ORAU TEAM
Dose Reconstruction Project for NIOSH

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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.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AP	anterior-posterior
Bq	becquerel
CHP	Certified Health Physicist
Ci	curie
cm	centimeter
cpm	counts per minute
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
dpm	disintegrations per minute
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
Emax	maximum energy
EU	enriched uranium
ft	foot
g	gram
GM	geometric mean
GSD	geometric standard deviation
$H^*(d)$	ambient dose equivalent
HEU	highly enriched uranium
HIS-20	Health Physics Information System (database)
$H_p(d)$	personal dose equivalent
$H_{p,slab}(d)$	personal dose equivalent (slab phantom)
HPS	Health Physics Services (company)
hr	hour
HSDB	Health Sciences Database
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
ISO	isotropic
keV	kiloelectron-volt, 1,000 electron-volts
kg	kilogram
LANL	Los Alamos National Laboratory
Lc	critical level
LOD	limit of detection

MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mm	millimeter
mo	month
mR	milliroentgen
mrad	millirad
mrem	millirem
mSv	millisievert
nCi	nanocurie
NCRP	National Council on Radiation Protection and Measurements
NDRP	Neutron Dose Reconstruction Project
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
ORNL	Oak Ridge National Laboratory
ORAU	Oak Ridge Associated Universities
OSL	Optically Stimulated Luminescence
PNAD	personal nuclear accident dosimeter
PNL	Pacific Northwest Laboratory
POC	probability of causation
ppb	parts per billion
qtr	quarter
R	roentgen
RFETS	Rocky Flats Environmental Technology Site
RFP	Rocky Flats Plant
RHRS	Radiological Health Records System
ROT	rotational
SOE	stationary operating engineer
SRDB	Site Research Database
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
wk	week
yr	year
§	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 historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

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

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

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

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

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

6.1.1 Purpose

This 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 Section 6, Occupational External Dosimetry, of the Rocky Flats 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 the *External Dose Reconstruction Implementation Guideline* (NIOSH 2006).

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 (2006), this document identifies how to adjust the historical occupational external recorded dose to account for current scientific methods and protection factors.

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.

6.2 EXTERNAL DOSIMETRY OVERVIEW

Over the years, RFP used a variety of dosimeters to measure occupational ionizing radiation dose. 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 and a 1-mm cadmium filter. For the plutonium areas, in 1960, a brass filter with half the filtration of the cadmium filter was added to cover half of the open window. 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 6-1).

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 6-2). 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 open

Figure 6-1. ORNL-style film badge (including brass filter).

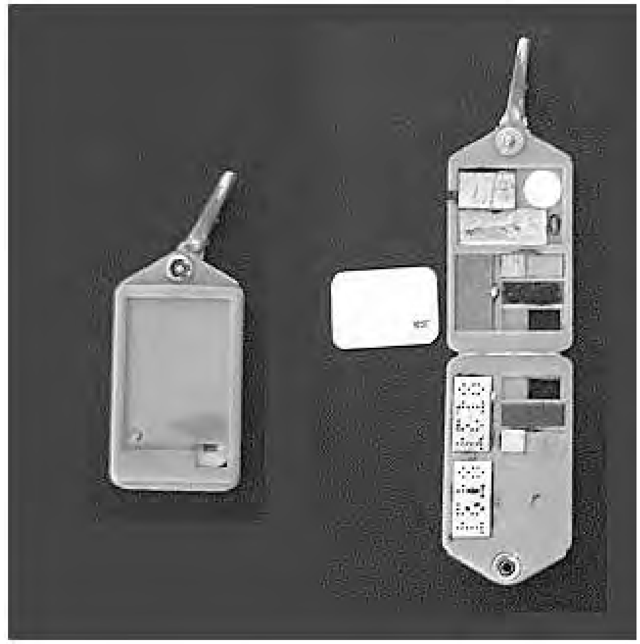

Figure 6-2. RFP multielement film badge.

window. Film was used for neutron dose measurement. This badge contained a PNAD and was an interim badge (Figure 6-3) 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 Harshaw Chemical Company (Figure 6-4). 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.

Figure 6-3. RFP interim TLD/film badge.

Figure 6-4. RFP Harshaw badge.

In 1983, an automated Panasonic dosimetry system was introduced at RFP (Figure 6-5). This badge contains two Panasonic dosimeters, one for measuring photon and beta dose and one for measuring neutron dose. The beta/photon dosimeter contains two TLD phosphors and a lead filter over one of the elements. The neutron dosimeter contains three neutron-sensitive elements and one neutron-insensitive element under cadmium or tin filters. This badge includes a PNAD (Baker 2002).

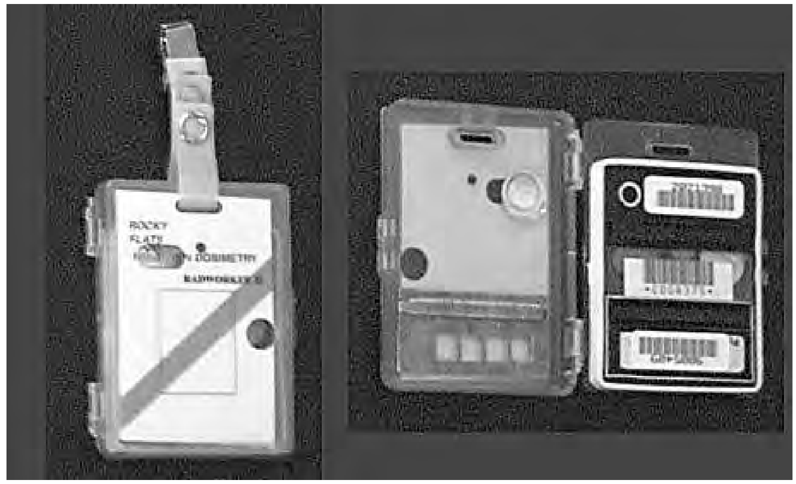

Figure 6-5. RFP Panasonic dosimeter.

Table 6-1 summarizes the history of dosimeter use at RFP. The implementation dates listed in the table and used throughout this document are not exact. In many cases, dosimeters were phased in over a period of 1 to 3 yr. Determining from an individual employee's dosimetry record which dosimeter was worn is not possible, which adds a degree of uncertainty to dose reconstruction. Further research is necessary to identify exact dates for each dosimeter type.

The following sections discuss each of these dosimeter types in relation to each necessary dose reconstruction parameter.

6.3 INTERPRETING THE EXTERNAL DOSIMETRY RECORD

When NIOSH requests an individual dosimetry record (file), the Rocky Flats Environmental Technology Site (RFETS) Radiological Health Department provides a significant amount of effort in reviewing and organizing the external dosimetry records. Both hard-copy and electronic files are reviewed. RFETS provides comments if discrepancies are found. If there are hard-copy results that are not in the electronic file, the electronic file is updated. If the electronic file includes a reading that is not indicated in the paper file, it is noted as a comment but left in place. The assumption favorable to claimants is to include discrepant data in the annual total, unless notes explain why the data should not be included [1].

External dosimetry results are reported as:

- Penetrating (Pen) or deep - deep dose + neutron
- Skin - shallow dose + neutron
- Forearm (measured or estimated)
- 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 on a routine basis, but estimated the hand dose using the forearm dose measured by a wrist badge and the application of a hand-to-wrist ratio (see Section 6.10).

Table 6-1. External dosimeter history.

	Beta/gamma					Neutron		Extremity	
			Filtration						
Year	**Holder**	**Detector**	**Deep**	**Shallow**	**Processor**	**Detector**	**Processor**	**Holder**	**Detector**
1951[a]	SS ORNL design	Std. X-ray	1-mm Cd	None	LANL	Track Plate	LANL	SS ORNL design	Std. X-ray
1952									
1953									
1954									
1955									
1956					HPS		HPS		
1957						NTA Film			
1958					RFETS		RFETS		
1959									
1960			1/2 brass[b]					1/2 brass[c]	
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									

	Beta/gamma					Neutron		Extremity	
			Filtration						
Year	Holder	Detector	Deep	Shallow	Processor	Detector	Processor	Holder	Detector
1991	(DOELAP)							Panasonic	UD-813AS11
1992									
1993									
1994									
1995									
1996									
1997									
1998									
1999								(DOELAP)	
2000									
2001									
2002									
2003									
2004									
2005	InLight™	OSL[d]			Landauer	CR-39	Landauer	Luxel®	OSL

a. Dates are approximate, overlap occurred during changeover (Baker 2002).
b. Brass not used on beta open window (Baker 2002).
c. Brass not used on beta open window, no brass on wrist side (Baker 2002).
d. OSL = Optically Stimulated Luminescence dosimeter.

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
- 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 (Author unknown, no date) [2].

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 on the report cards of 1 mrem per measurement. 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 (RFP, no date) 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 from the archive at the Federal Center 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.

6.3.3 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 current electronic database, HIS-20, 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 an identical structure to RHRST_ED_TLD_HISTORY, contains post-1991 data. The records are 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.

Dose History Hard-Copy File Contents
The RFP Radiological Health organization reviews 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 are 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. A review of the rest of the external dosimetry file might indicate some detail of what went into the annual total. After 1975, this report provides 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 2003 and the result of review of these records by James M. Langsted [3]:

- 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 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.

  During the transition between the Harshaw and the Panasonic badges, RFP used a code to indicate the source of the dosimetry result [4]:

  - 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 Detail 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 Radiological Health Records System (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:

- 1951–1976, quarterly dose history (RHRS data will provide a neutron/gamma breakdown)
- 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 6-2 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 [6], 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 [7]. 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.

Table 6-2. Interpretation of reported data [5].

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 6-11 & 6-18 and Section 6.8.2.1. Deep dose Extremity dose Skin dose (see Section 6.3 and 6.6.1.2, last paragraph).	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 <u>is</u> 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 not included in the DDE and SDE values. Otherwise, a zero indicates a monitored exposure reported as zero.	Blank indicates an unreported 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.
Health Physics External Exposure Activity Run Yearly (Figure A-6)	Quarterly total of dose in mrem according to Tables 6-11 & 6-18 and Section 6.8.2.1. Penetrating dose, Extremity dose (see Section 6.10), Skin dose (see Sections 6.3 & 6.6.1.2, last paragraph). 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 6-11 & 6-18 and Section 6.8.2.1.	Zero indicates no measured dose under that filter	Blank indicates reading not available. For neutron badge (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.

Code	Explanation
1	Gamma/beta dosimeter
2	Gamma/X-ray dosimeter
3	Neutron dosimeter
Dose column labels	
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)

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-8 and Section 6.3.3.2)	Quarterly totals are mrem according to Tables 6-11 & 6-18 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.
External Dosimetry (TLD) Detail (Figure A-9 and Section 6.3.3.2)	Individual dosimeter results are mrem according to Tables 6-11 & 6-18 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 6-11& 6-18 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 6-11 & 6-18.	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 6-11 & 6-18 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 6-11 & 6-18.	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.
Occupational Radiation Exposure Information (Figure A-15)	This report shows dose in <u>rem</u> according to Tables 6-11 & 6-18. 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.

6.3.5.2 Neutron Dose Reconstruction Project File

The Neutron Dose Reconstruction Project (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; therefore, 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), and the use of these data in dose reconstructions is detailed in ORAUT (2005a).

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.

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[2] 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 6-6. 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.

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

[2] 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).

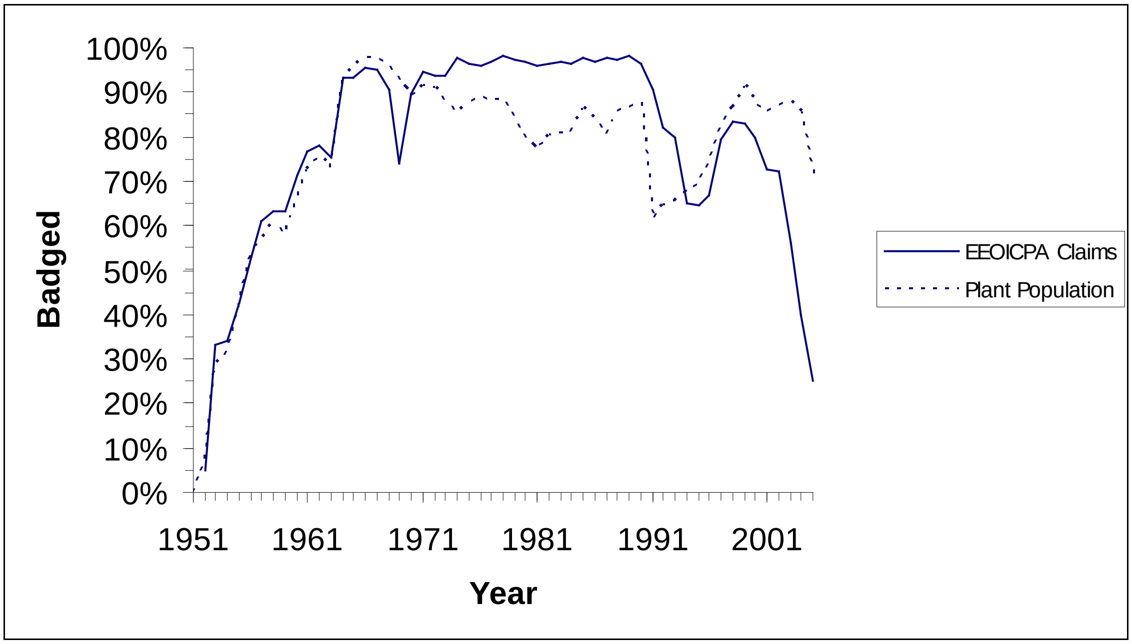

Figure 6-6. Portion of plant population badged.

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 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 6-6a. 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 "diluted" by those monitored employees that did not work in the production areas.

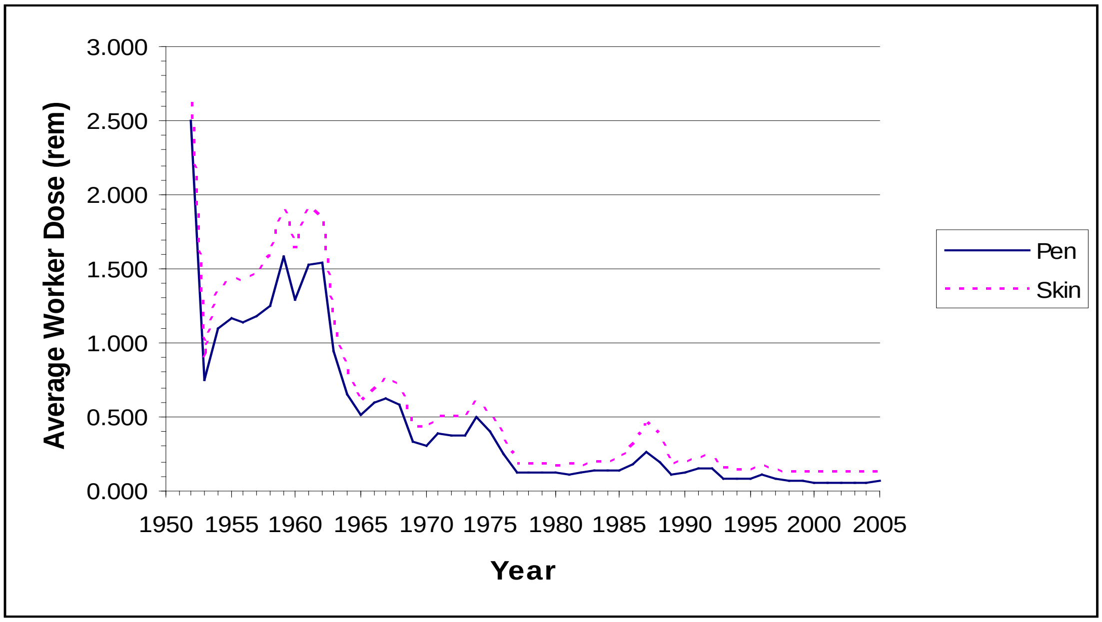

Figure 6-6a. Average measured worker dose (data from ORAU 2006d).

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. In later years, dosimetry was exchanged on semimonthly, monthly, and quarterly frequencies. In the 1990s, exchange frequencies went to monthly, quarterly, and semiannually. An option for annual exchanges was identified, but never used.

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 by the author of this report, James M. Langsted. 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 6-3 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.

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 (no date) [8]. 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 [9]. 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

Table 6-3. Conservatively determined default dosimeter exchange frequencies.[a,b]

Year	Chemical operators		Metallurgical operators		Maintenance workers	Support personnel	Analytical laboratory technicians	Site support personnel	Radiation control technicians	D&D workers
	Pu	U	Pu	U						
1951	bw	bw	bw	bw	m	m	bw	m	bw	m
1952	bw	bw	bw	bw	m	m	bw	m	bw	m
1953	bw	bw	bw	bw	m	m	bw	m	bw	m
1954	bw	bw	bw	w	m	bw	bw	m	bw	bw
1955	bw	bw	bw	w	m	bw	bw	m	bw	bw
1956	bw	bw	bw	w	m	bw	bw	m	bw	bw
1957	bw	bw	bw	w	m	bw	bw	m	bw	bw
1958	w	w	w	w	m	bw	bw	m	w	bw
1959	w	bw	w	w	m	bw	bw	m	w	bw
1960	w	w	w	w	m	m	bw	m	w	m
1961	bw	bw	bw	w	m	m	w	m	bw	m
1962	bw	bw	bw	w	m	m	w	m	bw	m
1963	bw	m	bw	bw	m	m	q	m	bw	m
1964	bw	m	bw	m	q	m	q	q	bw	m
1965	m	--	m	m	q	q	q	q	m	q
1966	m	--	m	m	m	q	q	q	m	q
1967	bw	--	bw	m	m	q	q	q	bw	q
1968	bw	--	bw	m	m	m	m	m	bw	m
1969	bw	--	m	m	m	m	m	m	m	m
1970	bw	--	m	m	m	m	m	m	m	m
1971	bw	--	m	m	m	m	m	m	m	m
1972	bw	--	m	m	m	m	m	m	m	m
1973	bw	--	m	m	m	m	m	m	m	m
1974	bw	--	m	m	m	m	m	m	m	m
1975	bw	--	m	m	m	m	m	m	m	m
1976	bw	--	m	m	m	m	m	m	m	m

a. bw = biweekly (every 2 wk), assumed because it is favorable to claimants over semimonthly (twice per month); m = monthly; q = quarterly; w = weekly.
b. Source: Study described in Section 6.4.2.

was reported as zero (RFETS 2001). This policy is consistent with the LODs reported elsewhere in this TBD.

6.4.5 Recorded Dose Practices

Table 6-4 provides a summary of the calculations used to determine the recorded dose at RFP.

Table 6-4. Summary of historical recorded dose practices.[a]

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

a. $Ow_{density}$ = open window (measured density); Ow_{dose} = open window (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[d]; 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.
d. 1.14 or 1.17 or nonlinear factor.

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 6-3 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 must be assumed. This assumption is favorable to claimants.

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. This would be the situation, for example, if an individual received a cumulative dose of 2,140 mrem in a given year at a facility that had a monthly monitoring frequency and where the maximum permissible exposure limit was 1,000 mrem/mo. The minimum number of months in which this dose could have been received is 3. Therefore, the maximum number of missed dose months would be 9, and the minimum would be zero because the dose could have been received evenly throughout the year. The central estimated number of months should be the median, or 5; however, the upper bound would be 9 (NIOSH 2006).

Quarterly or annual limits:

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

Table 6-5 divides these dose limits into exchange frequencies. Either the dosimetry records or the default values from Table 6-3 should be used to determine or estimate the exchange frequency and number of reported zeros. Using the methodology of NIOSH (2006), 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 [10]. 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 [11].

Corrections were noted in the dose record when calculation or computer errors occurred [12]. 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

Table 6-5. 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.

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. The assumption favorable to claimants is that the dosimeter was lost; dose should be assigned for that period using dosimetry data from before and after that period (dose reconstructors should consider the approach of Watson et al. 1994).

6.5.4 Exposure Geometry

NIOSH has determined that an assumption of 100% anterior-posterior (AP) exposure for dose reconstructions is favorable to claimants. An alternative approach is presented below.

Because little information is available on the exposure geometry for an individual, estimates have been made by the author using professional judgment (NIOSH 2006, 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 [13]. 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 6-6 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 [14]. Table 6-7 lists these fractions, which are rounded.

Table 6-6. Exposure geometry calculation.

Major job category	Hands-on work (time)	Source geometry	Calculated dose received	
			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 6-7. Exposure geometry defaults for major job categories.

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

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 [15]. 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 6-8 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 6-8. 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
	Outside apron	1.9	1	1
Unprotected area	Under apron	1	1.2	1
	Outside apron	1.9	1	1

Although this field study was performed using Panasonic dosimeters, the use of 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 6-8 will be applied.

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 (RFETS 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 minimus* levels. Recycled DU received from Fernald contained 2.8 ppb plutonium, 389 ppb neptunium, and 8,550 ppb technetium. A small quantity of recycled highly enriched uranium (HEU) received at RFP in 1955 contained 0.007 ppb plutonium, 2.5 ppb neptunium, and 9.12 ppb technetium. When contained within the uranium materials processed at RFP, these levels are insignificant in relation to external exposure (DOE 2000).

RFETS (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 indicates that no contaminant accumulation occurred as a result of the melting and casting process (RFETS 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 (RFETS 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

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 four retired dosimetry program managers. Each of these individuals was asked if they recalled this issue or actions taken in response to such a problem. None of the four recalled storage-board background as a problem. Most recalled that elevated storage background was not significant and did not affect the dosimetry results [16].

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 [17].

For dosimeters collected in March 2000 through 2003, badge storage board background dosimeter results were used. The background dosimeter results were averaged over a five-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 (one sigma) times the previous (1977 - February 2000) standard background [18]. This information indicates that background in excess of that identified in the Technical Basis Document for Rocky Flats Plant Occupational Environmental Dose (ORAU 2006b, Table 4-3). As indicated above, this dose was subtracted as dosimeter background and indicates an elevated ambient level of external radiation (ORAUT 2003a). This may need to be addressed for best estimate Dose Reconstructions.

6.6 PHOTON DOSE

6.6.1 Energy Groups

The NIOSH IREP software for calculating the POC (NIOSH 2006) contains three photon energy bands:

- Below 30 keV
- 30 to 250 keV
- Above 250 keV

Separation of the dose from each energy band is required.

6.6.1.1 Default Exposure Spectra

Very little spectroscopy data that indicate the gamma spectrum in RFP work areas have been found. To estimate the gamma spectrum to which workers were exposed, MicroShield 5.03 (Grove Engineering 1998) was used. With the use of the MicroShield decay feature, radionuclide source concentrations (DOE 1980) for weapons-grade plutonium, enriched uranium, 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. Depleted and enriched uranium were routinely handled in the open with no shielding. Plutonium was almost exclusively handled in gloveboxes that provided shielding from the materials. The MicroShield 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 6-9 presents these results.

Table 6-9. Photon energy distributions.[a]

Shield	Energy (keV)	Fresh Pu	10-yr Pu	30-yr Pu	Fresh EU	10-yr EU	30-yr EU	Fresh DU	10-yr DU	30-yr DU
None	<30	Not applicable			0%	0%	0%	0%	0%	0%
	30–250				100%	99%	98%	100%	3%	3%
	>250				0%	1%	2%	0%	97%	97%
1/16 inch steel	<30	0%	0%	0%	Not applicable					
	30–250	100%	85%	88%						
	>250	0%	15%	11%						

a. Source: EU = enriched uranium.

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 [19]. Low-energy (<30-keV) photon exposure is estimated from reported penetrating and skin photon dose by the algorithms in ORAUT (2005b).

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 6-9. 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 enriched uranium 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 enriched uranium, 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 6-10.

Table 6-10. Default photon energy distributions.

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

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)* [20]. Use of this data in dose reconstructions is detailed in ORAUT (2005b).

Three-Element Dosimeter

As indicated in Section 6.2, the three-element film dosimeter used at RFP from 1960 to 1969 had an open window (dose indicated under OW in the reports), a 1-mm thick cadmium (CD) filter, and a brass (BR) filter that provided half the filtration of the CD filter. The brass filter was added to measure more accurately the 60-keV photons.

Some dosimetry records (illustrated in Figure A-7) indicate the dose determined by 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 (from the plutonium areas), the skin dose was calculated as a sum of each of the three windows (OW + CD + BR). The penetrating dose was calculated by adding CD, BR, and 35% of the OW readings. 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. Different algorithms were used for uranium area beta exposures (Table 6-4).

To reconstruct the plutonium area low- and intermediate-energy photon dose between 1960 and 1969 properly, the following reverse algorithm should be applied:

$$\gamma_{<30keV} = \frac{Skin - Pen}{0.65} \qquad (6\text{-}1)$$

$$\gamma_{30-250keV} = Skin - \gamma_{<30keV} \qquad (6\text{-}2)$$

This method effectively recreates the measured dose from under the BR and CD filters, which represent the 30- to 250-keV dose. An alternative approach to determining the intermediate-energy (30- to 250-keV) photon dose is simply to sum the BR and CD doses, if available in the energy employee's dose record submitted by DOE. The low-energy (<30-keV) photon dose can be determined by simply using the OW dose reading.

Two-Element Dosimeter

The RFP two-element dosimeter used before 1960 effectively could not measure the 60-keV photons; therefore, the penetrating dose for the plutonium areas was calculated using Pen = 50% OW + CD. Based on the BR to CD ratio observed in plutonium worker dosimetry data that was reviewed, this method is surprisingly accurate in determining the dose contribution from 30- to 250-keV photons (96% in comparison to the three-element dosimeter). The disadvantage is that using only the penetrating dose will underestimate the total photon dose (low and intermediate energy). As a result, the following method should be used to estimate the dose from low-and intermediate-energy photons:

$$\gamma_{<30keV} = \frac{Skin - Pen}{0.5} \tag{6-3}$$

$$\gamma_{30-250keV} = Pen \tag{6-4}$$

At first glance, it could appear that these calculations overestimate the low-energy dose from the plutonium areas (i.e., part of the skin dose is being counted twice, so the sum of the low-and intermediate-energy doses exceeds the original skin dose). This effect results because the intermediate-energy photon dose was underestimated due to the absence of the 60-keV photon dose contribution. The original reported skin dose is actually underestimated. The addition of 50% of the OW dose to the penetrating dose appears to correct the Pen for this underestimation (i.e., the relative ratio of the 60-keV photon dose to the OW dose contribution is about 0.5). Review of the DuPont energy response curves for Type 502 and 508 films indicates that the densitometer difference between exposure to 17-keV photons and 60-keV photons is significant. It is believed that the low-energy photon film response dominated the OW densitometer measurements, and the 60-keV photons were therefore not effectively measured.

Comparing these two methods on two plutonium worker data sets, the calculated low- to intermediate-energy dose ratio is approximately the same at approximately 0.8. The skin-to-penetrating dose ratio is also similar at around 0.7, as well as the OW/CD dose ratio at about 1.45. As a result, it is believed that the methods outlined above accurately reflect the plutonium area low- (<30-keV) and intermediate-energy (30- to 250-keV) dose contributions.

After 1968, RFP used TLDs to measure photon and beta dose. The TLD materials used were much more tissue-equivalent and the response much less energy-dependent. Dosimeters were calibrated to more appropriate radiation energies, and filter design had advanced. It is believed that these dosimeters performed substantially better than film.

It is reasonable to assume that for plutonium workers, the skin dose includes the shallow dose from photons. For uranium workers, the skin dose can be assumed to include electrons.

The measured results trend of the dosimeters worn at Rocky Flats Plant is shown in Section 6.4.1 (Figure 6-6a).

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.

The LANL dosimetry results were calibrated in roentgens (ORAUT 2005c, Section 6E.9).

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 6-11 summarizes dose units to use for organ dose conversion factors.

Table 6-11. Photon dose units for use with organ dose conversion factors[a].

Period	Unit
1951–1982	roentgens
1982–2005	$H_p(10)$

a. Source: See Section 6.6.2.1.

Conversion to organ dose is accomplished using the factors provided in Appendix A of NIOSH 2006. Plutonium-specific photon dose conversion factors are provided in Table 4.1a of NIOSH 2006 and should be applied for plutonium exposures at RFP.

6.6.3 Missed Dose

Section 2.1.2 of NIOSH (2006) recommends the use of the limit of detection (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 open window 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 less sensitive DuPont 1290 film. The 1290 film was not processed unless the 580 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 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 by the author to be similar to that for the Hanford dosimeter [21].

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 6-12 lists photon LODs for the RFP dosimeters.

Table 6-12. 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 (2006). For the period from 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 the dose reconstruction guidance discuss this estimate. In this case, the estimate is assumed to have a lognormal distribution (NIOSH 2006, 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 2005d) discusses the response of this dosimeter. These documents address the significant over-response of film to low photon energies. The dosimeter (open window) was calibrated with low-energy photons. To correct for this over-response, a portion of the open-window dose was added to the deep dose measured under the 1-mm cadmium filter. There is evidence (Falk, no date) [22] 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 over-response.

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 [23].

Quantitative information is available for the RFP Panasonic dosimeter (RFETS 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

Exposure geometry is common to all types of radiation exposure, as addressed in Section 6.5.4.

6.6.5 Uncertainty

The *External Dose Reconstruction Guideline* (NIOSH 2006) describes methods for quantification of laboratory uncertainty associated with reading film and TLDs. These methods provide a statistical treatment of the variability associated with reading dosimeters in the laboratory.

6.6.5.1 Film

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 (NRC 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 (2006) 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* (NRC 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 6-13), and it affects the estimate of the upper 95% confidence dose above 27 mR. Table 6-13 lists uncertainties for photon film dose.

Table 6-13. 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

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 * mean were removed from use. Assuming that the chip response had a normal distribution such 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 (2006), and assuming the critical level (Lc) is the LOD estimated in Section 6.3.1 of this TBD, Table 6-14 lists the upper 95% confidence doses.

Table 6-14. 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

6.6.5.2.2 Panasonic Thermoluminescent Dosimeter

Table 6-15 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 (2006). 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 (RFETS 2001), and the relative standard deviation at high readings is the standard deviation of the DOELAP performance test results (RFETS 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 [24].

Table 6-15. Uncertainty for DOELAP-accredited TLD photon dose.

Dose (mrem)	Upper 95% confidence dose (mrem)		
	Panasonic dosimeter	DOELAP-accredited Panasonic dosimeter	
	1983–1989	1990–1998	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.

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 (2006). 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$)
- $>$20 MeV ($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 6-16 lists this information.

Table 6-16. Neutron dose measurements divided into energy groups.

Location	Dose rate (rem/hr)	Avg. energy (MeV)	Portion of dose from neutron energy range < 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		0.006	0.006	0.437	0.552	0.000
Building 707 low dose pit	2.88E-04		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			0.035	0.017	0.687	0.261	
Standard deviation			0.031	0.010	0.117	0.130	

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 6-16. Table 6-17 lists the default values selected from Table 6-16 for dose reconstruction [25].

Table 6-17. 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 (2006) indicates the use of radiation weighting factors 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 radiation weighting factor 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 6-17 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) radiation weighting factors were combined to determine a dose multiplier (column 4 of Table 6-17). 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 <u>Calibration Factor</u>

6.7.2.1 Dosimeter-Specific Quality Factor Conversion

The correction factor to convert from NCRP (1971) quality factors used in the neutron spectra measurements and the ICRP (1991) radiation weighting factors is discussed in Section 6.7.1.2 and listed in Table 6-17. Conversion to organ dose is accomplished using the factors provided in Appendix A of NIOSH 2006.

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 2005c, Section 6E.9).

Neutron film was initially calibrated with an apparently unmoderated polonium-beryllium (PoBe) 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 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 1968). 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 6-18 summarizes the dose units to use for organ dose conversion factors.

Table 6-18. 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 Section 6E.7 of ORAUT (2005c). 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 (ORAUT 2005a) assembled a processing history that is summarized in Table 6-19. 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 6-19. Neutron film track counting detail.

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	--

Mann and Boss (1963) determined that a typical background film for 2 wk 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 (RFETS 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 6-20 includes this value.

Table 6-20. 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

6.7.3.2 Number of Zero Readings

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

6.7.3.3 Unmonitored Energy Range

NTA film is a poor detector of neutron energies below 500 to 800 keV (Griffith et al. 1979; Wilson et al. 1990). Before 1963, RFP appears to have calibrated neutron film with a variety of unmoderated neutron sources. RFP recognized that dosimetry results were not consistent with instrument measurements and that low-energy neutrons were not measured by the film. A project was initiated in 1962 to improve neutron film dosimeter calibration (Mann and Boss 1963).

Before 1963, neutron dose from neutrons below approximately 800 keV probably was not detected. To determine how much dose was potentially missed, the neutron measurements performed in RFP work areas (Brackenbush et al. 1989) were corrected for ICRP (1991) radiation weighting factors and the fraction of the dose from neutrons of less than 800 keV was determined. Table 6-21 lists these values.

Table 6-21. Potential missed neutron dose for early film dosimeters.

Location	ICRP 60 rem/hr	Below 800 keV
Building 771 fluorinator line	1.13E-03	52%
Building 776 molten salt glovebox	3.25E-03	60%
Building 776 molten salt storage vault	1.67E-02	29%
Building 776 drum storage	4.46E-02	57%
Building 707 high dose pit	1.18E-03	22%
Building 707 low dose pit	5.26E-04	29%
Building 707 oxide can	2.53E-03	47%
Building 707 plutonium ingot	3.70E-03	16%

There appears to be no distinct pattern in these data. It is appropriate to take an approach favorable to claimants and select the largest value of 60%. Therefore, the total neutron dose from RFP measurements before 1964 (1951 to 1963) should be multiplied by 2.5 before applying the factors from Table 6-17.

In 1962, RFP began a project to refine neutron dosimeter calibration to match the neutron spectra in the production areas more accurately. Mann and Boss (1963) documented an effort to develop a calibrated PuF_4 source with various moderators. The spectra from the moderator configurations of this source were compared with neutron spectra measurements taken in the plutonium production areas with a precision long counter and a series of paraffin moderators. This resulted in dosimeter calibrations that more accurately matched the exposure spectra. No missed dose correction is required for RFP neutron film dosimeters after 1963.

The RFP TLD neutron dosimeter systems (Harshaw and Panasonic) were calibrated using variously moderated spectra. There is no need for missed neutron dose corrections. After 1990, the Panasonic TLD system was DOELAP-accredited, which supports the decision to forego a missed neutron dose correction.

6.7.3.4 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 to be assigned a notional neutron dose by the NDRP if they were not monitored for neutrons. Beta-gamma worksheets for other buildings were not used.

The NDRP reread neutron films (where available) with appropriate quality controls and reevaluated the neutron doses. Notional neutron doses were determined for plutonium workers with missing or unreadable films and for non-neutron-monitored workers in plutonium production buildings (Falk et al. 2005).

To provide a correction favorable to claimants until NDRP data became available, it was appropriate to use the neutron correction ratio in *Report of Epidemiologic Analyses Performed for Rocky Flats Production Workers Employed Between 1952-1989* (Ruttenber et al. 2003). These analyses used a combination of workplace instrument measurements and Harshaw and Panasonic TLD results to estimate correction ratios for total penetrating doses. These ratios provide an estimate for the total penetrating dose (gamma + neutron), which provides an initial correction for the identified bias in the neutron film reading. This correction should be applied to personnel who worked in the noted neutron buildings from 1951 to 1967. When the NDRP was completed, a more accurate neutron dose became available for each plutonium worker who was monitored for neutrons. An updated ratio was generated from these data for use with unmonitored workers in this work area. Table 6-22 lists the initial correction ratios that were used.

Table 6-22. Correction ratios for identified neutron film reading deficiencies.

Building	Mean	Standard deviation
771	1.99	0.92
Other neutron buildings[a]	1.13	0.82

a. Buildings 123, 774, 776, 777, 779, 886, 991, and others if record suggests neutron monitoring

The NDRP developed neutron-to-gamma ratios for use on that project; the values are shown in Table 6-23, and their derivation is documented in the NDRP report (Falk et al. 2005). It is appropriate to use these values for those buildings and years, and other plutonium exposure situations at RFP. Uranium exposure is addressed below.

6.7.3.5 Default Neutron-to-Gamma Ratio

To complete the neutron-to-gamma ratio coverage for the life of the Plant, the ORAU Team developed geometric mean (GM) and geometric standard deviation (GSD) ratios from the available RFP worker files (ORAUT 2005a). These data are shown in Table 6-24, and the derivation is documented in the reference. As indicated in the referenced text, the overall average is appropriate to use from 1970 to 1976.

Table 6-23. NDRP-developed neutron-to-gamma ratios (Falk et al. 2005).

Building	1952–1958[a]	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
71	1.4	1.4	2.8	1.7	2.2	2.3	3.1	1.2	0.6	0.7	1.3	1.5
76	0.6	0.6	0.6	0.6[b]	0.6[b]	0.6[b]	0.6[b]	0.4	0.3	0.4	0.9	2.1
77	1.3	1.3	1.6[b]	1.6[b]	1.6[b]	1.6	1.6	0.8	0.5	0.6	0.9	0.9
76,77,78[d]	1.3	1.3	1.6	1.6	1.6	1.6	1.6	0.8	0.5	0.6	0.9	2.1
91	3.6	3.6	6.8	7.4	10[c]	10[c]	10[c]	3.3	1.2	2.1[b]	2.1	7.3
All Others	1.2	1.2	1.8	1.8	2.3	2.3	3.0	0.9	0.5	0.6	1.2	1.5

(a) Extrapolated from ratio for 1959,

(b) Assigned from the higher of the ratios for the previous or next year with data,

(c) Upper bound value,

(d) Ratios for combined Building designation 76,77,78 or for Building 78 are assigned from the higher of the ratios for the year for Building 76 and Building 77.

Note: The N:G ratio is the ratio of the sum of the NDRP neutron doses divided by the sum of the gamma doses for paired sets of the NDRP neutron dose and the gamma dose of record for that monitoring period.

Table 6-24. ORAU Team-developed neutron-to-gamma ratios (ORAUT 2005a).

Year	GM	GSD	Year	GM	GSD	Year	GM	GSD	Year	GM	GSD
1977	0.33	3.31	1984	0.41	3.07	1991	0.29	2.41	1998	0.39	3.03
1978	0.57	2.53	1985	0.42	3.37	1992	0.4	2.03	1999	0.45	2.79
1979	0.37	3.31	1986	0.49	2.93	1993	0.61	1.93	2000	0.6	1.8
1980	0.43	2.57	1987	0.36	3.56	1994	0.41	2.35	Overall	0.42	3
1981	0.51	2.41	1988	0.6	2.83	1995	0.35	2.28			
1982	0.4	2.4	1989	0.36	3.5	1996	0.26	4.1			
1983	0.42	3.01	1990	0.35	3.77	1997	0.44	2.18			

As discussed in Sections 6.3 and 6.3.1, RFP reported:

- Deep dose + neutron as penetrating (Pen) or deep
- Shallow dose + neutron as Skin

In the early years, the neutron and gamma dose values were not retained and only the penetrating value remains. In this case, it is necessary to estimate the neutron and photon dose for dose reconstruction. Ruttenber et al. (2003) addressed this issue by assuming a 2:1 neutron/gamma ratio for Building 771, 0.5:1 for other buildings with a potential for neutron exposure (Buildings 123, 774, 776, 777, 779, 886, 991, and other buildings if the record suggests neutron monitoring), and 0:1 for all other RFP facilities. This assumption is based on measurements taken at RFP and was appropriate to use until the NDRP was completed and provided better information for neutron-monitored individuals. It is appropriate to use these more refined values as they become available.

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.

6.7.4.2 Exposure Geometry

The worker exposure geometry for neutron dose is similar to that for photons, which is discussed in Section 6.5.4.

6.7.5 <u>Uncertainty</u>

6.7.5.1 Film

The NDRP has evaluated film uncertainty. Uncertainty for neutron film results are taken from that study as reported in ORAUT (2005a).

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 (2006) is used.

The initial Panasonic TLD algorithm was evaluated during development (RFP, no date). 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 (RFETS 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 6-25 lists the uncertainties for these dosimetry systems.

Table 6-25. Uncertainty for TLD neutron dose measurements.

Dose (mrem)	Upper 95% confidence dose (mrem)			
	Harshaw TLD dosimeter	Panasonic dosimeter	DOELAP-accredited Panasonic dosimeter	
	1971–1982	1983–1990	1991–1992	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.

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 is electron exposure.

Figure 6-7 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 (Emax) beta particles from ^{234m}Pa, the most energetic contributor to the beta exposure.

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 [26].

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 d) and can be conservatively assumed to be present at these levels. Figure 6-8 shows the relative dose rate in relation to energy. DU would be similar to the natural uranium used for this experiment.

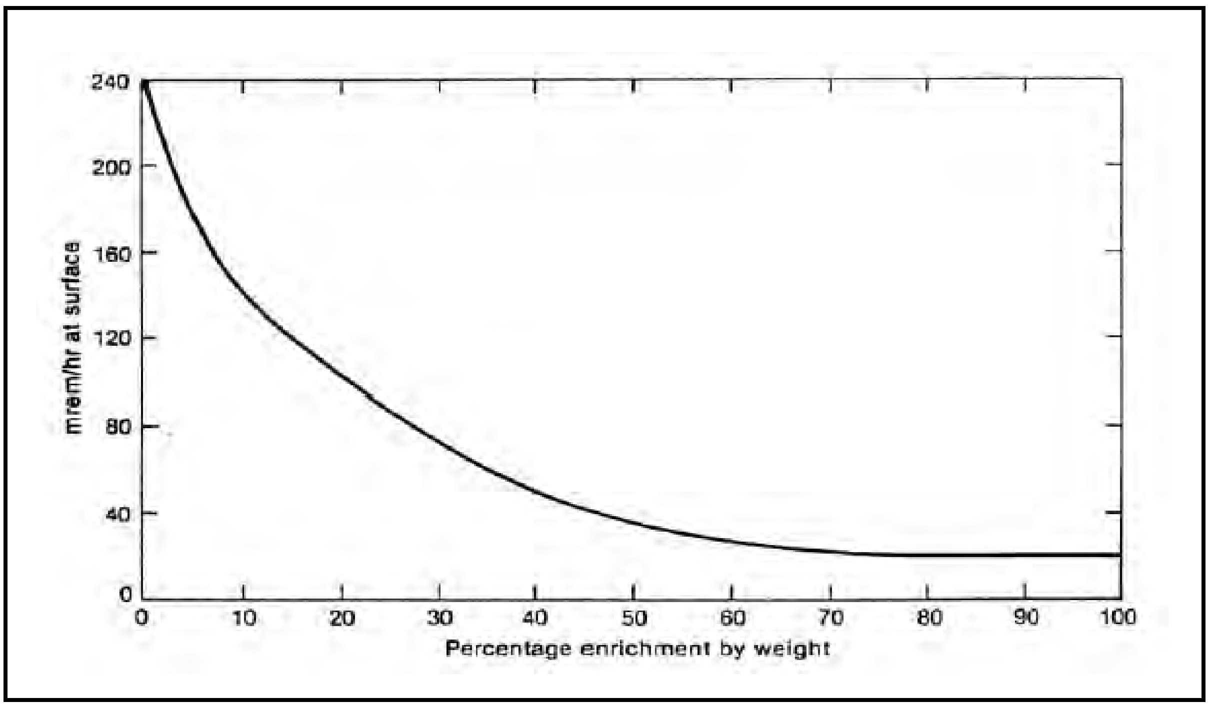

Figure 6-7. Estimated beta dose rate from uranium metal at various enrichment levels (DOE 2001).

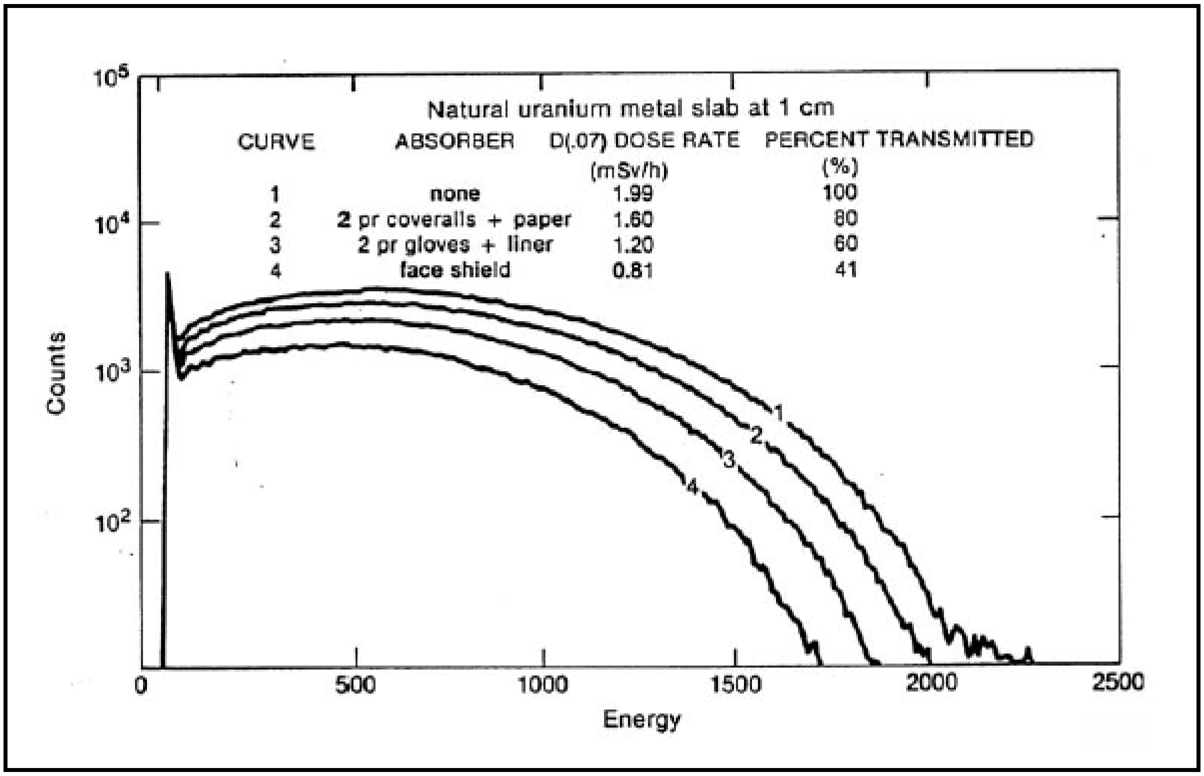

Figure 6-8. Shallow dose rate from natural uranium slab (DOE 2001).

6.8.1.2 Reported Dose to Energy Groups

NIOSH (2006) 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.

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 milli<u>rad</u> per hour. The radiation weighting factor 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 open-window film calibrated to a uranium slab. ORAUT (2004, 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 (2004, 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 6-26.

Table 6-26. 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 open-window (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 (RFETS 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 6-26.

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 [27]. 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 (RFETS 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 (2006) was used to determine the uncertainty (upper 95% confidence dose) for film readings. This method is based on a statistical discussion in *Film Badge Dosimetry in Atmospheric Nuclear Tests* (NRC 1989).

6.8.5.1 Film

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 the *External Dose Reconstruction Implementation Guideline* (NIOSH 2006) 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* (NRC 1989). This TBD analysis used a similar uncertainty estimation methodology and developed a spreadsheet that matched the illustration given in NRC (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 6-27 lists these upper 95% confidence doses.

Table 6-27. 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 (2006), and assuming that the critical level (Lc) is the beta LOD estimated in Section 6.8.3.1 of this TBD, Table 6-28 lists the upper 95% confidence dose.

Table 6-28. 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 6-29 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 (2006). 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 (RFETS 2001), and the relative standard deviation at high readings is the standard deviation of DOELAP performance test results (RFETS 2001; Stanford 1990). The reasonable worst-case value (high-energy photons + neutrons mixture from RFETS 2001, Table 11) was selected to provide a result that is favorable to claimants.

Table 6-29. Uncertainty for DOELAP-accredited TLD beta dose.

	Upper 95% confidence dose (mrem)		
	Panasonic dosimeter	**DOELAP-accredited Panasonic dosimeter**	
Dose (mrem)	**1983–1989**	**1990–1998**	**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 (2006).

DU 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 upon 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. This instrument typically has a 33.3% ±1% (cpm/dpm) efficiency for DU.

DU consists of 99.8% ^{238}U by weight. Table 6-30 lists the other isotopes.

Table 6-30. DU mixtures (DOE 1980).

	Mixture		
	Ci/g (mix)		
Isotope	Alpha	Beta	nCi/g (mix)
Th-231		4.90E-09	
Th-234		3.40E-07	340
U-234	3.70E-08		37
U-235	4.90E-09		4.9
U-238	3.40E-07		340
Total	3.82E-07	3.45E-07	726.8

It is favorable to claimants to assume that the DU is 1 yr old. This allows for ingrowth of progeny to achieve secular equilibrium. A decay calculation using MicroShield 5.03 (Grove Engineering 1998) was performed. Table 6-31 lists the full set of decay isotopes.

Dose calculation might utilize software such as VARSKIN (recommended in NIOSH 2006) 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. During this period the guideline was 3 rem/qtr. Therefore, the missed dose estimate for unbadged individuals working in radiologically controlled areas would be one-half of 10% of 3 rem/qtr or 600 mrem/yr. A lognormal distribution should be assumed, with the upper 95% dose estimate for these individuals therefore estimated to be 1.2 rem (NIOSH 2006).

An RFP External Dosimetry coworker study has been performed and is documented in OTIB-0058 (ORAU 2006d). The coworker study document addresses the application of these results to the dose reconstructions as appropriate.

Table 6-31. One-year-old DU.

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

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

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 2006c)].

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 open-window (thin Mylar) version.

In 1991, RFP switched to a Panasonic model UD-813AS11 (custom design) dosimeter in a plastic wrist holder (RFETS 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 open window for beta and low-energy photon dose measurements. The dosimeter, which has undergone DOELAP performance testing, is documented in RFETS (2000b).

RFP never used finger rings on a routine basis but estimated the hand dose using the forearm 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 RFETS (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; RFETS 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

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here again in the Attributions section of the document, with information provided to identify the source and justification for each associated item. Conventional references are provided in the next section of this document, linking data, quotations, and other information to documents available for review on the ORAU Team servers.

Much of the information in this TBD was authored by James M. Langsted, Certified Health Physicist (CHP), and some is based on his recollections of his operations experience and administration of the programs in the radiation dosimetry programs at RFP.

[1] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Discussion in June 2005 with Ken Savitz, RFP dosimetry database and records professional, indicated that dosimetry results that are posted in the paper-copy record but not included in the HIS-20 database are noted on the dosimetry data review sheet. It is favorable to claimants to use this data because in this case the worker would be credited for this dose, rather than not considering that dose.

[2] Author unknown (no date) was transmitted by e-mail. It has been submitted to the ORAU Team Site Research Database (SRDB) and is accessible as a formal reference.

[3] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006.

During the development of this document, Mr. Langsted reviewed many NIOSH claim files and interpreted the dosimetry record contained in those files based on his experience with the dosimetry programs and recordkeeping systems at RFP.

[4] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted was involved in the initial implementation of the Panasonic dosimetry system in 1989. During the transition period it was necessary to distinguish the source of the dosimetry data (the new Panasonic system or the old loose-chip Harshaw system). This code scheme was identified as a solution and implemented by the programmers during the database modification necessary to accept the Panasonic dosimetry system data.

[5] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. This table was developed by Mr. Langsted based on his review of the reports in various NIOSH claim files and his understanding of the dosimetry recordkeeping processes used at RFP. In many of these cases, Mr. Langsted does not have direct experience during the periods when those reports were generated but is making assumptions based on the pattern of data shown in these worker reports.

[6] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted is aware of each of these additional sources of data as documented in each of the explanatory paragraphs.

[7] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has discussed the job history card with the previous manager of Radiological Health at RFP, and the manager of the RFP NDRP. Both have verified the existence and content of these data.

[8] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has discussed the processing of film with a previous professional health physicist in the RFP dosimetry department during part of the film-processing period. This individual verified that the film calibration factors (beta or soft gamma) used for processing a specific badge were selected based on the building to which the worker was assigned.

[9] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has reviewed many external dosimetry reports and NIOSH claim files. In all of these reports it is clear that the doses were reported down to zero with no reporting threshold. Doses ranging from 1 mrem upward have been observed.

[10] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has reviewed many external dosimetry reports and NIOSH claim files. In all of these reports it is clear that unlabeled doses are in millirem. If they were in rem, there would be many exposures in excess of the regulatory limits (2 rem/qtr or later 5 rem/yr). If this were the case, there would be evidence of concern (and investigation) recorded on at least some of the reports.

[11] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Several times in 2006, Mr. Langsted has talked with the manager of the RFP dosimetry organization from approximately 1958 to 1969. This individual corroborated that overexposures would have been noted on the reports and in the hard-copy health physics file.

[12] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006.

Mr. Langsted has observed many indications of doses corrected in the health physics (written) files. There was apparently a computer error that resulted in incorrect dose reported on the printed record. This error was discovered and corrected in both the computer file (as noted on the printed record) and on the printed record itself.

[13] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has made estimates based on his observation of operations in the production buildings during his experience at RFP as an Operational Health Physicist.

[14] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted's observation of the production areas indicates that Building 771 had considerable process piping in the overhead (above the worker's head) while Buildings 776/777 and Building 707 (metal production) had considerably less. As discussed in the text, the ISO geometry accounts for overhead exposure while the ROT geometry does not.

[15] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. In 2005, Mr. Langsted interviewed a previous Health Physics manager and discussed the use of lead aprons at RFP. This individual recalled the use of lead aprons as discussed in the text.

[16] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. In 2005, Mr. Langsted interviewed four Health Physics managers. Each of these individuals was asked specifically about this issue and replied in the negative.

[17] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted has reviewed RFP dosimetry program memoranda available on the ORAU Team servers and found indication of the start and end dates of this practice.

[18] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. In 2005, Mr. Langsted interviewed Ken Savitz from the RFP radiological health organization and determined that a 5-qtr rolling average was calculated for badge board background. This information was obtained from the external dosimetry group at RFP and analyzed in a spreadsheet to determine the variability indicated in the text.

[19] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. This assumption was developed in discussion with Tim Taulbee, a NIOSH health physicist. This value is based on assumptions as discussed in the text and review of other ORAU TBDs for plutonium facilities. The value was assumed at the direction of Mr. Taulbee after his discussion with other NIOSH health physicists.

[20] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. This analysis was provided by Tim Taulbee, NIOSH health physicist. Mr. Taulbee performed the analysis using the skin dose as reported by the RFP dosimetry program (Table 6-4).

[21] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. The Hanford dosimeter used similar dosimeter elements (Harshaw chips). Although the process equipment was somewhat different, the physics of the dosimetry process is the same and the LOD was assumed by Mr. Langsted to be similar.

[22] Falk (no date) was captured from the personal files of Roger B. Falk and has been documented in the ORAU Team SRDB as a formal reference.

[23] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. No measurement of the TLD badge exposure geometry has been found. As the badge is rotated in relation to the exposure source, the design of the badge is such that the TLD chip is exposed with less of the shield covering the chip. This would exhibit similar edge-effect response as would the film badge.

[24] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. The same badge system, including dosimeter type, case, dosimeter reader, and calibration system, was used. Although differing procedures were used for the program, Mr. Langsted believes it is reasonable to assume that the reading variability would be similar.

[25] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted could identify no discernable pattern in the data presented in Table 6-16. Therefore, he determined that using the mean values would provide the most representative neutron distribution for the neutron fields presented in the cited study.

[26] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Mr. Langsted worked as an Operational Health Physicist at RFP in Building 444. At that time, uranium foundry workers wore leather gloves while working with the material. It was necessary to dispose of the gloves periodically when the dose rate measured on them exceeded a certain level. This limited the hand doses from the uranium and uranium progeny from the gloves.

[27] Langsted, James M., CHP. MH Chew & Associates. Principal Health Physicist. July 2006. Dosimeters that measure skin dose must have a thin covering over the dosimeter to measure accurately the low-energy radiations that result in a component of the skin dose. This fact has been recognized and incorporated into the design of all dosimeters at RFP. This was implemented as open-window film (covered only with paper of the film packet) or the thinly covered skin TLD crystals. The very-low-energy beta particles that do not penetrate these coverings similarly cannot penetrate the protective epidermal layer of the skin and do not result in biologically significant skin dose.

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GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

film density
See *optical density*.

film dosimeter
A small packet of film in a holder that attaches to a wearer.

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

fissionable
Material capable of undergoing fission.

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

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

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

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

neutron film dosimeter
A film dosimeter that contains a neutron track emulsion, type A film packet.

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

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

operating area
Designation of major onsite operational work areas.

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

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

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

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

pit
Nuclear weapon core, made of fissionable material.

quality factor, *Q*
A modifying factor used to derive dose equivalent from absorbed dose.

radiation
Alpha, beta, neutron, and photon radiation.

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

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

rem
A unit of dose equivalent equal to the product of the number of rad absorbed and the quality factor. The word derives from roentgen equivalent in man.

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

shallow absorbed dose (D_s)
The absorbed dose at a depth of 0.007 cm in a material of specified geometry and composition.

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

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

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

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

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

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

whole-body dose
Commonly defined as the absorbed dose at a tissue depth of 1.0 cm (1,000 mg/cm^2); however, also used to refer to the recorded dose.

X-ray
Ionizing electromagnetic radiation of external nuclear origin.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

LIST OF FIGURES

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 2 of 16

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	[redacted]
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 6-4-02, page 1.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

Page 3 of 16

Occupational Dose Report

Name:

Employee #:

SSN:

Year	Deep Dose	Skin Dose	Extremity	Lens of Eye
1951				[redacted]
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 6-4-02, page 2.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 4 of 16

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 3-10-03, page 1.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 5 of 16

Submitted by: KSAVITZ
Sorted by: Plant ID

Dosimetry History by Individual

Date: 10-MAR-2003 ..: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 3-10-03, page 2.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
Page 6 of 16

Submitted . KSAVITZ
Sorted by: Plant ID

Dosimetry His..ry by Individual

Date: 10-MAR-2003 .:00
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	CALCULATED				OFFICIAL	100	189			15	
29-SEP-1978 00:00	30-SEP-1978 00:00	CALCULATED				OFFICIAL	162	209		320	47	
30-OCT-1978 00:00	31-OCT-1978 00:00	CALCULATED				OFFICIAL	127	131		159	4	
29-NOV-1978 00:00	30-NOV-1978 00:00	CALCULATED				OFFICIAL	34	38		76	4	
30-DEC-1978 00:00	31-DEC-1978 00:00	CALCULATED				OFFICIAL	20	27		56	5	
30-JAN-1979 00:00	31-JAN-1979 00:00	CALCULATED				OFFICIAL	42	64		80	12	
27-FEB-1979 00:00	28-FEB-1979 00:00	CALCULATED				OFFICIAL	26	39		126	6	
30-MAR-1979 00:00	31-MAR-1979 00:00	CALCULATED				OFFICIAL	37	44		96	6	
29-APR-1979 00:00	30-APR-1979 00:00	CALCULATED				OFFICIAL	42	156		200	96	
30-MAY-1979 00:00	31-MAY-1979 00:00	CALCULATED				OFFICIAL	28	68		71	25	
29-JUN-1979 00:00	30-JUN-1979 00:00	CALCULATED				OFFICIAL	35	52		101	16	
30-JUL-1979 00:00	31-JUL-1979 00:00	CALCULATED				OFFICIAL	28	44		114	8	
30-AUG-1979 00:00	31-AUG-1979 00:00	CALCULATED				OFFICIAL	61	67		310	6	
29-SEP-1979 00:00	30-SEP-1979 00:00	CALCULATED				OFFICIAL	45	65		179	20	
30-OCT-1979 00:00	31-OCT-1979 00:00	CALCULATED				OFFICIAL	86	117		197	27	
29-NOV-1979 00:00	30-NOV-1979 00:00	CALCULATED				OFFICIAL	49	74			8	
30-DEC-1979 00:00	31-DEC-1979 00:00	CALCULATED				OFFICIAL	9	18		123	9	
30-JAN-1980 00:00	31-JAN-1980 00:00	CALCULATED				OFFICIAL	50	62		204	12	
28-FEB-1980 00:00	29-FEB-1980 00:00	CALCULATED				OFFICIAL	43	56		293	7	
30-MAR-1980 00:00	31-MAR-1980 00:00	CALCULATED				OFFICIAL	43	51		162	6	
29-APR-1980 00:00	30-APR-1980 00:00	CALCULATED				OFFICIAL	50	54		227	4	
30-MAY-1980 00:00	31-MAY-1980 00:00	CALCULATED				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 3-10-03, page 3.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

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

YR.	MAN #	NAME		QUARTERLY ACCUMULATED SKIN	PEN	HAND	CURRENT YEAR ACCUMULATED SKIN	PEN	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

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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	200	
2	16		71	3				120						120	120	
2	16		71	2				45	17	18	60	31	6	80	78	97
2	18		71	3				227						227	227	
2	18		71	2				110	22	2	200	86	13	134	173	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	64	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

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

6574

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

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

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
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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
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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
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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	21	Internal	NR	Total	21

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

Reported Lifetime Dose**

External	1233	Internal	2220	Total	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 6-4-02.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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```
*********************************************************************************
* RADIATION HEALTH RECORDS SYSTEM - View TLD Data              Page 1      V93013*
*********************************************************************************
* H&S ID          SSN                  Last Name                                *
* First Name            Middle      Last Name                 From      To      *
*                                                                               *
*   - -                                                                         *
* Activity  Time Curr Curr Curr Curr Curr Curr                                  *
* Date      Code Neut Gamm Pen  Skin Hand 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      *
*                           1    1    1    1                                    *
*                                                                               *
*                                                                               *
*                                                                               *
*                                                                               *
*                                                                               *
* 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
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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 Termination Report dated 9-17-96, page 1.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS

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	S	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 Termination Report dated 9-17-96, page 2.

ATTACHMENT A
EXAMPLE EXTERNAL DOSIMETRY RECORD DOCUMENTS
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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
Page 1 of 2

Chemical Operators
Primary job duties included 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 generally worked side-by-side with production operators.

ATTACHMENT B
MAJOR JOB CATEGORIES
Page 2 of 2

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.