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FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/20/2004	00	New Technical Basis Document for the Rocky Flats Site – Occupational External Dose. First approved issue. Initiated by Robert Meyer.
02/08/2007	01	Approved Revision to incorporate NIOSH-requested material, responses to questions by dose reconstructors, responses to Advisory Board on Radiation and Worker Health review, and attribution of certain statements in document. Constitutes a total rewrite of document. Added Section 6.11, Attributions and Annotations. Worker Outreach comments pertaining to CT-0205 and CT-0209 have been addressed. Incorporates internal and NIOSH formal review comments. The Worker Outreach comments from the June 23, 2004, meeting of the United Steelworkers of America Local 8031 and Rocky Flats Security Officers Local Union 1 are addressed as follows: Lead aprons and port covers, Section 6.5.5; Neutron Dose Reconstruction Project, Sections 6.3.5.2, 6.4.2, and 6.7.3.4; and exposure geometry and gloveboxes, Sections 6.5, 6.6.4, 6.7.4, and 6.8.4. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Robert Meyer.
08/14/2007	02	Approved Revision 02 initiated to capture Advisory Board comments associated with the June 2007 Advisory Board meeting. The following OTIBs have been incorporated into this document during this revision: ORAUT-OTIB-0027, ORAUT-OTIB-0050, and ORAUT-OTIB-0058. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Task Manager. Initiated by Mutty M. Sharfi.
10/20/2010	02 PC-1	Page change initiated to update references and NIOSH required language on pages 10 and 11 in Section 6.1. Corrected text inconsistencies to indicate that non-affected original neutron dose, in addition to NDRP neutron dose, should be used in the reconstruction. Original neutron dose, in addition to notional neutron dose, should not be used in dose reconstruction. These changes occurred in pages 48 and 49 in Section 6.7.3.3. Updated references throughout and on page 65 in the Reference Section. No sections were deleted. No changes occurred as a result of formal internal review. Incorporates formal NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.
01/14/2019	03	Revision initiated to capture Advisory Board comments and items associated with SEC-00192. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AP	anterior-posterior
AWE	Atomic Weapons Employer
Bq	becquerel
Br	brass (filter)
Cd	cadmium (filter)
Ci	curie
CY	calendar year
d	day
D&D	decontamination and decommissioning
DDE	deep dose equivalent
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
dpm	disintegrations per minute
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EU	enriched uranium
ft	foot
g	gram
GM	geometric mean
GSD	geometric standard deviation
H(d)*	ambient dose equivalent at depth *d* in millimeters in tissue
HEU	highly enriched uranium
HIS-20	Health Physics Information System (database)
Hp(d)	personal dose equivalent at depth *d* in millimeters in tissue
Hp,slab(d)	personal dose equivalent (slab phantom) at depth *d* in millimeters in tissue
hr	hour
HSDB	Health Sciences Database
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
ISO	isotropic
keV	kiloelectron-volt, 1,000 electron-volts
LANL	Los Alamos National Laboratory
lb	pound
LOD	limit of detection
MeV	megaelectron-volt, 1 million electron-volts
mm	millimeter
mo	month
mR	milliroentgen

mrad	millirad
mrem	millirem
nCi	nanocurie
NCRP	National Council on Radiation Protection and Measurements
NDRP	Neutron Dose Reconstruction Project
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH-Division of Compensation Analysis and Support Claims Tracking System
NTA	nuclear track emulsion, type A
ORNL	Oak Ridge National Laboratory
ORAU	Oak Ridge Associated Universities
OTIB	ORAU Team technical information bulletin
OW	open window
PER	program evaluation report
PNAD	personal nuclear accident dosimeter
PNL	Pacific Northwest Laboratory
POC	probability of causation
qtr	quarter
R	roentgen
RFP	Rocky Flats Plant
RHRS	Radiological Health Records System
ROT	rotational
SEC	Special Exposure Cohort
SOE	Stationary Operating Engineer
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
w_R	radiation weighting factor
yr	year
μCi	microcurie
§	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 Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in sections 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means "a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling." 42 U.S.C. § 7384l(5). On the other hand, a DOE facility is defined 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 [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program);" and with regard to which DOE has or had a proprietary interest, or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee's eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility's designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees (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

6.1.1 Purpose

This technical basis document (TBD) is one part of the overall Rocky Flats Plant (RFP) site profile. The site profile describes plant facilities and processes, historical information related to occupational internal and external doses, and environmental data for use if individual worker recorded doses are unavailable. This document contains Part 6, Occupational External Dosimetry, of the RFP site profile. It provides necessary background information and critical data for the dose reconstructor to perform individual dose reconstructions. Dose reconstructors will use this information as needed to evaluate external occupational doses for EEOICPA claims.

6.1.2 Scope

RFP operations played an important role in the U.S. nuclear weapons program. These operations included production of fissionable weapons components and waste management. This TBD contains supporting documentation to assist in the evaluation of occupational external doses from these processes using the methodology in 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 RFP operations. An objective of this document is to provide supporting technical data to evaluate, with assumptions favorable to claimants, the external RFP occupational doses that can reasonably be associated with worker radiation exposures covered under EEOICPA legislation. These doses include occupational external exposures in RFP facilities and onsite exposures to RFP environmental releases. This document addresses the evaluation of unmonitored and monitored worker exposure and missed dose. Consistent with NIOSH (2007), this document identifies how to adjust the historical occupational external recorded dose to account for current scientific methods and protection factors.

Only a limited assessment of neutron doses can be performed before 1970. Unmonitored and notional neutron doses from 1952 through 1966 cannot be reconstructed under the EEOICPA. Between 1967 and 1970, unmonitored and notional neutron doses should be replaced with external coworker doses. Reported Neutron Dose Reconstruction Project (NDRP) and unaffected original neutron dose can be used for all years.

This site profile can be a tool when performing dose reconstructions for RFP workers. The Integrated Modules for Bioassay Analysis (IMBA) computer code is a tool useful for internal dose calculations. Information on measurement uncertainties is an integral component of the NIOSH approach. This document describes how to evaluate uncertainty associated with RFP exposure and dosimetry records.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 6.11.

6.1.3 Special Exposure Cohort

The Secretary of the U.S. Department of Health and Human Services has designated the following class of RFP workers as an addition to the SEC (Sebelius 2013):

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Rocky Flats Plant in Golden, Colorado, from April 1, 1952 through December 31, 1983, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in*

combination with work days within the parameters established for one or more other classes of employees included in the Special Exposure Cohort.

NIOSH has determined that doses to unmonitored RFP workers from neptunium, thorium, and ^{233}U (and its associated ^{232}U and ^{228}Th progeny) cannot be reconstructed from April 1, 1952, through December 31, 1983, inclusive (NIOSH 2013). The class includes all workers during the SEC period.

Based on the inability to reconstruct unmonitored doses from 1952 through 1983, as described above, all dose reconstructions for monitored workers during the SEC period are considered partial dose reconstructions. If monitoring data are available for workers in the SEC, dose is to be assigned as appropriate based on that data. Unmonitored neutron doses before 1967 have been identified as infeasible and therefore cannot be bounded. It is not feasible to reconstruct unmonitored neutron doses, in a bounding manner, before 1967; therefore, this TBD does not provide dose reconstruction guidance for unmonitored neutron doses before 1967. For all other years, external dose records and/or an unmonitored external dose reconstruction approach are provided. However, such dose reconstructions are still considered partial dose reconstructions because of the determination that exposure to neptunium, thorium, and ^{233}U (and its associated ^{232}U and ^{228}Th progeny) during the SEC period cannot be bounded.

6.2 EXTERNAL DOSIMETRY OVERVIEW

Over the years, RFP used a variety of dosimeters to measure occupational ionizing radiation dose (Figure 6-1). Between 1951 and 1959, the Plant used a stainless-steel film badge based on an Oak Ridge National Laboratory (ORNL) design (Baker 2002). This was a two-element film badge with an open window (OW) and a 1-mm cadmium (Cd) filter. For the plutonium areas, in 1960, a brass (Br) filter with half the filtration of the cadmium filter was added to cover half of the OW. This provided separation of the 60-keV photons from the lower energy component. Very little information has been found on the performance of this dosimeter (Figure 6-2).

In 1964, a plastic film badge was introduced at RFP that included additional filters. In addition to the photon dosimetry system, this badge contained a personal nuclear accident dosimeter (PNAD; Figure 6-3). This portion of the badge was not used for routine personnel dosimetry (Baker 2002).

In 1969, a combination film and thermoluminescent dosimeter (TLD) badge was introduced at RFP, using TLD chips to measure photon dose. There were three TLDs in the lower part of the badge, covered with the same brass filter (two chips) and a thin cover (one chip) providing an OW. Film was used for neutron dose measurement. This badge contained a PNAD and was an interim badge (Figure 6-4) until the introduction of the TLD neutron system (Baker 2002).

In 1971, a full TLD badge was introduced at RFP that used TLD chips manufactured by the Harshaw Chemical Company (Figure 6-5). Referred to as the "Harshaw badge," it contained a four-chip albedo neutron dosimeter (Falk 1971). Although the dosimeter did have a location for including a neutron film, this feature was not used. Photon measurement used three filter-covered TLDs, similar to those in the previous badge. This badge contained a PNAD.

In 1983, an automated Panasonic dosimetry system was introduced at RFP. This badge contained two Panasonic dosimeters, one for measuring photon and beta dose and one for measuring neutron dose. The beta/photon dosimeter contained two TLD phosphors and a lead filter over one of the elements. The neutron dosimeter contained three neutron-sensitive elements and one neutron-insensitive element under cadmium or tin filters. This badge included a PNAD (Baker 2002).

		Beta/gamma				Neutron		Extremity	
			Filtration						
Year	**Holder**	**Detector**	**Deep**	**Shallow**	**Processor**	**Detector**	**Processor**	**Holder**	**Detector**
1951	SS ORNL	Std. X-ray	1-mm Cadmium	None	LANL	Track plate	LANL	SS ORNL	Std. X-ray
1952									
1953									
1954									
1955									
1956					HPS		HPS		
1957						NTA film			
1958					Rocky Flats		Rocky Flats		
1959									
1960			1/2 Brass					1/2 Brass	
1961									
1962									
1963									
1964	Plastic		Multiple	Multiple					
1965									
1966									
1967									
1968									
1969	Interim plastic	TLD-700							
1970									
1971	Harshaw					TLD-600/700		Harshaw	TLD-600/700
1972									
1973									
1974									
1975									
1976									
1977									
1978									
1979									
1980									
1981									
1982									
1983	Panasonic	UD-802				UD-809			
1984									
1985									
1986									
1987									
1988									
1989									
1990									
1991				DOELAP				Panasonic	UD-813AS11
1992									
1993									
1994									
1995									
1996									
1997									
1998									
1999								DOELAP	
2000									
2001									
2002									
2003									
2004									
2005	InLight	OSL			Landauer	CR-39	Landauer	Luxel	OSL

HPS = Health Physics Services; LANL = Los Alamos National Laboratory; NTA = nuclear track emulsion, type A; OSL = optically stimulated luminescence dosimeter; SS = stainless steel. Dates are approximate, overlap occurred during changeovers (Baker 2002). 1960: Brass not used on beta OW; no brass on wrist side of extremity holder (Baker 2002).

Figure 6-1. External dosimeter history.

Figure 6-2. ORNL-style film badge (including brass filter).

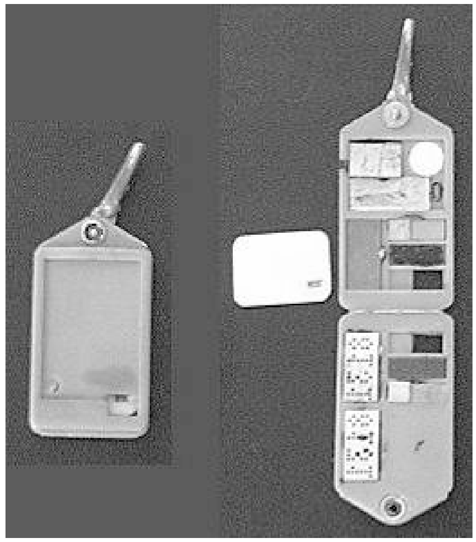

Figure 6-3. RFP multielement film badge.

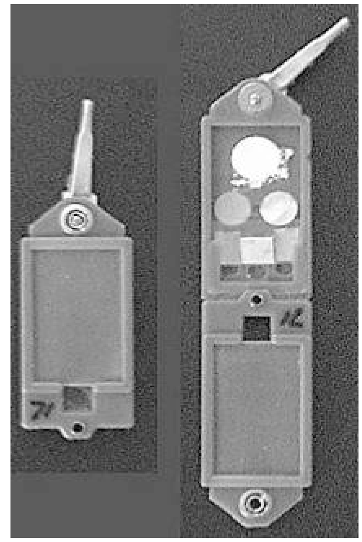

Figure 6-4. RFP interim TLD/film badge.

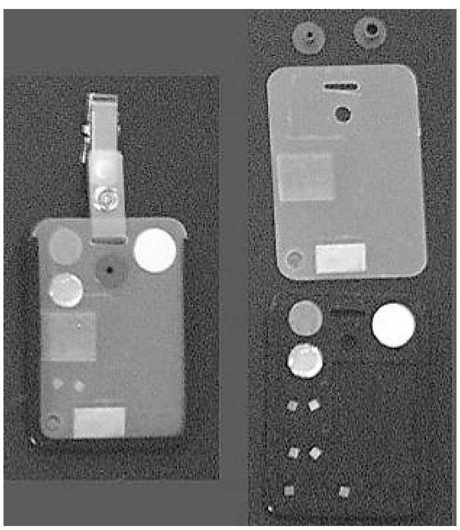

Figure 6-5. RFP Harshaw badge.

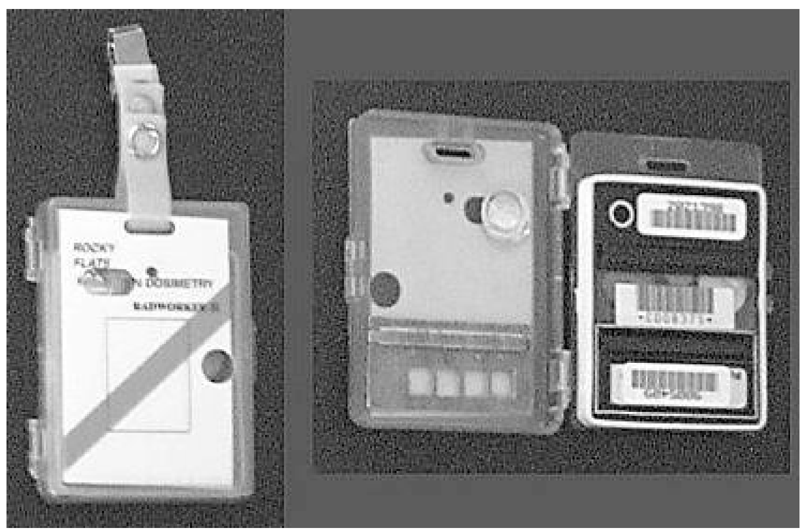

Figure 6-6. RFP Panasonic dosimeter.

6.3 INTERPRETING THE EXTERNAL DOSIMETRY RECORD

External dosimetry results are reported as:

- Penetrating (Pen) or deep (deep dose + neutron),
- Skin (shallow dose + neutron),
- Forearm (measured or estimated), and
- Hand (estimated).

The penetrating or deep dose is reported as the sum of the deep gamma and the neutron dose. The skin dose is reported as the deep dose unless the low-energy detector on the dosimetry badge indicated a response greater than the deep dose, in which case shallow gamma plus neutron were reported (Falk 1976). RFP did not use finger rings; however, wrist badges were used to assess the dose to the forearm. Hand dose was assessed using the dose measured by the wrist badge, and the application of a hand-to-wrist ratio (see Section 6.10).

6.3.1 Dosimetry Records Systems

In the 1950s, external dosimetry data were handwritten and reported manually. In the 1960s and early 1970s, information was maintained on early computer systems. The detailed data have not been carried forward. For the early years, the dose detail has been lost, and only quarterly totals are available. As noted, RFP typically summed the deep gamma dose and the neutron dose into a *penetrating* value. In the early years, the neutron and deep gamma numbers were not retained and only the penetrating value remains.

Electronic systems for which detailed data have been maintained include:

- HSDB (Health Sciences Database), 1976 to 1990;
- RHRS (Radiological Health Records System), 1990 to 1999; and
- HIS-20 (Health Physics Information System, Canberra Industries), 1999 to 2006.

In general, data migrated from one system to another. Little is known, or at least documented, about the precise method and decisions made during the migration of the HSDB data to the RHRS. However, the result of examining the contents of the data tables and hard-copy reports can be described.

6.3.2 Observed Data Discrepancies

The observations in Sections 6.3.2 and 6.3.3 are the result of an examination of available RFP dosimetry records (Savitz undated).

6.3.2.1 Rounding

The electronic data in RHRS and many of the reports contain both gamma and neutron components as well as a deep dose equivalent (DDE). A manageable problem is exhibited by the rounding of individual deep dose values as well as the yearly or quarterly totals. It appears that rounding to the nearest millirem value occurred on the external deep dose after the values were added to calculate the DDE. In many cases, this results in a discrepancy of 1 mrem per measurement on the report cards. Depending on the exchange frequency for a particular worker, there could be a difference of several millirem.

6.3.2.2 Deep Dose Not Equal to Gamma Plus Neutron Doses

In this case, the problem is clearly not due to rounding but rather to a discrepancy between the deep dose components and the deep dose value that is stored separately. The magnitude of the discrepancy is greater than 1 mrem. Two specific situations have been identified, as described in the following sections.

6.3.2.2.1 Possible Algorithm Issue

A group of results for one period (roughly July to October 1984) appears to indicate a reporting problem with the dosimetry algorithm used to calculate dose equivalents. In general, these results contain a gamma component that was calculated to be zero and a neutron dose that was calculated to be between about 15 and 50 mrem. However, the deep dose on both the report cards and in the electronic record was zero.

A review of a paper copy of the dose algorithm from that time (Author unknown undated) and discussion with the algorithm developer indicated that the algorithm was developed in such a way that it should not have been possible to have a zero gamma dose with a nonzero neutron dose. In such a case, the algorithm would set the neutron dose to zero.

In these cases, however, the deep dose is reported as zero, and the neutron component was not set to zero before it was reported.

6.3.2.2.2 Possible Manual Correction

In another group of records, the deep dose is much greater than the sum of the gamma and neutron components. In the electronic data, these records appear during a period identified as 1976. A review of a number of these records found, in all cases, a letter in the file instructing the staff to modify the individual’s data due to a dose reconstruction or reevaluation. It appears that dose components were not provided in the letter and, therefore, were not made to add up to the deep dose.

The 1976 date in the electronic record appears to have no relationship to the actual date associated with the dose record. According to the reports, many of the actual doses were assigned from 1984 to 1986.

6.3.2.3 Shallow Dose Minus Neutron Dose is Less than Photon Dose

The shallow dose is reported in the Dosimetry History by Individual. After 1976, if the reported shallow dose, after subtracting the neutron dose, is less than the photon dose, the shallow dose should be assumed to be zero.

6.3.3 Database Table-Specific Issues

Two database tables contain the external dosimetry data in RHRS, as discussed in the following sections. Each table has specific information on the external monitoring period, and the distinctions between the tables are notable.

6.3.3.1 RHRST_ED_TLD_HISTORY

This table contains external dosimetry data for years generally before 1991, the time of RHRS implementation. These data migrated from earlier computer records systems such as the HSDB. Most of the records contain only a date referred to as “Activity Date.” In general, this Activity Date is close to the dosimeter return date if the actual return date is available.

To migrate these data to the HIS-20 electronic database, an issue date had to be fabricated. Because the Activity Date is closer to the return date and there was no information on the exchange frequency, the issue date was set to 1 d before the return date.

6.3.3.1.1 1976 Records (Individual Employed After 1976)

This table contains a record dated December 31, 1976, for every individual in the database who was hired before 1989, even if they did not start work until after that date. This appears to have been an artifact from the initial migration of data from HSDB to RHRS. Therefore, a data record for 1976 might appear in Health Physics file reports called External Dosimetry (TLD) Detail (from RHRS) and Dosimetry History by Individual (from HIS-20) when the individual was not yet hired.

Zero Dose Records
As a general rule, these records are not attributed to the individual, and they report a deep dose of zero.

Nonzero Dose Records
A 1976 record appears occasionally with a deep dose greater than zero. Such records are regarded as valid, and the official dose is attributed to the individual even though it is outside the employment period (see Section 6.3.2.2.2).

6.3.3.1.2 1976 Records (Individual Employed Before 1976)

For individuals employed before 1976, the 1976 record represents a lump sum total of the deep dose for all previous years. However, the details for each year should be available during a review of report cards for an individual.

In addition, a database from the Colorado Department of Health was used to replace the lump sum with an annual deep dose value (Ruttenber et al. 2003). Again, there is no electronic source for the deep dose components (neutron and gamma) or for skin and extremity values.

6.3.3.1.3 Post-1976 Records

Because the only date available before 1991 was the Activity Date, records can appear in reports that are outside the employment period. The Activity Date was used to document a “wear period” if there was no knowledge of the frequency of the dosimetry exchange. Therefore, the records might appear before the hire date or after the termination date.

6.3.3.2 RHRST_ED_TLD_DOS

This table, which has a structure identical to RHRST_ED_TLD_HISTORY, contains post-1991 data. The records result from a download of the external dosimetry computer system called FALCON. This system collects and processes data directly from the Panasonic TLD readers. The records generally contain values for each column, including a variety of dates such as issue date, return date, and activity date.

There could be discrepancies between the monitoring period and the employment period. Individuals who did not check out properly might not have an accurate employment termination date. In addition, the computer systems typically documented the dates that the person wore dosimetry rather than the employment period. This is particularly true for subcontractors.

6.3.3.2.1 Dose History Hard-Copy File Contents

The RFP Radiological Health organization reviewed the individual dose record and summarizes it in an Occupational Dose Report worksheet (Attachment A, Figures A-1 and A-2). This document shows the measured dose on an annual basis and summarizes the available dose data from the printed record in the rest of the file. These data were compared with the computerized data, which are in the Dosimetry History by Individual report (Figures A-3, A-4, and A-5). Before 1976, the data were entered on an annual basis. After 1975, this report provided a dosimeter-by-dosimeter reading. The End Date indicates the end of the wear period. Comparison with the previous End Date can indicate the exchange frequency. If the Begin Date was not known, it was set to 1 d before the End Date. In this case, it can be assumed that the badge was worn from approximately the day after the previous End Date to the indicated End Date for that period.

Several other reports are included, some of which contain more dosimetry result detail. The following observations are from Savitz (undated) and the result of review of these records by James M. Langsted (ORAUT 2018a):

- Early years are reported on the Health Physics External Exposure Run, which provides a quarterly breakdown. Even though dosimeters might have been exchanged more frequently, data are summarized by quarter and more detailed data are not included.

- The 1953 to 1958 report Health Physics External Exposure Activity Run Yearly (Figure A-6) contains a quarterly summary of the exposure data for an individual. The dose equivalent values reported are Skin, Pen (penetrating; the deep dose to the whole body), and Hand (regarded as the dose to the extremity, if monitored).

- The 1959 to 1963 report Health Physics Yearly External Exposure Run (Figure A-7) contains all details for each measurement for an individual. Each reading is on a separate line, which reveals the frequency of the monitoring. The dose equivalents are reported as Skin, Penet (the deep dose to the whole body), and Wrist (the dose to the extremity, if monitored).

- The 1964 report Health Physics External Exposure Activity Run Yearly (Figure A-8) appears to be a transition report. It contains a quarterly summary of exposure data for an individual. The dose equivalent values reported are Skin, Pen (the deep dose to the whole body), and Hand (the dose to the extremity, if monitored).

- The External Dosimetry (TLD) Detail, Computerized Information Through xx-xx-xx or External Dosimetry (TLD) Detail, Computerized Information for CY (calendar year) 19xx report (Figure A-9) provides dosimeter reading detail for the years indicated. The Activity Date indicates the nominal (a few days to either side) end date of the dosimeter wear period. In the context of this report, Time Code indicates the identified exchange period for the badge:

  - Time Code 1, semimonthly (twice per month)
  - Time Code 2, monthly
  - Time Code 3, annual
  - Time Code 4, quarterly

  For the period this report was used, the shortest routine exchange period was semimonthly as indicated and not biweekly as discussed in Section 6.4.2.

  Time Codes are typically seen in dosimetry records from the late 1970s through the late 1980s. For 1990, where there is a single badge with an end of the year date, or the end of employment date for the year, the DR should assume an annual badge exchange. Note that for 1990, there is typically no Time Code listed for the dosimeter result. After review of claim data, it was determined that time codes after 1990 should not be used for determining a badge exchange frequency because they are no longer accurately entered.

During the transition between the Harshaw and the Panasonic badges, RFP used a code to indicate the source of the dosimetry result (ORAUT 2018a):

- Type code C (calculated): Panasonic badge result (calculated in Panasonic computer system), no wrist dosimeter data
- Type code R (raw): Harshaw badge chip readings (raw chip readings, result calculated in RHRS database system), no wrist dosimeter data
- Type code H (hybrid): Panasonic badge result and Harshaw wrist dosimeter chip readings

- The Health Physics External Radiation Exposure Report for Year XX (also known as *report card*) (Figure A-10) provides quarterly totals for the year. Because dose limits were on a per-quarter basis, the purpose of this report was to monitor compliance with these limits. The dosimeter detail was lost.

- The 1965 to 1989 Health Physics External Radiation Exposure Report contains a quarterly summary of exposure data for an individual. The dose equivalent values reported are Pen (the deep dose to the whole body), Skin, and Hand (the dose to the extremity, if monitored). In addition, these reports contain a lifetime (career) deep dose for exposure at RFP. After 1976, a column was added to the report for a value described as Forearm. This dose equivalent appears to be similar to that for the hand. In 1977, the dose to the hand was set to the greater of the skin of the whole body and the measurement calculated from the actual wrist dosimeter (Falk 1976).

- For individuals employed after 1976 and until about 1986, there might occasionally be a report called External Dosimetry (TLD) Detail. This report contains greater detail on each measurement made during this period and a breakdown of gamma and neutron components.

- The Radiation Dosimetry Individual Lifetime Report (Figure A-11) provides very little detail other than a verification of the Reported Lifetime Dose. This includes offsite doses (from previous employers), which should be detailed in the file.

- The RHRS Data report (Figure A-12) provides details of the dosimeter results. The advantage of this report is that it shows the breakdown of the deep dose into neutron and gamma components.

- The Radiation Dosimetry Detail Report, Termination Report (Figures A-13 and A-14) provides a verification of lifetime and post-1987 exposure.

- The Occupational Radiation Exposure Information (Figure A-15) provides annual Whole Body, Hand, Forearm, and accumulated RFP whole-body (ACCUM AT RF) doses. The whole-body dose is assumed to be penetrating.

These data enable compilation of an external dosimetry history, as follows:

- <u>1951–1976</u>. Quarterly dose history (RHRS data will provide a neutron/gamma breakdown),
- <u>1959–1964</u>. Dosimeter exchange history, and

- 1977–2005. Dosimeter exchange history.

In some cases, additional data are available. The dose reconstructor is responsible for using the information in this TBD to provide assumptions favorable to claimants to fill in unavailable detail for a claimant's external dosimetry record.

6.3.4 Interpretation of Dosimetry Data

Table 6-1 provides detail for the interpretation of the values, zeros, and blanks encountered in the RFP reports detailed in the previous section.

6.3.5 Additional Data Available

There are additional sources of information, which are known to exist (ORAUT 2018a), that contain detail that is not in the dose history file. These data might provide detail useful to refining dose estimates for some workers.

6.3.5.1 Rocky Flats Work History File

The RFP Human Resources department kept job assignment records for many years on 5- by 7- in. cards (ORAUT 2018a). Images of these cards could provide a further indication of the type(s) of work performed by the worker. This information is not in the dose history file.

6.3.5.2 Neutron Dose Reconstruction Project File

The NDRP provided an updated assessment of the neutron exposures that monitored workers received while performing work in the RFP plutonium production facilities from 1952 to 1970. The NDRP reassessed the neutron doses either by rereading neutron films and plates used to monitor workers for neutron exposures or by estimating the neutron doses for periods when a worker was not monitored for neutron exposures while working in a plutonium-related building. The focus of the NDRP was neutron dose, so the study contains data primarily on plutonium workers and not on uranium and other workers who were unlikely to be monitored for neutron exposure. The study has provided NDRP-generated results for those workers in the study for whom there are EEOICPA claims. These data are described in the NDRP protocol document (Falk et al. 2005).

When records indicate an energy employee worked in a plutonium facility before 1971, and no NDRP data exists in the dosimetry records, additional effort should be made to verify the existence or absence of NDRP data for a specific energy employee.

6.3.5.3 Job Exposure Matrix

A DOE-funded study performed by the University of Colorado Health Sciences Center and the Colorado Department of Public Health and Environment (Ruttenber et al. 2003) developed a Job Exposure Matrix that identified the building assignment and a job title snapshot during September for each year from 1952 to 1989. This matrix was matched with external dosimetry results, and it could provide dose distributions for groups and job titles to assist in estimating dose for unmonitored workers. On April 4, 2006, NIOSH reviewed the data available from this project and concluded that the material is valuable for epidemiological studies but is of limited utility for NIOSH dose reconstruction.

Table 6-1. Interpretation of reported data (ORAUT 2018a).[a]

Report	Reported quantity	Interpretation of zeros	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
Occupational Dose Report Hand-generated summary of dosimetry record (see Figures A-1 and A-2 and Section 6.3.3.2)	Annual totals in mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1. Deep dose Extremity dose Skin dose (see Section 6.3 and 6.6.1.2).	Zero indicates a monitored exposure reported as zero.	Blank indicates unmonitored during that period. Form does not indicate if individual was onsite during unmonitored period.	See Section 6.3.2.	Evidence is that at RFP, if employee was monitored, results were reported. Between 1964 and the early 1990s, all onsite individuals were monitored with a body badge. See Section 6.4.1.
Dosimetry History by Individual Computer-generated summary of dosimetry (see Figures A-3, A-4, and A-5 and Section 6.3.3.2) See Note a. below	Annual total through 1976 and individual dosimeter results thereafter in mrem (see references above) DDE SDE-SK (skin) SDE-EX (extremity) Neutron (neutron is included in DDE and SDE before 1977). LDE–irrelevant to dose reconstruction.	Before 1977, a zero in the neutron field should be disregarded. During this period, the neutron dose is included in both the DDE and the SDE and is not available separately. After 1976, the neutron dose is reported in the Neut. column and is included in the SDE values. Otherwise, a zero indicates a monitored exposure reported as zero.	Blank indicates a nonreported value for that period or dosimeter exchange.	See Section 6.3.2.	Entries are not provided for periods when the individual was not employed at RFP. A missing result in a series of continuous dosimetry results is probably the result of a missed dosimeter exchange. See Section 6.5.3.

Report	Reported quantity	Interpretation of zeros	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
Health Physics External Exposure Activity Run Yearly (Figure A-6)	Quarterly total of dose in mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1 Penetrating dose, Extremity dose (see Section 6.10), Skin dose (see Sections 6.3 and 6.6.1.2). These totals might result from multiple dosimeter exchanges during the quarter.	Zero indicates monitored dose reported as zero.	Blank indicates dosimetry result was not measured for that period. Extremity dosimeters were not worn by all individuals.	See Section 6.3.2. Annual Hand totals are based only on measured Hand values for that year.	Blanks indicate that individual was not monitored for that dose.
Health Physics Yearly External Exposure Run Dosimeters exchanged biweekly (Figure A-7) (see codes indicated below)	Units are mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1.	Zero or blank indicates no measured dose under that filter	For gamma/beta and gamma/X-ray badges (Codes 1 and 2), a blank result indicates a zero reading. This is based on a review of records of this type showing only positive and blank readings for a badge. For neutron badges (Code 3), neutron dose is placed in B/CD column and other columns are left blank because they are not used.	Sheet shows only individual dosimeter results.	"Type 0" in fifth column seems to indicate that neutron dosimeter was either lost, unreadable, or below the detection limit. This has not been determined. Assumptions favorable to claimants should be made.
Health Physics External Exposure Activity Run, Yearly (Figure A-8 and Section 6.3.3.2)	Quarterly totals are mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1.	Zeros indicate total for dosimeters all reporting zero	Blank indicates individual was not monitored during that quarter	This is a summary report. If individual results are available, they should match.	A blank indicates that the individual was not monitored during that period, either because the worker was not onsite or was not expected to exceed some currently applicable administrative limit.

Report	Reported quantity	Interpretation of zeros	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
External Dosimetry (TLD) Detail (Figure A-9 and Section 6.3.3.2)	Individual dosimeter results are mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1. Dosimetry results calculated as indicated in Section 6.3.	Doses reported down to zero. Zero indicates dosimeter response less than background value used.	Blank indicates an unusual situation where part of dosimetry result is not available. If dosimeter result is not available, no entry will be recorded.	Individual dosimeter results are totaled for quarter or CY on other reports.	Between 1964 and the early 1990s, all onsite individuals were monitored with a body badge. See Section 6.4.1. If dosimeter result is missing, either individual did not exchange badge or was not a site employee.
Health Physics Annual External Radiation Exposure Report for Year XX (Figure A-10)	Quarterly totals are mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1. Dosimetry results calculated as indicated in Section 6.3.	For body badge results, zeros indicate a sum of zeros reported for all external dosimetry results during that quarter. It is likely that individuals were monitored with a body badge but did not receive an extremity dosimeter. In this case, a zero in the Hand column indicates the individual was likely unmonitored for extremity dose.	A blank indicates that a dosimetry result was not obtained for that period. This could be because the individual was not employed, not monitored, or did not submit a badge during that period. A blank in the Hand column indicates that the individual was not monitored for extremity dose.	This is a rollup of dosimetry results for quarter and should be consistent with annual dose reported elsewhere.	If a zero is reported, it is a result of external dosimetry results of zero. After 1976, if the hand dose equals the skin dose, this indicates that the hand was not separately monitored and the skin dose was used to estimate the hand dose. Before 1977, the measured hand dose was reported.
Radiation Dosimetry Detail Report, Individual Lifetime Report (Figure A-11)	This report shows only deep (Pen) dose in mrem according to Tables 6-10 and 6-17.	A zero indicates that external dosimetry measurements were performed resulting in a total of zero.	Blanks indicate no external dosimetry measurements were performed. Occupational exposure from other facilities is available only if reported to RFP. Often other facility exposure records were not available.	This is a rollup of data for the period indicated. It includes other facility exposure if available. Observed data discrepancies as indicated in Section 6.3.2 are possible in these totals.	For unmonitored individuals, fields will show a blank when no external dosimetry measurements were recorded.

Report	Reported quantity	Interpretation of zeros	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
Radiation Health Records System – View TLD Data (Figure A-12)	Individual dosimeter results are in mrem according to Tables 6-10 and 6-17 and Section 6.8.2.1. Dosimetry results calculated as indicated in Section 6.3. Time Code and Type are as explained in Section 6.3.3.2.	Zeros in all fields except background (BK-1 and BK-2) indicate a measured dosimetry result of zero. Zeros in the background fields are irrelevant for Type C records and, for Type H or Type R records, indicate the background values that have been used in correcting the reported dosimetry results.	It is not clear if blanks are present on this report. If they do exist, they should be interpreted as no external dosimetry measurement was recorded for that period.	These individual results are rolled up into annual totals.	The Activity Date indicates the approximate end of the dosimeter wear period. This date, used with the Time Code (exchange frequency) indicates the presence of missing dosimeters. A gap indicates a lost dosimeter, a dosimeter worn for multiple periods, or a period for which the individual was not monitored.
Radiation Dosimetry Detail Report, Termination Report (Figures A-13 and A-14)	This report shows only deep (Pen) dose in mrem according to Tables 6-10 and 6-17.	Zeros in the data for a specific year indicate an external dosimetry measurement of zero. If the internal and external data for a specific year are blank, the zero in the TEDE and TODE fields for that year are incorrect and should be blank. A zero in the Cumulative or Lifetime fields indicates that all measurements contributing to that total are zero.	In the data for specific years, blanks indicate that no external dosimetry measurements were recorded for that year.	This is a rollup of dosimetry results that might be available elsewhere in worker external dosimetry record files. Observed data discrepancies as indicated in Section 6.3.2 are possible in these totals.	For completely unmonitored individuals, the Cumulative and Lifetime external dose fields show zeros. Unmonitored periods would be undetectable in this report.

Report	Reported quantity	Interpretation of zeros	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
Occupational Radiation Exposure Information (Figure A-15)	This report shows dose in rem according to Tables 6-10 and 6-17. Penetrating dose is reported for whole body and extremity dose is reported as both forearm and hand. Extremity dosimetry is further explained in Section 6.8.2.1.	Zeros indicate an annual total of zero based on both external dosimetry results of zero and unmonitored periods.	Blanks should not be present on this report.	This is a rollup of dosimetry results that might be available elsewhere in worker external dosimetry record files. Observed data discrepancies as indicated in Section 6.3.2 are possible in these totals.	This report includes both monitored and unmonitored periods. It is impossible to determine the unmonitored periods from this report.

a. LDE = lens of the eye dose equivalent; SDE = shallow dose equivalent; TEDE = total effective dose equivalent; TODE = total organ dose equivalent.

Report codes for Health Physics Yearly External Exposure Run

Code	Explanation
1	Gamma/beta dosimeter
2	Gamma/X-ray dosimeter
3	Neutron dosimeter

Dose column labels

Code	Explanation
B/CD	Body/cadmium
B/BR	Body/brass
B/OW	Body/open window
W/BR	Wrist/brass
W/OW	Wrist/open window
SKIN	Skin dose
PENET or PEN	Penetrating dose (equivalent to deep dose)
WRIST	Extremity dose (as measured by wrist dosimeter)

6.4 HISTORICAL ADMINISTRATIVE PRACTICES

6.4.1 Badged Population

When plant operations began in 1951, there was no external dosimetry, and there was not much radioactive material at the Plant. In September 1952, dosimeters became available for use. Some individuals in Building 991[1] received neutron dosimeters. The use of dosimetry expanded to other RFP production operations.

For some radiation workers, no neutron monitoring at all was performed during the period from 1952 through 1970. For other workers, from 1967 to 1970, nuclear track emulsion, type A (NTA) film badges were issued but not evaluated after they were used (Falk et al. 2005).

Two analyses were performed to indicate the portion of the plant population that was monitored using external dosimetry. The results are shown in Figure 6-7. The solid line indicates a manual analysis that was performed on the data in all of the NIOSH EEOICPA claim files that were available in October 2005. At that time, 1,046 claimant files were available for analysis. The broken line indicates a computer analysis that was performed on the RFP external dosimetry database. Over 288,000 employee-years of data were evaluated. This shows the portion of the plant population that was monitored.

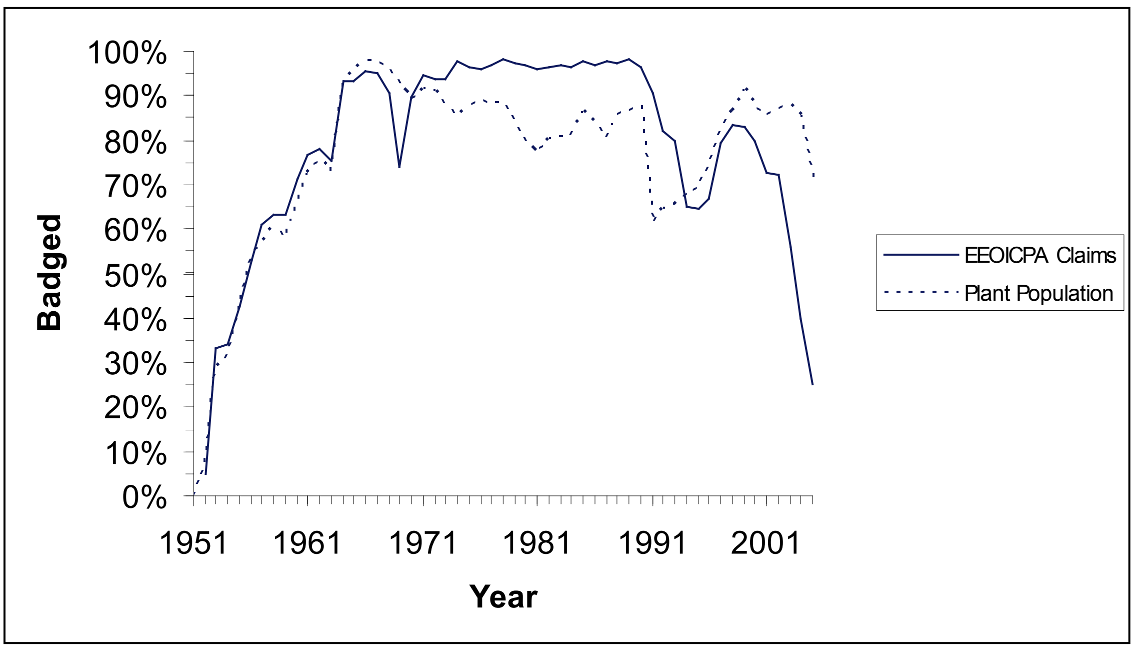

Figure 6-7. Portion of plant population badged.

A steady increase occurred until 1964, when the security badge was incorporated in the dosimetry badge, which ensured that each individual wore a dosimetry badge (Putzier 1982). This design was maintained until 1991 (Jens 1990), when the security badge was separated from the dosimeter and individuals unlikely to receive occupational radiation exposure greater than 100 mrem/yr were no longer issued dosimeters. The dip in 1969 is probably a result of the personnel displacement from the Building 776 fire. The disparity between the EEOICPA claim data and the population data is thought to be the result of multiple hires and terminations that were not accurately recorded in the electronic

[1] In the early years, two-digit building numbers were used. These were later changed to corresponding three-digit numbers. For example, Building 81 became Building 881. Buildings 371 and 771 present the only case in which there could be confusion, but the change to three-digit numbers took place well before Building 371 was built; therefore, Building 71 always refers to Building 771.

data. When the claim files are reviewed, these data are refined based on the paper records and a more accurate data set is used for the analysis. The reduction in badging that began in 1991 is the result of an effort by the site Radiological Protection organization to identify personnel unlikely to exceed the exposure criteria for radiological workers (100 mrem/yr) and to discontinue badging of those personnel. The increase in 1998 was the result of rebadging personnel to perform decontamination and decommissioning (D&D) work, and the reduction at the end was the result of discontinuing badging after the completion of D&D work (which could result in significant worker dose).

For some plutonium workers, neutron monitoring was not provided until the early 1960s, and their doses of record might not include significant contributions from neutron exposure received before being issued a neutron dosimeter. These workers included most of the employees working in Building 71 (now Building 771). Only a small number (10 to 18) of these employees were monitored for neutron exposure, and that monitoring occurred only from October 1956 to September 1957 (Falk et al. 2005).

A group of plutonium workers [the plutonium metal (foundry) workers in Building 71] was not monitored for whole-body, penetrating gamma, and X-ray doses until February 1957. Instead, they were issued only a wrist dosimeter (Falk et al. 2005).

The average dose trend for monitored individuals is shown in Figure 6-8. This trend is influenced by the number of workers monitored. For example, when only some workers were monitored, those selected generally had the highest potential for exposure, and the average would be higher. When all site employees were monitored, the average was reduced by those monitored employees who did not work in the production areas.

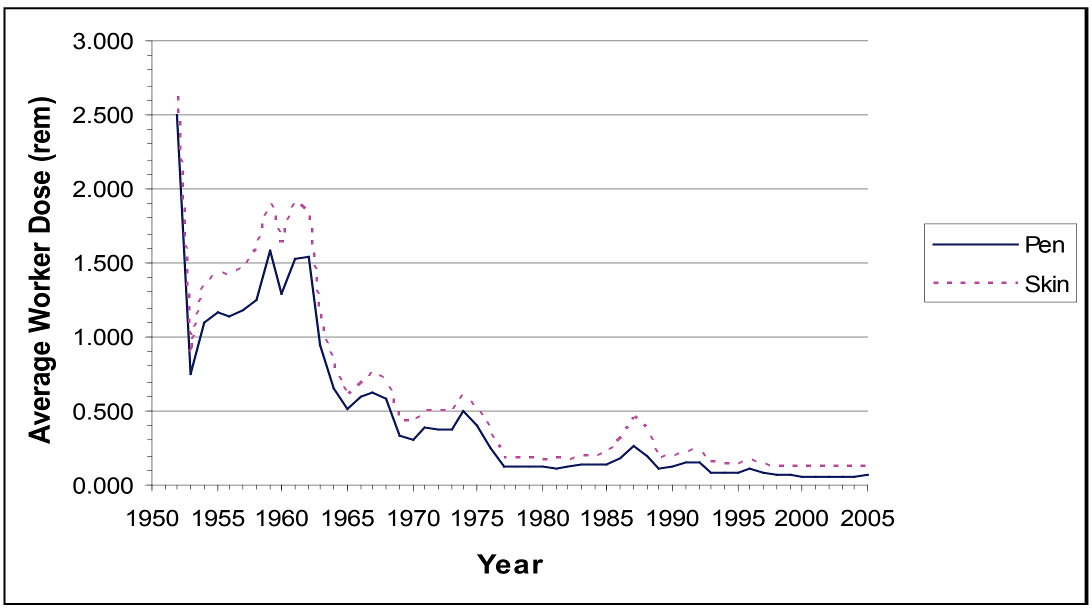

Figure 6-8. Average measured worker dose (data from ORAUT 2007a).

6.4.2 Badge Exchange Frequency

The determination of badge exchange frequencies was based on the potential for external dose and the necessity to control dose to administrative limits. Badges were exchanged at various frequencies. Early dosimetry was exchanged on a weekly basis, which later became biweekly (as illustrated in Figure A-7), semimonthly (twice per month), and monthly. It is not clear when the change from biweekly to semimonthly occurred. Before 1991, dosimetry was generally exchanged on semimonthly, monthly, quarterly, and annual frequencies. After 1990, exchange frequencies generally went to monthly, quarterly, and semiannually.

Badge exchange frequency records have not been maintained. If individual dosimeter readings were maintained, the exchange frequency for an individual can be determined by reviewing the external dose record. After 1976, the dose record shows a dosimeter reading for each exchange. For earlier years, the dose has been combined into quarterly records for which the exchange frequency has been lost, although it is reasonable to assume that badges were exchanged at least quarterly (see Figures A-3 to A-15 as documented in Section 6.3.3.2).

To determine the exchange frequencies used before 1976, original dosimetry laboratory worksheets were reviewed (ORAUT 2018a). Many of these worksheets have been assembled as part of the NDRP. Dosimetry laboratory worksheets from 1951 to 1970 were assembled and organized. A sample was obtained during preparation of this report by selecting the September folder for each year. A review of each worksheet determined the exchange frequency, building, and dosimeter type (photon, beta, or neutron). These data were organized and reviewed to determine the most frequent exchange for the major job categories (see Attachment B) by year. The worksheets do not indicate job assignment. It was necessary to evaluate the job category based on the building and exchange frequency. In cases where multiple exchange frequencies were indicated for a major job category, the more frequent exchange frequency was selected. This provides an assumption favorable to claimants when determining missed dose. Dosimetry worksheets are not readily available for 1970 to 1976, so exchange frequencies were extrapolated forward for those years. Table 6-2 lists the results of this analysis. These are the default values to use if the exchange frequency cannot be determined. If no job category can be determined, the dose reconstructor should use the most frequent exchange rate for that year. For semimonthly badge exchanges, biweekly exchange should be assumed (26 exchanges per year instead of 24) when an approach favorable to claimants is desired.

In 1991 and 1992, the Dosimetry History by Individual may have actual badge begin and end dates for the dosimeters during that time. In some cases, the Dosimetry History by Individual will report sequentially numbered begin and end dates (i.e., 30-MAR-1991 and 31-MAR-1991). There could also be other dosimetry records indicating an “Activ_Date” or “Activity_Date” with, typically, March, June, September, and December badges. In these cases, when actual badge begin and end dates are not provided, a quarterly exchange frequency should be assumed.

6.4.3 Field-Specific Calibration Factors

Film dosimeters required the use of workplace-specific calibration factors, so it was necessary to know the facility in which the individual worked (ORAUT 2018a). Individuals sometimes worked in other facilities on temporary or overtime assignments, which the Dosimetry department could not detect. Area-specific calibration factors were necessary to evaluate readings from the X-ray/gamma dosimeters used in the plutonium areas and the beta/gamma dosimeters used in the uranium areas. Exposure of the dosimeter in a different field could not be detected, which introduced a source of uncertainty.

TLD systems use more tissue-equivalent detection elements (ORAUT 2006a, Section A.2.1.2), which do not require a field-specific calibration factor. This source of uncertainty is minimal with these dosimeters.

6.4.4 Minimum Reported Dose

RFP appears to have embraced a philosophy of reporting dose down to zero between 1951 and 1992 (ORAUT 2018a). In 1993, the Plant adopted a minimum reported dose threshold to remove the bias associated with reporting low doses and truncating doses calculated to be small negative numbers to zero. In 1993, a minimum reported dose level of 10 mrem was adopted. Any dose below this level was reported as zero (KHC 2001). This policy is consistent with the limits of detection (LODs) reported elsewhere in this TBD.

6.4.5 Recorded Dose Practices

Table 6-3 provides a summary of the calculations used to determine the recorded dose at RFP.

6.5 COMMON ISSUES

This section discusses issues common to external photon, neutron, and electron dose measurement at RFP. These issues are addressed further only if there is an issue specific to that type of dose measurement.

6.5.1 Number of Zero Readings

At present, available dosimetry records do not consistently provide individual dosimeter results for all of the early years. Therefore, it is often necessary to estimate the dosimeter exchange frequency for some or all of the period from 1951 to 1976. Table 6-2 provides an estimate based on major job category. If an individual's job assignment cannot be determined, the most frequent dosimeter exchange used during that year should be assumed. This assumption is favorable to claimants.

Table 6-2. Conservatively determined default dosimeter exchange frequencies.[a,b]

Year	Chemical operators, Pu	Chemical operators, U	Metallurgical operators, Pu	Metallurgical operators, U	Maintenance workers	Support personnel	Analytical laboratory technicians	Site support personnel	Radiation control technicians	D&D workers
1951	Biweekly	Biweekly	Biweekly	Biweekly	Monthly	Monthly	Biweekly	Monthly	Biweekly	Monthly
1952	Biweekly	Biweekly	Biweekly	Biweekly	Monthly	Monthly	Biweekly	Monthly	Biweekly	Monthly
1953	Biweekly	Biweekly	Biweekly	Biweekly	Monthly	Monthly	Biweekly	Monthly	Biweekly	Monthly
1954	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Biweekly	Biweekly
1955	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Biweekly	Biweekly
1956	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Biweekly	Biweekly
1957	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Biweekly	Biweekly
1958	Weekly	Weekly	Weekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Weekly	Biweekly
1959	Weekly	Biweekly	Weekly	Weekly	Monthly	Biweekly	Biweekly	Monthly	Weekly	Biweekly
1960	Weekly	Weekly	Weekly	Weekly	Monthly	Monthly	Biweekly	Monthly	Weekly	Monthly
1961	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Monthly	Weekly	Monthly	Biweekly	Monthly
1962	Biweekly	Biweekly	Biweekly	Weekly	Monthly	Monthly	Weekly	Monthly	Biweekly	Monthly
1963	Biweekly	Monthly	Biweekly	Biweekly	Monthly	Monthly	Quarterly	Monthly	Biweekly	Monthly
1964	Biweekly	Monthly	Biweekly	Monthly	Quarterly	Monthly	Quarterly	Quarterly	Biweekly	Monthly
1965	Monthly	Not Applicable	Monthly	Monthly	Quarterly	Quarterly	Quarterly	Quarterly	Monthly	Quarterly
1966	Monthly	Not Applicable	Monthly	Monthly	Monthly	Quarterly	Quarterly	Quarterly	Monthly	Quarterly
1967	Biweekly	Not Applicable	Biweekly	Monthly	Monthly	Quarterly	Quarterly	Quarterly	Biweekly	Quarterly
1968	Biweekly	Not Applicable	Biweekly	Monthly	Monthly	Monthly	Monthly	Monthly	Biweekly	Monthly
1969	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1970	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1971	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1972	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1973	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1974	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1975	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly
1976	Biweekly	Not Applicable	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly	Monthly

a Biweekly (every 2 weeks), assumed because it is favorable to claimants over semimonthly (twice per month).
b. Source: Study described in Section 6.4.2.

Table 6-3. Summary of historical recorded dose practices.[a]

Period and dosimeter	Dosimeter measured quantities	Compliance dose quantities
1951–1956, Two-element film (photon) + track plate (neutron)	$Ow_{dose} = (Ow_{density} – Cd_{density}) \times CF_{net\ Ow}$ $Cd_{dose} = Cd_{density} \times CF_{Cd}$ N_{dose} = neutron tracks × $CF_{neutron}$	$Pen = Cd_{dose} + 0.5 \times Ow_{dose} + N_{dose}$ $Skin = Cd_{dose} + Ow_{dose} + N_{dose}$
1957–1959, Two-element film + NTA film	$Ow_{dose} = (Ow_{density} – Cd_{density}) \times CF_{net\ Ow}$ $Cd_{dose} = Cd_{density} \times CF_{Cd}$ N_{dose} = neutron tracks × $CF_{neutron}$	$Pen = Cd_{dose} + 0.5 \times Ow_{dose} + N_{dose}$ $Skin = Cd_{dose} + Ow_{dose} + N_{dose}$
5/1953–10/1970, Two-element film (beta)	$Ow_{dose} = (Ow_{density} – Cd_{density}) \times CF_{net\ Ow}$ $Cd_{dose} = Cd_{density} \times CF_{Cd}$ (no neutron measured)	$Pen = Cd_{dose}$ $Skin = Cd_{dose} + Ow_{dose}$
3/1960– (Bldg. 71), 1/1963– (other Pu), 2/1968 (Bldg. 81 and 91) –1962, Three-element film + NTA film	$Ow_{dose} = (Ow_{density} – f \times Br_{density}) \times CF_{net\ Ow}$ $Br_{dose} = (Br_{density} – Cd_{density}) \times CF_{net\ Br}$ $Cd_{dose} = Cd_{density} \times CF_{Cd}$ N_{dose} = neutron tracks × $CF_{neutron}$	$Pen = Cd_{dose} + Br_{dose} + 0.35 \times Ow_{dose} + N_{dose}$ $Skin = Cd_{dose} + Br_{dose} + Ow_{dose} + N_{dose}$
1963–1969, Multiple-element film + NTA film	$Ow_{dose} = (Ow_{density} - f \times Br_{density}) \times CF_{net\ Ow}$ $Br_{dose} = (Br_{density} - Cd_{density}) \times CF_{net\ Br}$ $Cd_{dose} = Cd_{density} \times CF_{Cd}$ N_{dose} = neutron tracks × $CF_{neutron}$	$Pen = Cd_{dose} + Br_{dose} + 0.35 \times Ow_{dose} + N_{dose}$ $Skin = Cd_{dose} + Br_{dose} + Ow_{dose} + N_{dose}$
1969–1970 1/1970, (Bldg. 771), 4/1970 (other Pu Bldgs) –10/1970 (all others)[b] TLD + NTA film	$G_{dose} = P_{TLD}$ $S_{dose} = S_{TLD}$ N_{dose} = neutron tracks × $CF_{neutron}$	$Pen = G_{dose} + N_{dose}$ $Skin = S_{dose} + N_{dose}$
1971–1982 TLD-700 + TLD-600/700	$G_{dose} = P_{TLD}$[c] $S_{dose} = S_{TLD}$ N_{dose} = determined from albedo algorithm	$Pen = G_{dose} + N_{dose}$ $Skin = S_{dose} + N_{dose}$ if Skin < Pen, then Skin = Pen
1983–1989, Panasonic UD-802 + UD-809	Photon deep Photon/Beta shallow Neutron	Pen = photon deep + neutron Skin = photon/beta shallow + neutron
1990–2004, Panasonic UD-802 + UD-809	$H_{s,gamma}$ $H_{d,gamma}$ $H_{s,beta}$ N_{dose}	$H_d = H_{d,gamma}$ + neutron $H_s = H_{s,gamma} + H_{s,beta}$ + neutron

a. $Ow_{density}$ = OW (measured density); Ow_{dose} = OW (determined dose); $Cd_{density}$ = cadmium filter (measured density); Cd_{dose} = cadmium filter (determined dose); $Br_{density}$ = brass filter (measured density); Br_{dose} = brass filter (determined dose); f = factor to correct for brass attenuation of X-rays (1.14 or 1.17 or nonlinear factor); N_{dose} = neutron dose; CF = calibration factor determined from calibration films.
b. Except some groups in Building 444 and miscellaneous other groups.
c. Average of two crystals, or one crystal if one crystal is zero.

Once the estimated exchange frequency has been established, the number of zero readings must be estimated. For the majority of the time, estimates of zero readings can be obtained using actual or inferred data in relation to reported doses and reported zeros from the dosimetry files. If the number of zero measurements cannot be determined from the record, determination of the missed dose becomes more complex. When only summary dose is known, the number of zero doses can 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, using the methodology in NIOSH (2006c).

Quarterly or annual limits:

- 1951–1967. 3 rem/qtr (Figure A-10),
- 1968–1992. 5 rem/yr (observed in Rockwell 1985), and
- 1993–2005. 2 rem/yr (DOE 1992).

Table 6-4 divides these dose limits into exchange frequencies. Either the dosimetry records or the default values from Table 6-2 should be used to determine or estimate the exchange frequency and number of reported zeros. Using the methodology of NIOSH (2006c), it is possible to develop an appropriate estimate of the number of zeros, and ultimately the missed dose, using either approach.

6.5.2 Discrepancies

If the employee's record contains discrepancies, it is favorable to the claimant to use the higher dose in the dose reconstruction. Care must be taken to interpret dose numbers properly if units were not specified. RFP routinely used milliroentgen or millirem as the unit of dose. If a number has no unit indicated, it is probably not in rem (ORAUT 2018a). It is highly unlikely that a record would show a dose greater than the quarterly or annual limit without an additional record indicating an overexposure (ORAUT 2018a).

Corrections were noted in the dose record when calculation or computer errors occurred (ORAUT 2018a). Such corrections were usually noted on the hard-copy report, and a notation was entered if the electronic record was updated. If the record was updated and the update noted, the correction should not be applied again. If there is no obvious notation to indicate the incorporation of a correction, the approach more favorable to claimants is to incorporate the correction in the dose used for reconstruction.

6.5.3 Missing Entry

If the dosimetry history contains a missing entry, this probably indicates that the individual missed the dosimeter exchange and that the next dosimeter includes the dose from both exchange periods. A less likely indication is that the badge was lost and no dose was assigned for that period. A period of 3 months is defined as a short gap based on the fact that the site routinely reported quarterly summary data. The assumption favorable to claimants is that the dosimeter was lost; dose should be assigned for that gap period using the following approach or coworker data:

- If short gaps (i.e., 3 months or less for monthly monitoring or 1 quarter for quarterly monitoring) in the individual's dosimetry records exist and is bounded on both ends by dosimetry data, the average between of individual's adjacent monitoring data should be used to fill in the gaps in their dosimetry data. For 1969 and 1970, refer to Section 6.5.8 of this TBD for guidance on gap filling.

- If large gaps (i.e., greater than 3 months for monthly monitoring or greater than 1 quarter for quarterly monitoring) in the individual's dosimetry records exist or the period is not bounded by dosimetry data, external coworker dose data or ambient dose data should be used to fill in the gaps in their dosimetry data. For 1969 and 1970, refer to Section 6.5.8 of this TBD for guidance on the assignment of external coworker dose.

Consideration should be given to actions that might provide a basis for a gap in monitoring, such as the quality of the reported monitoring data, change in job category, work location, documented absence from work, or any administrative action.

6.5.4 Exposure Geometry

NIOSH has determined that an assumption of 100% anterior-posterior (AP) exposure for dose reconstructions is favorable to claimants. Glovebox workers could have experienced exposure geometry characteristics that could result in an underestimation of reconstructed organ doses. NIOSH has issued a technical information bulletin to address this issue (NIOSH 2011).

Table 6-4. Dose limits (rem) based on exchange frequency.[a]

Year	Limit (rem)	Period (yr)	52 Weekly	26 Semimonthly	24 Bimonthly	12 Monthly	4 Quarterly	2 Semiannually
1951	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1952	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1953	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1954	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1955	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1956	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1957	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1958	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1959	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1960	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1961	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1962	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1963	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1964	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1965	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1966	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1967	3	0.25	0.231	0.462	0.500	1.000	3.000	Not used
1968	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1969	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1970	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1971	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1972	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1973	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1974	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1975	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1976	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1977	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1978	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1979	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1980	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1981	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1982	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1983	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1984	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1985	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1986	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1987	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1988	5	1	0.096	0.192	0.208	0.417	1.250	Not used
1989	5	1	0.096	0.192	0.208	0.417	1.250	2.500
1990	5	1	0.096	0.192	0.208	0.417	1.250	2.500
1991	5	1	0.096	0.192	0.208	0.417	1.250	2.500
1992	5	1	0.096	0.192	0.208	0.417	1.250	2.500
1993	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1994	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1995	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1996	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1997	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1998	2	1	0.038	0.077	0.083	0.167	0.500	1.000
1999	2	1	0.038	0.077	0.083	0.167	0.500	1.000
2000	2	1	0.038	0.077	0.083	0.167	0.500	1.000
2001	2	1	0.038	0.077	0.083	0.167	0.500	1.000
2002	2	1	0.038	0.077	0.083	0.167	0.500	1.000
2003	2	1	0.038	0.077	0.083	0.167	0.500	1.000

a. Source: See Section 6.5.1.

The analysis considered alternative geometry considerations as follows. Because little information is available on the exposure geometry for an individual, estimates have been made by the author using professional judgment (NIOSH 2007, Section 4.4.1) for each major job category (Attachment B). To estimate the exposure geometry for major job categories, engineering judgment was used and a simple calculation was performed. The fraction of the dose received via each geometry is a product of the dose rate and exposure duration that each worker experienced. Workers experienced a higher dose rate when working hands-on with radioactive material and a lower dose rate as they performed other tasks in the radiation control area. An estimate of the fraction of hands-on time was chosen for each major job category (ORAUT 2018a). Selection of source geometry was based on an assumed configuration (selected by the author) of the radioactive material to which the workers were exposed. From this, a relative dose was estimated for hands-on work (1 ft away) and non-hands-on work (4 ft away), using simple rules of thumb. These were combined to estimate the fraction of the dose received via the AP geometry (hands-on) or other geometries for the balance of the exposure (ICRP 1996). Table 6-5 presents these results. The non-AP exposure was estimated to come from either the rotational (ROT) or isotropic (ISO) geometry. The difference is that ISO geometry encompasses exposure from all angles (including above and below) while ROT encompasses only exposure from all horizontal directions to the upright individual. Chemical operators receive doses from above and below due to pipes in the overhead and near the floor. All others were assumed to receive their non-AP doses from the ROT geometry (ORAUT 2018a). Table 6-6 lists these fractions, which are rounded.

Table 6-5. Exposure geometry calculation (% dose received).

Major job category	Hands-on work (time)	Source geometry	AP	ISO or ROT
Chemical operators	25%	Line	57%	43%
Metallurgical operators	75%	Point	98%	2%
Maintenance workers	75%	Plane	98%	2%
Support personnel	5%	Plane	46%	54%
Analytical laboratory tech.	75%	Point	98%	2%
Site support personnel	0%	Plane	0%	100%
Radiation control technicians	10%	Plane	64%	36%
D&D workers	75%	Plane	98%	2%

Table 6-6. Exposure geometry defaults for major job categories.

Major job category	AP	ISO	ROT
Chemical operators	50%	50%	0%
Metallurgical operators	100%	0%	0%
Maintenance workers	100%	0%	0%
Support personnel	50%	0%	50%
Analytical laboratory tech.	100%	0%	0%
Site support personnel	0%	0%	100%
Radiation control technicians	60%	0%	40%
D&D workers	100%	0%	0%

6.5.5 Lead Aprons

Lead aprons were available and used for a limited number of tasks at RFP. Interviews with early Health Physics managers indicated that they were not widely used in the early years. Lead aprons were used for specific tasks at different times throughout the day when operators worked in proximity with kilogram quantities of plutonium outside gloveboxes. When engaged in activities such as bagout operations and packaging and handling completed assemblies, workers often used lead aprons. Major job categories (see Attachment B) that were likely to use lead aprons for specific activities include Chemical Operators and Metallurgical Operators (including Nondestructive Testing Technicians). The standard procedure was to wear the dosimeter under the lead apron to measure the dose to the torso (ORAUT 2018a). This does not, however, account for exposure to the extremities, upper arms, head, and neck.

Available RFP external dosimetry procedures were reviewed. A June 15, 1991, procedure instructs workers to wear the dosimeter under the lead apron, but a March 16, 1992, draft indicates that the badge should be worn outside of (and taped to) the lead apron. Versions of this procedure after this date all support wearing the badge on the outside of the lead apron. In March 1992, a field study was performed in two storage vaults at RFP (Passmore 1992). This study measured Panasonic dosimeter response both outside and inside a lead apron fitted on a dosimetry phantom. The results of this study indicated that dosimeters placed under the apron detected neutrons to a significantly greater extent than the dosimeters placed on the outside of the apron. It is believed that the neutron albedo effect (low-energy neutrons reflected back into the badge) is disturbed on the outside of the lead apron. It is also interesting that the lead apron resulted in a reduction of less than 15% in the photon dose under the apron. The results of this study are applicable to dose received by workers while wearing aprons. Table 6-7 lists the suggested bias correction factors, which derive from the largest values shown in the Passmore (1992) study. The lead apron correction factors were taken as the maximum measured values conservatively rounded up. Thus, they represent a maximizing best estimate of the factor and are applied as a constant.

Table 6-7. Bias correction factors for application to dose received while wearing a lead apron.

Cancer location	Dosimeter location	Neutron dose	Deep photon dose	Shallow photon dose
Protected area	Under apron	1	1	1
Protected area	Outside apron	1.9	1	1
Unprotected area	Under apron	1	1.2	1
Unprotected area	Outside apron	1.9	1	1

Although this field study was performed using Panasonic dosimeters, the albedo phenomenon was used in the Harshaw dosimeter. These bias correction factors are appropriate for application to dose measured by the Harshaw dosimeter while wearing a lead apron. The film and neutron track plate neutron dosimeters used at RFP (before 1971) did not utilize the albedo phenomenon for dosimetry. Therefore, it is not appropriate to use these bias correction factors for neutrons in that era. It is appropriate to use these factors for photon doses measured with the film dosimeters.

Adjustment to dose for use of protective lead aprons depends on the location of the cancer site in relation to the lead apron. The aprons covered the body from the shoulders to below the knee, but did not cover the arms. In later years, wraparound aprons were worn. The change in apron design has little effect on dose reconstruction if a 100% AP exposure is assumed (see Section 6.5.4). If the cancer site is under the apron, there is no adjustment (i.e., the factor is 1.0) because a dosimeter under the apron will reasonably measure a dose to the cancer site. If the cancer site is in an area not protected by an apron, and for which the dosimeter-measured dose might be too low, the recommended adjustment factor as listed in Table 6-7 will be applied.

If location of dosimeter is unknown, the more favorable to the claimant scenario should be assumed.

6.5.6 Recycled Uranium

Some forms of uranium metal were recycled and reprocessed within the weapons complex. There is a concern that workers could have been exposed to transuranic elements or fission products contained in these materials. Recycled uranium use at RFP was carefully reviewed and documented (KHC 2000a). It was determined that a very small fraction (0.03%) of the depleted uranium (DU) processed at RFP was known to have resulted from recycled uranium processing, and this material contained plutonium, neptunium, and technetium below *de minimis* levels.

KHC (2000a) identified two processes that had the potential for concentrating or releasing transuranic elements or fission products. These processes must be considered in relation to their potential for an external exposure hazard that was not adequately measured by the external dosimetry used at the time. The two processes with potential to concentrate the recycled uranium contaminants were vacuum melting and casting and the "chip roaster."

Information from Fernald initially indicated that the vacuum melting and casting of uranium could be a potential concentration point. The "dross" or "skull" that formed on the top of the casting was more radioactive than the casting. The higher radioactivity was a result of the separation of uranium decay progeny (thorium and protactinium) and potentially the separation of transuranic or fission product contaminants. RFP did not perform analyses for these constituents at that time. Data from the Specific Manufacturing Capability Project at Fernald indicate that no contaminant accumulation occurred as a result of the melting and casting process (KHC 2000a). Even if concentration did occur, the external exposure potential from these contaminants would be a small fraction of the exposure from the concentrated uranium decay progeny and would have been adequately measured by the external dosimetry systems in use at the time.

The conversion of DU oxide in the RFP chip roaster in Building 444 was identified as a potential concentration point for recycled uranium contaminants. In this operation, turnings from machining activities and dross from the melting operation were converted to oxide. RFP has no direct analytical information on contaminant concentrations in the uranium oxide, but associated emissions monitoring indicates no increased levels of transuranic elements (KHC 2000a). Again, concentration of these contaminants would not present an external exposure hazard that would not have been adequately monitored by the external dosimetry systems in use at that time.

6.5.7 Potential Elevated Background Subtraction

ORAUT-PROC-0060, *Occupational Onsite Ambient Dose Reconstruction for DOE Sites* (ORAUT 2006b) identifies a concern that background dose in excess of that identified as onsite ambient background was removed at the time the dosimeters were processed if the background dosimeters received elevated exposure because of their storage in locations where background dose rates were high.

From the start of radiological operations at RFP in 1951 until January 1976, dosimeter background appears to have been determined from either laboratory blanks or control dosimeters that were stored on the storage boards with the dosimeters. There was some discussion that, in that period, storage boards might have been moved to lower dose locations because the background dose from the facility was unacceptably high. To validate (or dispute) this fact, a records review and interview program were initiated. Approximately 18 boxes of external dosimetry program records were reviewed. These records included weekly and monthly status reports from the 1950s, 1960s, and 1970s as well as some technical documents from that period. Approximately 500 pages of documents were identified as potentially relevant to this issue. No evidence of an identified high-background problem was found. No evidence of action to reduce storage-board background was found.

Interviews were conducted with [redacted] retired [redacted] managers. Each of these individuals was asked if they recalled this issue or actions taken in response to such a problem. None recalled storage-board background as a problem. Most recalled that elevated storage background was not significant and did not affect the dosimetry results (ORAUT 2018a).

From this review, it is concluded that elevated ambient levels of external radiation were not a problem at RFP during the period from 1951 to 1976.

From 1977 to February 2000, a plant-wide standard background was subtracted (ORAUT 2018a).

For dosimeters collected in March 2000 through 2003, badge storage-board background dosimeter results were used. The background dosimeter results were averaged over a 5-quarter rolling period and subtracted from the measured dosimeter value. An analysis of this process indicate the average background used was 1.14 ± 1.16 (1 standard deviation) times the previous standard background (1977 to February 2000) (ORAUT 2018a). This information indicates that the background is in excess of that identified in ORAUT-TKBS-0011-4, *Rocky Flats Plant – Occupational Environmental Dose* (ORAUT 2007a, Table 4-3). As indicated above, this dose was subtracted as dosimeter background and indicates an elevated ambient level of external radiation (ORAUT 2005a).

6.5.8 Badge Reading Policy, 1969 to 1970

In 1969 and 1970, RFP implemented a policy of not routinely reading badges for some "low risk" workers. The film badges were exchanged as usual but were not read unless circumstances required it. A zero was then recorded in the workers record. Therefore, all reported zeros for film badges between 1969 and 1970, excluding gamma badges reread for the NDRP, are suspect and should not be used in reconstructing external dose. The worker should be treated as an unmonitored worker. Results reported below the LOD/2, but above zero, are considered valid, and should be used to assess missed dose.

Site quarterly summary data and available NDRP gamma data should be used in conjunction with coworker dose for addressing zeros in the dose record. Gaps in site quarterly summary dosimetry during this time period should not be assessed using adjacent cycle data in accordance with guidance in Section 6.5.3. Gaps in NDRP dosimetry during this time period can be assessed using adjacent cycle data in accordance with guidance in Section 6.5.3.

When assessing a quarter with site quarterly summary data, and no NDRP data, the assignment of coworker dose is based on guidance in Attachment A of ORAUT (2018b). When using site quarterly summary data, the default badge exchange frequencies for 1969 and 1970 in Table 6-2 should be used.

The amount of coworker assigned, when assessing DOE quarterly data, is determined as follows:

1. A quarterly result that was originally a zero in the dosimetry records should be assigned the total number of coworker months in a quarter (consider the impact of partial employment during the quarter, if applicable). Skip the remaining steps below. Otherwise,

2. Determine the number of badges in a quarter based on the badge exchange frequency (consider the impact of partial employment during the quarter, if applicable).

3. A quarterly result that is censored to zero after the LOD/2 process should be treated as a single badge. Proceed to Step 11.

4. Divide the quarterly summary positive results by the dose limits in Table 6-4 for the appropriate badge exchange frequency for 1969 and/or 1970.

5. Round up the fractional number of positive badges in Step 4 to the nearest whole number.

6. Subtract the total number of positive badges determined in Step 5 from the total number of badges in Step 2. Limit the number of positive badges determined in Step 8 by the number of badges in a quarter in Step 2.

7. Divide the quarterly summary positive results by the LOD for 1969 and/or 1970.

8. Round up the fractional number of positive badges in Step 7 to the nearest whole number.

9. Subtract the total number of positive badges determined in Step 8 from the total number of badges in Step 2. Limit the number of positive badges determined in Step 8 by the number of badges in a quarter in Step 2.

10. Determine the median number of reported badges by averaging the results of Step 6 and Step 9. Do not round the number of this result.

11. Determine the number of badge exchange periods for the quarter that need coworker assigned by subtracting the result of Step 3 or Step 10, whichever is applicable, from the number of possible badges in Step 2. Do not round the number of this result.

12. Determine the amount of coworker months for a quarter by dividing the number of badge exchange periods determined in Step 11 by the total number of badges in a quarter and multiplying by the total number of months in a quarter.

6.5.9 Gammacell 220 Cobalt-60 Irradiator

There may have been more than one Gammacell 220 at Rocky Flats. The unit as designed had up to 7 sealed cylinders, each containing up to 3,500 Ci of ^{60}Co (RFETS 1993, pp. 4-5). Separate RFP reports in September 1969 (Kazanjian and Brown 1969, pp. 12, 14) and November 1971 (Lombardi and Donovan 1971, p. 13) describe radiolysis experiments using a Gammacell 220 containing about 3,500 Ci of ^{60}Co. The *Rocky Flats Envision* newsletter claimed in September 1999 that the Gammacell 220 being removed had been at RFP since late 1960s with an initial ~21,000 Ci of ^{60}Co (Nogues 1999, p. 2). Documentation shows the Gammacell 220 in B779, Room 218, was certified with an initial ^{60}Co activity of 21,900 Ci in April 1971 (RFETS 1999c, p. 3) and weighed 8,250 lb (RFETS 1993, p. 4). The ^{60}Co was contained in up to 7 cylinders, arranged radially around the active volume (RFETS 1993, p.5), into which samples were lowered for exposure. The sealed cylinders of ^{60}Co were inaccessible (Ballenger 1992, p. 8) and remained in the irradiator. The size and weight of the Gammacell 220 was such that it had to be lowered through a hole cut in the floor of Room 218 into Room 121 below (RFETS 1999a, undated a, undated b).

A former [redacted] manager responsible for the Gammacell 220 indicated that the unit was rarely used from 1979 until its removal in 1999 [Interview conducted on 01 Feb 2017]. The Gammacell was transferred to JL Shepherd in San Fernando, California after its removal from B779 (RFETS 1998b, 1999).

A ^{60}Co orphan source appeared to be linked in the document with the Gammacell 220 ^{60}Co irradiator (RFETS 1993–2002). The 287-page document describes the orphan source in a Radiological Deficiency Report on the first three pages (RFETS 1993–2002, pp 2-4):

- It was found in a cabinet in Building 779, Room 125 (November 1998);
- It was originally reported to have been disposed of in March 1995;
- There was no accompanying source registry tag;
- No other descriptive information (activity, physical form, etc.) was provided;
- It appears finally to have been disposed of in November 1998.

The remainder of the document consisted of the engineering design package for removing the Gammacell 220 from Building 779 and for its disposal (RFETS 1999b). The Gammacell was located in Room 218 of B779 (RFETS undated a).

The project for removal and disposition of the Gammacell 220 began in May 1999 and was completed in October 1999 (RFETS 1998a, 1999b). The orphan source found in B779, Room 125, was not connected to the Gammacell 220 irradiator. There would have been significantly more concern than was expressed in the Radiological Deficiency Report if the orphan source contained even a fraction of the ^{60}Co encapsulated in each of the Gammacell 220 source cylinders. The orphan source and the Gammacell 220 were in separate rooms in B779. The Gammacell 220 source cylinders were inaccessible and could not be removed for storage in a cabinet. Integrity tests and verification of the Gammacell 220 sources occurred before removal of the irradiator and after the orphan source was discovered (RFETS 1999d, p. 3).

The *Operational Health Physics Audit Report of Radioactive Sources and Radiation Producing Devices* (Rockwell 1987) report provides source control requirements and leak test documentation for the Gammacell 220, for the period 1972 to 1989 and before March 1987, at RFP. It indicates that leak tests of 21 ^{60}Co sources, with a total activity of 22,249 Ci, showed no leaking sources (Rockwell 1987, pp. 5, 6). A September 1992 Operational Safety Analysis of the Gammacell 220 cites hazard controls for elevated gamma levels and loss of containment (RFETS undated c, pp. 4-6):

- A gamma alarm next to the source warned personnel if they need to evacuate;
- Chirpers were worn during operations to warn of release of radioactivity;
- Complete company clothing including safety glasses was worn;
- Full-face respiratory protection was in the operator's possession and ready for use.

An October 1992 RFP Health Physics Report specified semiannual leak tests of ^{60}Co sealed sources with activity >10 µCi (Patel 1992, p. 6). A June 1993 sealed source registry safety evaluation of the Gammacell 220 (registry no. NR-220-D-107-S) specifies leak test intervals not to exceed six months using techniques capable of detecting 0.005 µCi (11,100 dpm) (RFETS 1993, p. 7) (note that this is the U.S. Nuclear Regulatory Commission criterion for leak testing today). A June 1999 Radioactive Source Report specified a semiannual leak test frequency for the Gammacell 220, noting that the last leak test was in January 1999 and the next was scheduled for July 1999 (RFETS 1999c, p. 3). Some leak test results of the Gammacell 220 are available in job specific contamination surveys from 1998 on:

- February 1998. Results of <200 dpm/100 cm^2 removable beta were reported for 15 sample locations on the Gammacell exterior surfaces (RFETS 1998d, pp. 3, 4);

- August 1998. Two sample locations had <6,200 dpm/100 cm^2 removable beta (RFETS 1998c, pp. 3, 5);

- January 1999. Three sample locations had <45.3 dpm/100 cm^2 (less than the minimum detectable amount) removable beta (RFETS 1999d, pp. 3, 5).

No quantitative leak test results are available during or before 1989. However, a 1987 report indicates that of 21 sources (22,249 Ci total activity) surveyed there were no leaking ^{60}Co sealed sources (Rockwell 1987, pp. 5, 6). Therefore, it is assumed that source integrity verification requirements existed sometime before 1989, and that some leak test measurements were conducted. In addition, unmonitored personnel exposure from leaking ^{60}Co sources (including the Gammacell 220) are unlikely. If the Gammacell 220 had leaked, the resulting contamination would have been detected in later surveys, some documentation of which has been captured. Therefore, no additional exposures need to be assessed associated with the Gammacell 220.

6.6 PHOTON DOSE

6.6.1 Energy Groups

The NIOSH Interactive RadioEpidemiological Program (IREP) software for calculating the probability of causation (POC) (NIOSH 2007) contains three photon energy bands:

- Below 30 keV,
- 30 to 250 keV, and
- Above 250 keV.

Separation of the dose from each energy band is required.

6.6.1.1 Default Exposure Spectra

There is limited spectroscopy data that indicate the gamma spectrum in RFP work areas. To estimate the gamma spectrum to which workers were exposed, radionuclide source concentrations (DOE 1980) for weapons-grade plutonium, enriched uranium (EU), and DU were used (freshly separated material) and then decayed for 10 and 30 yr. These decay times enable an understanding of the material to which workers were exposed. DU and EU were routinely handled in the open with no shielding. Plutonium was almost exclusively handled in gloveboxes that provided shielding from the materials. The calculation assumed large pieces of material (infinitely thick in relation to the photon path length in that material) and 1/16-in. stainless steel as the shielding provided by the glovebox. Table 6-8 presents these results.

Table 6-8. Photon energy distributions.

No shielding

Energy (keV)	Fresh EU	10-yr EU	30-yr EU	Fresh DU	10-yr DU	30-yr DU
<30	0%	0%	0%	0%	0%	0%
30–250	100%	99%	98%	100%	3%	3%
>250	0%	1%	2%	0%	97%	97%

1/16-in. steel shielding

Energy (keV)	Fresh Pu	10-yr Pu	30-yr Pu
<30	0%	0%	0%
30–250	100%	85%	88%
>250	0%	15%	11%

Plutonium processed at RFP has varied in age from freshly separated to wastes that have been stored on the site for many years. Using the default assumption that the material is freshly separated maximizes the dose from the 30- to 250-keV photons. Low-energy photons that are shielded in this analysis do, in fact, escape the glovebox through open glove ports and unleaded windows as well as from oxide coated on the interior surfaces of the gloves, especially when they are pulled outside the glovebox for storage to prevent them from being caught in machinery (DOE 2003). It has been estimated that approximately 25% of the dose is from <30-keV photons (ORAUT 2018a). Low-energy (<30-keV) photon exposure is estimated from reported penetrating and skin photon dose by use of the algorithms in Section 6.6.1.2.

Protactinium-234m is a decay product in the ^{238}U (DU) decay chain and emits a 2.29-MeV beta particle. Therefore, a significant quantity of photons from bremsstrahlung radiation is produced and contributes photons of intermediate energy (30 to 250 keV). These photons are not included in

Table 6-8. Bremsstrahlung radiation can contribute up to 40% of the photon dose from uranium metal (DOE 2001). This decay product grows in fairly rapidly and is present in equilibrium quantities for most DU that was processed at RFP. It is appropriate to use the default assumption for DU that 50% of the dose is contributed by photons in the 30- to 250-keV photon energy range and 50% of the dose is a result of exposure from photons in the >250-keV photon energy range.

Although EU has significantly less in-growth of ^{234m}Pa, ^{235}U and its decay products emit 185.7-keV photons 57% of the time and 143.8-keV photons 11% of the time. These photons dominate the measured photon energy spectra. Therefore, for EU, it is appropriate to use the default assumption that all of the photon dose is a result of exposure in the 30- to 250-keV photon energy range. This assumption is favorable to claimants. The default assumptions are shown in Table 6-9.

Table 6-9. Default photon energy distributions for gamma dose rates from field measurements.[a]

Energy (keV)	Plutonium	EU	DU
<30	25%	0%	0%
30–250	75%	100%	50%
>250	0%	0%	50%

a. In cases where the material source is unknown the most favorable to the claimant scenario, that is plausible for the given claim, should be applied.

Table 6-9 of the RFP External TBD indicates a default photon energy distribution of 25% <30 keV and 75% 30-250 keV for plutonium facilities. This energy distribution refers to general photon fields, and would be used only if gamma dose rate data from field measurements were available instead of dosimetry results. The 25% <30 keV and 75% 30-250 keV photons energy split in Table 6-9 for plutonium workers would apply in a rare case where a worker was unmonitored and dose might need to be assigned using external dose rate data in the claim.

The RFP energy distributions applied for plutonium facilities for recorded dosimetry data or coworker dose data for dose reconstruction are shallow dose assigned as 100% <30 keV photons, and photon deep dose assigned as 100% 30-250 keV photons. The assumption of photon deep dose assigned as 100% 30–250 keV photons is claimant-favorable based on fresh plutonium from Table 6-8. The shallow and photon doses based on RFP dosimetry results for the appropriate eras are assigned in accordance with the algorithms in Section 6.6.1.2.

6.6.1.2 Dosimeter-Indicated Photon Energy

In the discussion below, a portion of the skin dose as reported in the records for plutonium facility workers is interpreted as exposure to low-energy photons (<30 keV) and not strictly as *Hp(0.07)* (ORAUT 2018a).

6.6.1.2.1 Pre-1960

The two-element film dosimeter used at RFP before 1960 had both OW and cadmium (Cd) filter components. Some dosimetry records indicate that the dose was determined from the film darkening under each dosimeter element, as well as the recorded skin and penetrating dose values. Based on review of some of these data and data after 1960, the skin dose in this era was calculated as a sum of each of the two windows (OW + Cd). The dosimeter could not effectively measure the 60-keV photons, and the reported penetrating (Pen) dose was therefore calculated from the measured OW and Cd component doses using the algorithm Pen = 50% • OW + Cd, and the reported Skin dose was calculated as Skin= OW + Cd. The addition of 50% of the recorded OW dose to the recorded Cd dose was determined by Rocky Flats staff to correct the reported Pen dose for this underestimation (i.e., the relative ratio of the 60-keV photon dose to OW dose contribution was determined to be about 0.5).

Therefore, the sum of the low-energy (<30 keV photons or >15 keV electrons) and the photon doses (30- to 250-keV and/or >250-keV photons as applicable) exceeds the original reported skin dose. As a result, the following method should be used to estimate the low-energy photon dose for plutonium workers, intermediate/high-energy photons for plutonium and uranium workers, and the >15-keV electrons for uranium workers:

$$electrons_{>15\text{keV}} \text{ or } photon_{<30\text{keV}} = [Skin - Pen] \div 0.5 = OW \qquad (6\text{-}1)$$

$$photon_{(30-250\text{keV})} + photon_{(>250\text{keV})} = Pen = CD + 0.5OW \qquad (6\text{-}2)$$

The equations above should be used with the facility radiation characteristics listed for Rocky Flats facilities in Tables 6-10 for plutonium, DU, or EU facilities to assign measured dose in the appropriate electron and photon ranges and proportions. The use of these equations might lead to a slight overestimate of electron dose. Alternatively, if original component data are available in the dosimetry record, Pen and Skin doses can be calculated using the Cd and OW results.

6.6.1.2.2 <u>1960 to 1970</u>

The three-element film dosimeter used at RFP from 1960 to 1969 also had an OW, a Cd filter, and an additional brass (Br) filter providing half the filtration of the Cd. The Br filter was added to more accurately measure the 60-keV photons. This dosimeter was phased out during the year 1970.

Some dosimetry records (see Figure A-7) indicate that the dose was determined from the film darkening under each dosimeter element, as well as the recorded skin and penetrating dose values. Based on review of some of these data, the skin dose in this era was calculated as a sum of each of the three windows (OW + Cd + Br). The penetrating dose was calculated by adding the Cd + Br + 35% • OW. The 35% OW addition to the deep dose was a DOE weapons complex standard practice during this period (including the Hanford and Savannah River Sites) to account for some low-energy photon (<30 keV) contribution to deep dose.

To properly reconstruct the low-energy and intermediate-energy photon dose between 1960 and 1970, the following reverse algorithm should be applied:

$$electron_{>15\text{keV}} \text{ or } photon_{<30\text{keV}} = [Skin - Pen] \div 0.65 = OW \qquad (6\text{-}3)$$

$$photon_{30-250\text{ keV}} + photon_{>250\text{keV}} = Skin - \left(electron_{>15\text{keV}} \text{ or } photon_{<30\text{keV}}\right) = BR + CD \qquad (6\text{-}4)$$

The equations above should be used with the facility radiation characteristics listed for Rocky Flats facilities in Tables 6-10 for plutonium, DU, or EU facilities to assign measured dose in the appropriate electron and photon ranges and proportions. As an alternative, if original component data are available in the dosimetry record, Pen and Skin doses can be calculated using the Cd, Br, and OW results.

6.6.1.2.3 <u>1970 to Present</u>

Starting in 1970, RFP used TLDs to measure photon dose, which provided substantially better performance than film. The TLD materials used were much more tissue-equivalent and the response much less energy-dependent. Dosimeters were calibrated to more appropriate photon energies, and filter design had advanced. Although various chip and filter combinations were used, the data in DOE dosimetry files do not generally include dose from individual components similar to the Cd, Br, and OW categories from the film era. Because doses in the era of TLD dosimetry at RFP are felt to provide accurate measurements of skin and deep doses, the following relationships should be used for this period:

$$electrons_{>15\text{keV}} \text{ or } photon_{<30\text{keV}} = Skin - Pen \tag{6-5}$$

$$photon_{30-250\text{ keV}} + photon_{>250\text{keV}} = Pen \tag{6-6}$$

The equations above should be used with the facility radiation characteristics listed for Rocky Flats facilities in Tables 6-10 for plutonium, DU, or EU facilities to assign measured dose in the appropriate electron and photon ranges and proportions.

6.6.2 Calibration Factor

6.6.2.1 Reported-Dose-to-Organ-Dose Conversion Factor Units

Standard X-ray film was initially used for photon dosimetry at RFP. This film was processed by Los Alamos National Laboratory (LANL). This was followed by a period in which a subcontractor performed the processing, after which RFP took over the processing.

According to ORAUT-TKBS-0010-6, *Los Alamos National Laboratory – Occupational External Dose*, the LANL dosimetry results were calibrated in roentgens (ORAUT 2013).

When RFP provided the film dosimetry, it appears that roentgens continued as the unit of calibration (Mann 1967). It is reasonable to assume that this continued until calibration of the Panasonic TLD dosimetry system, which was performed using DOE Laboratory Accreditation Program (DOELAP) sources at Pacific Northwest Laboratory (PNL). DOELAP sources have been used since that time. The personal dose equivalent [*Hp(10)*] is the appropriate unit to use for this period. Table 6-10 summarizes dose units to use for organ dose conversion factors.

Table 6-10. Photon dose units for use with organ dose conversion factors.[a]

Period	Unit
1951–1982	roentgens
1982–2005	*Hp(10)*

a. Source: See Section 6.6.2.1.

Conversion to organ dose is accomplished using the factors provided in Appendix A of NIOSH (2007). Plutonium-specific photon dose conversion factors are provided in Table 4.1a of that document and should be applied for plutonium exposures at RFP.

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 initially used at RFP is similar to that developed at the University of Chicago and used at other U.S. Atomic Energy Commission (AEC, a DOE predecessor agency) sites. All of these badges used X-ray film surrounded with a metal badge holder. They had an OW and an area covered with 1 mm of silver, tin, or cadmium (Alvarez et al. 2003). A PNL study of this two-element dosimeter (Wilson et al. 1990) identified a detection level of about 40 mR at the upper 95% confidence level for radium gamma radiation. Improved film, implemented at Hanford in 1960 (Wilson et al. 1990), reduced this detection level to about 15 mR. Information found at RFP indicated that a DuPont 558 film packet was used in 1964 (Mann 1964). This packet contained a DuPont 508 sensitive film and the insensitive DuPont 1290 film. The 1290 film was not processed unless the 508 film was too exposed to read. It is not clear if RFP used the earlier 502 film or, if so, when it changed to the 508 film. Hanford changed to 508 film in 1960 (Wilson et al. 1990). It is favorable to claimants to assume that RFP used the less sensitive 502 film until 1960 and then used the more sensitive 508 film. The film LOD selected is that determined by Wilson et al. (1990) for the Hanford badge.

In 1969, RFP started using Harshaw TLD chips to measure photon dose. Again, this dosimeter was similar to one used at Hanford. Wilson et al. (1990) identified an estimated detection level of 20 mR for radium gamma detection. The LOD information has not been identified specifically for TLD implementation at RFP, but is believed to be similar to that for the Hanford dosimeter (ORAUT 2018a).

The switch at RFP to the Panasonic dosimeter in 1983 achieved improved sensitivity. Information on the LOD during this period has not been identified, so the value of 20 mrem, similar to that achieved in 1982, is recommended as favorable to claimants.

In 1992, a study was performed to reduce the variability in low-dose measurements. An uncertainty criterion incorporated in the algorithm resulted in more stable dose measurements at low doses. This resulted in an estimated LOD of 10 mrem. A dose-reporting threshold of 10 mrem was implemented. Any dose below this was reported as zero. Table 6-11 lists photon LODs for the RFP dosimeters.

Table 6-11. Photon LODs.[a]

Period	LOD
1951–1968	40 mR
1968–1982	20 mR
1983–1992	20 mrem
1993–2004	10 mrem
2005	5 mrem

a. Source: See Section 6.6.3.1.

6.6.3.2 Number of Zero Readings

Section 6.5.1 of this TBD discusses the determination of the number of zero readings.

6.6.3.3 Determination of Missed Dose

Determination of missed dose is performed using *LOD*/2 times the number of zero readings, as discussed in Section 2.1.2.2 of NIOSH (2007). For the period 1977 to 2005, the number of zero readings can be determined directly from the dosimetry data. The missed dose is assumed to have a lognormal distribution with central tendency *nLOD*/2, and the upper 95% dose is *nLOD*, where *n* is the number of zero readings. If the number of zero readings cannot be determined, it must be estimated under the assumption that prorated dose limits were not exceeded. Section 6.5.1 of this TBD and Section 2.1.2.3 of NIOSH (2007) discuss this estimate. In this case, the estimate is assumed to have a lognormal distribution (NIOSH 2007, Section 2.1.2.4).

6.6.3.4 Unmonitored Energy Range

All dosimeter types used at RFP were calibrated and their responses were corrected for photon energies that result in worker dose in the work areas (low-energy X-rays, americium photons, and high-energy photons). No corrections for unmonitored photon energy range are appropriate.

Baker (2002) states that the two-element film dosimeter used at RFP was similar to those used at other sites. The Savannah River Site TBD (ORAUT 2005a) discusses the response of this dosimeter. These documents address the significant overresponse of film to low photon energies. The dosimeter (OW) was calibrated with low-energy photons. To correct for this overresponse, a portion of the OW dose was added to the deep dose measured under the 1-mm cadmium filter. There is evidence (Falk undated) that this correction was used at RFP. This indicates that the early film dosimeter was corrected for energy response. No missed photon dose correction factor is appropriate for this dosimetry system.

The multielement film dosimeter used at RFP provided better energy response to measure worker dose more accurately. Although little information is available on this dosimetry system, it appears that corrections were incorporated to prevent missed photon dose (Baker 2002; Putzier 1982, p. 1). Therefore, no missed photon dose correction factor is appropriate for this dosimetry system.

Harshaw TLD chips were used at RFP in an interim neutron film/photon TLD badge and then in the RFP TLD badge. These dosimeter elements were shielded and of various thicknesses. Most importantly, the TLD elements were relatively tissue-equivalent in relation to photon response (ORAUT 2006a, Section A.2.1.2) and unlikely to have missed photon dose in an energy range to which workers were exposed. No missed dose correction is appropriate for this dosimetry system.

The initial implementation of the Panasonic TLD system was based on a range of DOELAP exposure categories. The response of the dosimeter was evaluated in relation to these exposures, and the algorithm was derived from these exposures. Therefore, the initial implementation of the Panasonic TLD system and the later DOELAP-accredited operation of that system are unlikely to have missed photon dose in an energy range to which workers could be exposed. No missed-dose correction is appropriate for this dosimetry system.

6.6.4 Geometry

6.6.4.1 Angular Dependence

The film dosimeters used at RFP had varying angular responses. Dosimeters were not always exposed perpendicularly, which resulted in varying responses in relation to actual worker exposure.

The film dosimeter experienced an apparent increase in dose when exposed from the edge because photons were able to expose the film without passing through the filter. RFP has generated limited experimental exposure data that demonstrate this phenomenon qualitatively. Edge-on exposure with 60-keV photons indicated a factor of 4 overresponse.

TLD dosimeters are likely to experience the same problem. No information on this issue in relation to the neutron film/photon TLD badge or the Harshaw TLD badge photon response has been found (ORAUT 2018a).

Quantitative information is available for the RFP Panasonic dosimeter (KHC 2001, Section 04.06.2). The dosimeter was tested in 1993 and 1996. For eight DOELAP exposure categories, element responses generally decreased as the angle increased. For angles of incidence from –30° to +30°, the ratio of reported dose to delivered dose ranged from 0.88 to 0.99 for photons.

There are insufficient data to identify an angular dependence correction to apply to any of the dosimeters. Because any correction would reduce the dose, or in the case of the Panasonic dosimeter increase the dose only slightly, not including a correction factor is generally favorable to claimants.

6.6.4.2 Exposure Geometry

A 100% AP exposure geometry for all external doses at Rocky Flats should be applied, in accordance with Section 6.5.4.

6.6.5 Uncertainty

OCAS-IG-001 describes methods for quantification of laboratory uncertainty associated with reading film and TLDs (NIOSH 2007). These methods provide a statistical treatment of the variability associated with reading dosimeters in the laboratory.

6.6.5.1 Film

RFP used film to measure photons between 1951 and 1969. The DuPont 558 film packet with the sensitive 508 film was used in 1964 (Mann 1964). The 508 film was the successor to 502 film, and each has a useful range from 10 or 20 mR up to approximately 10 R (Lalos 1989). It is not clear if RFP used 502 film or, if so, 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. This method is detailed in *Film Badge Dosimetry in Atmospheric Nuclear Tests* (Lalos 1989). The discussion of this method cites sensitivity parameters for 502 film. A spreadsheet was developed using these parameters to match the example provided and then modified with RFP-specific parameters. RFP densitometer readings appear to be a factor of 1,000 greater than those illustrated in the example. It is believed, based on review of the records, that these density units are thousandths (*milli*-) density units. The results are consistent with the example when this assumption is used. A review of dosimetry worksheets indicated that density readings were recorded to the nearest whole number; therefore, the densitometer reading uncertainty is assumed to be ±0.5 density unit. A review of RFP density-to-dose conversion charts from 1966 to 1968 made a determination of film sensitivity possible. Using this parameter, the upper 95% confidence doses for various dosimeter readings were calculated.

Although the uncertainty is lower at higher exposures, the National Research Council methodology recognizes that additional uncertainty contributed by variability in calibration, film processing, and reading the calibration curve prevents the upper 95% confidence dose from falling below 120% of the reported exposure. This limitation has been applied here (Table 6-12), and it affects the estimate of the upper 95% confidence dose above 27 mR. Table 6-13 lists uncertainties for photon film dose.

Table 6-12. Uncertainty for photon film dose.

Dose (mR)	Upper 95% confidence photon dose (mR)
1	6
2	7
5	10
10	15
20	25
50	60
100	120
200	240
500	600
1,000	1,200
2,000	2,400

Table 6-13. Uncertainty for loose-chip TLD photon dose.

Dose	Upper 95% confidence dose (mrem) 1969–1982
1	21
2	22
5	25
10	30
20	40
50	72
100	126
200	239
500	585
1,000	1,166
2,000	2,330

A default value of 1.2 can be used for the photon film dose uncertainty multiplier.

6.6.5.2 Thermoluminescent Dosimeter

TLDs provided improved photon dosimetry. This section estimates the uncertainty associated with this type of dosimeter for the early years of use and then discusses the measured uncertainties after 1983 when DOELAP performance testing began.

6.6.5.2.1 Loose-Chip Thermoluminescent Dosimeters

Harshaw TLD chips were used to measure photon dose at RFP from 1969 to 1982. These chips were carried in a dosimeter holder but were removed to be read (thus the term *loose*). A calculation was performed to estimate the uncertainty associated with reading the photon dose from these dosimeters.

Little information has been found that describes the variability of response when these chips were in service. A chip sorting procedure was used to remove chips from service that had responded outside set criteria (Link and Pennock 1983). The procedure was to expose the chips to a 1,000-mrem dose equivalent using a ^{137}Cs source. The chips were then read, and any that responded outside the ±0.165 of the mean were removed from use. Assuming that the chip response had a normal distribution so that 5% of the chips were removed during the sorting process (an assumption favorable to claimants), the upper and lower cutoffs would have to be 1.96 standard deviations above/below the existing chip population. Therefore, the initial chip population standard deviation is (0.165 × 1,000) ÷ 1.96 = 84.18 or 8.4%. Performing a Monte Carlo simulation on this distribution, removal of the chips outside the criteria results in a truncated normal distribution with a standard deviation of 7.4%. The higher 8.4% result was selected as a parameter that describes the chip population routinely used to measure dose (an assumption favorable to claimants). Using the Simplified Dosimetry Uncertainty calculation recommended by NIOSH (2007), and assuming the critical level is the LOD estimated in Section 6.3.1 of this TBD, Table 6-13 lists the upper 95% confidence doses.

If all individual dosimeter readings are over 100 mrem, then a factor of 1.26 can be used. Otherwise, a default value of 2.0 should be used for the photon TLD dose uncertainty multiplier.

6.6.5.2.2 Panasonic Thermoluminescent Dosimeter

Table 6-14 summarizes the uncertainty associated with DOELAP-accredited Panasonic dosimeter dose readings. These values were calculated using the TLD uncertainty methodology referenced in Section 2.1.1.3.2 of NIOSH (2007). Uncertainty is quantified in the dosimetry program documentation available for a DOELAP-accredited program. The standard deviation for null readings is from a study performed at RFP (KHC 2001), and the relative standard deviation at high readings is the standard deviation of the DOELAP performance test results (KHC 2001; Stanford 1990). The reasonable worst case values from these studies were selected to provide a result favorable to claimants. No data are available for the initial algorithm implementation of the Panasonic dosimetry system (1983 to 1989). Similar performance to that after 1990 is assumed (ORAUT 2018a).

Table 6-14. Uncertainty for DOELAP-accredited TLD photon dose (upper 95% confidence dose in mrem).

Dose	Panasonic dosimeter, 1983–1989	DOELAP-accredited Panasonic dosimeter, 1990–1998	DOELAP-accredited Panasonic dosimeter, 1999–2004
1	1	1	1
2	2	2	2
5	6[a]	6[a]	6[b]
10	12	12	12
20	25	25	24
50	61	61	59
100	123	123	118
200	245	245	235
500	614	614	588
1,000	1,227	1,227	1,176
2,000	2,455	2,455	2,353

a. 1.23 multiplier for any dose greater than 2 mrem.
b. 1.18 multiplier for any dose greater than 2 mrem.

A default value of 1.23 for 1983 to 1998 and 1.18 for 1999 to 2004 can be used for the photon TLD dose uncertainty multiplier.

6.7 NEUTRON DOSE

6.7.1 Energy Groups

The measured neutron dose must be divided into energy groups consistent with the dose conversion factors provided in Appendix B of NIOSH (2007). These energy groups and the associated radiation weighting factors (w_R) from International Commission on Radiological Protection (ICRP) Publication 60 (ICRP 1991) are:

- <0.01 MeV (w_R = 5),
- 0.01 to 0.1 MeV (w_R = 10),
- 0.1 to 2 MeV (w_R = 20),
- 2 to 20 MeV (w_R = 10), and
- >20 MeV (w_R = 5).

The analysis in this section is based on neutron spectra measured at RFP (Brackenbush et al. 1989).

6.7.1.1 Exposure Spectra

In August and September 1988, PNL provided technical assistance to RFP for neutron and photon dose measurements (Brackenbush et al. 1989). This activity performed multisphere neutron measurements in representative high-neutron dose situations. The measurements included production locations, mockup situations in which plutonium parts were in a glovebox where measurements could be performed, and waste storage locations. Neutron shielding similar to that experienced by workers in that area was in place. Relatively long (several-day) measurements were required to acquire sufficient dose to achieve accurate results.

The neutron spectra were determined from the multisphere measurements and presented in the PNL report. Dose rate was derived from neutron flux density information and flux-to-dose conversion factors from National Council on Radiation Protection and Measurements (NCRP) Report 38 (NCRP 1971). No neutron flux was identified for energies greater than 20 MeV. For this TBD, the dose rate information was divided into energy groups as required for NIOSH dose reconstruction. Table 6-15 lists this information.

Table 6-15. Neutron dose measurements divided into energy groups (fraction of dose per energy group).[a]

Location	Dose rate (rem/hr)	Avg. energy (MeV)	<10 keV	10–100 keV	0.10–2 MeV	2–20 MeV	>20 MeV
Building 771 fluorinator line	6.07E-04	0.33	0.090	0.028	0.678	0.204	0.000
Building 771 Tank 554	4.65E-03	0.91	0.025	0.014	0.600	0.361	0.000
Building 776 molten salt glovebox	1.71E-03	0.45	0.038	0.023	0.840	0.099	0.000
Building 776 molten salt storage vault	8.84E-03	0.39	0.085	0.015	0.711	0.189	0.000
Building 776 drum storage	2.46E-02	0.63	0.027	0.034	0.689	0.250	0.000
Building 707 high dose pit	7.35E-04	1.96	0.006	0.006	0.437	0.552	0.000
Building 707 low dose pit	2.88E-04	0.92	0.015	0.009	0.758	0.218	0.000
Building 707 oxide can	1.43E-03	0.85	0.018	0.019	0.676	0.286	0.000
Building 707 plutonium ingot	1.98E-03	1.00	0.014	0.002	0.791	0.193	0.000
Mean	N/A	N/A	**0.035**	**0.017**	**0.687**	**0.261**	N/A
Standard deviation	N/A	N/A	**0.031**	**0.010**	**0.117**	**0.130**	N/A

a. N/A = not applicable.

6.7.1.2 Reported Dose to Energy Groups

This information does not show a clear pattern. Therefore, it is appropriate to apportion dose based on the mean breakdown listed in Table 6-15. Table 6-16 lists the default values selected from Table 6-15 for dose reconstruction (ORAUT 2018a).

Table 6-16. Default neutron energy distribution.

Neutron energy intervals	Fraction of dose (NCRP 38)	Dose multiplier (ICRP 60)	Dose multiplier[a]
<10 keV	0.035	2.13	0.0755
10–100 keV	0.017	1.86	0.0309
0.1–2 MeV	0.687	1.91	1.31
2.0–20 MeV	0.261	1.32	0.345
>20 MeV	0	None	None

a. Multiply the reported dose by these factors to determine the ICRP 60 neutron dose for each neutron energy interval.

The doses and fractions discussed above are based on quality factors published in NCRP (1971). NIOSH (2007) indicates the use of w_Rs from ICRP Publication 60 (ICRP 1991). To perform this correction, the neutron energy deposition values in rad for each energy were multiplied by the ICRP w_R to determine the corrected dose equivalent. These values were totaled for each neutron energy interval used in this dose reconstruction and compared with the value determined previously using quality factors from NCRP (1971). Column 3 of Table 6-16 lists the multipliers that were determined for each neutron energy interval. The fraction of the dose using NCRP (1971) quality factors and the dose multiplier using ICRP (1991) w_Rs were combined to determine a dose multiplier (column 4 of Table 6-16). The neutron dose reported in the worker's dose record should be multiplied by these factors to determine the ICRP (1991) neutron dose for each neutron energy interval.

6.7.2 Calibration Factor

6.7.2.1 Dosimeter-Specific Quality Factor Conversion

The correction factors to convert from NCRP (1971) quality factors used in the neutron spectra measurements and the ICRP (1991) w_Rs are discussed in Section 6.7.1.2 and listed in Table 6-16. Conversion to organ dose is accomplished using the factors provided in Appendix A of NIOSH (2007).

6.7.2.2 Reported-Dose-to-Organ-Dose Conversion Factor Units

RFP initially used neutron track plates. These dosimetry elements were provided and processed by LANL. DDE is the unit determined to be appropriate (ORAUT 2013).

Neutron film was initially calibrated with an apparently unmoderated polonium-beryllium source. In 1962 or 1963, this was changed to plutonium fluoride (PuF_4) (Mann and Boss 1963). The dose rate assigned to the source was the total dose for an energy of 1.4 MeV from the National Bureau of Standards Handbook 63 (NBS 1957). A set of polyethylene moderators was constructed. The spectra from these moderated sources compared well with work area spectra measured with a precision long counter and a series of paraffin moderators fitted over the counter (Mann and Boss 1963). Ambient dose equivalent [$H^*(10)$] is appropriate for this dosimeter.

Harshaw TLDs at RFP were initially calibrated using a 210-g PuF_4 source built at RFP and calibrated at the LANL standard pile, which was established as a neutron flux standard (Mann and Boss 1963). A set of polyethylene moderators was constructed to provide various degrees of moderation. The bare PuF_4 source dose rate was calculated using neutron spectra from an unknown reference document and quality factors published in DOE Orders (Falk 1975). The dose rates for the moderated spectra were measured with currently available neutron dose rate instrumentation. The PuF_4 source was placed in storage in about 1975 and replaced with a commercially manufactured and calibrated ^{252}Cf source. The calculation of the dose rate used a published spectrum and dose rate (Barker 1969). A set of polyethylene moderators was manufactured for this source and ambient dose equivalent rates were determined in a manner similar to that used for the PuF_4 source. Therefore, the ambient dose equivalent [$H^*(10)$] is the appropriate unit for this period.

Panasonic TLDs at RFP were calibrated with DOELAP exposure standards. In the early 1980s, PNL was developing the neutron standards that were used for the original DOELAP performance testing. The development of all Panasonic dosimeter algorithms used at RFP was based primarily on these exposures. Therefore, the DDE [$H_{p,slab}(10)$] is appropriate.

Table 6-17 summarizes the dose units to use for organ dose conversion factors.

Table 6-17. Neutron dose units for use with organ dose conversion factors.

Period	Unit
1951–1983	$H^*(10)$
1983–2005	$H_{p,slab}(10)$

6.7.3 Missed Dose

6.7.3.1 Limit of Detection

LANL processed neutron track plates for RFP from 1951 to 1956. The performance of this system is documented in ORAUT (2013). The minimum detectable dose is identified as <50 mrem.

In 1957, RFP switched to NTA film that was processed and read by a subcontractor. Little is known about this processing period, so again an LOD of 50 mrem is assumed.

Beginning in July 1958, RFP processed NTA film at the site. The NDRP (Falk et al. 2005) assembled a processing history that is summarized in Table 6-18. Based on a background (blank) reading of 16 tracks per 10 mm^2 reported by Mann and Boss (1963) for 1962, LODs were calculated based on the most conservative calibration factor.

Table 6-18. Neutron film track counting detail.[a]

Date	Determined positive	Calibration ($mrem/track/mm^2$)	LOD (mrem)
1959	>2 × blank	40	128
1960	>2 × blank	40	128
1961	>1.5 × blank	40	96
1962	>blank + 1.65 × sqrt(blank)	40 or 100	226
1963	>blank + 1.65 × sqrt(blank)	100	226
1964	>2 × blank	100 or 70	320
1965	>2 × blank or all	70 or 40	224
1966	All	110	Not determined

a. sqrt = square root.

Mann and Boss (1963) determined that a typical background film for 2 weeks had 16 tracks per 10 mm^2. Using three times the standard deviation of the background and a 10-mrem/track calibration factor, the minimum detectable dose is 120 mrem.

Based on the LOD, the value most favorable to claimants was selected for each year. The estimates from Mann and Boss (1963) were used for years when LODs were not used or not known.

In 1971, RFP started using an albedo neutron TLD. Documentation of the research performed to develop this dosimeter (Falk 1971) indicates a practical lower neutron dose limit of 10 to 20 mrem in the presence of a photon dose as high as 100 mrem. The upper limit of this estimate was selected as the LOD for this dosimeter.

In 1983, the Panasonic UD-809 dosimeter was introduced at RFP to measure neutrons. Data are not available on the LOD for this dosimeter system. Because the hardware is the same as that used in 1990, it was assumed to be similar to performance of the system at that time. The assumed LOD is 32 mrem.

In 1990, an algorithm update was incorporated in the Panasonic dosimetry system (Stanford 1990). The documentation cites a minimum detectable neutron dose of 15 to 32 mrem for a moderated ^{252}Cf source.

In 1993, an algorithm update was incorporated in the Panasonic dosimetry system (KHC 2001) to include element reading uncertainty controls to reduce large dose fluctuations at low dose. This update, which has passed DOELAP performance testing, results in a stated minimum response for routine RFP neutron fields of approximately 15 mrem. Table 6-19 includes this value.

6.7.3.2 Number of Zero Readings

Section 6.5.1 of this TBD discusses the number of zero readings.

Table 6-19. Neutron LODs (mrem).

Period	LOD
1951–1958	50
1959–1960	128
1961	120
1962–1963	226
1964	320
1965	224
1966–1970	120
1971–1982	20
1983–1992	32
1993–2004	15
2005	20

6.7.3.3 Neutron Dose Reconstruction Project

In the early 1990s, RFP addressed the issue of neutron film processing. It had been long recognized that, in the dosimetry laboratory, human factors associated with reading large numbers of neutron films under a microscope can significantly affect neutron dosimetry results. A pilot study in 1994 reevaluated neutron doses for selected plutonium workers. This study indicated that the original evaluations of films might have contained significant errors, and that the resultant neutron doses might be significantly higher or lower than the doses actually received. The NDRP was initiated to provide current and former radiation workers an assessment of the neutron exposure received in the plutonium production facilities. The scope of this project covered 1952 to 1970.

Two methods were used to identify workers for evaluation by the NDRP. The initial method was identification of workers using the neutron dosimetry worksheets. These sheets identified those workers assigned neutron-sensitive elements (i.e., neutron films or glass plates). A portion of the neutron worksheets indicates issue of neutron dosimeters to personnel whose home building assignment was not a plutonium production building (such as Buildings 21, 22, 23, 34, 44, 81, and 86). These individuals worked in non-neutron buildings but were issued neutron dosimeters because they occasionally performed work activities in plutonium production buildings. Examples of these job descriptions include guards, radiation monitors, technical researchers, and uranium process operators.

The second identification method was through use of the beta-gamma worksheets for plutonium production buildings. The analysis used only the beta-gamma worksheets from the plutonium production buildings (any building with a number starting with 7), Buildings 91 and 86, and the combined worksheets for Buildings 21, 22, and 23. The rosters from the beta-gamma worksheets for these buildings were used to identify workers. Beta-gamma worksheets for other buildings were not used.

The NDRP data are in three main types of image files. The NDRP protocol document contains detailed descriptions of the content of these files (Falk et al. 2005).

- Neutron Dose Summary. Yearly summary of the neutron dose components, the errors associated with the values, and reconstructed gamma dose.
- Neutron Dose Detail. Details, by exchange period in a given year, of the neutron dose components.
- Individual Timeline. Further details by exchange period in a given year about the original neutron dose, calculation of NDRP dose, building location, and penetrating gamma dose.

The total neutron dose needed for dose reconstruction consists of three quantities that are listed in the summary and detail presentations. These quantities are:

- Original neutron dose. The original neutron dose equivalent that was read from the film or glass plate.

- Non-affected original neutron dose. The original neutron dose equivalent that was not affected by an NDRP dose based on a reread film or glass plate. A blank in this field indicates either that the original neutron dose was affected or that there was no original neutron dose on the dosimetry worksheet for a given monitoring period.

- NDRP neutron dose. The neutron dose estimate from the NDRP evaluation (from reread films or glass plates). A blank in this field indicates either that the original neutron dose was verified to be correct or that the original film or plates were unreadable.

- Notional neutron dose. The neutron dose equivalent estimated by the NDRP evaluation for each gap. Notional dose is a weighted combination of two dose determination methods. Method 1 is based on the worker's average neutron dose per day obtained from films reevaluated by the NDRP for a given calendar year and building. Method 2 is based on applying an average neutron-to-gamma ratio to reported penetrating gamma doses for a given building and calendar year. Section 11.3 of Falk et al. (2005) contains a comprehensive description of the notional dose calculation. A blank in this field indicates that the original dose report was correct or that the reread film or plate (dose under the "NDRP Neutron Dose" heading) was adequate to replace the original film, or that there was no indication of neutron exposure based on the buildings the employee was in and that there was no gamma dose that could be used to estimate the exposure.

The Neutron Dose Summary file provides error values for the annual doses in the form of standard deviations (1 sigma) for the NDRP and notional doses. The NDRP and notional doses have normal distributions with 1-sigma error values. The non-affected dose also has a normal distribution, but dose reconstructors must calculate the error associated with this component in accordance with NIOSH (2007).

Only a limited portion of the NDRP neutron dose components can be used in dose reconstructions:

- 1952 through 1966. Only reported non-affected original neutron dose and NDRP neutron dose should be used in the reconstruction. Original and notional doses should not be used in the reconstruction of neutron doses. During periods where only original and notional doses are reported, the worker should be treated as an unmonitored worker. Unmonitored neutron dose cannot be reconstructed during this period. However, where only original and notional doses are reported for a badge and there is adequate adjacent NDRP or non-affected original neutron data for a claim, these neutron dose short term gaps (i.e., 3 months or less) can be filled in according to NIOSH 2007. The dose estimate is still considered a partial estimate.

- 1967 through 1970. Only reported non-affected original neutron dose and NDRP neutron dose should be used in the reconstruction. Original and notional doses should not be used in the reconstruction of neutron doses. During periods where only original and notional doses are reported, the worker should be treated as an unmonitored worker. Original and notional neutron dose short term gaps (i.e., 3 months or less) may be filled in based on adjacent cycle non-affected original neutron dose and NDRP data. Coworker data should be used in reconstructing unmonitored neutron dose during this period for larger gaps in the neutron dosimetry data.

The NDRP also reported gamma doses. These doses only include those gamma doses that were in some way used to estimate neutron dose and, therefore, are usually less than the DOE dosimetry reports from the site. In some cases, the gamma dose in the NDRP evaluation files is greater than the penetrating gamma dose reported in the DOE site dosimetry files. In that event, the greater dose should be used for maximizing and best-estimate cases. The smaller dose may be used for minimizing cases.

For workers who had wrist dosimetry but no whole-body dosimetry, the NDRP project calculated a reconstructed gamma dose based on a ratio of wrist to whole-body dose. Both the Summary file and the gamma section of the Individual Timeline file list this dose denoted by an asterisk (*). Because this gamma dose does not appear in the original DOE data, dose reconstructors should add it to the reconstruction.

The Individual Timeline files provide gamma data for each readout cycle that was needed to estimate neutron dose. As discussed above, the gamma data are not necessarily complete for any year (including 1970), because that was not the purpose of the NDRP evaluation and so the data cannot be used to directly estimate the number of recorded zeros. However, the reported positive results can be subtracted from the maximum number of likely zeros based on this TBD; this would represent the maximum number of zeros possible. The minimum number of zeros can be estimated by directly counting reported zeros in the Individual Timeline file. A best estimate of zeros can be determined using the original site quarterly DOE data and the approach from ORAUT (2018b). These data will allow more accurate estimation of the number of recorded zero doses for purposes of calculating the missed gamma dose using the LOD/2 method. The missed zeros using original site quarterly DOE data and the approach from ORAUT (2018b) can be compared with the number of zeros based on the NDRP data, and the higher of the two should be assigned.

Blank NDRP gamma badges through 1968 are considered zeros. Because missed dose is determined based on site quarterly data in the DOE data using the approach in ORAUT (2018b), any comparison of zeros with the NDRP gamma would not underestimate the missed dose assigned. This is reasonable because all the reported positive dose is accounted for in the comparison between the original reported DOE doses and the NDRP gamma doses, and assigning coworker dose for blank NDRP badges for quarters with DOE data would overestimate the external gamma dose.

6.7.3.4 Default Neutron-to-Gamma Ratio

The Oak Ridge Associated Universities (ORAU) Team developed geometric mean (GM) and geometric standard deviation (GSD) neutron-to-photon ratios from the available RFP worker files and supervisor dosimetry reports. Tables 6-20 and 6-21 list the values for the periods from 1970 to 1976 and from 1977 to 2000, respectively.

6.7.4 <u>Geometry</u>

6.7.4.1 Angular Dependence

Film neutron dosimeters generally record a slightly increased dose when exposed from forward angles other than perpendicular. It is favorable to claimants to ignore this slight difference.

The Panasonic dosimeter was evaluated for angular dependence. For neutron fields, the element responses generally decreased as the angle between the incident radiation and the plane perpendicular to the TLD increased. For angles of incidence from –30° to +30°, the ratio of reported dose to delivered dose ranged from 0.87 to 1 for neutrons. This slight variability does not warrant a specific correction.

Table 6-20. RFP lognormal neutron-to-photon ratio values, 1970 to 1976.[a]

Year	Neutron-to-photon ratio GM (semimonthly exchange)	GSD	95th percentile	Neutron-to-photon ratio GM (monthly exchange)	GSD	95th percentile
1970	1.61[a]	3.45	12.4	N/A	N/A	N/A
1971	1.61	3.45	12.4	N/A	N/A	N/A
1972	1.32	2.15	4.64	0.8	2.63	3.94
1973	1.32[c]	2.15	4.64	N/A	N/A	N/A
1974	0.68	3.01	4.16	N/A	N/A	N/A
1975	0.67	3.31	4.82	N/A	N/A	N/A
1976	0.95	3.59	7.81	0.78	4.29	8.55

a. N/A = not applicable.

b. Data for 1970 were not available. This value is the greater of the ratios for 1969 and 1971. The high neutron-to-gamma ratio in 1971 for Building 771 is reasonable from a process aspect, and extrapolating that ratio back to 1970 also is reasonable. In the aftermath of the 1969 plutonium fire in Buildings 776 and 777, the salvaged plutonium oxide had to be converted back to plutonium metal, a process done in Building 771. Building 771 had a huge backlog for relatively pure plutonium (little americium, low gamma) to be reprocessed, which was staged in the 776 to 771 tunnel and any other possible staging area in the vicinity. In addition, PuF_4 (a high neutron source) seemed to be generated faster in Building 771 than it could be reduced to metal, which also caused a staging problem in or near the process areas in Building 771 until the backlog could be reduced.

c. Data for 1973 were not available. This value is the greater of the ratios for 1972 and 1974.

Table 6-21. ORAU Team-developed neutron-to-gamma ratios.

Year	GM	GSD	Year	GM	GSD
1977	0.33	3.31	1990	0.35	3.77
1978	0.57	2.53	1991	0.29	2.41
1979	0.37	3.31	1992	0.4	2.03
1980	0.43	2.57	1993	0.61	1.93
1981	0.51	2.41	1994	0.41	2.35
1982	0.4	2.4	1995	0.35	2.28
1983	0.42	3.01	1996	0.26	4.1
1984	0.41	3.07	1997	0.44	2.18
1985	0.42	3.37	1998	0.39	3.03
1986	0.49	2.93	1999	0.45	2.79
1987	0.36	3.56	2000	0.6	3
1988	0.6	2.83	Overall	0.42	3
1989	0.36	5.5			

6.7.4.2 Exposure Geometry

A 100% AP exposure geometry for all external doses at Rocky Flats should be applied, in accordance with Section 6.5.4.

6.7.5 Uncertainty

6.7.5.1 Film

The NDRP has evaluated film uncertainty. For this reason, uncertainty of film neutron dosimeters is not discussed in this TBD.

6.7.5.2 Thermoluminescent Dosimeter

Falk (1971) describes the Harshaw TLD system development. That document describes field tests in RFP plutonium production facilities. The results indicate “that the survey dose range is consistently within 20 percent of the TLD neutron dose indication.” Therefore, for the Harshaw neutron dosimeter, a 95% confidence interval of 20% has been selected, and the standard deviation is 20% ÷ 1.96 = 10.2%. The methodology for TLD uncertainty in NIOSH (2007) is used.

The initial Panasonic TLD algorithm was evaluated during development (Author unknown undated). The results of the evaluation stated, “A large number of (relative) biases in the range –0.100 to +0.100 and the paucity of the (relative) biases outside the ±0.200 range indicate a robust, effective algorithm.” Based on this evaluation, the maximum relative bias of 0.206 was selected as the 95% confidence interval, and a standard deviation of 0.206 ÷ 1.96 = 10.5% was thereby determined.

The Stanford (1990) algorithm upgrade was tested during DOELAP performance testing. The unmoderated neutron dose category resulted in a standard deviation of 0.072. This value was selected to determine the upper 95% confidence dose during this period.

The 1993 algorithm upgrade (KHC 2001) was tested during 1999 DOELAP performance testing. The unmoderated neutron dose category resulted in a standard deviation of 0.065. A mixture of neutrons with both low- and high-energy photons was tested. The worst case standard deviation was 0.09. This value was selected to determine the upper 95% confidence dose for all dates after the implementation of this algorithm.

Table 6-22 lists the uncertainties for these dosimetry systems.

Table 6-22. Uncertainty for TLD neutron dose measurements (upper 95th% confidence dose in mrem).

Dose (mrem)	Harshaw TLD dosimeter, 1971–1982	Panasonic dosimeter, 1983–1990	DOELAP-accredited Panasonic dosimeter, 1991–1992	DOELAP-accredited Panasonic dosimeter, 1993–2004
1	1.25	1.25	1.21	1.23
2	2.43	2.44	2.32	2.38
5	6.01[a]	6.04[b]	5.72[c]	5.89[d]
10	12	12	11	12
20	24	24	23	24
50	60	60	57	59
100	120	121	114	118
200	240	241	228	235
500	600	603	571	588
1,000	1,200	1,206	1,141	1,176
2,000	2,400	2,412	2,282	2,353

a. 1.20 multiplier for 5 mrem or greater.
b. 1.21 multiplier for 5 mrem or greater.
c. 1.14 multiplier for 5 mrem or greater.
d. 1.18 multiplier for 5 mrem or greater.

Default values of 1.2 for 1971 to 1982, 1.21 for 1983 to 1990, 1.14 for 1991 to 1992, and 1.18 for 1993 to 2004 can be used for the neutron TLD dose uncertainty multiplier.

6.8 ELECTRON DOSE

Beta radiation fields are usually the dominant external radiation hazard in facilities that require contact work with unshielded forms of uranium. This was the case at RFP for EU and DU work. It should be assumed that the skin dose reported in RFP dosimetry records for uranium workers results from electrons with energies greater than 15 keV.

Figure 6-9 shows estimated beta dose rates from a semi-infinite slab of uranium metal at various enrichment levels. For uranium enrichments up to 30%, the beta radiation field is dominated by contributions from ^{238}U decay products. For DU, therefore, dose involves essentially the 2.29-MeV (maximum) beta particles from ^{234m}Pa, the most energetic contributor to the beta exposure.

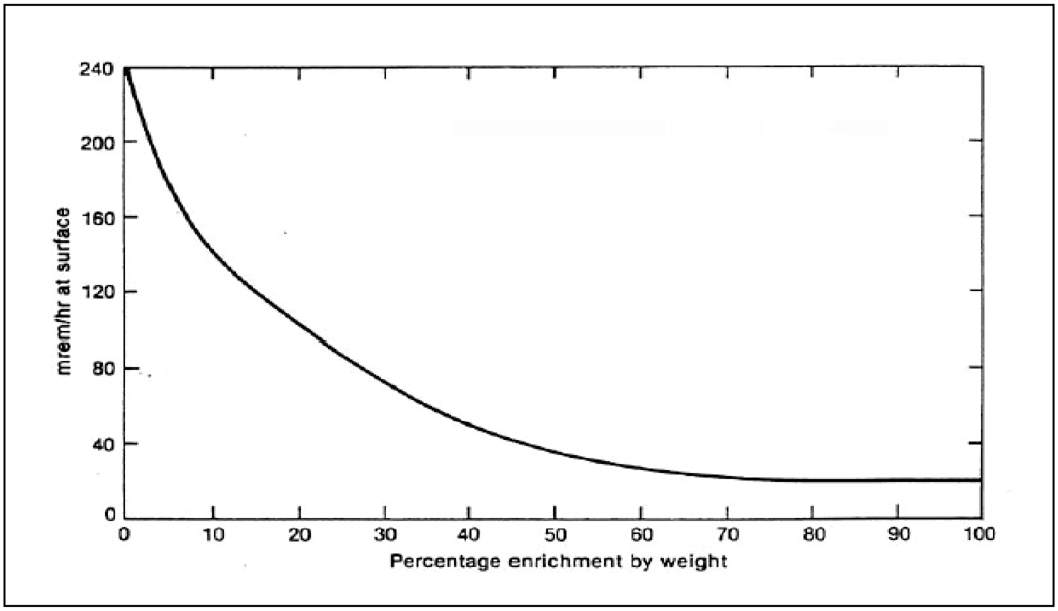

Figure 6-9. Estimated beta dose rate from uranium metal at various enrichment levels (DOE 2001).

Processes that separate and sometimes concentrate beta-emitting uranium daughters are not uncommon in DOE uranium facilities. The uranium foundry operations at RFP produced skull that resulted in high beta dose rates. Surface beta dose rates on the order of 1 to 20 rad/hr have been observed at some DOE facilities. Exposure control is complicated by the fact that considerable contact work takes place in facilities that process uranium metal. At RFP, large foundry ingots were generally handled by lifting devices, but machined uranium parts were handled with gloved hands. RFP did have problems with elevated beta dose rates from contamination on leather gloves worn during foundry operations (ORAUT 2018a).

6.8.1 Energy Groups

6.8.1.1 Exposure Spectra

The beta spectrum from uranium is highly dependent on the quantity of progeny in the uranium, which in turn is dependent on the enrichment level of the uranium. DU progeny grow into secular equilibrium relatively quickly (~30 days) and can be conservatively assumed to be present at these levels.

Figure 6-10 shows the relative dose rate in relation to energy. DU would be similar to the natural uranium used for this experiment.

6.8.1.2 Reported Dose to Energy Groups

NIOSH (2007) indicates that because extensive research in the areas of dosimeter wear location, electron energy spectra, and film response is required to convert dose readings to shallow dose properly, "… the exposure is assumed to be equal to the shallow dose [*Hp(0.07)*], recognizing that this is an overestimation of the true shallow dose. Until further research is conducted, this assumption is considered reasonable." This assumption is favorable to claimants for RFP. Additional guidance for calculating shallow dose can be found in ORAUT-OTIB-0017, *Interpretation of Dosimetry Data For Assignment of Shallow Dose* (ORAUT 2005b).

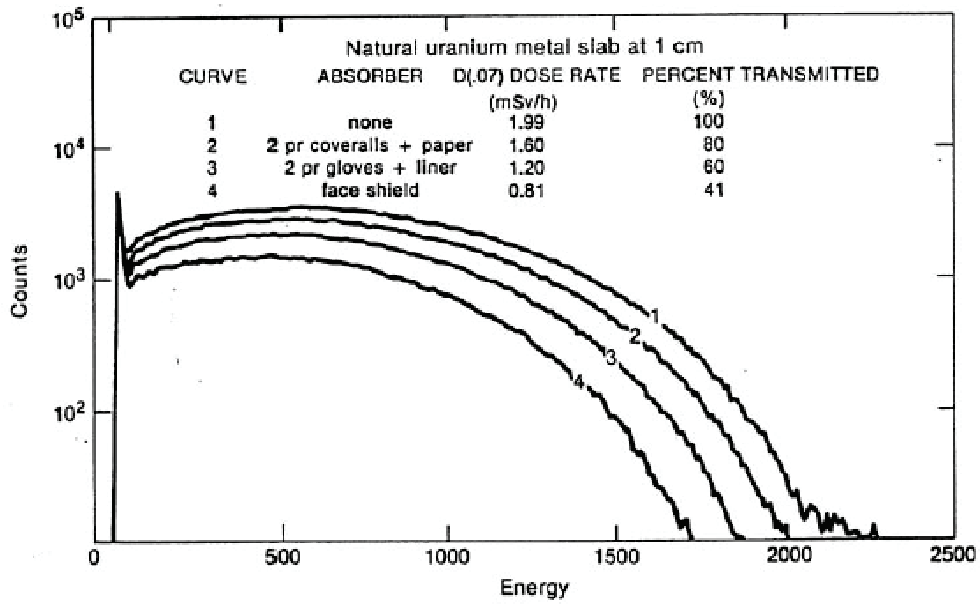

Figure 6-10. Shallow dose rate from natural uranium slab (DOE 2001).

6.8.2 Calibration Factor

6.8.2.1 Reported-Dose-to-Organ-Dose Conversion Factor Units

Film dosimeters at RFP appear to have been calibrated in contact with uranium slabs. Although RFP documents in the 1960s report the dose rate from a uranium slab as 240 mR/hr, 240 mrad/hr, and 240 mrem/hr at the surface, it is assumed these were inaccurate references to a dose rate in millirad per hour. The w_R for electrons at all energies is 1 (ICRP 1991); therefore, reported beta doses are equivalent to rem. This value is used directly for the *Hp(0.07)* dose.

6.8.3 Missed Dose

6.8.3.1 Limit of Detection

Beta dosimetry at RFP used OW film calibrated to a uranium slab. ORAUT (2007b, Section 6.5.2) states that the minimum detectable beta dose would have been similar to that for photons. Therefore, 40 mrem was selected as the minimum detectable beta dose appropriate for the film dosimetry period.

Harshaw TLDs were used for beta detection starting in 1969. ORAUT (2007b, Section 6.5.2) states that the minimum detectable dose would have been similar to that for photons. Wilson et al. (1990) determined that the Hanford TLD system had a 20-mR minimum detectable dose. RFP TLD measurements were similar. A minimum detectable dose of 20 mrem beta (shallow) is appropriate for RFP during this period.

The algorithm initially developed for Panasonic TLD system implementation in 1983 contains a constraint to ensure that the shallow dose equivalent does not fall below 0.9 times the deep dose from photons. Therefore, the shallow minimum detectable dose is 0.9 times that determined for deep dose photons (20 mrem) for this system. The minimum detectable shallow dose for this period was determined to be 20 × 0.9 = 18 mrem (shallow) as indicated in Table 6-23.

Table 6-23. Beta LODs (mrem).

Period	LOD
1951–1968	40
1969–1982	20
1983–1989	18
1990–1992	80
1993–2004	15
2005	5

In 1990, the algorithm for the Panasonic dosimetry system was improved. The documentation for this algorithm cites "… a minimum reportable beta dose of 25% of the total shallow dose (photon plus beta) or approximately 80 mrem for DU…" (Stanford 1990). It also states that "… beta doses delivered to radiation workers in the plant environments will likely be overestimated." A decision to use the maximum 80-mrem (shallow) minimum detectable dose was made to be favorable to claimants. This is a significant increase in the minimum detectable beta dose. A review of the algorithm documentation (Stanford 1990) indicated that a constraint was incorporated into the algorithm to report beta dose only if the net OW (element 1) value was over 25 mR (^{137}Cs exposure response). This net element reading is determined by subtracting the expected photon response and the expected neutron response for that element, as determined by the relationship with other dosimeter elements in the badge. These calculations would result in significant variability in the net element 1 response, and it is assumed that the constraint was included to reduce the variability in the resultant beta dose estimate to an acceptable level. The result is a significantly higher minimum detectable dose, however. This constraint appears to have been removed in the next algorithm update.

In 1993, an algorithm update was incorporated in the Panasonic dosimetry system (KHC 2001) to include element-reading uncertainty controls to reduce large dose fluctuations at low dose. This update has passed DOELAP performance testing and results in a stated minimum response for routine RFP beta fields of approximately 15 mrem (shallow) (Author unknown 1993). This value has been incorporated in Table 6-23.

6.8.3.2 Number of Zero Readings

The number of zero readings is determined as discussed in Section 6.5.1 of this document.

6.8.3.3 Unmonitored Energy Range

Film and TLD are believed to respond to beta energies of dosimetric importance (ORAUT 2018a). There is therefore no unmonitored energy range for which a correction factor is appropriate.

6.8.4 Geometry

6.8.4.1 Angular Dependence

The sensitive dosimeter elements are mounted in a dosimetry badge. The assembled badge displays severe angular dependence to beta exposure, but in most cases normal worker movement tends to average out some of this dependence (DOE 2001).

For beta fields, 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°. For angles of incidence from –30° to +30°, the ratio of reported dose to delivered dose ranged from 0.36 to 0.59 for beta particles (KHC 2001, Section 04.06.2). However, based on the averaging effect cited in DOE (2001), no angular correction factor is proposed.

6.8.4.2 Exposure Geometry

Exposure geometry is not a significant issue with skin exposure. Nonpenetrating radiations do not significantly expose tissue in other than perpendicular exposures.

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* (Lalos 1989).

6.8.5.1 Film

RFP used film to measure beta dose between 1951 and 1968. This is the same film described in Sections 6.3.1 and 6.5.1 of this TBD. The method in NIOSH (2007) was used to determine the laboratory uncertainty (upper 95% confidence dose) for film readings. This method is detailed in *Film Badge Dosimetry in Atmospheric Nuclear Tests* (Lalos 1989). This TBD analysis used a similar uncertainty estimation methodology and developed a spreadsheet that matched the illustration given in Lalos (1989). A review of RFP density-to-beta dose conversion charts from 1966 to 1968 determined film sensitivity. A saturation density for DuPont 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 77 mrad and above. Table 6-24 lists these upper 95% confidence doses.

Table 6-24. Uncertainty for beta film readings.

Dose (mrad)	Upper 95% confidence dose (mrad)
1	17
2	18
5	21
10	26
20	36
50	66
100	120
200	240
500	600
1,000	1,200
2,000	2,400

6.8.5.2 Thermoluminescent Dosimeter

TLDs provided improved beta dosimetry. Harshaw TLD chips were used to measure beta dose at RFP from 1969 to 1982. This section estimates the uncertainty associated with this type of dosimeter for the early years of use and then discusses the measured uncertainty when DOELAP performance testing was initiated.

6.8.5.2.1 Loose-Chip Thermoluminescent Dosimeters

Harshaw TLD chips were used to measure beta dose in parallel with photon dose. As with the photon TLD uncertainty, the chip-sorting procedure was used to estimate the standard error associated with the beta TLD measurements. Using the Simplified Dosimetry Uncertainty calculation recommended by NIOSH (2007), and assuming that the critical level is the beta LOD estimated in Section 6.8.3.1 of this TBD, Table 6-25 lists the upper 95% confidence dose.

Table 6-25. Uncertainty for loose-chip TLD beta dose.

Dose (mrad)	Upper 95% confidence dose (mrad), 1969–1982
1	21
2	22
5	25
10	30
20	40
50	72
100	126
200	239
500	585
1,000	1,166
2,000	2,330

6.8.5.2.2 Panasonic TLD Dosimeter

Table 6-26 lists the uncertainty associated with DOELAP-accredited Panasonic dosimeter dose readings. These values were calculated using the TLD uncertainty methodology described in Section 2.1.1.3.2 of NIOSH (2007). This method recognizes that the elements of the uncertainty are quantified in the dosimetry program documentation available for a DOELAP-accredited program. The standard deviation for null readings is from a study performed at RFP (KHC 2001), and the relative standard deviation at high readings is the standard deviation of DOELAP performance test results (KHC 2001; Stanford 1990). The reasonable worst case value (high-energy photons + neutrons mixture from KHC 2001, Table 11) was selected to provide a result that is favorable to claimants.

Table 6-26. Uncertainty for DOELAP-accredited TLD beta dose (upper 95% confidence dose in mrem).

Dose (mrem)	Panasonic dosimeter, 1983–1989	DOELAP-accredited Panasonic dosimeter, 1990–1998	DOELAP-accredited Panasonic dosimeter, 1999–2004
1	1.19	1.19	1.19
2	2.29	2.29	2.28
5	6[a]	6[a]	6[a]
10	11	11	11
20	22	22	22
50	56	56	56
100	112	112	112
200	224	224	223
500	561	561	558
1,000	1,122	1,122	1,116
2,000	2,243	2,243	2,231

a. 1.12 multiplier for any dose greater than 2 mrem.

6.8.6 Skin Contamination

Skin contamination incidents were routinely reported at RFP on a contamination report. Information generally indicates the location of the skin contamination and the initial count. The area of the contamination might not be available and should be estimated in the manner described in Section 2.3.3 of NIOSH (2007).

Depleted uranium is the RFP production material that would result in the greatest skin dose from surface contamination. The progeny potentially contained in the material would result in a beta exposure to the skin.

The contamination reports do not indicate the length of time that the contamination was present on the skin. An assumption that is favorable to claimants is that the contamination was present for 4 hr. This is a reasonable worst case assumption that, for example, the individual received contamination at the beginning of the shift, did not take a midmorning break, and discovered the contamination during monitoring when leaving the production area at lunch. Once the contamination was discovered, initial decontamination would be performed in the production building, which would result in removal of most of the contamination. Before 1970, self-monitoring equipment was not readily available, and an assumption favorable to claimants of 8 hr is appropriate.

Values in the contamination reports are typically in counts per minute. RFP typically used a Geiger-Müller pancake probe to perform uranium surveys.

DU consists of 99.8% ^{238}U by weight. Table 6-27 lists the other isotopes.

Table 6-27. DU mixtures (DOE 1980).[a]

Isotope	Ci/g (mix), alpha	Ci/g (mix), beta	nCi/g (mix)
Th-231	N/A	4.90E-09	N/A
Th-234	N/A	3.40E-07	340
U-234	3.70E-08	N/A	37
U-235	4.90E-09	N/A	4.9
U-238	3.40E-07	N/A	340
Total	3.82E-07	3.45E-07	726.8

a. N/A = not applicable.

It is favorable to claimants to assume that the DU is 1 year old. This allows for ingrowth of progeny to achieve secular equilibrium. A decay calculation using MicroShield 5.03 (Grove Engineering 1998) was performed. Table 6-28 lists the full set of decay isotopes.

Table 6-28. Activity per gram, 1-year-old DU.

Nuclide	Ci	Bq	Nuclide	Ci	Bq
Ac-227	1.63E-15	6.04E-05	Po-215	1.28E-15	4.75E-05
Bi-210[a]	6.69E-19	2.47E-08	Po-218	7.00E-17	2.59E-06
Bi-211	1.28E-15	4.75E-05	Ra-223	1.28E-15	4.75E-05
Bi-214[a]	7.00E-17	2.59E-06	Ra-226	7.21E-17	2.67E-06
Fr-223	2.25E-17	8.34E-07	Rn-219	1.28E-15	4.75E-05
Pa-231	1.04E-13	3.84E-03	Rn-222	7.00E-17	2.59E-06
Pa-234[a]	5.44E-10	2.01E+01	Th-227	1.39E-15	5.15E-05
Pa-234m	3.40E-07	1.26E+04	Th-230	3.33E-13	1.23E-02
Pb-210[a]	7.10E-19	2.63E-08	Th-231[a]	4.90E-09	1.81E+02
Pb-211	1.28E-15	4.75E-05	Th-234[a]	3.40E-07	1.26E+04
Pb-214[a]	7.00E-17	2.59E-06	Tl-207	1.28E-15	4.74E-05
Po-210	2.16E-19	7.99E-09	U-234	3.70E-08	1.37E+03
Po-211	3.50E-18	1.30E-07	U-235	4.90E-09	1.81E+02
Po-214	6.99E-17	2.59E-06	U-238	3.40E-07	1.26E+04

a. Significant progeny (included in VARSKIN Mod 3).

Dose calculation might utilize software such as VARSKIN (recommended in NIOSH 2007) or other appropriate means.

6.9 UNMONITORED INDIVIDUALS

6.9.1 In Production Areas

In the early 1950s only groups expected to receive doses greater than 10% of the radiation protection guideline (called the *threshold dose* at RFP) would receive dosimeters. Attachment C documents the RFP external dosimetry coworker study. The data from the coworker study should be used to address unmonitored dose for this group of workers.

6.9.2 Outside Production Areas

After about 1990, many individuals at RFP who did not work in radiological areas were not badged. The site radiological protection organization determined that these individuals were unlikely to exceed 100 mrem of occupational exposure in a CY.

For individuals who worked outside the radiologically controlled areas, environmental exposure would be a better estimate of their exposure [see the latest version of Section 4.0, Environmental Dose, of this site profile (ORAUT 2007a)].

6.10 EXTREMITY DOSIMETRY

Extremity dosimeters were used at RFP. Between 1951 and 1970, the site used an ORNL-designed film dosimeter similar to that used for the body badge (Baker 2002). The dosimeter was worn on the wrist and modified with a brass filter similar to the body badge. Little performance information is available on this badge, but it probably performed similarly to the body badge of that period.

In 1971, RFP switched to an in-house-designed wrist dosimeter with four Harshaw chips (Link and Pennock 1983; Baker 2002). This badge contained two TLD-600 and two TLD-700 chips that enabled neutron and photon dose determination. Uranium workers received an OW (thin Mylar) version.

In 1991, RFP switched to a Panasonic model UD-813AS11 (custom design) dosimeter in a plastic wrist holder (KHC 2000b; Baker 2002). This dosimeter contains two ^{6}Li-borate elements and two ^{7}Li-borate elements that enable neutron dose measurement. Two of the elements are under a thin OW for beta and low-energy photon dose measurements. The dosimeter, which has undergone DOELAP performance testing, is documented in KHC (2000b).

RFP did not use finger rings; however, wrist badges were used to assess the dose to the forearm. Hand dose was assessed using the dose measured by the wrist badge and the application of a hand-to-wrist ratio. Falk (1976) documents hand-to-wrist ratios of 1.5 for Buildings 771 and 559, and 2.5 for all other buildings. Section 05.04 of KHC (2000b) indicates a ratio of 3 was implemented in approximately 1992 as a conservative estimate based on the results of several studies.

Many RFP workers did not receive extremity (wrist) dosimeters. In such cases, the wrist (forearm) dose was assigned as the measured skin (shallow) dose, and the hand dose was assigned the same value. If an extremity dosimeter was worn and the value was less than the skin dose measured by the body badge, the assumption was made that the extremity dosimeter was not worn and the skin dose was assigned as the wrist dose. If the extremity dosimeter did measure a dose greater than the body badge, the extremity measurement was assigned to the wrist and a hand-to-wrist ratio was used to estimate the dose to the hand. Several studies over the years determined the hand-to-wrist ratio (Falk 1976; KHC 2000b).

Additional information on these dosimeters will be required for dose reconstruction for shallow dose to the extremity, if necessary.

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

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

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

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

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

film density
See *optical density*.

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

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.

fissionable
Capable of undergoing fission by capturing neutrons, including fast neutrons. Uranium-238 is fissionable. Fissionable indicates both spontaneous and induced fission.

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

gamma ray
See *gamma radiation*.

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

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

neutron

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

neutron film dosimeter

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

nuclear track emulsion, type A (NTA)

Film made by the Eastman Kodak Company that is sensitive to fast neutrons. 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.

open window (OW)

Area of a film dosimeter that has little to no radiation shielding (e.g., only a holder and visible light protection). The open window measures nonpenetrating as well as penetrating dose, which minimizes the potential for beta radiation to contribute to the interpreted penetrating dose. See *film dosimeter*.

operating area

Usually refers to a major operational work area at a site.

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.

personal dose equivalent, $H_p(d)$

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. In 1993 the International Commission on Radiological Measurement and Units recommended *Hp(d)* as the dose quantity for radiological protection.

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.

pit

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

quality factor (Q, QF)

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*.

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.

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

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

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

shallow dose equivalent [SDE, *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.

silver shield
The 1-mm-thick shields covering the film packet in early film dosimeters.

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

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

X-ray radiation
Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including 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)

Occupational Dose Report

Name: [redacted] Employee #: [redacted]

SSN: [redacted] Status: Terminated

Year	Deep Dose	Skin Dose	Extremity	Lens of Eye
1951-1979 *	1110	1045	15	
1980	23	23	23	
1981	0	0	0	
1982	2	2	2	
1983	24	39	39	
1984	0	0	0	
1985	0	0	0	
1986	53	69	69	
1987	0	0	0	
1988	0	0	0	
Pre-1989 Dose	1212	1178	146	
1989	21	25	25	
1990	0	0	0	
1991				
1992				
1993				
1989-1993 Dose	21	25	25	
1994				
1995				
1996				
1997				
1998				
1999				
2000				
2001				
2002				
2003				
2004				
2005				
RFETS Total	1233	1203	171	

RADIOLOGICAL RECORDS

Reviewed by: [redacted]

Date Reviewed: 6-4-02

INTERNAL DOSIMETRY

Reviewed by:

Date Reviewed:

Offsite Dose Summary

Total TEDE

Site	TEDE

* details for this time period on page 2 (if available)

dose by year.xls Page 1 of 2 krs

Figure A-1. Occupational Dose Report reviewed June 4, 2002.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Occupational Dose Report

Name: ______________________ **Employee #:** ____________

SSN: ____________

Year	Deep Dose	Skin Dose	Extremity	Lens of Eye
1951				
1952				
1953	30			
1954				
1955				
1956				
1957				
1958				
1959				
1960				
1961				
1962				
1963				
1964	84	84	0	
1965	50	50		
1966	232	234		
1967	0	0	0	
1968	47	55		
1969	3	3		
1970	47	0	0	
1971	98	98	0	
1972	75	75	0	
1973	44	46	0	
1974	209	209	0	
1975	165	165	0	
1976	11	11	0	
1977	0	0	0	
1978	0	0	0	
1979	15	15	15	
RFETS Total	1110	1045	15	

RADIOLOGICAL RECORDS

Reviewed by: ____________

Date Reviewed: 6-4-02

INTERNAL DOSIMETRY

Reviewed by: ____________

Date Reviewed: ____________

Offsite Dose Summary (continued)

Site	TEDE

dose by year.xls Page 2 of 2 krs

Figure A-2. Occupational Dose Report reviewed June 4, 2002.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Submitted . KSAVITZ
Sorted by: Plant ID

Dosimetry His ry by Individual

Date: 10-MAR-2003 . .00
Page: 1

Criteria Selected

Plant ID: [redacted]

Plant ID: [redacted] **Name:** [redacted] [redacted] [redacted]

Begin Date	End Date	Dosimeter Category	Process ID	Dosimeter Type	Wear Location	Record Type	DDE*	SDE-SK	LDE	SDE-EX	Neut.	PSE
07-MAR-1955 00:00	31-DEC-1955 00:00	CALCULATED				OFFICIAL	0	0			0	
01-JAN-1956 00:00	31-DEC-1956 00:00	CALCULATED				OFFICIAL	18	35			0	
01-JAN-1957 00:00	31-DEC-1957 00:00	CALCULATED				OFFICIAL	166	307			0	
01-JAN-1958 00:00	31-DEC-1958 00:00	CALCULATED				OFFICIAL	1041	1813			0	
01-JAN-1959 00:00	31-DEC-1959 00:00	CALCULATED				OFFICIAL	642	912			0	
01-JAN-1960 00:00	31-DEC-1960 00:00	CALCULATED				OFFICIAL	610	760		157	0	
01-JAN-1961 00:00	31-DEC-1961 00:00	CALCULATED				OFFICIAL	1330	1619			0	
01-JAN-1962 00:00	31-DEC-1962 00:00	CALCULATED				OFFICIAL	1509	1610			0	
01-JAN-1963 00:00	31-DEC-1963 00:00	CALCULATED				OFFICIAL	1671	1941			0	
01-JAN-1964 00:00	31-DEC-1964 00:00	CALCULATED				OFFICIAL	1490	1689			0	
01-JAN-1965 00:00	31-DEC-1965 00:00	CALCULATED				OFFICIAL	1300	1390		321	0	
01-JAN-1966 00:00	31-DEC-1966 00:00	CALCULATED				OFFICIAL	2881	3160		3385	0	
01-JAN-1967 00:00	31-DEC-1967 00:00	CALCULATED				OFFICIAL	1558	2069		3922	0	
01-JAN-1968 00:00	31-DEC-1968 00:00	CALCULATED				OFFICIAL	1715	2392		4664	0	
01-JAN-1969 00:00	31-DEC-1969 00:00	CALCULATED				OFFICIAL	1262	1757		2935	0	
01-JAN-1970 00:00	31-DEC-1970 00:00	CALCULATED				OFFICIAL	1229	1263		1659	0	
01-JAN-1971 00:00	31-DEC-1971 00:00	CALCULATED				OFFICIAL	456	475		1092	0	
01-JAN-1972 00:00	31-DEC-1972 00:00	CALCULATED				OFFICIAL	559	603		3843	0	

All dose equivalents are expressed in millirem.
* - indicates deep dose equivalent only. Neutron dose is not added.

Figure A-3. Dosimetry History by Individual query report dated March 10, 2003.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Submitted by: KSAVITZ
Sorted by: Plant ID

Dosimetry History by Individual

Date: 10-MAR-2003 [illegible]:00
Page: 2

Plant ID: [redacted] Name: [redacted] [redacted] [redacted]

Begin Date	End Date	Dosimeter Category	Process ID	Dosimeter Type	Wear Location	Record Type	DDE*	SDE-SK	LDE	SDE-EX	Neut.	PSE
01-JAN-1973 00:00	31-DEC-1973 00:00	CALCULATED				OFFICIAL	987	1093		3838	0	
01-JAN-1974 00:00	31-DEC-1974 00:00	CALCULATED				OFFICIAL	1131	1253		3250	0	
01-JAN-1975 00:00	31-DEC-1975 00:00	CALCULATED				OFFICIAL	620	688		1483	0	
01-JAN-1976 00:00	31-DEC-1976 00:00	CALCULATED				OFFICIAL	179	233		656	0	
30-JAN-1977 00:00	31-JAN-1977 00:00	CALCULATED				OFFICIAL	19	28		73	4	
27-FEB-1977 00:00	28-FEB-1977 00:00	CALCULATED				OFFICIAL	0	0		49	0	
30-MAR-1977 00:00	31-MAR-1977 00:00	CALCULATED				OFFICIAL	7	15		69	6	
29-APR-1977 00:00	30-APR-1977 00:00	CALCULATED				OFFICIAL	14	44		72	30	
30-MAY-1977 00:00	31-MAY-1977 00:00	CALCULATED				OFFICIAL	40	48		83	8	
29-JUN-1977 00:00	30-JUN-1977 00:00	CALCULATED				OFFICIAL	10	36		38	5	
30-JUL-1977 00:00	31-JUL-1977 00:00	CALCULATED				OFFICIAL	3	26			23	
30-AUG-1977 00:00	31-AUG-1977 00:00	CALCULATED				OFFICIAL	19	43		129	20	
29-SEP-1977 00:00	30-SEP-1977 00:00	CALCULATED				OFFICIAL	82	97			6	
30-OCT-1977 00:00	31-OCT-1977 00:00	CALCULATED				OFFICIAL	21	38		84	5	
29-NOV-1977 00:00	30-NOV-1977 00:00	CALCULATED				OFFICIAL	16	17		94	1	
30-DEC-1977 00:00	31-DEC-1977 00:00	CALCULATED				OFFICIAL	69	134		267	46	
30-JAN-1978 00:00	31-JAN-1978 00:00	CALCULATED				OFFICIAL	81	211		239	31	
27-FEB-1978 00:00	28-FEB-1978 00:00	CALCULATED				OFFICIAL	20	23		114	3	
30-MAR-1978 00:00	31-MAR-1978 00:00	CALCULATED				OFFICIAL	44	73		228	5	
29-APR-1978 00:00	30-APR-1978 00:00	CALCULATED				OFFICIAL	69	75		202	6	
30-MAY-1978 00:00	31-MAY-1978 00:00	CALCULATED				OFFICIAL	43	58			14	
30-JUL-1978 00:00	31-JUL-1978 00:00	CALCULATED				OFFICIAL	121	139		273	11	

All dose equivalents are expressed in millirem.
* - indicates deep dose equivalent only. Neutron dose is not added.

Figure A-4. Dosimetry History by Individual query report dated March 10, 2003.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Submitted ... KSAVITZ　　　　Dosimetry His...ry by Individual　　　　Date: 10-MAR-2003 ...:00
Sorted by: Plant ID　　　　Page: 3

Plant ID: [redacted]　　Name: [redacted]　[redacted]　[redacted]

Begin Date	End Date	Dosimeter Category	Process ID	Dosimeter Type	Wear Location	Record Type	DDE*	SDE-SK	LDE	SDE-EX	Neut.	PSE
30-AUG-1978 00:00	31-AUG-1978 00:00	CALCULAT ED				OFFICIAL	100	189			15	
29-SEP-1978 00:00	30-SEP-1978 00:00	CALCULAT ED				OFFICIAL	162	209		320	47	
30-OCT-1978 00:00	31-OCT-1978 00:00	CALCULAT ED				OFFICIAL	127	131		159	4	
29-NOV-1978 00:00	30-NOV-1978 00:00	CALCULAT ED				OFFICIAL	34	38		76	4	
30-DEC-1978 00:00	31-DEC-1978 00:00	CALCULAT ED				OFFICIAL	20	27		56	5	
30-JAN-1979 00:00	31-JAN-1979 00:00	CALCULAT ED				OFFICIAL	42	64		80	12	
27-FEB-1979 00:00	28-FEB-1979 00:00	CALCULAT ED				OFFICIAL	26	39		126	6	
30-MAR-1979 00:00	31-MAR-1979 00:00	CALCULAT ED				OFFICIAL	37	44		96	6	
29-APR-1979 00:00	30-APR-1979 00:00	CALCULAT ED				OFFICIAL	42	156		200	96	
30-MAY-1979 00:00	31-MAY-1979 00:00	CALCULAT ED				OFFICIAL	28	68		71	25	
29-JUN-1979 00:00	30-JUN-1979 00:00	CALCULAT ED				OFFICIAL	35	52		101	16	
30-JUL-1979 00:00	31-JUL-1979 00:00	CALCULAT ED				OFFICIAL	28	44		114	8	
30-AUG-1979 00:00	31-AUG-1979 00:00	CALCULAT ED				OFFICIAL	61	67		310	6	
29-SEP-1979 00:00	30-SEP-1979 00:00	CALCULAT ED				OFFICIAL	45	65		179	20	
30-OCT-1979 00:00	31-OCT-1979 00:00	CALCULAT ED				OFFICIAL	86	117		197	27	
29-NOV-1979 00:00	30-NOV-1979 00:00	CALCULAT ED				OFFICIAL	49	74			8	
30-DEC-1979 00:00	31-DEC-1979 00:00	CALCULAT ED				OFFICIAL	9	18		123	9	
30-JAN-1980 00:00	31-JAN-1980 00:00	CALCULAT ED				OFFICIAL	50	62		204	12	
28-FEB-1980 00:00	29-FEB-1980 00:00	CALCULAT ED				OFFICIAL	43	56		293	7	
30-MAR-1980 00:00	31-MAR-1980 00:00	CALCULAT ED				OFFICIAL	43	51		162	6	
29-APR-1980 00:00	30-APR-1980 00:00	CALCULAT ED				OFFICIAL	50	54		227	4	
30-MAY-1980 00:00	31-MAY-1980 00:00	CALCULAT ED				OFFICIAL	37	44		106	7	

All dose equivalents are expressed in millirem.
* - indicates deep dose equivalent only. Neutron dose is not added.

Figure A-5. Dosimetry History by Individual query report dated March 10, 2003.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

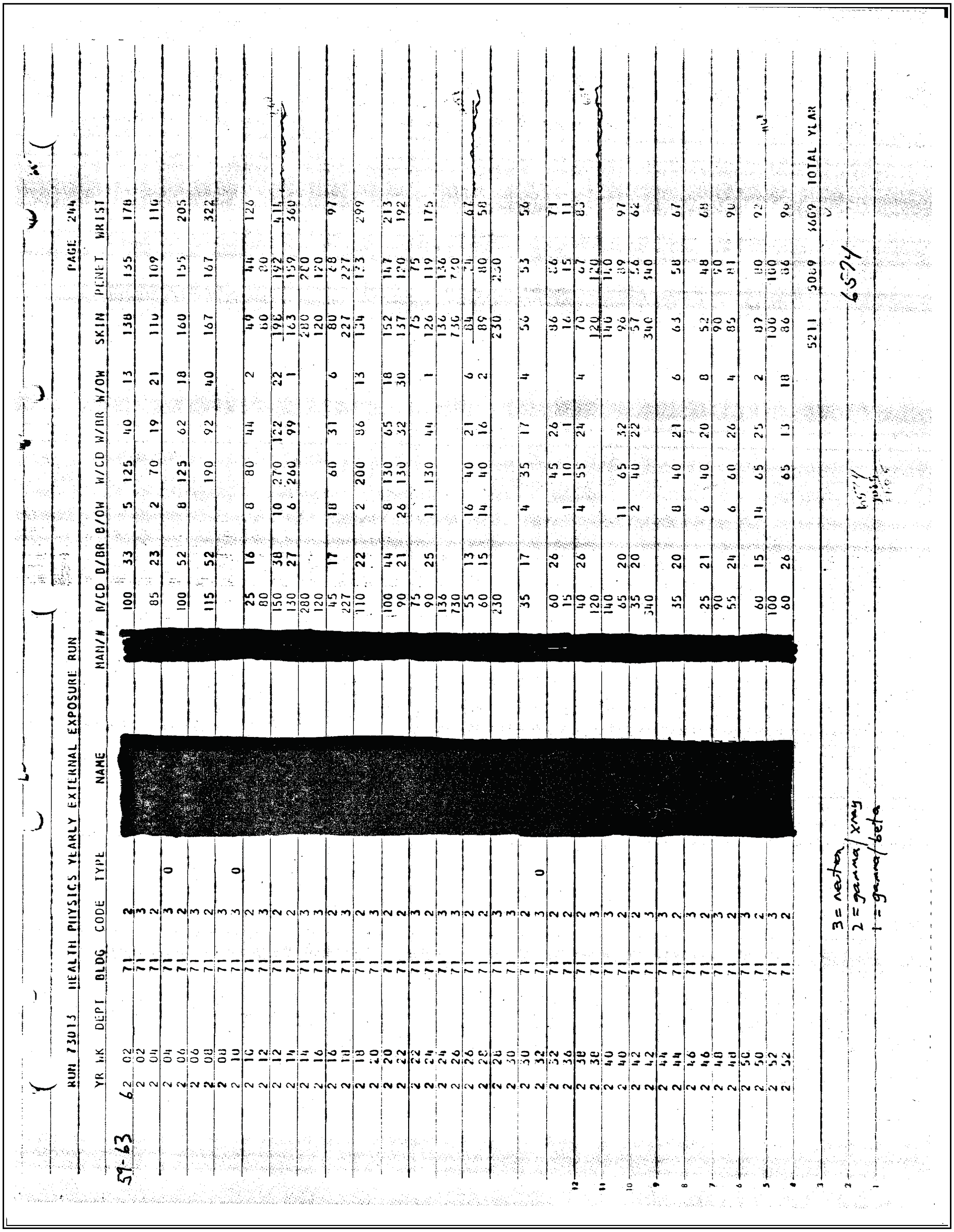
(.LTH PHYSICS EXTERNAL EXPOSURE ACTIVITY RUN Y(.LY DOSES IN MREM (

YR.	MAN #	NAME		QUARTERLY ACCUMULATED SKIN	QUARTERLY ACCUMULATED PEN	QUARTERLY ACCUMULATED HAND	CURRENT YEAR ACCUMULATED SKIN	CURRENT YEAR ACCUMULATED PEN	CURRENT YEAR ACCUMULATED HAND
58	[redacted]		1ST QUARTER	448	263	10			
			2ND QUARTER	239	150	560			
			3RD QUARTER	165	115	216			
			4TH QUARTER	316	229	541			
							1168	757	1327
57			1ST QUARTER	120	103				
			2ND QUARTER	75	62	94			
			3RD QUARTER	427	382	145			
			4TH QUARTER	138	93				
							760	640	239
56			1ST QUARTER	420	210	290			
			2ND QUARTER	130	25	185			
			3RD QUARTER	25	10	155			
			4TH QUARTER	120	30	215			
							695	275	845
55			1ST QUARTER	130	80	195			
			2ND QUARTER	405	230	320			
			3RD QUARTER	165	95	170			
			4TH QUARTER	115	10	385			
							815	415	1070
54			1ST QUARTER	215	45				
			2ND QUARTER	140	0				
			3RD QUARTER	120	0				
			4TH QUARTER	1015	415	1110			
							1490	460	1110
53			1ST QUARTER						
			2ND QUARTER	210	210				
			3RD QUARTER	110	110	77			
			4TH QUARTER	305	80				
							625	400	77

A zero indicates a "O" dose received.
A blank indicates that no film badge was worn.

Figure A-6. Health Physics Yearly External Exposure Activity Run, 1953 to 1958.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)



59-63

RUN 73013 HEALTH PHYSICS YEARLY EXTERNAL EXPOSURE RUN PAGE 244

YR	WK	DEPT	BLDG	CODE	TYPE	NAME	MAN/#	B/CD	B/BR	B/OW	W/CD	W/BR	W/OW	SKIN	PENET	WRIST
62	02		71	2		[redacted]	[redacted]	100	33	5	125	40	13	138	135	178
2	02		71	3												
2	04		71	2				85	23	2	70	19	21	110	109	110
2	04		71	3	0											
2	06		71	2				100	52	8	125	62	18	160	155	205
2	06		71	3												
2	08		71	2				115	52		190	92	40	167	167	322
2	08		71	3												
2	10		71	3	0											
2	10		71	2				25	16	8	80	44	2	49	44	126
2	12		71	3				80						60	80	
2	12		71	2				150	38	10	270	122	22	198	192	415
2	14		71	2				130	27	6	260	99	1	163	159	360
2	14		71	3				280						280	280	
2	16		71	3				120						120	120	
2	16		71	2				45	17	18	60	31	6	80	68	97
2	18		71	3				227						227	227	
2	18		71	2				110	22	2	200	86	13	134	133	299
2	20		71	3												
2	20		71	2				100	44	8	130	65	18	152	147	213
2	22		71	2				90	21	26	130	32	30	137	120	192
2	22		71	3				75						75	75	
2	24		71	2				90	25	11	130	44	1	126	119	175
2	24		71	3				136						136	136	
2	26		71	3				730						730	730	
2	26		71	2				55	13	16	40	21	6	84	74	67
2	28		71	2				60	15	14	40	16	2	89	80	58
2	28		71	3				230						230	230	
2	30		71	3												
2	30		71	2				35	17	4	35	17	4	56	53	56
2	32		71	3	0											
2	32		71	2				60	26		45	26		86	86	71
2	36		71	2				15		1	10	1		16	15	11
2	38		71	2				40	26	4	55	24	4	70	67	83
2	38		71	3				120						120	120	
2	40		71	3				140						140	140	
2	40		71	2				65	20	11	65	32		96	89	97
2	42		71	2				35	20	2	40	22		57	56	62
2	42		71	3				340						340	340	
2	44		71	3												
2	44		71	2				35	20	8	40	21	6	63	58	67
2	46		71	3												
2	46		71	2				25	21	6	40	20	8	52	48	68
2	48		71	3				90						90	90	
2	48		71	2				55	24	6	60	26	4	85	81	90
2	50		71	3												
2	50		71	2				60	15	14	65	25	2	87	80	92
2	52		71	3				100						100	100	
2	52		71	2				60	26		65	13	18	86	86	96
														5211	5069	5609 TOTAL YEAR

6574

3 = neutron
2 = gamma/xray
1 = gamma/beta

Figure A-7. Health Physics Yearly External Exposure Run, 1959 to 1963.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

RUN 72-303-8 HEALTH PHYSICS EXTERNAL EXPOSURE ACTIVITY RUN YEARLY DATE OF RUN 02-02-65 DOSES IN MREM PAGE 1224

				QUARTERLY ACCUMULATED			QUARTERLY ALLOWED			CURRENT YEAR ACCUMULATED			CURRENT YEAR ALLOWED		
YR	MAN#	NAME		SKIN	PEN	HAND	SKIN	PEN	HAND	SKIN	PEN	HAND	SKIN	PEN	HAND
64			1ST QUARTER	190	182	1021	8400	1400	21000						
			2ND QUARTER	200	194	1326	2400	400	6000						
			3RD QUARTER	110	110	599	8400	1400	21000						
			4TH QUARTER	102	93	243	7200	1200	18000						
										602	579	3189	31200	11960	78000

Figure A-8. Health Physics Yearly External Exposure Activity Run, 1964.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

ROCKWELL INTERNATIONAL - ROCKY FLATS PLANT
EXTERNAL DOSIMETRY (TLD) DETAIL
COMPUTERIZED INFORMATION THROUGH 12-31-86
DOSES IN MILLIREM
10:26 THURSDAY, MARCH 12, 1987

------------------ EMPNO=[redacted] NAME=[redacted] YEAR=1981 ------------------

ACTIVITY DATE	TIME CODE	CURRENT NEUTRON	CURRENT GAMMA	CURRENT PEN	CURRENT SKIN	CURRENT HAND	CURRENT FOREARM	BK 1	TYPE
01/31/81	2	3	2	5	5	5	5	15	
02/28/81	2	0	0	0	0	0	0	15	
03/31/81	2	0	0	0	0	0	0	15	
06/30/81	2	20	9	29	29	29	29	17	
07/31/81	2	2	2	4	9	9	9	16	
08/31/81	2	0	0	0	0	0	0	16	
09/30/81	2	11	1	12	12	12	12	16	
10/31/81	2	3	1	4	4	4	4	15	
11/30/81	2	0	0	0	0	0	0	14	
12/31/81	2	5	7	12	26	26	26	17	
YEAR		44	22	66	85	85	85		

------------------ EMPNO=[redacted] NAME=[redacted] YEAR=1982 ------------------

ACTIVITY DATE	TIME CODE	CURRENT NEUTRON	CURRENT GAMMA	CURRENT PEN	CURRENT SKIN	CURRENT HAND	CURRENT FOREARM	BK 1	TYPE
01/31/82	2	1	24	25	25	25	25	15	
02/28/82	2	4	26	30	30	30	30	11	
03/31/82	2	3	8	11	11	11	11	17	
04/30/82	2	2	4	6	8	8	8	16	
05/31/82	2	0	0	0	0	0	0	17	
06/30/82	2	26	6	32	32	32	32	16	
07/31/82	2	0	27	27	27	27	27	19	
09/30/82	2	3	3	6	6	6	6	26	
10/31/82	2	10	7	17	17	17	17	13	
12/31/82	2	45	3	48	55	55	55	32	
YEAR		94	108	202	211	211	211		

------------------ EMPNO=[redacted] NAME=[redacted] YEAR=1983 ------------------

ACTIVITY DATE	TIME CODE	CURRENT NEUTRON	CURRENT GAMMA	CURRENT PEN	CURRENT SKIN	CURRENT HAND	CURRENT FOREARM	BK 1	TYPE
01/31/83	2	55	24	79	84	84	84	15	
03/31/83	4	0	0	0	0	0	0	33	
06/30/83	4	0	0	0	0	0	0	43	
09/30/83	4	0	0	0	0	0	0	41	
12/31/83	4	12	13	25	25	25	25	31	
YEAR		67	37	104	109	109	109		

Figure A-9. External Dosimetry Detail, 1981 to 1983.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

HEALTH PHYSICS EXTERNAL RADIATION EXPOSURE REPORT FOR YEAR 67
DOSES IN MREM

MAN	NAME		PEN	SKIN	HAND
[redacted]	[redacted]	1ST QUARTER	1439	1524	1725
		2ND QUARTER	960	1007	139
		3RD QUARTER	1199	1238	754
		4TH QUARTER	1214	1279	0
		YEAR TOTAL	4812	5048	2618
		YEAR ALLOW	12000	30000	75000

LIFETIME ACC DOW	26727
LIFETIME ACC OTHER	
TOTAL	26727
LIFETIME ALLOW	95000

Figure A-10. Health Physics External Radiation Exposure Report, 1967.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Rocky Flats Environmental Technology Site
Radiological Health
Radiation Dosimetry Detail Report
Individual Lifetime Report

Doses Reported in millirem **Report Date:** **04-Jun-02**

SSN: **Badge:** **Name:**

Company: **EG&G INC. ROCKY FLATS** **Department:** **ORGAN**

Exposure From Other Facilities for 2002

Deep	CEDE	TEDE	Organ	CDE

Internal Dose From Rocky Flats for 2002

Date	Nuclide	CEDE	Total

Total Dose Equivalents for 2002*

Total Effective Dose Equivalents	TEDE	Organ Dose Equivalent	CDE	TODE
	NR	Bone Surfaces	NR	NR
		Lungs	NR	NR
		Liver	NR	NR
		Red Bone Marrow	NR	NR
		Gonads	NR	NR
		Kidney	NR	NR

* Includes doses from Rocky Flats and Off-site for Year of Report

Cumulative TEDE Reported Since 1/1/1989**

External		Internal		Total	
	21		NR		21

(Deep dose + CEDEs from reported intakes since 1/1/1989)

Reported Lifetime Dose**

External		Internal		Total	
	1233		2220		3453

(Deep dose + CEDEs from reported intakes)

** Doses include Off-site doses Reported to Rocky Flats

Figure A-11. Radiation Dosimetry Individual Lifetime Report dated June 4, 2002.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

RADIATION HEALTH RECORDS SYSTEM - View TLD Data   Page 1   V93013

H&S ID   SSN   Last Name

First Name   Middle   Last Name   From   To

Activity Date	Time Code	Curr Neut	Curr Gamm	Curr Pen	Curr Skin	Curr Hand	Curr Farm	Bk-1	Bk-2	Gpen	Gskn	Beta	Type
16-DEC-91	2	0	16	16	20	20	20	0	0	16	20	0	C
30-SEP-91	2	0	12	12	12	12	12	0	0	12	12	0	C
31-MAR-91	2	0	6	6 34	6 44	10 50	6 44	31	0	6	6	0	H
02-MAR-91	2	0	0	0	8	8	8	0	0	0	8	0	C
29-DEC-90	3	0	1	1	1	1	1	0	0	1	1	0	C

Press <PF3> next page   <Ctrl/F4> select (Clear, Print, Exit) screen

Count: *5   <Replace>

Figure A-12. Radiation Health Records System – TLD Data.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Page 1

Rocky Flats Environmental Technology Site
Radiological Health
Radiation Dosimetry Detail Report
Termination Report

All Doses Reported in millirem (mrem) Report Date: 17-SEP-96

Company Name: KAISER-HILL ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Employee Number: [redacted] Name: [redacted] SSN: [redacted] Org Code: 81740

EXTERNAL DOSIMETRY DATA FOR 1996

Dosimeter Results

		Effective Dose Equivalents			Dose Equivalents			
Begin	Ending	Neutron	Gamma	Deep	Skin	Ext	Hand	LOE
---------	---------	-------	------	------	------	------	------	------
		------	------	------	------	------	------	------
Sum								

INTERNAL DOSIMETRY DATA
From Intakes Occurring in 1996

Committed Effective Dose Equivalents			Committed Dose Equivalent					
Intake Date	Radionuclide	CEDE	Gonads	Breast	Marrow	Lung	Thyroid	Bone
-----------	-----------------	------	------	------	------	-------	-------	-------

Figure A-13. Radiation Dosimetry Detail Report, Termination Report dated September 17, 1996.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

Page 2

Rocky Flats Environmental Technology Site
Radiological Health
Radiation Dosimetry Detail Report
Termination Report

All Doses Reported in millirem (mrem) Report Date: 17-SEP-96

Company Name: KAISER-HILL ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Employee Number: [redacted] Name: [redacted] SSN: [redacted] Org Code: 81740

EXPOSURE FROM OTHER FACILITIES FOR 1996

Name	From	To	DDE	LDE	SDEWB	SDEME	CEDE	CDE	TEDE	TODE	F	R	E	P
Sum														

TOTAL DOSE EQUIVALENTS FOR 1996

Total Effective Dose Equivalents	TEDE*
	0

Total Organ Dose Equivalent	TODE*
Gonads	0
Breasts	0
Red Bone Marrow	0
Lungs	0
Thyroid	0
Bone Surfaces	0

* Includes Previous Exposure from other Facilities if applicable.

CUMULATIVE TEDE AT ROCKY FLATS SINCE 1/1/89

External	Internal	Total
0	0	0

(Deep dose + CEDEs from intakes since 1/1/89)

ROCKY FLATS LIFETIME DOSE

External	Internal	Total
11,072	15,410	26,482

(Deep dose + CEDEs from intakes since hire date)

Figure A-14. Radiation Dosimetry Detail Report, Termination Report dated September 17, 1996.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS (continued)

ROCKWELL INTERNATIONAL
AEROSPACE OPERATIONS
ROCKY FLATS PLANT
OCCUPATIONAL RADIATION EXPOSURE INFORMATION
FOR
EMPLOYEE NO. YEAR 88

	EXTERNAL RADIATION			INTERNAL RADIATION		
	DOSE EQUIVALENTS IN REM					
	WHOLE BODY	HAND	FOREARM	SYSTEMIC DEPOSITION		LUNG DOSE EQUIVALENT
YEAR TOTAL	.034	.034	.034	PU	5 NCI	0.63 REM
ACCUM AT RF	13.658			OTHER	0 NCI	

Figure A-15. Occupational Radiation Exposure Information, 1988.

ATTACHMENT B
MAJOR JOB CATEGORIES

Chemical Operators
Primary job duties included highly enriched uranium (HEU) (Building 881) and plutonium (Building 771/371) metal reprocessing using dissolution, fluorination, calcine, and other wet chemistry methods to purify metal in preparation for foundry casting operations. Molten salt processing (Building 776) was an exceptionally high neutron process. Other typical job duties included waste treatment (Building 774/374) for waste solutions generated across RFP.

Metallurgical Operators
Primary job duties included casting (Building 881), rolling and pressing HEU (Building 883), plutonium (Building 776/ 707), and DU (B444/447 and 883). Exposures tended to be less than those to Chemical Operators. Machinists, Assemblers, Material Analysts, and Welders had similar exposures.

Nondestructive Testing Technicians had similar, but probably lower, exposures because work was often done on completed pits that inherently shielded fissile materials. Experimental Operators had similar, but probably higher, exposures because they often worked with prototype systems or processes that lacked shielding and other radiological controls as the regular production processes.

Maintenance Workers
Typical trades (i.e., machinists, pipefitters, welders, carpenters, painters, electricians) had varied exposures because they often did more intrusive work on contaminated systems than production personnel. Examples of intrusive work include repairing leaks on process lines (pipefitters), refractory replacement in casting and heat treat furnaces (carpenters), repair of mechanical systems (machinists) and repair of instruments and controllers inside gloveboxes and other systems (electricians), painting over contamination (painters).

Support Personnel
This category includes Clerk Packers, Metrology Technicians, Janitors, and Handymen, who worked in process areas but did little or no hands-on work with radioactive materials. Exposures would be incidental to working in rooms with process equipment (metallurgical and chemical operations).

Analytical Laboratory Technicians
These individuals worked primarily in Building 559 (plutonium samples) or Building 881 (HEU/DU samples) and probably had lower exposures than operators who performed hands-on work with significantly higher material quantities.

Site Support Personnel
Stationary Operating Engineers (SOEs, also known as Boiler Vent Operators), Security Guards, Shift Managers, and Configuration Control Authority personnel performed little if any hands-on work, but had routine access to process areas. SOEs monitored exhaust systems, waste tanks, and process waste lines. Exposures would be incidental to working in rooms with process equipment (metallurgical and chemical operations).

Radiation Control Technicians
Radiation Control Technicians probably had exposures from supporting production chemical and metallurgical processes. Some exposures probably occurred during decontamination activities, surveys of contaminated areas, upset conditions. They generally performed no hands-on work, but typically worked side-by-side with production operators.

ATTACHMENT B
MAJOR JOB CATEGORIES (continued)

D&D Workers
D&D work includes draining actinide systems, decontamination, size reduction and removal of contaminated equipment, gloveboxes, piping, ductwork, exhaust systems, waste packaging of removed equipment, low-level, and transuranic wastes. Work is often in high (>2,000 dpm removable) airborne contamination areas with Derived Air Concentration levels from >0.1 to 106. Personal protection equipment includes Air Purifying Respirator, Powered Air Purifying Respirator, or PremAir supplied air. There were some high exposures due to direct work with highly radioactive equipment and contamination events.

ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT

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ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

C.1 GENERAL APPROACH

As described in ORAUT-OTIB-0020, *Use of Coworker Dosimetry Data for External Dose Assignment*, the general approach to the development of coworker data for cases without external monitoring data is to assign either 50th- or 95th-percentile doses with the intent that the assigned doses represent, but do not underestimate, the doses that would have been assigned if the worker had been monitored (ORAUT 2011).

C.2 APPLICATIONS AND LIMITATIONS

Some RFP workers could have worked at one or more other major sites in the DOE complex during their employment histories. Therefore, the data in this attachment must be used with caution to ensure that, for likely noncompensable cases, unmonitored external doses from multiple site employments have been overestimated. This typically requires the availability of the recorded doses or external coworker dosimetry data for all relevant sites.

The data in this attachment address penetrating radiation from gamma and neutron radiation and nonpenetrating radiation from electron and/or low-energy photon radiation. External onsite ambient dose should be applied as specified in the latest revision of ORAUT-PROC-0060*, Occupational Onsite Ambient Dose Reconstruction for DOE Sites* (ORAUT 2006b).

Neutron coworker doses before 1967 are not covered in this attachment. In conjunction with *SEC Petition Evaluation Report, Petition SEC-00030*, neutron coworker doses cannot be created that would ensure that a bounding exposure is assigned. Therefore, neutron coworker doses should not be assigned before 1967 (NIOSH 2006).

C.3 COWORKER DATA DEVELOPMENT

Dosimetry data for monitored RFP workers in the HIS20 database and the NDRP database were selected for this evaluation. HIS20 was the last system used at the RFP for the retention of occupational radiation exposure data. The NDRP database is a compilation of the dosimetry data reevaluated by the project and includes gamma and neutron dosimetry data from 1952 to 1970. The information in these systems contains data that have been transferred from previous electronic systems and hard-copy health physics files (Falk et al. 2005).

For plutonium workers, the NDRP reported building-specific cycle data between 1952 and 1970. These were converted to daily dose rates based on the length of the exchange period. The daily dose rates were then prorated to represent a full year of monitored employment. After 1970, HIS20 annual data were prorated to account for partial years of employment based on an analysis of the length of monitored employment associated with the data. The data were prorated so coworker doses that represent a full year of monitored employment could be derived; this permits the dose reconstructor to assign appropriate doses based on specific employment dates and job descriptions.

For uranium workers, HIS20 annual data from 1952 to 2005 were prorated to account for partial years of employment based on an analysis of the length of monitored employment associated with the data. The data were prorated so coworker doses that represent a full year of monitored employment could be derived; this permits the dose reconstructor to assign appropriate doses based on specific employment dates and job descriptions.

ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

The validity of the data that were used for coworker dose development was confirmed by selecting a sampling of beta-gamma film badge worksheets (handwritten records) and comparing them to data for penetrating radiation listed in the HIS20 database.

Each beta-gamma worksheet contains film badge results for numerous workers for a given building and quarter. For each worker-year, four sheets of quarterly data are combined to comprise the annual beta-gamma dose record. Thirty such worker-years were examined and compared to data for the same worker-year.

Of the 30 worker-years compiled (which represent data for 30 individuals), 22 (73%) were complete in that all quarterly data were found and the total annual dose was in agreement. For 5 worker-years (17%), one-quarter of the beta-gamma worksheet data was not found, but the annual total calculated without that missing quarter agreed with the HIS20 database. For 3 worker-years (10%), some quarterly beta-gamma worksheet data were not found or were blank and the annual totals did not agree with the HIS20 database. In all three of those instances, the HIS20 database annual values were higher than the data from the beta-gamma worksheets.

C.4 ADJUSTMENT FOR MISSED DOSE

According to OCAS-IG-001, missed doses are assigned for reported zero readings for each monitoring cycle to account for the possibility that doses were received but either not recorded by the dosimeter or not reported by the site (NIOSH 2007). In addition, reported dose values less than one-half the applicable minimum detection limits are assigned as missed dose. Annual maximum potential missed doses are calculated by multiplying the number of zero or unrecorded badge readings by the reported dosimeter LOD and summing the results. These values are used as the 95th percentile of a lognormal distribution to calculate the POC, which is determined by DOL. Therefore, Parameter 1 input in IREP is equal to the calculated maximum annual missed doses multiplied by 0.5, and the Parameter 2 input is equal to 1.52. These values represent the GM and GSD, respectively, for each year of analysis.

C.4.1 Plutonium Workers (Before 1971)

For pre-1971 plutonium workers, dose is based on a daily dose rate assigned continuously for every day of the year. Therefore, missed dose is not applicable when a calculated dose rate could be determined. If the calculated dose rate was determined to be zero, missed dose was assigned for the entire year. The average exchange rate was determined based on recorded cycle exchange rates for the given building and year. This exchange rate was then used to estimate the expected number of badge exchanges for a year.

C.4.2 Plutonium (After 1970) and Uranium (all years) Workers

The assignment of maximum potential missed doses for monitored workers is particularly significant for 1954 to 1962, when RFP workers could have been monitored weekly. Table C-1 lists the maximum annual missed dose by monitoring period.

ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Table C-1. Missed external doses (rem).

Monitoring period	Penetrating LOD	Nonpenetrating LOD[a]	Exchange frequency	Maximum potential annual missed penetrating dose	Maximum potential annual missed nonpenetrating dose
1952–1953	0.04	0.05	Semimonthly[b]	0.960	1.200
1954–1962	0.04	0.05	Weekly[b]	2.080	2.600
1963–1964	0.04	0.05	Semimonthly[b]	0.960	1.200
1965–1966	0.04	0.05	Monthly[b]	0.480	0.600
1967–1968	0.04	0.05	Semimonthly[b]	0.960	1.200
1969–1976	0.02	0.03	Semimonthly[b]	0.480	0.720
1977–1992	0.02	0.03	Monthly[c]	0.240	0.360
1993–2005	0.01	0.02	Monthly[c]	0.120	0.240

a. Based on analysis of nonpenetrating LODs for other DOE sites in ORAUT-OTIB-0017 (ORAUT 2005b). Specific RFP data for nonpenetrating LOD are not available at this time.
b. Based on maximum potential exchange frequency.
c. The exchange frequency was not defined. It is based on a review of claim data evaluated under the EEOICPA Subtitle B program.

C.5 SPECIAL CONSIDERATIONS

Certain aspects of the external dosimetry practices at RFP were considered in the analysis of the site data. These include:

- Conservatively determined default dosimeter exchange frequencies were used. Not all RFP employees would have had dosimetry exchanged at these frequencies

- During the process of prorating HIS20 doses to account for partial years of employment, it was discovered that artificially short or long wear periods had been entered in the HIS20 database. These artificial periods were entered because only one date (usually the end date) was available in the electronic data from previous database systems. To avoid skewing the overall dataset with artificially high or low prorated dose, data with a wear period less than or equal to 0.1 yr or greater than 1.25 year were excluded from the analysis described below.

- Inclusion of NDRP data in the HIS20 database led to the development of tables of data for penetrating and nonpenetrating dose that include and exclude the NDRP values. To determine neutron dose for the period from 1952 to 1969, neutron-to-photon ratios defined in the NDRP study (Falk et al. 2005) were used. Table C-2 defines the neutron-to-photon ratios for 1970 to 1976.

Neutron-to-photon ratio values for 1970 to 1976 were developed by analyzing records that contain dosimetry reports to supervisors. Data were available for workers on a semimonthly dosimeter exchange cycle for 1971, 1972, 1974, 1975, and 1976. Data for workers on a monthly exchange cycle were available for 1972 and 1976. Neutron-to-photon ratio values for the semimonthly exchange cycle were used in this document because:

- A semimonthly exchange cycle was applied to missed external dose for this period (see Table C-1).

- The neutron-to-photon ratio values for semimonthly exchange were equal to or greater than the monthly exchange values.

ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Table C-2. Lognormal neutron-to-photon ratio values, 1970 to 1976.

Year	Neutron-to-photon ratio GM (semimonthly exchange)	GSD	95th percentile	Neutron-to-photon ratio GM (monthly exchange)	GSD	95th percentile
1970	1.61[a]	3.45	12.4	N/A[b]	N/A	N/A
1971	1.61	3.45	12.4	N/A	N/A	N/A
1972	1.32	2.15	4.64	0.8	2.63	3.94
1973	1.32[c]	2.15	4.64	N/A	N/A	N/A
1974	0.68	3.01	4.16	N/A	N/A	N/A
1975	0.67	3.31	4.82	N/A	N/A	N/A
1976	0.95	3.59	7.81	0.78	4.29	8.55

a. Data for 1970 were not available. This value is the greater of the ratios for 1969 and 1971. The high neutron-to-gamma ratio in 1971 for Building 771 is reasonable from a process aspect, and extrapolating that ratio back to 1970 also is reasonable. In the aftermath of the 1969 plutonium fire in Buildings 776 and 777, the salvaged plutonium oxide had to be converted back to plutonium metal, a process done in Building 771. Building 771 had a huge backlog for relatively pure plutonium (little americium, low gamma) to be reprocessed, which was staged in the 776 to 771 tunnel and any other possible staging area in the vicinity. In addition, PuF_4 (a high neutron source) seemed to be generated faster in Building 771 than it could be reduced to metal, which also caused a staging problem in or near the process areas in Building 771 until the backlog could be reduced.

b. N/A = not applicable.

c. Data for 1973 were not available. This value is the greater of the ratios for 1972 and 1974.

Table C-2 lists the neutron-to-photon ratios for this period. The individual ratios for available data were analyzed, and they fit lognormal distributions.

As described below, an approach favorable to claimants was adopted in the development of coworker dose summaries; this approach was intended to account for any underestimation of doses to radiological workers at the RFP based on these considerations.

C.6 COWORKER ANNUAL DOSE SUMMARIES

Based on the described information and approaches, RFP coworker annual external dosimetry summaries were developed for use in the evaluation of external penetrating and nonpenetrating dose for certain workers who were potentially exposed to workplace radiation but for whom there is no or limited monitoring data from DOE. These summaries were developed using the following steps:

C.7 PLUTONIUM WORKERS

C.7.1 1952 to 1970

Step 1. As described above, for data from between 1952 and 1970, dose is based on a daily dose rate assigned continuously for every day of the year.

Step 2. When the calculated dose rate was determined to be zero, missed dose was assigned for the entire year. The average exchange rate was determined based on recorded cycle exchange rates for the given building and year. This exchange rate was then used to estimate the expected number of badge exchanges for a year.

Step 3. The 50th- and 95th-percentile annual coworker gamma and neutron doses were derived from the doses calculated in Step 1 and 2.

Step 4. Table C-3 lists the results of the coworker analysis of the NDRP data. These percentile doses should be used for RFP plutonium workers with no or limited monitoring data through

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the use of the methodologies in Section 7.0 of ORAUT-OTIB-0020 (ORAUT 2011). In general, the 50th-percentile dose can be used as a best estimate of a worker's dose when professional judgment indicates that the worker was probably exposed to intermittent low levels of external radiation. The 50th-percentile dose should generally not be used for workers who were routinely exposed. For routinely exposed workers (i.e., workers who were expected to have been monitored and routinely exposed), the 95th-percentile dose should be applied. However, other options are available through the guidance in ORAUT-OTIB-0020. For instance, for cases in which routine monitoring data exist and coworker dose is used to supplement missing quarters or years, the percentile dose should be the one that is consistent with the recorded doses unless there is reason to believe that the worker's job or location differs significantly from that held during the year in which the dose was recorded. For workers who are unlikely to have been exposed, external onsite ambient dose should be used rather than coworker doses.

Step 5. For instances where there was no building-specific data, the annual dose was based on the higher of the two adjacent years.

Step 6. In instances where nonpenetrating dose is needed for dose estimation, Table C-5 values should be used.

Step 7. Table C-6 lists the penetrating dose values (as described in the steps above) that have been adjusted using the guidance in Section 8.0 of ORAUT-OTIB-0052, *Parameters to Consider When Processing Claims for Construction Trade Workers* (ORAUT 2014). This guidance is applicable for construction trade workers who meet the criteria in Section 3.0 of that document. Because ORAUT-OTIB-0052 does not provide an adjustment factor for nonpenetrating dose, the guidance in Step 6 should be used to derive the nonpenetrating dose component for construction trade workers.

C.7.2 1971 to 2005

Step 1. As described above, for data from 1971 to 2005, the reported penetrating dose, which represents annual summary data, was modified for each worker to account for partial years of employment. This adjustment was made by analyzing the dosimetry wear dates in the HIS20 database. For example, if the average employment period for all RFP employees in the NIOSH-Division of Compensation Analysis and Support Claims Tracking System (NOCTS) was 11 months in a particular calendar year, the reported annual doses were multiplied by 12/11 (1.09). This permits the dose reconstructor to assign an appropriate prorated dose to account for partial years of employment or potential exposure.

Step 2. One-half of the maximum potential annual missed doses listed in Table C-1 were added to the reported annual doses from Step 1 (with the exception of reported positive doses, in which case the maximum missed dose was reduced by the dose that corresponded to one badge exchange, because it is not possible that all individual badge results were zero if a positive annual dose was reported).

Step 3. The 50th- and 95th-percentile annual coworker gamma doses were derived from the doses from Step 2 by ranking the data into cumulative probability curves and extracting the 50th- and 95th-percentile doses for each year.

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Step 4. Table C-4 lists the results of the coworker analysis. These percentile doses should be used for RFP workers with no or limited monitoring data through the use of the methodologies in Section 7.0 of ORAUT-OTIB-0020 (ORAUT 2011). In general, the 50th-percentile dose can be used as a best estimate of a worker's dose when professional judgment indicates that the worker was probably exposed to intermittent low levels of external radiation. The 50th-percentile dose should generally not be used for workers who were routinely exposed. For routinely exposed workers (i.e., workers who were expected to have been monitored and routinely exposed), the 95th-percentile dose should be applied. However, other options are available through the guidance in ORAUT-OTIB-0020. For instance, for cases in which routine monitoring data exist and coworker dose is used to supplement missing quarters or years, the percentile dose should be the one that is consistent with the recorded doses unless there is reason to believe that the worker's job or location differs significantly from that held during the year in which the dose was recorded. For workers who are unlikely to have been exposed, external onsite ambient dose should be used rather than coworker doses.

Step 5. Neutron and gamma dose component values are listed in Table C-4. Neutron and gamma components of the penetrating dose for 1970 to 1976 were separated using the neutron-to-photon ratio values in Section 6.2 of this document. Neutron and gamma components of the penetrating dose for 1977 to 2005 were separated using neutron-to-photon ratio values.

Step 6. In instances where nonpenetrating dose is needed for dose estimation, Table C-5 values should be used.

Step 7. Table C-7 lists penetrating dose values (as described in the steps above) that have been adjusted using the guidance in Section 8.0 of ORAUT-OTIB-0052 (ORAUT 2014). This guidance is applicable for construction trade workers who meet the criteria in Section 3.0 of that document. Because ORAUT-OTIB-0052 does not provide an adjustment factor for nonpenetrating dose, the guidance in Step 6 should be used to derive the nonpenetrating dose component for construction trade workers.

C.8 URANIUM WORKERS

Step 1. As described above, for data from 1952 to 2005, the reported penetrating dose, which represented annual summary data, was modified for each worker to account for partial years of employment. This adjustment was made by analyzing the dosimetry wear dates in the HIS20 database. For example, if the average employment period for all RFP employees in NOCTS was 11 months in a particular calendar year, the reported annual doses were multiplied by 12/11 (1.09). This permits the dose reconstructor to assign an appropriate prorated dose to account for partial years of employment or potential exposure.

Step 2. One-half of the maximum potential annual missed doses listed in Table C-1 was added to the reported annual doses from Step 1 (with the exception of reported positive doses, in which case the maximum missed dose was reduced by the dose that corresponded to one badge exchange because it is not possible that all individual badge results were zero if a positive annual dose was reported).

Step 3. The 50th- and 95th-percentile annual coworker gamma doses were derived from the doses from Step 2 by ranking the data into cumulative probability curves and extracting the 50th- and 95th-percentile doses for each year.

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EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Step 4. Table C-5 lists the results of the coworker analysis. These percentile doses should be used for RFP workers with no or limited monitoring data through the use of the methodologies in Section 7.0 of ORAUT-OTIB-0020 (ORAUT 2011). In general, the 50th-percentile dose can be used as a best estimate of a worker's dose when professional judgment indicates that the worker was probably exposed to intermittent low levels of external radiation. The 50th-percentile dose should generally not be used for workers who were routinely exposed. For routinely exposed workers (i.e., workers who were expected to have been monitored and routinely exposed), the 95th-percentile dose should be applied. However, other options are available through the guidance in ORAUT-OTIB-0020. For instance, for cases in which routine monitoring data exist and coworker dose is used to supplement missing quarters or years, the percentile dose should be the one that is consistent with the recorded doses unless there is reason to believe that the worker's job or location differs significantly from that held during the years dose was recorded. For workers who are unlikely to have been exposed, external onsite ambient dose should be used rather than coworker doses. Also, for the 1969 to 1970 time period, the data from the HIS-20 database were analyzed without consideration of the zero readings due to issues regarding the accurate recording of "zero" dose readings during that period.

Step 5. In instances where nonpenetrating dose is needed for dose estimation, Table C-5 values should be used.

Step 6. Table C-8 lists penetrating dose values (as described in the steps above) that have been adjusted using the guidance in Section 8.0 of ORAUT-OTIB-0052 (ORAUT 2014). This guidance is applicable for construction trade workers who meet the criteria in Section 3.0 of that document. Because ORAUT-OTIB-0052 does not provide an adjustment factor for nonpenetrating dose, the guidance in Step 5 should be used to derive the nonpenetrating dose component for construction trade workers.

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EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

C.9 COWORKER DOSE TABLES

Table C-3. Annual external coworker doses for plutonium workers, 1952 to 1970 (rem/yr).

Building 71

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	0.216	1.752	Not applicable	Not applicable
1954	0.520[a]	3.340	Not applicable	Not applicable
1955	0.469	6.518	Not applicable	Not applicable
1956	0.456	4.890	Not applicable	Not applicable
1957	0.562	5.371	Not applicable	Not applicable
1958	0.556	6.309	Not applicable	Not applicable
1959	1.356	6.779	Not applicable	Not applicable
1960	0.574	3.546	Not applicable	Not applicable
1961	1.330	4.849	Not applicable	Not applicable
1962	1.069	4.105	Not applicable	Not applicable
1963	0.574	3.337	Not applicable	Not applicable
1964	0.261	2.320	Not applicable	Not applicable
1965	0.523	4.000	Not applicable	Not applicable
1966	1.192	6.037	Not applicable	Not applicable
1967	0.907	5.614	0.808	3.941
1968	0.678	3.468	0.991	6.935
1969	0.590	4.278	1.590	4.824
1970	0.120a	4.278c	1.675	5.110

Building 76

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	Not applicable	Not applicable	Not applicable	Not applicable
1954	Not applicable	Not applicable	Not applicable	Not applicable
1955	Not applicable	Not applicable	Not applicable	Not applicable
1956	Not applicable	Not applicable	Not applicable	Not applicable
1957	0.520[a]	2.699	Not applicable	Not applicable
1958	0.730	6.361	Not applicable	Not applicable
1959	1.616	6.153	Not applicable	Not applicable
1960	1.981	5.840	Not applicable	Not applicable
1961	2.451	5.319	Not applicable	Not applicable
1962	1.721	4.484	Not applicable	Not applicable
1963	1.616	4.563	Not applicable	Not applicable
1964	1.741	5.079	Not applicable	Not applicable
1965	0.913	5.342	Not applicable	Not applicable
1966	1.898	7.324	Not applicable	Not applicable
1967	0.706	6.486	0.971	2.774
1968	0.283	2.759	0.954	3.441
1969	0.065	1.570	1.217	2.292
1970	0.120[a]	1.102	1.703	2.738

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Building 77

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	Not applicable	Not applicable	Not applicable	Not applicable
1954	Not applicable	Not applicable	Not applicable	Not applicable
1955	Not applicable	Not applicable	Not applicable	Not applicable
1956	Not applicable	Not applicable	Not applicable	Not applicable
1957	0.480[a]	0.480[a]	Not applicable	Not applicable
1958	0.052	2.918	Not applicable	Not applicable
1959	0.261	2.868	Not applicable	Not applicable
1960	0.130	3.598	Not applicable	Not applicable
1961	1.121	5.214	Not applicable	Not applicable
1962	0.479	2.764	Not applicable	Not applicable
1963	0.815	4.343	Not applicable	Not applicable
1964	0.965	4.958	Not applicable	Not applicable
1965	0.754	3.682	Not applicable	Not applicable
1966	1.278	5.519	Not applicable	Not applicable
1967	1.454	5.299	1.048	1.966
1968	0.586	2.772	0.969	1.811
1969	0.088	1.991	0.717	1.325
1970	0.120[a]	2.392	2.060	2.873

Building 91

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	0.782	1.646	Not applicable	Not applicable
1953	0.332	2.257	Not applicable	Not applicable
1954	0.520[a]	0.782	Not applicable	Not applicable
1955	0.520[a]	0.913	Not applicable	Not applicable
1956	0.480[a]	0.521	Not applicable	Not applicable
1957	0.520[a]	0.521	Not applicable	Not applicable
1958	0.480[a]	0.521	Not applicable	Not applicable
1959	0.240[a]	0.521	Not applicable	Not applicable
1960	0.240[a]	0.261	Not applicable	Not applicable
1961	0.240[a]	0.521	Not applicable	Not applicable
1962	0.240[a]	0.519	Not applicable	Not applicable
1963	0.240[a]	0.587	Not applicable	Not applicable
1964	0.240[a]	0.417	Not applicable	Not applicable
1965	0.240[a]	0.706	Not applicable	Not applicable
1966	0.118	1.662	Not applicable	Not applicable
1967	0.240[a]	1.276	1.189[b]	1.669[b]
1968	0.240[a]	0.665	0.669	1.073
1969	0.120[a]	0.483	1.108	2.237
1970	0.209	1.322	1.108[b]	2.237[b]

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EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

All Buildings

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	0.782	1.646	Not applicable	Not applicable
1953	0.261	1.947	Not applicable	Not applicable
1954	0.520[a]	1.825	Not applicable	Not applicable
1955	0.240[a]	4.596	Not applicable	Not applicable
1956	0.130	3.859	Not applicable	Not applicable
1957	0.480[a]	3.702	Not applicable	Not applicable
1958	0.140	4.355	Not applicable	Not applicable
1959	0.782	5.788	Not applicable	Not applicable
1960	0.433	4.745	Not applicable	Not applicable
1961	1.051	5.058	Not applicable	Not applicable
1962	0.730	3.964	Not applicable	Not applicable
1963	0.548	3.807	Not applicable	Not applicable
1964	0.339	3.285	Not applicable	Not applicable
1965	0.393	3.852	Not applicable	Not applicable
1966	0.900	5.958	Not applicable	Not applicable
1967	0.482	5.137	0.873	3.134
1968	0.281	2.869	0.965	5.044
1969	0.135	2.997	1.348	4.356
1970	0.120[a]	1.200	1.314	4.248

a. Dose rate was determined to be zero; missed dose was applied based on the number of exchange cycles observed for that building.
b. Dose rate was based on the favorable to claimant dose rate associated with higher of adjacent year.

Table C-4. Annual external coworker doses for plutonium workers, 1971 to 2005 (rem).

Year	Photon 95th percentile	Photon 50th percentile	Neutron 95th percentile	Neutron 50th percentile	Number of monitored workers
1971	0.743	0.147	1.196	0.237	3,398
1972	0.799	0.163	1.054	0.215	3,282
1973	0.731	0.164	0.966	0.216	3,020
1974	1.119	0.296	0.761	0.201	2,687
1975	0.796	0.240	0.533	0.161	2,489
1976	0.424	0.127	0.402	0.121	2,424
1977	0.415	0.086	0.174	0.036	3,740
1978	0.492	0.085	0.207	0.035	4,176
1979	0.638	0.086	0.268	0.036	3,893
1980	0.523	0.085	0.220	0.035	3,752
1981	0.600	0.077	0.252	0.033	4,060
1982	0.697	0.085	0.293	0.036	4,851
1983	0.854	0.094	0.359	0.040	5,360
1984	0.848	0.100	0.356	0.042	5,673
1985	0.917	0.100	0.385	0.042	6,140
1986	0.961	0.129	0.404	0.054	4,942
1987	1.063	0.182	0.447	0.077	2,583
1988	0.870	0.140	0.366	0.059	2,778
1989	0.388	0.081	0.163	0.034	5,296
1990	0.203	0.091	0.085	0.038	3,369
1991	0.237	0.108	0.100	0.045	5,641
1992	0.188	0.105	0.079	0.044	5,831

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Year	Photon 95th percentile	Photon 50th percentile	Neutron 95th percentile	Neutron 50th percentile	Number of monitored workers
1993	0.146	0.056	0.061	0.024	5,313
1994	0.126	0.059	0.053	0.025	4,839
1995	0.141	0.056	0.059	0.024	4,130
1996	0.193	0.074	0.081	0.031	3,454
1997	0.248	0.060	0.104	0.025	3,718
1998	0.193	0.051	0.081	0.022	3,470
1999	0.136	0.050	0.057	0.021	3,655
2000	0.115	0.042	0.048	0.018	3,576
2001	0.112	0.042	0.047	0.018	3,443
2002	0.110	0.042	0.046	0.018	3,502
2003	0.089	0.042	0.038	0.018	3,373
2004	0.068	0.042	0.029	0.018	2,758
2005	0.123	0.050	0.052	0.021	955

Table C-5. Annual external coworker doses for uranium workers, 1952 to 2005 (rem).

Year	Penetrating, 95th percentile	Penetrating, 50th percentile	Nonpenetrating, 95th percentile	Nonpenetrating, 50th percentile	Number of monitored workers
1952	5.018	2.505	5.133	2.620	42
1953	4.190	0.751	4.553	0.892	319
1954	3.233	1.095	3.600	1.361	353
1955	4.411	1.165	5.266	1.431	529
1956	4.461	1.135	5.617	1.415	781
1957	5.136	1.177	6.004	1.454	918
1958	6.015	1.253	7.553	1.584	1,062
1959	7.186	1.581	8.002	1.908	1,063
1960	7.121	1.293	7.728	1.645	1,284
1961	7.850	1.527	8.201	1.923	1,638
1962	6.523	1.542	7.062	1.828	2,003
1963	5.955	0.940	6.232	1.104	2,176
1964	4.875	0.648	5.012	0.799	2,834
1965	3.533	0.511	3.663	0.598	2,826
1966	4.767	0.592	4.976	0.679	2,888
1967	4.379	0.627	4.735	0.761	2,902
1968	3.276	0.578	3.591	0.714	3,101
1969	3.588	0.680	3.788	0.824	3,471
1970	2.894	0.531	3.067	0.651	3,308
1971	1.938	0.384	2.096	0.500	3,398
1972	1.853	0.377	1.995	0.494	3,282
1973	1.697	0.380	1.848	0.497	3,020
1974	1.881	0.497	2.047	0.612	2,687
1975	1.329	0.401	1.525	0.516	2,489
1976	0.826	0.248	1.030	0.364	2,424
1977	0.589	0.122	0.699	0.177	3,740
1978	0.698	0.120	0.830	0.180	4,176
1979	0.906	0.122	1.074	0.180	3,893
1980	0.743	0.120	0.889	0.168	3,752
1981	0.853	0.110	1.008	0.180	4,060
1982	0.990	0.121	1.174	0.166	4,851
1983	1.212	0.134	1.440	0.193	5,360
1984	1.204	0.141	1.551	0.200	5,673

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Year	Penetrating, 95th percentile	Penetrating, 50th percentile	Nonpenetrating, 95th percentile	Nonpenetrating, 50th percentile	Number of monitored workers
1985	1.302	0.142	1.584	0.203	6,140
1986	1.365	0.183	1.860	0.301	4,942
1987	1.510	0.259	2.265	0.457	2,583
1988	1.236	0.199	1.614	0.373	2,778
1989	0.550	0.115	0.733	0.180	5,296
1990	0.288	0.130	0.435	0.201	3,369
1991	0.337	0.154	0.471	0.228	5,641
1992	0.267	0.150	0.421	0.235	5,831
1993	0.207	0.080	0.296	0.150	5,313
1994	0.179	0.084	0.242	0.142	4,839
1995	0.200	0.080	0.275	0.137	4,130
1996	0.274	0.105	0.357	0.168	3,454
1997	0.352	0.085	0.420	0.145	3,718
1998	0.275	0.073	0.337	0.130	3,470
1999	0.192	0.072	0.256	0.127	3,655
2000	0.164	0.060	0.224	0.120	3,576
2001	0.160	0.060	0.223	0.120	3,443
2002	0.157	0.060	0.215	0.120	3,502
2003	0.127	0.060	0.194	0.120	3,373
2004	0.097	0.060	0.164	0.120	2,758
2005	0.175	0.071	0.234	0.129	955

Table C-6. Annual external coworker doses for plutonium workers, 1952 to 1970, modified in accordance with ORAUT-OTIB-0052 (rem/yr) (ORAUT 2014).

Building 71

Year	Photon 50th percentile	Photon 95th percentile	Neutron 50th percentile	Neutron 95th percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	0.303	2.453	Not applicable	Not applicable
1954	0.728[a]	4.676	Not applicable	Not applicable
1955	0.657	9.125	Not applicable	Not applicable
1956	0.639	6.846	Not applicable	Not applicable
1957	0.786	7.519	Not applicable	Not applicable
1958	0.779	8.833	Not applicable	Not applicable
1959	1.898	9.490	Not applicable	Not applicable
1960	0.803	4.964	Not applicable	Not applicable
1961	1.862	6.789	Not applicable	Not applicable
1962	1.497	5.747	Not applicable	Not applicable
1963	0.803	4.672	Not applicable	Not applicable
1964	0.365	3.249	Not applicable	Not applicable
1965	0.732	5.600	Not applicable	Not applicable
1966	1.669	8.451	Not applicable	Not applicable
1967	1.269	7.860	1.132	5.518
1968	0.949	4.855	1.387	9.709
1969	0.825	5.989	2.227	6.754
1970	0.168[a]	5.989[b]	2.345	7.154

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Building 76

Year	Photon 50th-percentile	Photon 95th-percentile	Neutron 50th-percentile	Neutron 95th-percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	Not applicable	Not applicable	Not applicable	Not applicable
1954	Not applicable	Not applicable	Not applicable	Not applicable
1955	Not applicable	Not applicable	Not applicable	Not applicable
1956	Not applicable	Not applicable	Not applicable	Not applicable
1957	0.728[a]	3.778	Not applicable	Not applicable
1958	1.022	8.906	Not applicable	Not applicable
1959	2.263	8.614	Not applicable	Not applicable
1960	2.774	8.176	Not applicable	Not applicable
1961	3.431	7.446	Not applicable	Not applicable
1962	2.409	6.278	Not applicable	Not applicable
1963	2.263	6.388	Not applicable	Not applicable
1964	2.437	7.110	Not applicable	Not applicable
1965	1.278	7.479	Not applicable	Not applicable
1966	2.657	10.254	Not applicable	Not applicable
1967	0.989	9.081	1.360	3.884
1968	0.396	3.863	1.335	4.818
1969	0.091	2.197	1.703	3.209
1970	0.168[a]	1.543	2.385	3.833

Building 77

Year	Photon 50th-percentile	Photon 95th-percentile	Neutron 50th-percentile	Neutron 95th-percentile
1952	Not applicable	Not applicable	Not applicable	Not applicable
1953	Not applicable	Not applicable	Not applicable	Not applicable
1954	Not applicable	Not applicable	Not applicable	Not applicable
1955	Not applicable	Not applicable	Not applicable	Not applicable
1956	Not applicable	Not applicable	Not applicable	Not applicable
1957	0.672[a]	0.672[a]	Not applicable	Not applicable
1958	0.073	4.086	Not applicable	Not applicable
1959	0.365	4.015	Not applicable	Not applicable
1960	0.183	5.037	Not applicable	Not applicable
1961	1.570	7.300	Not applicable	Not applicable
1962	0.670	3.869	Not applicable	Not applicable
1963	1.141	6.080	Not applicable	Not applicable
1964	1.351	6.942	Not applicable	Not applicable
1965	1.055	5.155	Not applicable	Not applicable
1966	1.789	7.726	Not applicable	Not applicable
1967	2.036	7.419	1.467	2.753
1968	0.820	3.881	1.357	2.535
1969	0.123	2.787	1.004	1.855
1970	0.168[a]	3.349	2.885	4.022

Building 91

Year	Photon 50th-percentile	Photon 95th-percentile	Neutron 50th-percentile	Neutron 95th-percentile
1952	1.095	2.304	Not applicable	Not applicable
1953	0.465	3.160	Not applicable	Not applicable
1954	0.728[a]	1.095	Not applicable	Not applicable
1955	0.728[a]	1.278	Not applicable	Not applicable

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EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Year	Photon 50th-percentile	Photon 95th-percentile	Neutron 50th-percentile	Neutron 95th-percentile
1956	0.672[a]	0.730	Not applicable	Not applicable
1957	0.728[a]	0.730	Not applicable	Not applicable
1958	0.672[a]	0.730	Not applicable	Not applicable
1959	0.336[a]	0.730	Not applicable	Not applicable
1960	0.336[a]	0.365	Not applicable	Not applicable
1961	0.336[a]	0.730	Not applicable	Not applicable
1962	0.336[a]	0.727	Not applicable	Not applicable
1963	0.336[a]	0.821	Not applicable	Not applicable
1964	0.336[a]	0.584	Not applicable	Not applicable
1965	0.336[a]	0.989	Not applicable	Not applicable
1966	0.165	2.327	Not applicable	Not applicable
1967	0.336[a]	1.786	1.665[b]	2.337[b]
1968	0.336[a]	0.931	0.936	1.503
1969	0.168[a]	0.676	1.551	3.131
1970	0.292	1.850	1.551[b]	3.132[b]

All buildings

Year	Photon 50th-percentile	Photon 95th-percentile	Neutron 50th-percentile	Neutron 95th-percentile
1952	1.095	2.304	Not applicable	Not applicable
1953	0.365	2.725	Not applicable	Not applicable
1954	0.728[a]	2.555	Not applicable	Not applicable
1955	0.336[a]	6.435	Not applicable	Not applicable
1956	0.183	5.402	Not applicable	Not applicable
1957	0.672[a]	5.183	Not applicable	Not applicable
1958	0.197	6.097	Not applicable	Not applicable
1959	1.095	8.103	Not applicable	Not applicable
1960	0.606	6.643	Not applicable	Not applicable
1961	1.472	7.081	Not applicable	Not applicable
1962	1.022	5.549	Not applicable	Not applicable
1963	0.767	5.330	Not applicable	Not applicable
1964	0.475	4.599	Not applicable	Not applicable
1965	0.551	5.393	Not applicable	Not applicable
1966	1.260	8.341	Not applicable	Not applicable
1967	0.675	7.192	1.223	4.388
1968	0.393	4.016	1.352	7.061
1969	0.189	4.195	1.887	6.098
1970	0.168[a]	1.680	1.840	5.947

a. Dose rate was determined to be zero; missed dose was applied based on the number of exchange cycles observed for that building.
b. Dose rate was based on the favorable to claimant dose rate associated with higher of adjacent year.

Table C-7. Annual external coworker doses for plutonium workers, 1971 to 2005, modified in accordance with ORAUT-OTIB-0052 (rem) (ORAUT 2014).

Year	Photon 95th-percentile	Photon 50th-percentile	Neutron 95th-percentile	Neutron 50th-percentile	Number of monitored workers
1971	1.004	0.171	1.617	0.275	3,398
1972	1.079	0.188	1.424	0.248	3,282
1973	0.984	0.190	1.299	0.251	3,020
1974	1.512	0.359	1.028	0.244	2,687
1975	1.059	0.281	0.710	0.189	2,489

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EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Year	Photon 95th-percentile	Photon 50th-percentile	Neutron 95th-percentile	Neutron 50th-percentile	Number of monitored workers
1976	0.546	0.131	0.519	0.124	2,424
1977	0.550	0.089	0.231	0.037	3,740
1978	0.658	0.085	0.276	0.035	4,176
1979	0.862	0.089	0.362	0.037	3,893
1980	0.702	0.085	0.295	0.035	3,752
1981	0.810	0.077	0.340	0.033	4,060
1982	0.945	0.086	0.397	0.036	4,851
1983	1.164	0.101	0.489	0.042	5,360
1984	1.156	0.108	0.486	0.046	5,673
1985	1.253	0.109	0.526	0.046	6,140
1986	1.315	0.149	0.552	0.063	4,942
1987	1.458	0.225	0.612	0.094	2,583
1988	1.187	0.165	0.499	0.069	2,778
1989	0.512	0.082	0.215	0.035	5,296
1990	0.253	0.097	0.106	0.041	3,369
1991	0.301	0.121	0.126	0.051	5,641
1992	0.232	0.116	0.098	0.049	5,831
1993	0.188	0.063	0.079	0.027	5,313
1994	0.161	0.067	0.068	0.028	4,839
1995	0.182	0.063	0.076	0.027	4,130
1996	0.255	0.088	0.107	0.037	3,454
1997	0.332	0.069	0.139	0.029	3,718
1998	0.255	0.057	0.107	0.024	3,470
1999	0.174	0.055	0.073	0.023	3,655
2000	0.146	0.042	0.061	0.018	3,576
2001	0.142	0.042	0.060	0.018	3,443
2002	0.139	0.042	0.058	0.018	3,502
2003	0.110	0.042	0.046	0.018	3,373
2004	0.080	0.042	0.034	0.018	2,758
2005	0.157	0.054	0.066	0.023	955

Table C-8. Annual external coworker doses for uranium workers, 1952 to 2005, modified in accordance with ORAUT-OTIB-0052 (rem) (ORAUT 2014).

Year	Penetrating 95th percentile	Penetrating 50th percentile	Nonpenetrating 95th percentile	Nonpenetrating 50th percentile	Number of monitored workers
1952	6.842	3.323	5.133	2.620	42
1953	5.681	0.867	4.553	0.892	319
1954	4.118	1.125	3.600	1.361	353
1955	5.768	1.224	5.266	1.431	529
1956	5.838	1.181	5.617	1.415	781
1957	6.782	1.240	6.004	1.454	918
1958	8.012	1.346	7.553	1.584	1,062
1959	9.653	1.805	8.002	1.908	1,063
1960	9.561	1.402	7.728	1.645	1,284
1961	10.583	1.730	8.201	1.923	1,638
1962	8.724	1.751	7.062	1.828	2,003
1963	8.153	1.132	6.232	1.104	2,176
1964	6.641	0.723	5.012	0.799	2,834
1965	4.858	0.627	3.663	0.598	2,826
1966	6.585	0.740	4.976	0.679	2,888

ATTACHMENT C
EXTERNAL COWORKER DOSIMETRY DATA FOR ROCKY FLATS PLANT (continued)

Year	Penetrating 95th percentile	Penetrating 50th percentile	Nonpenetrating 95th percentile	Nonpenetrating 50th percentile	Number of monitored workers
1967	5.947	0.694	4.735	0.761	2,902
1968	4.402	0.625	3.591	0.714	3,101
1969	4.931	0.860	3.788	0.824	3,471
1970	3.959	0.652	3.067	0.651	3,308
1971	2.622	0.446	2.096	0.500	3,398
1972	2.503	0.436	1.995	0.494	3,282
1973	2.284	0.441	1.848	0.497	3,020
1974	2.541	0.603	2.047	0.612	2,687
1975	1.769	0.470	1.525	0.516	2,489
1976	1.064	0.255	1.030	0.364	2,424
1977	0.781	0.127	0.699	0.177	3,740
1978	0.934	0.120	0.830	0.180	4,176
1979	1.224	0.127	1.074	0.180	3,893
1980	0.996	0.120	0.889	0.168	3,752
1981	1.150	0.110	1.008	0.180	4,060
1982	1.343	0.122	1.174	0.166	4,851
1983	1.653	0.143	1.440	0.193	5,360
1984	1.642	0.154	1.551	0.200	5,673
1985	1.779	0.154	1.584	0.203	6,140
1986	1.867	0.212	1.860	0.301	4,942
1987	2.070	0.319	2.265	0.457	2,583
1988	1.686	0.234	1.614	0.373	2,778
1989	0.727	0.117	0.733	0.180	5,296
1990	0.360	0.137	0.435	0.201	3,369
1991	0.427	0.171	0.471	0.228	5,641
1992	0.330	0.165	0.421	0.235	5,831
1993	0.267	0.090	0.296	0.150	5,313
1994	0.229	0.095	0.242	0.142	4,839
1995	0.258	0.090	0.275	0.137	4,130
1996	0.362	0.124	0.357	0.168	3,454
1997	0.471	0.098	0.420	0.145	3,718
1998	0.363	0.080	0.337	0.130	3,470
1999	0.247	0.078	0.256	0.127	3,655
2000	0.207	0.060	0.224	0.120	3,576
2001	0.202	0.060	0.223	0.120	3,443
2002	0.197	0.060	0.215	0.120	3,502
2003	0.156	0.060	0.194	0.120	3,373
2004	0.114	0.060	0.164	0.120	2,758
2005	0.223	0.077	0.234	0.129	955