIGNMENT
☐ 1-CHAMBER DOSIMETER ☒ 2-BETA-GAMMA FILM ☐ 3-NEUTRON FILM	200 mR	D-306

RADIATION EXPOSURE DATA

ACTUAL PERIOD METER WORN	TYPE OF RADIATION EXPOSURE
1.5 ☐ WEEK(S) ☐ DAY(S) ☒ HOUR(S)	☒ 1-BETA ☐ 3-X-RAY, ENERGY: ☒ 2-GAMMA ☐ 4-NEUTRON, ENERGY:

POSITION OF MONITORING METER DURING EXPOSURE

☐ 1-TOTAL BODY ☐ 2-HEAD ☐ 3-L. WRIST ☐ 4-R. WRIST ☒ 5-OTHER: Right Palm

TYPE OF WORK PERFORMED DURING EXPOSURE

Cleaning Thimble #3

BLDG. LOC. DURING EXPOSURE	WAS PERMANENT FILM BADGE WORN ALSO DURING EXPOSURE?	CHAMBER DOSIMETER READING	IS SPECIAL FILM BEING SENT FOR PROCESSING?
D-306	☒ YES ☐ NO	170 MR	☒ 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(.018)	Ag(.005)	D.W.	Ag or Cd (.0085)	Number of Tracks
10-1-65	.61	.58	.80	.48	
EFFECTIVE FILM DATE	FILM IDENT. NO.	EXPOSURES			
9-27-65	MJ-25	Beta 0 mrad	Gamma 480 mr	X-ray 80 mr	Neutron mrem

REMARKS:

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

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

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 Dy	γ	Neutro
		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 (continued)

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

ORS 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 (continued)

DOE Form EV-192
(3-79)
IMD 5001

U. S. DEPARTMENT OF ENERGY

TERMINATION OCCUPATIONAL EXPOSURE REPORT

REPORTING ORGANIZATION: Argonne Natl. Lab.
ADDRESS: 9700 S. Cass Ave. Argonne, Ill. 60439
PREPARED BY:
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
BIRTH (M M D D Y Y)
5. TERM. (M M D D Y Y)
CARD: 1

8. BEGIN (M M D D Y Y)
9. END (M M D D Y Y)
10. AREA EXP.
11. EXTERNAL EXPOSURE: 6576
12. TYPREC: I
13. TYPEXP: E
CARD: 2

14. BEGIN (M M D D Y Y)
15. END (M M D D Y Y)
16. ORGAN. CODE
17. INTERNAL EXPOSURE
18. METH. DOSE: M
19. ORGAN. CODE: B
20. UNIT
21. NUCLIDE(S) (L.J.)
22. TYPREC: I
23. TYPEXP: I
CARD: 3

17. INTERNAL EXPOSURE	18. METH. DOSE	19. ORGAN. CODE	20. UNIT	21. NUCLIDE(S) (L.J.)
	M	B	C	PU
	M	B	C	BETA EMITTERS
	M	B	C	GAMMA EMITTERS
	M	B	C	I 131

Figure A-16. Termination Occupational Exposure Report.

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE

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

Building	Section codes		Facility name	Years of operation (approximate)	Additional information	Facility type
	1980	Present				
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 (MWing 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

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE (continued)

Building	Section codes		Facility name	Years of operation (approximate)	Additional information	Facility type
	1980	Present				
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 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
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			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

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE (continued)

Building	Section codes		Facility name	Years of operation (approximate)	Additional information	Facility type
	1980	Present				
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 present 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	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 decommissioning of reactor completed 2000.	Reactor
331	QW	QW	EBWR	1956–1967	Reactor removed from shell in 1995 during decontamination and decommissioning. 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
340	MP		Experimental Animal Quarters	1950–	Housed animals irradiated in Building 202. Bone cancer research 1963 to 1980.	Radioactive Materials
350	SH	SR, VN	Fuel Fabrication Facility (now New Brunswick Laboratory, 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

ATTACHMENT B
FACILITIES BY BUILDING NUMBER AND SECTION CODE (continued)

Building	Section codes		Facility name	Years of operation (approximate)	Additional information	Facility type
	1980	Present				
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 pulses per second, 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. See the Acronyms and Abbreviations for facility names.
b. Blank = none.