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Dose Reconstruction
Project for NIOSH

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ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior (X-ray)
AEC	U.S. Atomic Energy Commission
CP	Cutie Pie (measurements)
DCF	dose-rate conversion factors
DE	dose equivalent
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
EE	Energy Employee
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
FFTF	Fast Flux Test Facility
GM	geometric mean
HEW	Hanford Engineering Works
HMPD	Hanford Multipurpose TLD
$H_p(d)$	Personal Dose Equivalent at depth d in tissue
IARC	International Agency for Research on Cancer
ICRP	International Committee for Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IREP	Interactive RadioEpidemiological Program
ISO	International Standards Organization
MED	Manhattan Engineer District
MDL	Minimum Detection Level
mm	millimeter
NBS	National Bureau of Standards (predecessor to NIST)
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NPEN	(Hanford) designation of nonpenetrating dose
NRC	National Research Council
NTA	Eastman-Kodak Nuclear Track, Type A emulsion
OCAS	Office of Compensation Analysis and Support
ORNL	Oak Ridge National Laboratory
OW	(Hanford) designation of open window (i.e., no filter) nonpenetrating dose
PEN	(Hanford) designation of penetrating dose
PFP	Plutonium Finishing Plant
PFPP	Plutonium Fuels Pilot Plant
PIC	Pocket Ionization Chamber (i.e., “Pencil” dosimeter)
PNNL	Pacific Northwest National Laboratory

POC	probability of causation
PRTR	Plutonium Recycle Test Reactor Facility
PUREX	Plutonium-Uranium Extraction Plant
R	Roentgen
RBE	Relative Biological Effectiveness
REDOX	Reduction Oxidation Plant
rem	radiation equivalent man
RMA	remote mechanical A (line) series of glove boxes
RMC	remotely operated series of glove boxes
S	(Hanford) designation of penetrating dose behind 1 mm thick silver filter
SRS	Savannah River Site
TBD	technical basis documents
TED	track-etch dosimetry
TEPC	Tissue Equivalent Proportional Counter
TLD	thermoluminescent dosimeter
WB	whole-body

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

Hanford was established in 1942 as a major government-owned nuclear weapons production site fabricating reactor fuel, eventually operating nine nuclear material production reactors and building five major chemical separation plants, and producing plutonium for nuclear weapons. Later operations included nonmilitary applications of nuclear energy. The purpose of this TBD is to describe the external dosimetry systems and practices at Hanford. This document discusses historical and current practices in relation to the evaluation of external radiation exposure of monitored and unmonitored workers.

6.1.2 Scope

Hanford played a crucial historical role in the U.S. nuclear weapons program producing plutonium for nuclear weapons and generating two-thirds of all nuclear waste, by volume, in the DOE complex (Gerber 1992). Certainly, the war-time operations at Hanford Engineering Works (HEW) were characterized by secrecy and the sheer magnitude of building the first-ever industrial-sized nuclear reactors, reprocessing, and plutonium handling facilities. Today, the Hanford Site houses large quantities of nuclear waste and is engaged in an extensive waste remediation project.

The methods and concepts of measuring occupational external doses to workers have evolved since the beginning of Hanford operations. An objective of this document is to provide a technical basis to evaluate external radiation exposure to workers that can reasonably be associated with Hanford operations under EEOICPA legislation. Consistent with NIOSH guidelines, this document identifies options to adjust historical recorded occupational external dose to account for current scientific methods and protection factors. In particular, this document presents the methods to prepare worker dose information for input to the NIOSH Interactive RadioEpidemiological Program (IREP).

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

6.2 EXTERNAL DOSIMETRY

Hanford operations involved several processes of the nuclear weapons development cycle (DOE 2002, 1997, 1996) and played a significant role in the U.S. nuclear weapons program. These processes include nuclear fuel fabrication; nuclear reactor operations; radiochemical separations; refining, finishing and storing plutonium; and handling the associated radioactive waste.

Hanford workers, especially those employed during the peak production decades of the 1950s and 1960s, have been exposed to radiation types and energies associated with the respective nuclear weapon development processes. Hanford utilized facility and individual worker monitoring methods to measure and control radiation exposures. Many Hanford records concern facility monitoring, safety evaluations, investigations, etc. Evaluations after many years or even decades after employment are difficult because of the extensive scope of facility, process, and worker information relevant to an individual worker's potential dose. Records of radiation doses to individual workers from personnel dosimeters worn by the worker and coworkers are available for Hanford operations beginning in 1944 (Buschbom and Gilbert 1993) and reviews of the Hanford personnel dose data for 10- and 15-year periods from Hanford startup in Parker (1954) and Keene (1960), respectively. Doses from these dosimeters were recorded at the time of measurement and routinely reviewed by Hanford operations and radiation safety staff for compliance with radiation control limits. The NIOSH External Dosimetry Implementation Guide (NIOSH 2006) has identified these records to represent the highest quality records for retrospective dose assessments. The information in this section pertains to analyzing

these records and does not address parameters regarding skin, testicular, or breast radiation dose that could result from acute beta (electron) radiation exposure under short-term accidental or incident nonroutine workplace exposure profiles. Nonpenetrating radiation during routine operations is also not addressed in this section [1]. Guidance in ORAUT-OTIB-0017 (ORAUT 2005a) should be used to assess shallow dose for Hanford claimants.

Radiation dosimetry practices were initially based on experience gained during several decades of radium and X-ray medical diagnostic and therapy applications. These methods were generally well advanced at the start of the Manhattan Engineer District (MED) program to develop nuclear weapons beginning in about 1940. The primary new challenges encountered by MED, and later Atomic Energy Commission (AEC), operations to measure worker dose to external radiation involved [2]:

- Comparatively large quantities of high-level radioactivity.
- Mixed radiation fields involving beta, photon (gamma and X-ray), and neutron radiation with low, intermediate, and high energies.
- Neutron radiation.

6.3 BASIS OF COMPARISON

Historically, since the start of the MED program in the early 1940s, various radiation dose concepts and quantities have been used to measure and record occupational dose. A basis of comparison for dose reconstruction (Fix et al. 1997a) is the Personal Dose Equivalent, $H_p(d)$, where d identifies the depth (in millimeters) and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 mm and is noted as $H_p(0.07)$. For penetrating radiation of significance to “whole-body” dose, d = 10 mm and is noted as $H_p(10)$. Both $H_p(0.07)$ and $H_p(10)$ are the radiation quantities recommended for use as the operational quantity to be recorded for radiological protection purposes by the International Commission on Radiation Units and Measurements (ICRU 1993). In addition, $H_p(0.07)$ and $H_p(10)$ are the radiation quantities used in the DOE Laboratory Accreditation Program (DOELAP), which has been used to accredit DOE personnel dosimetry systems since the mid-1980s (DOE 1986). The International Agency for Research on Cancer (IARC) Three Country Combined Study (Fix et al. 1997a) and IARC Collaborative Study (Thierry-Chef et al. 2002) selected $H_p(10)$ as the quantity to use for assessing error in recorded whole-body doses for workers in IARC nuclear worker epidemiologic studies.

The basis for comparison for neutron radiation is more complicated because historically, the calibration of dosimeters to measure neutron dose was based on different dose quantities such as First Collision Dose, Multiple Collision Dose, Dose Equivalent Index, etc. The numerical significance in using these dose quantities compared to the $H_p(10)$ dose used in current DOELAP performance testing represents an additional uncertainty in retrospective dose analyses. The relative value of the dose conversion factors for the respective neutron dose quantities used at Hanford has not been compared because, as noted in later sections, the response characteristics of the Eastman Kodak Nuclear Track Film Type A (NTA) was not adequate in Hanford workplace radiation fields [3].

6.4 DOSE RECONSTRUCTION PARAMETERS

Examinations of the beta, photon (X-ray, gamma ray), and neutron radiation type, energy, and geometry of exposure in the workplace and the characteristics of the respective Hanford dosimeter response are crucial to the assessment of bias and uncertainty of the original recorded dose in relation to the radiation quantity $H_p(10)$. The bias and uncertainty for current Hanford dosimetry

systems are well documented for $H_p(10)$ (Rathbone 2002). The performance of current dosimeters can often be compared with performance characteristics of historical dosimetry systems in the same, or highly similar, facilities or workplaces. In addition, current performance testing techniques can be applied to earlier dosimetry systems to achieve a consistent evaluation of historical dosimetry systems. Dosimeter response characteristics for radiation types and energies in the workplace are crucial to the overall analysis of error in recorded dose [4].

Overall, accuracy and precision of the original recorded individual worker doses and their comparability to be considered in using NIOSH (2006) guidelines depend on (Fix et al. 1997a):

- **Administrative practices** adopted by facilities to calculate and record personnel dose based on technical, administrative, and statutory compliance considerations.

- **Dosimetry technology**, which includes the physical capabilities of the dosimetry system, such as the response to different types and energies of radiation, in particular in mixed radiation fields.

- **Calibration** of the respective monitoring systems and similarity of the methods of calibration to sources of exposure in the workplace.

- **Workplace radiation fields** that might include mixed types of radiation, variations in exposure geometries, and environmental conditions.

An evaluation of the original recorded doses based on these parameters is expected to provide the best estimate of $H_p(10)$ and, as necessary, $H_p(0.07)$ for individual workers with the least relative overall uncertainty.

6.4.1 Hanford Historical Administrative Practices

Historically, Hanford had an extensive radiation safety monitoring program to measure exposure in the workplace using portable radiation instruments (Howell et al. 1989), contamination surveys, zone controls, and personnel dosimeters (Parker 1954; Wilson 1987). This was done directly or under the guidance of a specially trained group of radiation monitors (i.e., radiation protection technologists). The results from the personnel dosimeters were used to measure and record dose from external radiation exposure to Hanford workers throughout the history of Hanford operations (Wilson 1987). These dosimeters, as noted in the Health Instrument section of routine reports (Miller 1946; Parker 1948), include one or more of the following:

- Personnel whole-body (WB) beta/photon dosimeters
- Pocket Ionization Chamber (PIC) dosimeters
- Personnel extremity dosimeters
- Personnel whole-body neutron dosimeters

Hanford began operations in 1944 using in-house dosimeter and processing technical support. Hanford based its beta/photon film dosimetry methods on the dosimeter design developed at the Metallurgical Laboratory by Pardue, Goldstein, and Wollan (1944). This design was implemented at several of the MED sites. Hanford implemented its individual worker neutron dosimetry methods beginning in 1944 using PICs with a ^{10}B-enriched lining. In 1950, the NTA emulsion dosimeter capability was implemented [5].

Parameters concerning Hanford administrative practices significant to dose reconstruction include [6]:

- Policies to assign dosimeters to workers (Parker 1955).
- Policies to exchange dosimeters.
- Policies to record the measured dose and not using a notional dose (i.e., some identified value for lower dosed workers often based on a small fraction of the regulatory limit).
- Policies to estimate dose for missing or damaged dosimeters.
- Policies to replace destroyed or missing records.
- Policies to evaluate and record dose for incidents.
- Policies to obtain and record occupational dose to workers for other employer exposure.

Hanford policies appear to have been in place for all of these parameters (Parker 1948). Routine Hanford practices appear to have required assigning dosimeters to all workers who entered a controlled radiation area (Hart 1967). Dosimeters were exchanged on a routine schedule. All dosimeters were processed and the measured results were recorded and used to estimate dose. There appears to be no use of recorded notional doses, although there are issues of "missed" recorded dose for low-dosed dosimeters (see section on "missed dose") as well as recorded doses for individual dosimeters at levels less than the statistical Minimum Detection Level (MDL).

Early Hanford dosimetry procedures (HEW 1946) describe several aspects of the routine dosimetry program. Hanford workers entering operating areas were assigned dosimeters beginning in 1944. Trends in the number of monitored workers and the collective dose for these workers are shown in Figures 6-1 and 6-2. These figures illustrate the number of workers with positive recorded dose from photon and neutron radiation, respectively, along with the number of monitored workers. The trends in the respective figures do not show any abrupt changes that may be indicative of significant changes in photon dosimetry or assignment of dosimeters (Buschbom and Gilbert 1993). Figure 6-2 does illustrate abrupt changes in the number of workers with neutron dose greater than zero. This is discussed later in this section.

Administrative practices are generally described in Wilson (1987). A description of the content of the historical recorded dose values for each year by Fix, Carbaugh, and MacLellan (2001) and detailed information for each worker is in the NIOSH claim documentation. The claim documentation provides specific information to be evaluated regarding the recorded dose of record. There does not appear to be any significant administrative practice that would jeopardize the integrity of the recorded dose of record. Gilbert (1990) found agreement between the original paper records and computerized dose records. In addition, evaluations of Hanford film dosimeter results were examined in the 1960s at the University of Pittsburgh as part of the AEC Health and Mortality Study of Hanford workers (AEC 1966). The evaluation by University of Pittsburgh researchers was that the recorded dose data showed that "good quality control was exercised over the film badge calibration and processing procedures at Hanford over the years (i.e., 1944-61)."

6.4.2 Incidents

External radiation dose from worker involvement in incidents is included in the dose of record for Hanford workers. There have been significant incidents during the history of Hanford. A few primary incidents are described below:

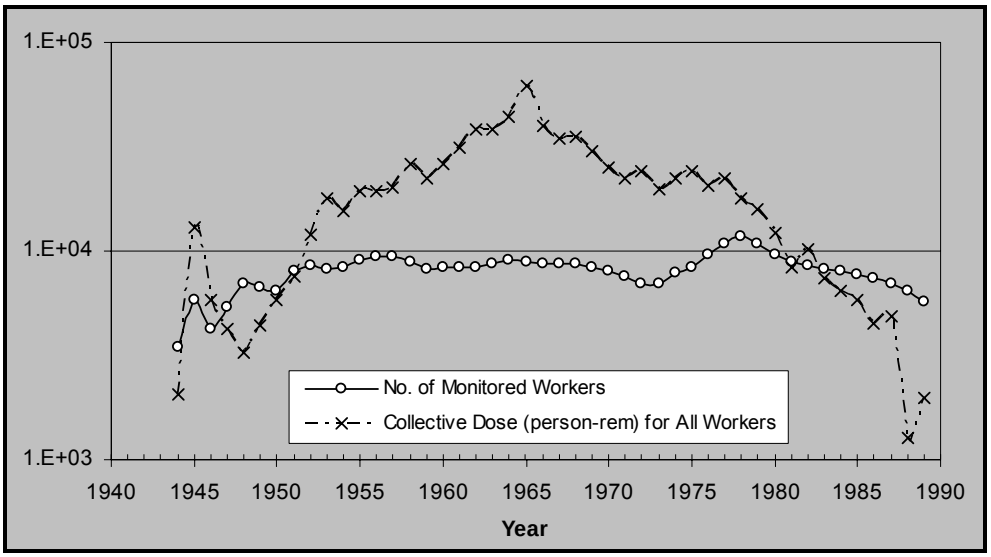

Figure 6-1. Trend in the collective dose for Hanford workers and the number of monitored Hanford workers, 1944–1989 [7].

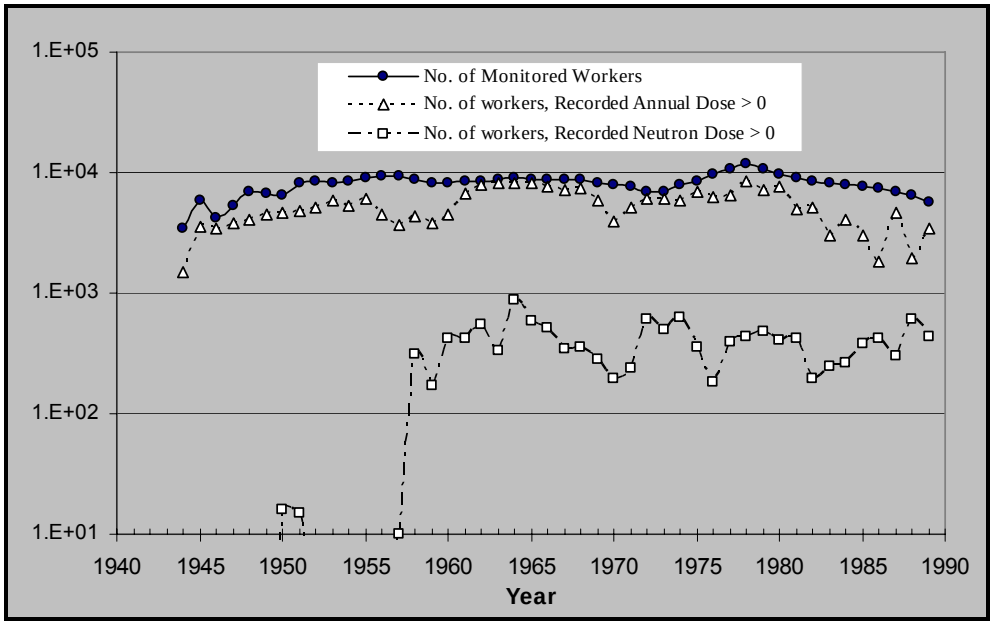

Figure 6-2. Trend in the number of Hanford monitored workers, the number of workers with recorded photon >0, the number of workers with recorded neutron dose >0, and the total collective dose, 1944–1989 [8].

P-11: The purpose of the P-11 facility was to test critical safe geometries to assist with design of the fuel reprocessing systems and systems at the 234-5 Plutonium Finishing plant. The P-11 processes were purposely operated near the edge of criticality to determine operational bounds. These bounds were exceeded resulting in a fire during 1950 in the atmospheric exhaust filter systems (Leonard 1952).

Recuplex: A criticality accident occurred on April 7, 1962, in a plutonium waste chemical recovery facility called Recuplex associated with the 234-5 building. Twenty-four workers were involved, including two patrolmen stationed at the entry gatehouse. Photon doses to workers were measured

with personnel dosimeters. Neutron doses were determined from whole body counts and blood activation measurements along with measurements of ^{32}P in hair and radioactivity in objects that were on the workers as well as threshold detectors and recording instruments in the building. The highest exposed worker received 23-30 rad from fast neutrons and 63 R to the central part of the body. This person also received about 42-54 rad from the fast neutron radiation to his eyes (Gamertsfelder et al. 1962).

^{241}Am Explosion: In 1976, a chemical explosion occurred at Hanford resulting in a nuclear chemical operator being extensively contaminated and receiving an intake of ^{241}Am by skin absorption and inhalation (see Hanford Site Profile Chapter 5).

N-Reactor: On December 16, 1977, an irradiated fuel discharge occurred exposing four workmen on an elevator resulting in personnel radiation exposures in excess of radiation safety limits. The incident was identified as a Class B occurrence (according to DOE Manual Chapter 0502) and an investigation committee formed to oversee the process of determination of cause for the accident and the process of dose reconstruction (United Nuclear Industries 1977).

6.4.3 Hanford Dosimetry Technology

Hanford external dosimetry practices are essentially the same as practices adopted at the MED Metallurgical (now University of Chicago) and Clinton (now Oak Ridge National Laboratory [ORNL]) laboratories in the early to mid-1940s. Parker (1945) described results of intercomparisons of dosimeter processing and exposure calculations between these three laboratories prior to declaring the Hanford system capable of routine dosimeter processing. Comparisons of dose interpretation among these MED/AEC sites and other sites were done through the years (Wilson 1960a, Wilson et al. 1990). All of these sites followed a similar evolution in dosimetry technology using PICs in addition to a two-element film dosimeter in the 1940s and early 1950s, leading to multielement film dosimeters in the later 1950s, followed by thermoluminescent dosimeters (TLDs) in the 1960s and 1970s. The adequacy of the respective dosimetry methods to measure radiation dose accurately is determined from the radiation type, energy, exposure geometry, etc., as described in later sections. The dosimeter exchange frequency was gradually lengthened, generally corresponding to the period of the regulatory dose controls (GE 1954). At the beginning of Hanford operations, a dose control of 1 mSv per day (100 millirem/day) was in effect. This was changed to a dose control of 3 mSv per week (300 millirem/week) and later to a limit of 50 mSv per year (5,000 millirem) in the later 1950s. Table 6-1 summarizes major operational events in the Hanford personnel dosimetry program.

Table 6-1. Hanford historical dosimetry events (Wilson 1987, Wilson et al. 1990).

Date	Description
1/1944	PICs used for a few months to measure dose for each worker prior to film dosimeter availability. Thereafter, PICs used in addition to film dosimeters.
10/1944	Two-element (i.e., open window and 1-mm silver filter) beta/photon film dosimeter issued to personnel. Film response under the silver filter was converted to personnel dose by comparing film optical density response with calibrated film response from ^{226}Ra. Minimum detectable dose based on laboratory irradiations was 0.3 mSv (30 millirem) (Wilson 1960b).
	Routine dosimeter exchange period was weekly.
1/1948	Beta/photon dosimeter exchange changed to biweekly.
1/1950	NTA was issued to personnel to measure neutron dose. Film exchange was weekly.
	Uranium used to calibrate open window beta response.
	Extremity film dosimeter use and processing began.
1952	Identified penetrating dose calculation as OW/5 + S, likely only in plutonium facilities, but actual practice not verified. As such, in this TBD, it is assumed that this was not done.

Date	Description
4/1957	Multielement film dosimeter use was implemented. This design permitted analysis of beta, gamma, and X-ray exposure to personnel.
5/1957	Monthly beta/photon film dosimeter exchange implemented.
7/1957	New dosimeter holder implemented exclusively for NTA film.
1958	Automated densitometer and computer analysis capability introduced to replace manually operated densitometer.
7/1958	NTA exchange changed to bi-weekly.
1962	Second multielement film dosimeter design implemented; replaced design used since 1957. This dosimeter incorporated nuclear accident capabilities in addition to routine personnel dosimetry.
1963	Quarterly film dosimeter exchange for nonradiological workers implemented.
3/1964	Tritium dose included in annual whole-body dose.
1966	Accumulated dose from 1944–1961 was rounded up to nearest multiple of 10 millirem (i.e., 2,487 to 2,490). Thereafter, all doses shown to nearest multiple of 10 millirem.
Late 1960s	Parallel field testing of new TLDs and film dosimeter conducted. Selected Hanford workers wore both dosimeters.
1/1971	Basic (one-chip) TLD implemented.
1/1972	Five-chip Hanford Multipurpose TLD (HMPD) implemented.
7/1978	Four-chip HMPD implemented.
1/1984	Five-chip HMPD reinstated.
Mid-1980s	On-phantom calibration of dosimeters implemented to conform to preliminary DOELAP performance testing criteria. Laboratory testing showed 8% and 4% increase, respectively, in dosimeter response for on-phantom exposure using ^{226}Ra or ^{137}Cs exposures.
1/1/1987	Routine photon calibration changed to ^{137}Cs from ^{226}Ra source. Overall change in recorded dose, described in Fix et al. (1982), was a 7% decrease from previous methods because of the decrease resulting from on-phantom calibration (-10%) and increase in recorded dose from the dose conversion factor (+3%).
1989	Hanford TLD is DOELAP-accredited for performance testing. Lower limit of detection, based on DOELAP protocol for laboratory irradiations, was about 0.2 mSv (20 millirem) for deep dose components.
1/1/1995	Commercial Harshaw dosimetry system replaced Hanford site-specific TLD. Routine dosimeter exchange is quarterly and monthly [9].

6.4.3.1 Beta/Photon Dosimeters

The following paragraphs describe the Hanford beta/photon dosimeters and period of routine use to provide the recorded dose of record.

Pocket Ionization Chamber, 1944. During January 1944, before the Hanford film dosimetry system was operational, PICs were used for a few months to provide the dose of record (Wilson 1987). PICs were issued to employees in duplicate (i.e., two to each worker) and exposures were recorded daily. PICs consist of an electrically charged chamber that indicates radiation exposure as the charge decreases. The decrease in charge occurs from radiation exposure (i.e., ionization) but may also occur from any cause that reduces charge such as humidity, physical impact, etc. As such, PICs typically over-estimate the exposure from routine handling and environmental effects (Watson 1957). Because of “false-positive” dose from routine handling and environmental effects, the lower of the two readings for each day was used to calculate the dose for comparison with the daily dose limits at that time. Following use as the earliest dosimeters, PICs have been used throughout the history of Hanford operations to provide administrative control of worker dose until the dosimeter being worn was processed and the dose calculated. It has been routine practice since at least the early 1950s to compare the doses measured with PICs and dosimeters and, for significant differences, to document the reason(s) for the discrepancy [10].

Two-Element Film Dosimeter, October 1944 to March 1957. The same design as that used at the Clinton Laboratory (now ORNL) and later by other MED/AEC/DOE laboratories. The Hanford design consisted of an open window and a 1-mm silver shield. Records of dosimeter film processing identify the regions of the dosimeter film as "OW" for open window and "S" for shielded. A calibration factor for each batch of film was used to convert measured optical density to dose. The optical density and the interpreted dose are included in the original Hanford dosimetry forms. Hanford implemented a two-element beta/photon dosimeter in 1944 based on the design developed by Pardue, Goldstein, and Wollan (1944) at the Metallurgical Laboratories. In 1952, the practice was begun to include 20% of the OW dose to the S dose to calculate the penetrating dose in plutonium facilities (Fix, Wilson, and Baumgartner 1997b). However, this practice has not been verified with the actual dosimeter processing results and recorded doses.

Another feature of the Hanford beta/photon film dosimeter was the use of 502-type film with a sensitive (lower radiation dose response) and an insensitive (typically accident-level dose response) side to each film packet. Normally, only the sensitive side of the film was useful for personnel dose assessment. However, Hanford individual worker personnel dose forms included space to record the insensitive film response. Prior to 1957, the processing data were recorded manually. Worker personnel dose forms were updated each year to enable staff to record dosimeter results directly for each dosimeter exchange period and each operating area. These forms were organized to enable manual entry of dosimeter results and to record the total annual and cumulative dose for each worker [11].

In 1958 (approximately), annual dose data were transferred to the newly implemented Hanford radiological computer database. During entry of the older records, a dose recorded prior to 1958 as a multiple of 5 millirem (i.e., 0, 5, 10,15, etc.) was rounded up to the first multiple of 10 millirem (i.e., 15 millirem became 20, etc.). This provided consistency with the new (computer-based) practice of recording dose only to the first multiple of 10 millirem (10, 20, 30, etc.). This practice is still in use [12].

Multielement Film Dosimeters, April 1957 to December 1971. Hanford used multielement film dosimeters to measure beta, X-ray, and gamma radiation dose components in one of two designs during the periods of 1958 to 1961 and 1962 to 1971, respectively. These "beta/photon" film dosimeters consisted of four shielded areas and provided a substantially improved capability to measure $H_p(0.07)$ and $H_p(10)$. Processing results (i.e., optical density) were recorded for the film response behind each filter and an algorithm was used to calculate the respective dose components. Thirty-five percent of the X-ray dose was assigned to the whole-body dose of record based on depth dose measurements in water at Hanford for 16 keV k-fluorescent X-ray (Wilson et al. 1990). Water closely simulates the radiation response of tissue. The whole-body dose also included the assigned neutron dose, as described in this chapter, and beginning in March 1964, the assigned tritium dose based on methods described in Chapter 5 along with other nuclide intake into the body. The tritium dose was recorded separately after 1987. The skin dose of record was calculated as the sum of the whole-body (i.e., penetrating, 35% of X-ray, neutron, and tritium) and nonpenetrating doses.

Thermoluminescent Dosimeter, January 1972 to December 1994. Hanford has used TLDs in a few configurations. A "Basic" TLD (Kathren 1970) with limited capability for beta and photon (X- and gamma ray) radiation was used from January 1, 1971, through about 1988. This dosimeter, which had one chip, was assigned to personnel with little or no potential to receive dose (Wilson 1987). Hanford Multipurpose TLDs (HMPDs) were used from January 1, 1972, through December 31, 1994, to measure beta, photon, and neutron radiation. HMPDs originally had a five-chip design, which was changed to a four-chip design in July 1977 (Glenn 1977) to enable use of a commercial reader system and then, returned to a five-chip design in January 1983 (Fleischman 1982) until the system was

replaced on January 1, 1995, with a commercial system. The same filtration was used in the HMPD through all the years of use. These dosimeters were assigned to personnel likely to work in radiation fields. The HMPD was first accredited for performance testing in 1989 by the DOELAP in beta, photon and neutron radiation categories. The system has been reaccredited during later (typically 2-year) accreditation cycles [13].

Commercial TLD System, January 1995–Present. Hanford implemented a commercial Harshaw TLD system on January 1, 1995. This system includes a four-chip beta/photon dosimeter and a separate neutron dosimeter. Technical characteristics are described in the Hanford External Dosimetry Technical Basis Manual (Rathbone 2002).

6.4.3.2 Neutron Dosimeters

Hanford has used three general types of neutron dosimeters, which differ substantially in their response to neutron radiation (Brackenbush et al. 1980).

- **Pocket Ionization Chamber.** Prior to 1950, Hanford relied on PICs with enriched ^{10}B liners to detect slow neutron exposure (Wilson 1987).

- **Neutron Track Emulsion.** The Hanford NTA neutron dosimeter was implemented on January 1, 1950, and used through December 31, 1971.

- **Thermoluminescent Dosimeter**. The HMPD for beta, photon, and neutron radiation was implemented on January 1, 1972. The HMPD was implemented as a 5-chip design with an automated reader system (Kocher et al. 1971). Hanford implemented a commercial Harshaw TLD system on January 1, 1995.

The following paragraphs describe the Hanford personnel neutron dosimeters and their periods of use (Fix, Wilson, and Baumgartner 1997b).

Pocket Ionization Chamber, Prior to 1950. Enriched ^{10}B liners were used in PICs to detect slow neutron exposure (Wilson 1987). This method is generally acceptable to detect the presence of slow neutrons but not for dose measurement. There is no recorded neutron dose for any Hanford worker prior to 1950 (Buschbom and Gilbert 1993).

NTA Film, January 1950 to December 1971. Hanford NTA film, which was introduced on January 1, 1950, was processed independently from the beta/photon film even though the NTA film was typically exchanged along with the beta/photon film. Prior to 1957, NTA film was housed in the two-element beta/photon dosimeter holder along with the beta/photon film. Beginning in 1958, the NTA film was housed in an NTA-specific holder assigned to personnel. There was space in the yearly forms manually prepared before 1957 to record the neutron dose. The Hanford policy to process NTA film varied historically but basically involved the practice to read all NTA film for the 200 West plutonium facilities and, for other Hanford facilities, to process the NTA only if the photon dose was at least 100 mrem. This was based on the observation (Watson 1959) that neutron dose was always accompanied by photon dose. For the other facilities, potential neutron dose was considered to be relatively small compared to the photon dose. A neutron dose is recorded for all Hanford workers assigned an NTA film. If it was not processed, a zero neutron dose is recorded. The earliest recorded neutron dose for Hanford workers occurred in 1950 (Buschbom and Gilbert 1993).

Five-Chip HMPD, January 1972 to June 1977. The five-chip HMPD incorporated a neutron dose capability that involved three of the five chips (i.e., 3, 4, and 5). The combination of these chips

provided capabilities to estimate thermal (i.e., slow) and fast neutron components with the capability (chip 5) for an accurate beta/photon response correction (i.e., neutron-sensitive chips also respond to photon and high-energy beta radiation) (Kocher et al. 1971). Effective July 1, 1977, the dose algorithm was changed to use data for only four of the chips (i.e., not chip 5) to utilize the four-chip cards that were being implemented (Wilson et al. 1990).

Four-Chip HMPD, July 1977 to December 1983. The HMPD dosimeter was modified to a four-chip design to accommodate introduction of a commercial reader system in the later 1970s that required the dosimeter cards to pivot around the center where chip 5 was located. Tens of thousands of HMPD cards were fabricated with chip 5 removed. These modified cards were used in the original five-chip holders.

Five-Chip HMPD, January 1984 to December 1994. Routine dose evaluation with the five-chip HMPD was returned to service effective on January 1, 1984. Several refinements were made to this system (Wilson et al. 1990) to prepare for DOELAP performance testing. The HMPD was first accredited by DOELAP for performance testing in neutron categories in 1989 and reaccredited every subsequent (typically 2-year) accreditation cycle thereafter.

Commercial TLD System, January 1995 to Present. Hanford implemented a commercial Harshaw TLD system beginning on January 1, 1995. The neutron dosimeter system was originally a combination TLD and track-etch dosimetry (TED) system but essentially the TLD capability was used for all routine dose evaluations. Routine use of the TED capability has been discontinued since it did not accurately measure worker dose in the workplace (Scherpelz et al. 2000).

6.4.4 Calibration

Potential error in recorded dose is dependent on the dosimetry technology response characteristics to each radiation type, energy, and geometry; the methodology used to calibrate the dosimetry system; and the similarity between the radiation fields used for calibration and the fields in the workplace. Early evaluations of Hanford workplace radiation fields were performed such as for uranium by McAdams (1949a), plutonium surface dose (Roesch 1957; Keene 1957), and neutron instruments by McAdams (1949b, 1950). The potential error is much greater for dosimeters with significant variations in response, such as the film dosimeters to low-energy photon radiation and the NTA and HMPD response to neutron radiation [14].

6.4.4.1 Hanford Beta/Photon Dosimeters

Hanford dosimeters were originally calibrated using ^{226}Ra gamma, uranium beta, and 80 keV X-rays (HEW 1946). Routine irradiation in air (i.e., no phantom) of calibration film was done for each batch of film. This included 10 exposure levels from 100 to 30,000 mR to ^{226}Ra gamma radiation, seven exposure levels from 100 to 5,000 mrads to uranium beta radiation, and 100 to 1,000 mR from 80 keV X-ray radiation (HEW 1946). Calibration films were processed with all personnel dosimeters. In the early 1950s, Hanford k-fluorescent X-ray capabilities were used to develop dosimeter response characteristics for the lower energy photon fields in plutonium facilities (Wilson 1987; Fix, Gilbert, and Baumgartner 1994; Wilson et al. 1990). Studies by Fix et al. (1982,1981) describe technical characteristics of Hanford recorded dose compared to the $H_p(10)$ dose based on work performed for Hanford's participation in the DOELAP performance testing that was formally required in the latter 1980s (DOE 1986). At that time, it was concluded that a 10% decrease in the recorded dose would result from on-phantom calibration irradiations. This effect is partially compensated by the 3% increase in recorded dose resulting from use of the ^{137}Cs dose to exposure conversion factor (Fix et al. 1982, Study 2).

No change in the recorded dose is proposed to account for the approximate 7% over-estimate in the recorded dose prior to the implementation of on-phantom calibration or other similar comparatively small changes because of the overall uncertainty of changes made over the years. Table C.2 of Wilson et al. (1990) lists a chronology of changes to the Hanford TLD system. Common sources of laboratory bias are listed in Table 6-2 for personnel beta/photon dosimeter calibration based on comparison of the recorded dose with $H_p(10)$. Wilson (1960b) measured a standard deviation of ±25% (one-sigma) based on laboratory irradiations performed to estimate the dosimetry detection level (i.e., about 30 mrem).

Table 6-2. Laboratory sources of uncertainty for beta/photon dosimeter calibration parameters [15].

Parameter	Historical description	Uncertainty[a]	Comment
In-air calibration	In the 1980s, Hanford began exposing calibration dosimeters on phantoms (used to simulate worker body). Previous calibrations do not include response from radiation backscatter response.	+10%	Recorded dose of record **too high**. Backscatter radiation from worker body is highly dependent on dosimeter design. Fix et al. (1982, Study 2) measured a bias of about 10% for ^{137}Cs gamma radiation with HMPD.
Radiation quantity	Before 1980s, Hanford dosimeter systems were typically calibrated to a photon beam measured as *exposure*.	-5%	For higher energy ^{226}Ra and ^{137}Cs gamma radiation used to calibrate dosimeters, this caused a slight (about 3%) **under-response** in recorded dose.
Tissue depth of dose	Historically, Hanford used an unspecified depth to estimate the deep dose.	±5%	The numerical effect of this for photon radiation is comparatively low. Hanford dosimeter designs had filtration density thickness of about 1,000 mg/cm^2 that would relate closely to the 1-cm depth in tissue.
Angular response	Hanford dosimeter system is calibrated using AP laboratory irradiations.	>300 keV, ~20%	Recorded dose of record likely **too low** since the dosimeter response is usually lower at non-AP angles. Effect is highly dependent on radiation type and energy.
Environmental stability	Hanford film dosimeter and TLD systems are subject to signal fade with time, heat, humidity, light, etc.	±10%	Recorded dose of record depends strongly on dosimetry parameters, such as when calibration dosimeters were irradiated and processed. Mid-cycle calibration minimizes effects.

a. Uncertainty estimate in recorded dose compared to $H_p(10)$ based on Hanford dosimeter laboratory studies.

Figure 6-3 shows the laboratory measured anterior-posterior (AP) photon energy response of the respective Hanford dosimeter systems. As noted in this figure, the film dosimeter OW response shows a significant over-response to lower energy photon radiation. Operationally, the over-response was so significant that some option was necessary to interpret the dosimeter response based on the anticipated radiation fields in the work environment. The ratio of the OW to the filtered film response was routinely used in dose evaluation (Larson and Roesch 1954) and there is reference to using a fraction (0.2) of the OW response to add to the penetrating dose in facilities with low-energy photons and no beta radiation (i.e., plutonium facilities) (Fix, Wilson, and Baumgartner 1997b). However, it has not been validated that this was actually done. An analysis of the bias in the nonpenetrating and penetrating dose is presented in Table 6-3. The Hanford recorded skin dose is calculated as the sum of the OW and S filtered film response. The recorded Hanford whole body (WB) dose is calculated using 20% of the OW film response in addition to the measured S film response using the historical Hanford dosimeter testing data in Appendix A of Wilson et al. (1990). As noted in this table, the calculated WB dose for the lower energy photons characteristic of Hanford plutonium facilities is conservatively estimated using this practice in comparison with $H_p(10)$. The practice is applicable only

to workers in Hanford plutonium facilities. Application of this practice to Hanford reactor and radiochemical facilities with primarily mixed beta and photon fields would result in a significant overestimate of $H_p(10)$ as noted in Table 6-3 for uranium and $^{90}Sr/^{90}Y$ exposures. As such, a recommendation that is favorable to claimants for plutonium workers only, is to apply the calculation of the WB dose using 20% of the OW dose in addition to the measured S dose pending confirmation that the historical Hanford WB dose does indeed include the 20% of the OW dose [16].

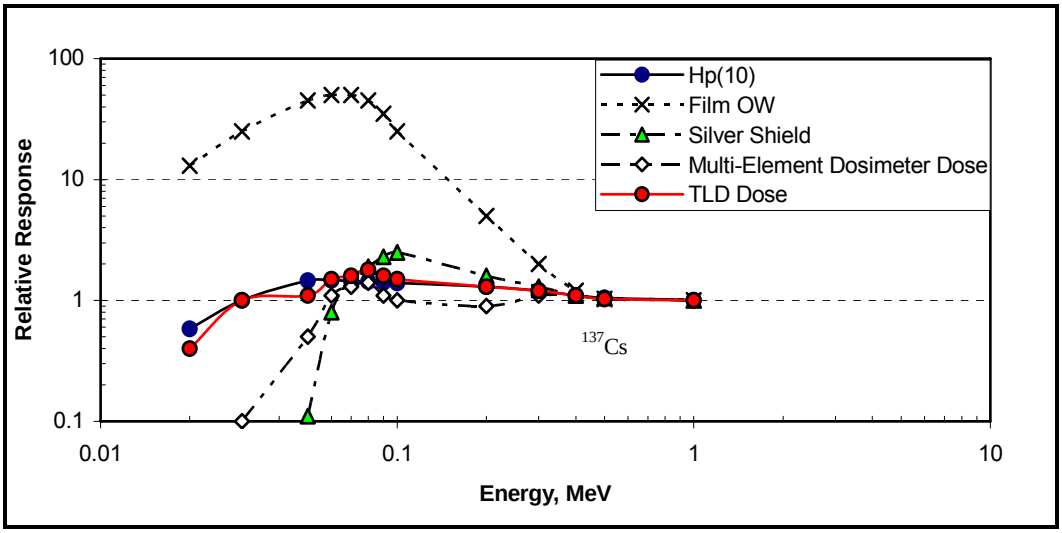

Figure 6-3. Measured Hanford dosimeter photon response characteristics (Wilson et al. 1990).

Table 6-3. Analysis of two-element film dosimeter dose.[a]

Source	Exposure (mR)[b]	Delivered dose, mrem[c]		Dosimeter dose		Recorded dose[d]	
		$H_p(0.07)$	$H_p(10)$	OW	S	Skin	WB
16 keV	40	43	15	353	7	360	78
	80	86	30	710	7	717	149
	160	173	61	2,213	3	2,216	446
59 keV	30	44	46	653	17	670	148
	50	74	77	1,237	23	1,260	270
	80	118	123	2,553	27	2,580	538
Cs-137	50	52	52	7	50	57	51
	240	247	247	10	247	257	249
	750	773	773	24	750	774	755
	1,000	1,030	1,030	47	1,000	1,047	1,009
Uranium	50	50	0	50	0	50	10
	240	240	0	250	0	250	50
	750	750	0	756	20	776	171
	1,000	1,000	0	1,000	23	1,023	223
Sr-90/Y-90[e]	50	50	0	103	3	106	24
	240	240	0	353	3	356	74
	750	750	0	1,370	13	1,383	287
	1,000	1,000	0	2,070	6	2076	420

a. PNL-7447, Appendix A, dosimeter data, average value shown in table.
b. Photon dose in mR and beta dose in mrad.
c. Exposure to dose conversion factors from DOELAP Standard (DOE 1986).
d. Skin Dose = OW + S, WB dose = S + 0.2 * OW.
e. Table shows factor of about 2 over-response to $^{90}Sr/^{90}Y$ based on uranium calibration [17].

6.4.4.2 Hanford Neutron Dosimeters

Historical aspects of Hanford neutron fields, NTA dosimeters, and calibration are described in Roesch (1951, 1954), Swanberg (1959) and Wilson (1960b, 1960c) and an historical evaluation of Hanford NTA and HMPDs described by Fix, Wilson, and Baumgartner (1997b). Table 6-4 lists common sources of laboratory bias for personnel neutron dosimeter calibration based on the expected comparison of the recorded dose with $H_p(10)$. Brackenbush et al. (1980) describes the energy response characteristics of NTA and TLD dosimeters, and these are characteristic of Hanford neutron dosimeters. Fundamentally, the NTA dosimeter is capable of an accurate dose estimate for higher energy neutron radiation greater than about 1 MeV because the NTA has a lower energy threshold of about 700 keV.

Table 6-4. Laboratory sources of uncertainty for neutron dosimeter calibration parameters.

Parameter	Historical description	Uncertainty[a]	Comment
Source energy spectra	Hanford has used many sources to calibrate dosimeters (Fix, Wilson, and Baumgartner 1997b) and perhaps in calibration geometries to degrade the spectra such as with the PuF_4 source.	±100%	The delivered dose used in calibrating neutron dosimeters, particularly the NTA, is **uncertain** as noted in Fix, Wilson, and Baumgartner (1997b) (see workplace radiation fields).
Radiation quantity [18]	Neutron dose quantities used to calibrate neutron dosimeter systems have varied historically; these quantities primarily include *first* and *multiple collision dose*, and neutron *dose equivalent index* factors.	±50%	This represents a significant and complicated issue, particularly for early neutron sources.
Angular response [19]	Hanford dosimeters calibrated using AP laboratory irradiations.	-50%	Recorded dose of record likely **too low** because dosimeter response is often lower at angles other than AP. Effect is highly dependent on energy.
Environmental stability [20]	NTA film dosimeter and TLD systems are subject to signal fade with time, heat, humidity, light, etc.	±50%	Recorded dose of record likely **too low** because of fading; however, this effect depends strongly on such routine dosimetry practices as when calibration dosimeters were irradiated.

a. Uncertainty in recorded dose compared to $H_p(10)$ based on laboratory studies.

The Hanford TLD (Kocher et al. 1971) has a comparatively high response to thermal neutrons and is generally used to measure neutron radiation scattered from the workers body (i.e., the Albedo effect). The NTA and TLD neutron dosimeters must be calibrated to neutron spectra similar to that present in the workplace for accurate dose results. There are many Hanford reports on technical aspects of neutron source calibration (Fix, Wilson and Baumgartner.1997b). Several address the controversy concerning whether a first-collision or multiple-collision neutron dose factor should be used. A significant change based on Hanford studies (Budd 1963) showed no significant statistical difference in response between NTA dosimeters exposed to PuBe and PuF_4 neutron source irradiations in-air and on-phantom. Based on this, the identified action was to change to the multiple-collision Relative Biological Effectiveness (RBE) dose from a single collision RBE dose effective with the 2-week period ending July 12, 1963. The difference in recorded dose between the two calibration references was an increase in recorded neutron dose of about 35%.

6.4.5 Workplace Radiation Fields

Hanford operations are characterized by significant complex beta, photon, and neutron radiation fields in Hanford reactor, irradiated fuel processing, plutonium handling, and radioactive waste facilities [21].

6.4.5.1 Hanford Beta/Photon Dosimeter Response Testing

In 1944, when the Hanford two-element dosimeter was being implemented, an intercomparison test was performed with the Metallurgical and Clinton laboratories to evaluate the respective dosimetry systems, which were essentially identical (Parker 1945). This testing led to the following conclusions:

- The badge systems at all three sites were satisfactory for adequate determination of gamma radiation exposure of personnel.
- The calibrations of all three laboratories were in agreement.
- More frequent calibrations at high exposures should be made.
- Greater attention to photometer reproducibility is desirable.

The evaluation also concluded that greater attention to beta and low-energy X-rays was needed at Hanford and that neutron films (i.e., NTA) are useful only for higher neutron exposures than will normally occur at Hanford. These statements were made in 1945 prior to operation of many of the Hanford facilities. Later, it became evident that mixed beta/photon radiation fields and neutron radiation presented a significant technical challenge, which led to ongoing research and development in Hanford dosimetry technology [22].

Several studies of Hanford film dosimeter performance, stability of latent image, etc., were performed during the 1950s (Wilson 1957a, 1957b, 1960a, 1960b, 1960c). As described in Wilson et al. (1990), many intercomparison and performance studies were done at Hanford and between Hanford and other MED/AEC/DOE facilities. These studies generally confirmed the acceptability of Hanford assessment of nonpenetrating and penetrating dose as defined at that time. Several studies of the HMPD were performed (Fix et al. 1981, 1982) in preparing for the DOELAP performance testing that included explicit identification of dose quantities (ANSI 1983, DOE 1986) as measured in comparison to what is now referred to as the *Personal Dose Equivalent*, $H_p(d)$, were d refers to a 0.07- or 10-mm depth in tissue. In general, only small changes (± 10%) were necessary to improve comparison in laboratory studies with $H_p(10)$, although additional changes were necessary to improve overall precision (Fix et al. 1982, Wilson et al. 1990).

In recent years, further studies of early dosimeter performance compared to $H_p(10)$ have been made because of its use in worker health effect studies. The IARC conducted a dosimeter intercomparison study to higher energy (i.e., >100 keV) photons of 10 commonly used dosimetry systems used throughout the world (Thierry-Chef et al. 2002). Two of the film dosimeter designs were from Hanford: (1) the two-element dosimeter design (identified as US-2) and (2) the multielement film dosimeter design (identified as US-8). The IARC Study considered that exposure to dosimeters worn by workers could be characterized as AP, rotational and isotropic irradiation geometries, or a combination thereof. Dosimeter response to selected photon energies was measured using two phantoms, which were used to simulate the effect of the worker's body on the measured dosimeter response. The first phantom was the International Standards Organization (ISO) water-filled slab phantom, which is used for dosimeter calibration and performance testing. The second was an anthropomorphic Alderson Rando Phantom, which is constructed from a natural human skeleton cast

material that has a tissue equivalent response. The results of IARC testing (for U.S. dosimeters only) are listed in Table 6-5. This table includes results for the DOE Savannah River Site (SRS) commercial TLD (US-22) that also participated in IARC testing. SRS dosimeter performance is expected to be representative of the Hanford TLD system.

Table 6-5. IARC testing results for U.S. beta/photon dosimeters (Thierry-Chef et al. 2002).

Geometry	Phantom	118 keV		208 keV		662 keV	
		Mean[a]	SD/Mean	Mean[a]	SD/Mean	Mean[a]	SD/ Mean
US-2 (Hanford two-element film dosimeter)							
AP	Slab	3.0	2.1	1.3	1	1.0	0.8
AP	Anthropomorphic	3.0	4.2	1.2	1.9	1.0	1.8
Rotational	Anthropomorphic	2.2	2	1.4	3	1.2	3.2
Isotropic	Anthropomorphic	1.5	4.4	1.1	1.6	1.0	2.7
US-8 (Hanford multielement film dosimeter)							
AP	Slab	1.0	1.5	1.0	0.8	0.8	1.7
AP	Anthropomorphic	0.8	9.5	0.9	6	0.8	1.8
Rotational	Anthropomorphic	1.2	1.9	1.2	17	1.1	1.8
Isotropic	Anthropomorphic	1.0	3	1.2	9	1.0	2.3
US-22 (SRS multielement thermoluminescent dosimeter)							
AP	Slab	0.9	4.4	0.9	3.9	0.9	3.5
AP	Anthropomorphic	0.8	3.1	0.9	2.1	0.9	3.9
Rotational	Anthropomorphic	1.1	3.1	1.2	1.5	1.0	4.1
Isotropic	Anthropomorphic	0.9	0.3	1.0	2.5	0.9	1.6

a. Ratio of recorded dose to Hp(10).

Hanford conducted intercomparison testing of all its historical film dosimeter designs using AP (Wilson et al. 1990) and angular (Fix et al. 1994) irradiations on an Alderson Rando phantom essentially identical to the phantom used in the IARC studies. These studies included lower-energy (i.e., <100 keV) photons that are significant in Hanford plutonium facilities. Data from Fix et al. (1994) and Wilson et al. (1990) are summarized in Table 6-6. The dosimeter results for energies greater than 100 keV are consistent with the IARC results, showing an over-estimate of $H_p(10)$ for the two-element dosimeter.

Table 6-6. Testing results for Hanford two-element and multielement film dosimeters for energy and angular response.[a,b]

Beam (energy, keV)	AP exposure			Rotational exposure		
	Film dosimeters			Film dosimeters		
	Two-element 1944–56	Multielement 1957–71	TLD 1972–present	Two-element 1944–56	Multielement 1957–71	TLD 1972–93
16[c]	0.1	0.9				
59[c]	0.27	1.1				
M150(70)	0.7	0.70	0.95	1.31	1.31	1.77
H150(120)	1.6	0.64	0.87	3.00	1.20	1.64
Cs-137(662)	1.0	1.0	1.0	1.46	1.46	1.46

a. Divide recorded dose by table value to estimate $H_p(10)$.
b. Based on Fix et al. (1994)
c. Based on Wilson et al. (1990).

For energies less than 100 keV, the two-element dosimeter will underestimate the photon dose without using some method of adjustment such as a fraction of the dosimeter OW or silver shielded response. This potential under-response is evident in the original University of Chicago two-element dosimeter energy response curve (Pardue, Goldstein, and Wollan 1944).

Another source of data to evaluate relative performance is presented in Nichols et al. (1972), in which data were collected from parallel field testing in 1970 and 1971 of the Hanford multielement film dosimeter and the HMPD that was implemented on January 1, 1972. Measurements were performed (some involving dosimeters placed on water-filled carboys) at 49 work locations in the Plutonium-Uranium Extraction Facility (PUREX), B-Plant, Plutonium Finishing Plant (PFP), 105-KE Building (reactor operating), 100-N (reactor not operating), and the 325-B, 325, and 327 Buildings. Table 6-7 lists the collective nonpenetrating and penetrating dose measured with the Hanford film dosimeter and HMPD and, when available, the open window (nonpenetrating) and closed window (penetrating) ionization chamber "Cutie Pie (CP)" measurements. This table includes measurements with selected calibration sources. The information in Table 6-7 generally shows acceptable agreement considering the variability in the field measurements are similar to those of the calibration sources. The nonpenetrating response of the film dosimeter was routinely calibrated with a uranium slab source, whereas a $^{90}Sr/^{90}Y$ source was routinely used to calibrate the HMPD nonpenetrating response. There is an approximate factor of 2 difference in dosimeter response between these two sources and this is shown in this table (i.e., for $^{90}Sr/^{90}Y$ source irradiation, 690 mrem for film versus 315 mrem for TLD).

Table 6-7. Workplace measured nonpenetrating and penetrating collective doses (Nichols et al. 1972).

Facility	Nonpenetrating, mrad			Penetrating, millirem		
	Film	TLD	CP	Film	TLD	CP
Purex	4,260	3,790	3,640	3,480	3,570	2,806
B-Plant	10,550	9,510	13,850	2,250	4,560	4,920
PFP	4,060	4,220	(np)	3,920	4,090	5,410
105-KE[a]	9,390	9,150	10,324	9,390	9,100	10,104
105-N[b]	12,070	13,440	7,880	12,030	13,050	7,350
325-B	1,100	1,250	(np)	1,100	1,250	1,760
325	3,690	5,710	5,100	2,640	2,850	3,220
327	870	1,090	(np)	870	1,090	2,260
Calibration sources						
Ra-226	260	310	(np)	260	310	300
PuF_4	60	100	(np)	60	100	(np)
Sr-90/Y-90[c]	690	315	(np)	0	100	275
Cf-252	135	180	(np)	135	180	(np)

np – not provided in Nichols et al. (1972).

a. Plant operating.
b. Plant not operating
c. Film calibrated with uranium slab. TLD is calculated with $^{90}Sr/^{90}Y$. There is about a factor of 2 difference; results in this table illustrate this.

The report by Nichols et al. (1972) described another aspect of these field studies that involved 150 personnel wearing beta/photon film dosimeters and HMPDs simultaneously during November 1970 and January 1971. Figures 6-4 and 6-5 present the comparison of the penetrating and nonpenetrating dose, respectively, for Hanford workers from several facilities including the PFP, which is the most likely workplace environment of potential problems. The photon spectrum at PFP does have a significant lower-energy component that is comparatively more difficult to measure and is likely to have varied historically. Significant fission product contamination of the plutonium is likely to have occurred in the beginning of Hanford operations.

During later years, there is significant ingrowth of ^{241}Am, and its 60-keV gamma radiation is often dominant (Roberson, Cummings, and Fix 1985; Fix 1988). It is apparent from Figure 6-4 that the penetrating dose compares reasonably well between the Hanford multielement film and the HMPD for all facilities although there appears from this data a potential bias in multielement film. Analysis of the potential bias in multielement film dosimeter results relative to the TLD results in the field test by

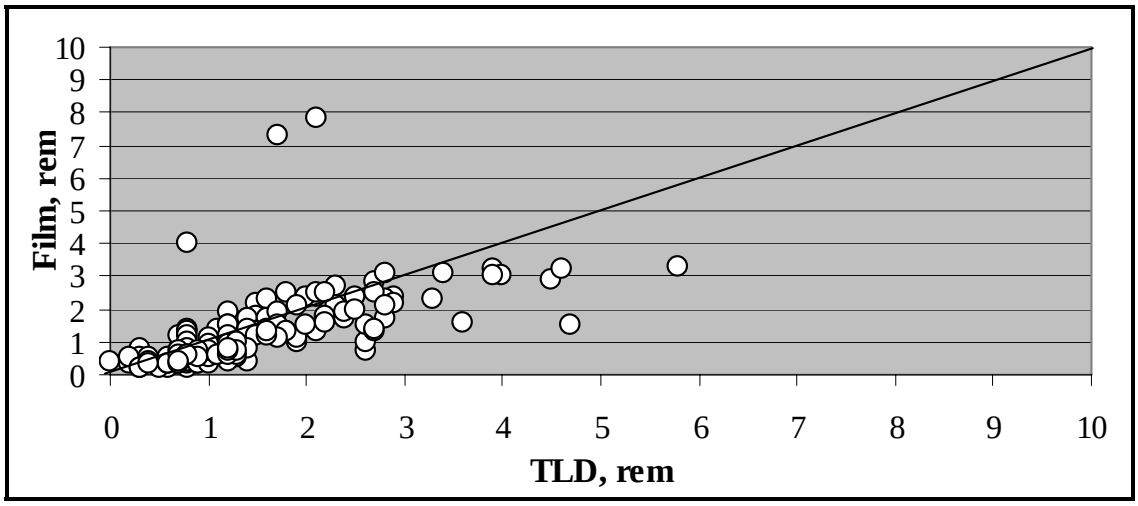

Figure 6-4. Comparison of Hanford film and TLD penetrating dose results (Nichols et al. 1972).

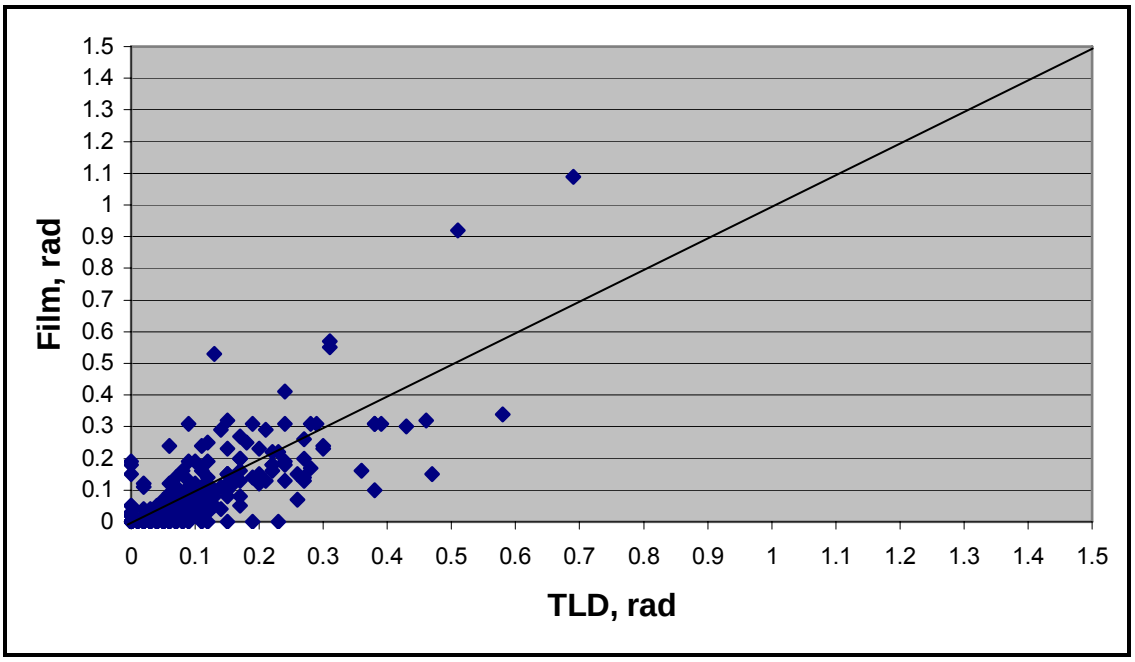

Figure 6-5. Comparison of Hanford film and TLD nonpenetrating dose results (Nichols et al. 1972).

Nichols et al. (1972) is difficult because of the many uncertainties concerning workers' practices to wear and position the dosimeters. Dosimeter nonpenetrating and penetrating response characteristics depend upon many parameters including the radiation type, energy and directional parameters as well as the worker orientation in the workplace. The collective dose for each of the facilities in which workers wore multielement film dosimeters and TLDs is presented in Table 6-7. The variability in workplace measurements in Table 6-7 is similar to the variability in the calibration source measurements using the three methods of measurement, each of which has different radiation type, energy, and geometry response characteristics.

A wide range of mixed beta and photon radiation and energies is characteristic of these facilities. The most significant difference in penetrating dose occurred at the B-Plant. This is likely associated with

the relatively high nonpenetrating radiation dose indicative of beta and lower-energy photons and the penetrating dose response of the HMPD to higher energy beta radiation as noted in Fix et al. (1982) and Wilson et al. (1990). The HMPD records a penetrating dose for higher energy beta radiation such as $^{90}Sr/^{90}Y$, when there should be none, because there is only 380 mg/cm^2 density thickness in the aluminum filter over the HMPD chip used to calculate the deep dose [23].

The performance of the multielement film dosimeter compared to $H_p(0.07)$ and $H_p(10)$ was analyzed using the multielement dosimeter results in Appendix A of PNL-7447. The results are presented in Table 6-8. This information provides good evidence that the multielement film dosimeter reasonably estimates $H_p(10)$ and $H_p(0.07)$.

Table 6-8. Analysis of multielement film dosimeter dose[a]

Source	Exposure (mR)[b]	Delivered dose, mrem[c]		Dosimeter dose			Recorded dose[d]	
		$H_p(0.07)$	$H_p(10)$	Beta	X-ray	Gamma	Skin	WB
16 keV	40	43	15	0	40	0	40	14
	80	86	30	16	78	7	101	34
	160	173	61	106	160	0	266	56
59 keV	30	44	46	0	64	24	88	46
	50	74	77	0	126	37	163	81
	80	118	123	0	216	50	266	126
^{137}Cs	50	52	52	0	0	50	50	50
	240	247	247	0	0	240	240	240
	750	773	773	0	0	726	726	726
	1,000	1,030	1,030	0	0	993	993	993
Sr-90/Y-90	50	50	0	74	0	0	74	0
	240	240	0	302	4	0	306	1
	750	750	0	1,000	16	0	1,016	6
	1,000	1,000	0	1,340	18	0	1,358	6

a. PNL-7447, Appendix A, dosimeter data, average value shown in table.
b. Photon dose in mR and beta dose in mrad.
c. Exposure to dose conversion factors from DOELAP Standard (DOE 1986).
d. Skin dose = Beta + X-ray + Gamma. Whole Body (WB) = gamma + 0.35 * beta

A report by Fix, Gilbert, and Baumgartner (1994) describes laboratory measurements of Hanford film and thermoluminescent dosimeter angular response characteristics used to estimate the bias and uncertainty in recorded Hanford Dose using methods developed by the National Research Council (1989) based on considerations of bias and uncertainty in radiological, environmental, and radiation field parameters. The report identifies biases and uncertainties in personnel dosimeter results for photon energies greater than 100 keV. Bias factors were found to primarily depend upon the photon radiation energy, the geometry, and the dosimetry system. Bias factors presented in this report are consistent with the IARC and Wilson et al. (1990) results presented in Tables 6-5 and 6-6, respectively. Additional discussion of results in this report is described under uncertainty in workplace beta/photon dose.

6.4.5.2 Hanford Workplace Beta/Photon Dosimeter Response

Field measurements of photon radiation spectra and dose have been performed on many occasions. Table 6-9 is a summary of several of those measurements that included the photon spectra. It is evident in these measurements that the vast majority of photon dose is higher energy photons with the exception of the plutonium facilities (308, 234-5) where 17 keV X-rays from plutonium and 60 keV photons from ^{241}Am are significant [24].

Table 6-9. Hanford workplace photon spectra measurements.[a]

Facility	Description	Measurements	Results[b]			Reference
308 Bldg.	Room background	Gamma	Am-241 (100%)			Fix et al. 1981
	Grinder hood bottom	Gamma	Am-241 (100%)			
	Pellet pressing station	Gamma	Am-241 (100%)			
327 Bldg.	Background A-cell	Gamma	Co-60 (85%), Cs-137 (8%), Mn-54 (8%)			
	Background G-cell	Gamma	Co-60 (79%), Cs-137 (9%), Mn-54 (12%)			
200W,2425	Evaporator building, NE corner	Gamma	Cs-137 (100%)			
200W, diversion boxes	241-TX-302-C catch tank	Gamma	Cs-137 (100%)			
	K2U	Gamma	Cs-137 (100%)			
	Rigging crew	TLD (Beta, gamma)	High energy, indicative of photon radiation			
B-Plant (225 Bldg)	A-Cell	Gamma	Cs-137 (100%)			
	Between B-C cells	Gamma	Cs-137 (100%)			
	Between D-E cells	Gamma	Cs-137 (100%)			
	F-cell	Gamma	Cs-137 (100%)			
	Room background	Gamma	Cs-137 (100%)			
271B	Pipe gallery –cell 9	TLD (Beta, gamma)	Indicative of ^{90}Sr/^{90}Y			
324 Bldg.	A-cell gallery	Gamma	Cs-137 (100%)			Fix et al. 1982
	C-cell gallery	Gamma	Cs-137 (100%)			
	Truck dock	Gamma	Cs-137 (100%)			
331 Bldg.	Office	Gamma	Tl-208 (90%), Cs-137 (10%)			
	Change room (SE)	Gamma	Tl-208 (8%), Cs-137 (92%)			
	Change room (toilet)		Tl-208 (64%), Cs-137 (36%)			
	Janitor's closet		Tl-208 (46%), Cs-137 (54%)			
340 Bldg.	340-A outside	Gamma	Cs-137 (100%)			
	Control room	Gamma	Cs-137 (100%)			
	Decon area	Gamma	Cs-137 (100%)			
	Operations office	Gamma	Cs-137 (100%)			
3730 Bldg	Irradiation room	Gamma	Co-60 (100%)			
	Hallway	Gamma	Co-60 (100%)			
234-5	Fluorinator hood	Gamma	<200 keV (99+%) 17 keV (~50%)			Roberson and Cummings 1985
			Photon energy, keV			
			<200	**200-2000**	**>2000**	
234-5, Vault 4	Vault 4 entrance	Gamma	13%	55%	33%	Roberson and Cummings, 1986
234-5, Vault 1	Phantom	Gamma	42%	55%	3%	
	Floor	Gamma	50%	48%	2%	
	Entrance	Gamma	17%	61%	22%	
234-5, MT Room	At hoods near entrance	Gamma	0%	83%	17%	
234-5, C-Line, Room B	Toward neutron source	Gamma	92%	7%	1%	
	Toward room A	Gamma	0%	98%	2%	
	Near entrance	Gamma	58%	28%	14%	

a. Only measurements that included photon spectra are listed.
b. Measured non-natural radionuclide significant to occupational exposure.

The extensive field validations of the Hanford film and HMPD in the late 1960s documented by Nichols et al. (1972) provide significant information on penetrating (PEN) and nonpenetrating (NPEN) dosimeter performance in several Hanford facilities and workplace conditions. The ratio of the positive (i.e., non-zero) HMPD and film nonpenetrating to penetrating response is shown in Figure 6-6. This figure implies generally higher ratios for the film in comparison to the HMPD. One reason for this is the routine use of uranium to calibrate the film as opposed to the use of ^{90}Sr/^{90}Y for the HMPD.

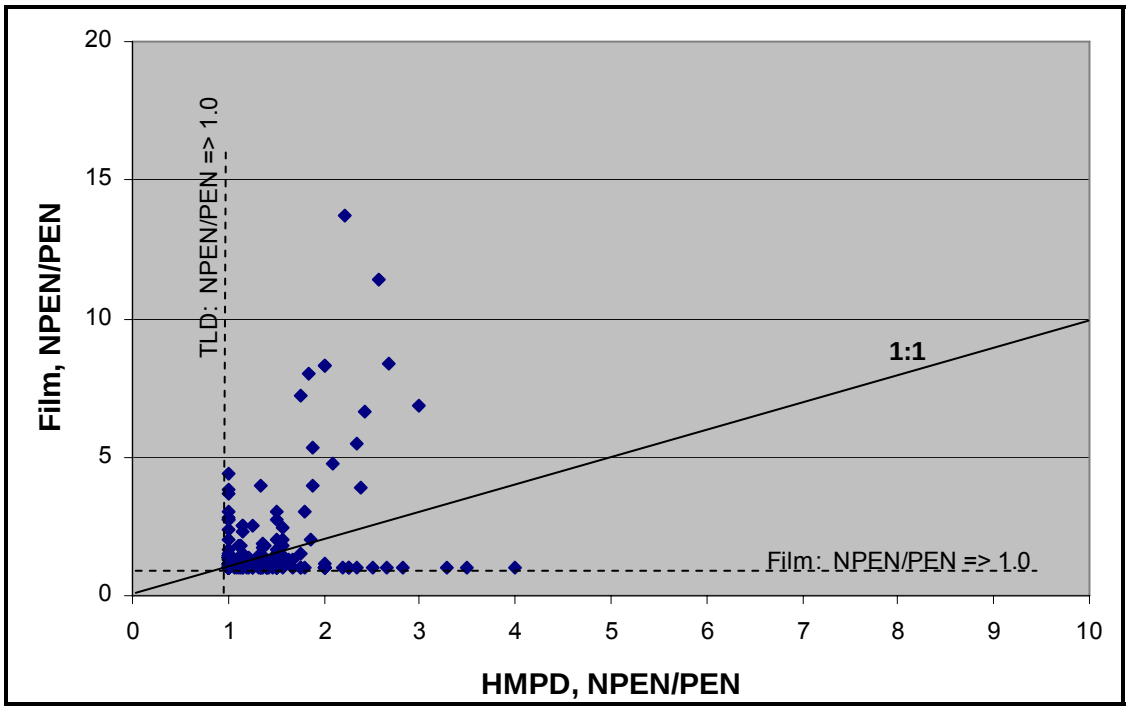

Figure 6-6. Ratio of nonpenetrating (NPEN) to penetrating (PEN) dose for HMPD and film parallel workplace measurements (Nichols et al. 1972).

As noted in Table 6-6, this results in TLD measurements that are higher than film measurements by a factor of two. As such, the respective film ratios in this figure should be divided by 2 for a direct comparison [25].

In addition, this figure shows that in all film dosimeter and TLD results, the reported NPEN dose was equal to or greater than the PEN dose (i.e., NPEN ≥ PEN).

6.4.5.3 Uncertainty in Beta/Photon Recorded Dose

Table 6-10 summarizes estimates of Hanford beta/photon personnel dosimeter parameters important to $H_p(10)$ performance in the workplace. Based on the respective field and laboratory measurements, Hanford dosimeters reasonably measure the $H_p(10)$ dose under most workplace radiation fields. The only process of concern is the potential under-response of the original two-element film dosimeter in plutonium facilities. It appears that the Hanford dosimetry staff was well aware of this issue. An 80-keV X-ray calibration was used at least as early as 1946 (HEW 1946). Later, the penetrating dose was calculated as the sum of 20% of the OW response plus the 1-mm silver response (Fix, Wilson, and Baumgartner 1997b). Hanford and IARC studies of the two-element dosimeter have shown an over-response of the actual $H_p(10)$ dose by a factor of about 2 to photons greater than 100 keV. A favorable to claimant approach is proposed to ignore this over-response because of the complexity of workplace photon energies and exposure geometries that tend to result in an under-estimate of the $H_p(10)$ dose. Minimal effect is expected from higher energy beta radiation contribution to the Hanford dosimeter penetrating dose response. The respective Hanford film dosimeters have filtration of approximately 1,000 mg/cm^2 (nearly equivalent to 1-cm depth in tissue) for those regions of the dosimeter used to measure the whole-body dose [26].

Table 6-10. Hanford workplace photon dosimeter $H_p(10)$ performance [27].

Parameter	Description	Bias[a]	Workplace response
Exposure geometry	Hanford dosimeter system calibrated using AP laboratory irradiations. Workplace exposure geometries are highly variable.	**>100 keV**: Two–element film Dosimeter, ~ +200% Others, ±25% **<100 keV:** Likely too low.	Potential bias in recorded dose is variable since it is expected that most workers change position in the radiation field. It is expected that the highest doses are associated with AP geometry where the work is being performed close to the radiation source. Effect is highly dependent on radiation energy.
Energy response	Response of dosimeter compared to tissue.	Response for all dosimeters ±25% with the exception for the two-element dosimeter that is too high around 100keV and too low around 17 keV.	Stated Hanford practice to include 1/5 of the shallow dose based on a 16-keV calibration to the deep dose for Hanford plutonium facilities workers could resolve this source of potential under-response.
Mixed fields	Dosimeters respond to beta and photon radiation.	Reasonable estimate of $H_p(10)$ dose is expected.	Filtration of about 1,000 mg/cm^2 over film dosimeter component used to calculate deep dose minimizes dosimeter response to beta radiation.
Missed dose	Doses less than MDL recorded as zero dose.	Recorded dose of record likely **too low.**	Hanford recorded doses <MDL for all years. The issue is significant, primarily in earlier years with frequent dosimeter exchange and film dosimeters with higher MDLs.
Environmental effects	Workplace heat, humidity, etc., fades dosimeter signal.	Recorded dose of record likely **too low.**	Hanford prepared calibration and personnel film at the same time, and irradiated calibration dosimeters for use in processing which would tend to maximize time for fading for calibration dosimeters but these dosimeters were not subject to the workplace environment.

a. Bias represented as percent or as the recorded dose compared to $H_p(10)$ based on judgment from laboratory and field measurements.

Wilson et al. (1990) identified bias factors for the respective Hanford facilities using each of the Hanford dosimetry systems. They defined the bias factor to be a ratio of the $H_p(10)$ dose to the recorded dose. These factors are presented in Table 6-11.

Fix, Gilbert, and Baumgartner (1994) conducted an evaluation of the historical Hanford dosimeter performance for photon energies >100 keV, which is generally applicable to all Hanford workplaces with the exception of plutonium facilities. The approach used in this report can be considered an elaboration of the approach used to quantify the bias and uncertainty in estimated doses for personnel exposed to radiation as a result of atmospheric testing of nuclear weapons between 1945 and 1962 (NRC 1989). The approach was developed by the National Research Council (NRC) Committee on Film Badge Dosimetry in Atmospheric Tests. It involved quantifying both bias and uncertainty from four sources and then combining them to obtain an overall assessment using methods used in the evaluation of bias and uncertainty for persons exposed to radiation from an atmospheric nuclear detonation (NRC 1989). In this approach, uncertainty is evaluated from laboratory uncertainty (i.e., calibration, processing), radiological uncertainty (i.e., spectrum, wearing, and backscatter), environmental uncertainty (i.e., consequences of light, moisture, and high temperatures), and uncertainty resulting from converting recorded measurements of exposure to estimates of deep dose.

Table 6-11. Uncertainty in beta/photon $H_p(10)$ in Hanford facilities (Wilson et al. 1990).

Facility type	Beta/photon field description	Dosimeter type	Bias factor range[a] Min.	Bias factor range[a] Max.	Comments
Fuel fabrication	Uranium beta and gamma radiation	Two-element film	0.5	1.6	Recorded whole body dose approximates $H_p(10)$ response results noted in this TBD.
		Multiple-element film	0.7	1.3	
		TLD	0.8	1.2	
Reactor	High energy beta and photon radiation.	Two-element film	0.5	1.7	Recorded whole body dose approximates $H_p(10)$ response results noted in this TBD since predominant photon energy >100 keV.
		Multiple-element film	0.7	1.4	
		TLD	0.8	1.2	
Fuel reprocessing	Generally mixed beta and photon radiation	Two-element film	0.5	1.6	Recorded whole body dose approximates $H_p(10)$ response results noted in this TBD since predominant photon energy >100 keV.
		Multiple-element film	0.7	1.3	
		TLD	0.7	1.3	
Plutonium finishing	Predominant photon energy <100 keV.	Two-element film	(b)	(b)	Significant uncertainty is associated with dose estimates in low-energy photon fields with the two-element dosimeter.
		Multiple-element film	1.0	2.0	
		TLD	0.6	1.4	
Waste and laboratory	Generally mixed beta and photon radiation	Two-element film	0.5	1.6	Recorded whole body dose closely approximates $H_p(10)$ response results noted in this TBD since predominant photon energy >100 keV.
		Multiple-element film	0.7	1.3	
		TLD	0.8	1.2	

a. Bias factor defined as ratio of $H_p(10)$ to recorded whole body photon dose.
b. No estimate provided by the authors.

The assessment at Hanford was based on the assumption that uncertainties from individual sources followed independent lognormal distributions. For each uncertainty source, a factor is assigned reflecting bias (B) and a 95% uncertainty factor (K); the uncertainty factor was determined so that the interval obtained by dividing and multiplying by this factor would include 95% of all observations. Assessment of these factors was based on careful evaluation of the available evidence, but because evidence was not adequate for rigorous statistical treatment of most uncertainties, subjective judgments were also required. Once the individual sources were evaluated, an overall bias factor was obtained by multiplication and an overall uncertainty factor obtained through lognormal propagation of errors. The results of this analysis for Hanford workers (for facilities other than plutonium facilities) are presented in Table 6-12.

Essentially all Hanford radiological work areas involved beta/photon radiation covering a wide range of energies characteristic of the radionuclides being handled in the respective facilities and processes. Radiation beta/photon fields characteristic of Hanford facilities can be generally classified according to the IREP code input, radiation types, and energy ranges based on Hanford field measurements, the types of radionuclides and processes in the respective Hanford facilities. This is presented in Table 6-13 [28].

6.4.5.4 Hanford Neutron Dosimeter Response Testing

The HMPD was implemented on January 1, 1972. Hanford dosimetrists had conducted detailed field measurements in the early 1970s to base the calibration of the TLD on the neutron energy spectra in the work environment. Studies reported by Nichols et al. (1972) involved the simultaneous placement

Table 6-12. Overall bias and uncertainty due to variation and uncertainties regarding energy levels and geometry in recorded dose as an estimate of deep dose. Fix, Gilbert, and Baumgartner (1994)

Hanford dosimetry system	Bias magnitude and range		Uncertainty factors	
	Overall bias[a]	Range in bias[b]	Systematic[c]	Random[d]
Two-element film (1944-56)	1.27	1.13–1.60	1.2	1.8
Multielement film (1957-71)	1.02	0.86–1.12	1.1	1.4
Multielement thermoluminescent (1972-83)	1.12	1.04–1.16	1.05	1.2
Multielement thermoluminescent (1984-93)	1.01	0.95–1.05	1.05	1.2
Commercial TLD[e] (1995-2003)	1.00	0.95-1.05	1.05	1.2

a. Based on the distribution of energy levels and geometry judged most likely. Divide recorded dose by the table's bias value to calculate deep dose. Note that this use of bias factor does not apply to plutonium facilities.
b. Range of overall bias factors based on alternative distributions of energy levels and geometry.
c. Systematic uncertainty resulting from lack of knowledge regarding actual distributions of energy levels and geometry.
d. Random uncertainty resulting from variation among workers in energy levels and geometry..
e. Performance equal to or better than previous Hanford dosimeters.

Table 6-13. Selection of beta and photon radiation energies and percentages for Hanford facilities.

Process/ buildings	Description	Operations		Radiation type	Energy selection, keV	%
		Begin	End			
Fuel fabrication	Produced reactor fuel and target assemblies from uranium.			Beta Photon	>15 30–250	100 100
	313, 306, 333	1945	1972			
Reactors	**During Operation:** Highly dispersed fields of higher-energy photon radiation fields from fission process, activation and fission product nuclides. Potentially narrow beams of higher energy neutron radiation from test ports, etc., into reactor core. Potential for significant airborne nuclides and there may be significant higher-energy beta radiation.			Beta photon	>15 30–250 >250	100 25 75
	Not in Operation: Highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides. No significant neutron radiation. There may be significant higher energy beta radiation during maintenance work resulting from fission products.					
	B-Reactor	9/26/44	1946			
		1948	2/12/68			
	D-Reactor	12/17/44	6/26/67			
	F-Reactor	2/23//45	6/25/65			
	H-Reactor	10/29/49	4/21/65			
	DR-Reactor	10/50	12/31/64			
	C-Reactor	11/18/52	4/25/69			
	KW-Reactor	12/54	2/1/70			
	KE-Reactor	2/55	1/28/71			
	N-Reactor	12/63	1/6/87			
	FFTF	2/9/80	12/93			
Processing plants	**Radiochemical Operations:** Highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides dominant to most exposure profiles. Potential for higher energy beta radiation during sampling and maintenance work from fission products.			Beta photon	>15 30–250 >250	100 25 75
	T Plant	12/26/44	3/56			
	B Plant	4/13/45	1956			
	S Plant (Redox)	1/51	12/67			
	C Plant	7/52	7/67			
	A Plant (Purex)	1/56	6/72			
		1983	1988			
	U Plant	3/52	1/58			
	UO_3 Plant	56				
Plutonium production	**Plutonium Component Production**: Plutonium is machined into weapon components using glove-box assembly process with predominant close anterior exposure to workers. Radiation characteristics in this area involve significant lower energy photons and neutron radiation.			Photon	<30 30–250	25 75

Process/ buildings	Description	Operations Begin	Operations End	Radiation type	Energy selection, keV	%
	Plutonium Storage: Radiation characteristics in this area generally involve dispersed lower energy neutron radiation and scattered photons, including 60-keV Am-241 gamma ray.					
	231-Z	1/16/45				
	Plutonium Finishing Plant (234-5Z)	1949	1980			
Calibrations	Hanford site calibration of instruments and dosimeters			Beta photon	>15 30–250 >250	100 25 75
	3745-A, 318	1945				
Waste handling	Radiation characteristics highly dependent on source of waste, but typically fission product nuclides (Sr/Y-90, Cs-137) are dominant.			Beta photon	>15 30–250 >250	100 50 50
	200 East and West	1953				

Hanford documentation (Roberson, Cummings, and Fix 1985; Roberson and Cummings 1986; Rathbun 1989).

of NTA dosimeters and TLDs on 2-gallon polyethylene jugs filled with water and placed at selected workplace locations. A tissue equivalent proportional counter (TEPC) was used to measure the dose from fast neutrons. Data from Nichols et al. (1972), which are summarized in Table 6-14, indicate wide variability between the results for the different measurement techniques. However, the data illustrate the general under-response of the NTA film dosimeter results compared with the TEPC and TLD results [29].

Table 6-14. Parallel workplace measured NTA and HMPD neutron dose. Nichols et al (1972)

	Fast neutron dose, millirem			
Location	**Snoopy**	**TEPC**	**NTA**	**TLD**
105-KE				
X-1	60	270	0	530
Top #23	1,400	1,700	470	4,100
Mon	0	0	0	60
Front face	50	900	0	250
308 Bldg.				
Rm 208	2,000	2,700	270	3,700
Corr #7	4,200	14,100	1,270	11,100
Vent rm	30	30	0	0
Rm C	700	730	70	870
234-5Z Bldg.				
17 DC	340	NM	0	100
HC-11	280	NM	0	180
9B top stairs	410	NM	100	440
9B under stairs	280	NM	60	450
Rm 221	410	790	170	460
Rm 192	510	620	950	490
Rm 192-C	150	230	310	240
Rm 193	380	500	770	600
2731-Z	200	NM	60	50

NM = not measured

A second type of workplace measurement reported by Nichols et al. (1972) involved personnel wearing TLDs and film dosimeters simultaneously. Figure 6-7 shows the comparison of the fast neutron dose component from both dosimeter types. It is apparent in this figure that there is a significant lower neutron dose for the NTA dosimeter compared to the TLD neutron doses for TLD neutron doses greater than about 50 mrem [30].

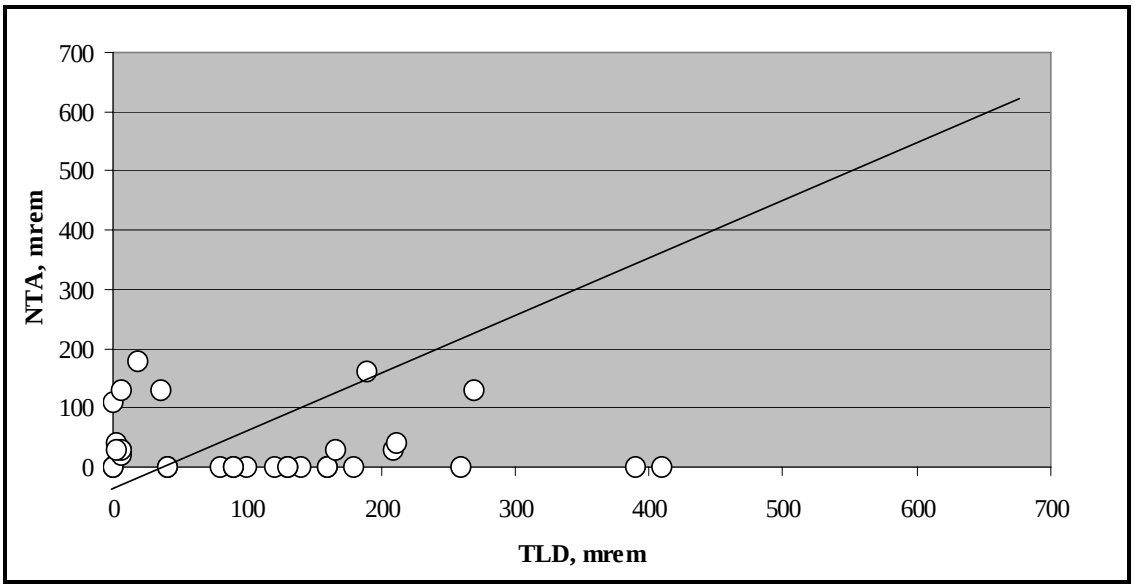

Figure 6-7. Comparison of Hanford PFP workplace NTA and HMPD neutron dose (Nichols et al. 1972).

Figure 6-8 shows the ratio of collective Hanford neutron dose to plutonium production. A slight increase in recorded neutron dose occurs in 1950 with the implementation of the NTA dosimeter. An increase occurs in the early 1960s, which conforms to the peak plutonium production years at Hanford. The significant peak in recorded neutron dose in 1972 is attributable to the large increase in recorded neutron dose with the HMPD. The HMPD responds to the thermal and intermediate neutron spectra that are not detected by the NTA film dosimeter [31].

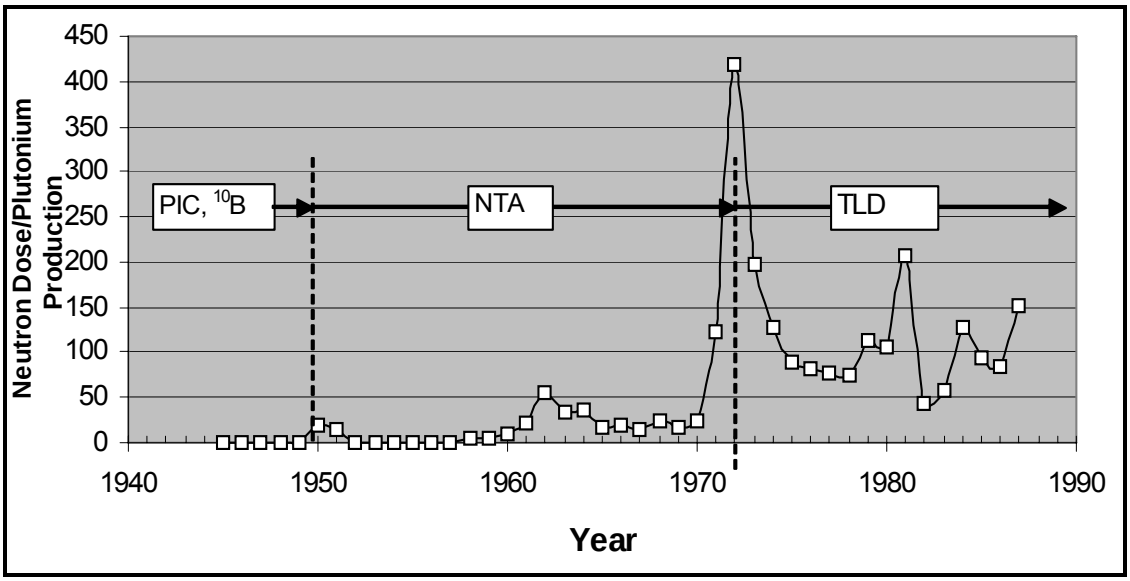

Figure 6-8. Ratio of annual Hanford collective neutron dose to plutonium production [32].

The AEC held a series of Personnel Neutron Dosimetry Workshops to address problems experienced by its sites concerning accurate measurement of neutron dose. The first workshop was held September 23–24, 1969 (Vallario, Hankins, and Unruh 1969), with the stated concern: "for intermediate energy (i.e., >0.4 ev to <700 keV) ... neutron sources, NTA personnel neutron

dosimeters cannot be effectively used. This leaves a gap in the personnel dosimetry program which at many installations may be quite serious." The workshops were generally limited to representatives from sites with active personnel neutron dosimetry programs and continued for a number of years. The 11th Workshop was held in 1991 (Rabovsky, Jones, and Pettengill 1991). The significance of the underestimated neutron dose became evident with studies being conducted to implement TLDs.

Following implementation of the HMPD on January 1, 1972, AEC headquarters staff conducted a detailed review of recorded neutron dose for Hanford personnel using a committee of technical experts from Hanford, SRS, and other AEC facilities (Biles 1972). Central to this investigation was the selection of 18 long-term Hanford workers for detailed evaluation. Fix, Wilson, and Baumgartner (1997b) analyzed this information using dosimetry data recorded through 1995. Table 6-15 lists three distinct periods of dose recording from 1950 through 1995 corresponding to the Hanford two-element, multielement, and thermoluminescent dosimeters.

Table 6-15. Recording periods for selected Hanford plutonium workers (Fix, Wilson, and Baumgartner 1997b).

Period	Description
1950–56	Involved use of original Hanford two-element dosimeter for nonpenetrating (shallow) and penetrating (deep) dose components and NTA film for neutron radiation.
1957–71	Involved use of Hanford multielement film dosimeter for nonpenetrating, X-ray, and penetrating dose components, and NTA film for neutron radiation.
1972–95	Involved use of Hanford TLD for beta, photon, and neutron dose components.

The 18 workers had the Hanford PFP as their primary work area at least during the 1970s. It is interesting to examine trends in this data. For example, Table 6-16 shows the ratios of recorded shallow to deep doses and recorded neutron to deep doses. The comparatively high shallow to deep ratio during the 1950-1956 period is likely to result from the significant over-response of this dosimeter to the low-energy photons prevalent in the PFP (Wilson et al. 1990). The data show increasing levels of recorded neutron dose, relative to the deep dose, for each succeeding dosimeter design.

Table 6-16. Ratio of recorded Hanford dose components (Fix, Wilson, and Baumgartner 1997b).

Recording period	Ratio (range)	
	Shallow/deep	Neutron/deep
1950–56	1.6 (1.1–3.7)	0.003 (0–0.06)
1957–71	1.2 (1.1–1.7)	0.4 (0.1–0.7)
1972–95	1.3 (1.1–1.5)	0.6 (0.1–1.6)

Moreover, it is possible to observe changes in relative dose components during (1) the 1957 period when the multielement film dosimeter was introduced along with the PuF_4 neutron source calibration that provided a calibration spectrum similar to the Hanford plutonium workplace, and (2) during the 1972 period when the HMPD was introduced. Nine of the 18 workers examined by Fix, Wilson, and Baumgartner (1997b) had dose histories that extended from 1950 or earlier through 1980 or later.

6.4.5.5 Hanford Workplace Neutron Dosimeter Response

Work areas at Hanford where there is a potential for neutron exposure include [33]:

- 100 Area
  105-B, 105-C, 105-D, 105-DR, 105-F, 105-H, 105-KE, 105-KW, 105-N reactors

- 200 Area
  221-U facility cinder block building attachment (known as 271-U)
  224-T facility to concentrate plutonium solutions and store sources
  231-Z plutonium isolation facility
  232-Z incinerator and leach facility
  234-5Z primary plutonium handling facility
  236-Z Recuplex/Plutonium Reclamation Facility
  242-Z americium recovery facility
  2736-Z plutonium vaults

- 300 Area
  308 Plutonium Fuels Pilot Plant (PFPP)
  309 Plutonium Recycle Test Reactor (PRTR)
  318 Radiological Calibrations Facility
  324 Chemical and Materials Engineering Laboratory
  3745A Calibrations Laboratory
  3745B Accelerator Facility

- 400 Area
  Fast Flux Test Facility (FFTF)

The circumstances of neutron exposure at these facilities are different and can be divided according to the facility of worker primary employment based on the method of primary neutron radiation generation. At the 200 and 300 Area plutonium facilities, neutron radiation is generated from plutonium either by spontaneous fission or, importantly, by alpha particle interaction with light elements such as oxygen, fluorine, and beryllium. These interactions are commonly referred to as alpha-n reactions. At the Hanford 100 and 400 Area nuclear reactor facilities, neutrons are generated by fission of uranium and plutonium in the reactor core. These two methods of neutron generation comprise the majority of the neutron exposure to workers at the Hanford site. As such, this TBD subdivides neutron exposure of workers according to these two general areas: 1) plutonium facilities and 2) reactor facilities. Neutron exposure at the 300 area laboratory facilities (e.g., 324) generally involved experiments related primarily to nuclear fuel development. This potential source of neutron radiation exposure of workers should be evaluated according to the two methods of neutron exposure (i.e., reactor or plutonium) that most closely fits the exposure pattern. There is little potential for significant unrecorded neutron dose in the 300 Area radiological calibration (318, 3745B) and accelerator (3745A) facilities because these are the facilities used to develop, test, and calibrate Hanford dosimetry and instrumentation systems [34].

Neutron spectra (Fix et al. 1981, 1982; Roberson, Cummings, and Fix 1985; Brackenbush, Baumgartner, and Fix 1991; Endres et al. 1996) and dose (Fix et al. 1981, 1982; Roberson, Cummings, and Fix 1985; Brackenbush, Baumgartner, and Fix 1991; Endres et al. 1996; Scherpelz, Fix, and Rathbone 2000) measurements have been performed at selected Hanford plutonium facilities on many occasions beginning in the 1970s with the availability of modern instrumentation. These measurements used several methods at different times to measure neutron dose, including TEPCs, which are considered to provide an accurate measurement of neutron dose (Brackenbush et al. 1991, Scherpelz et al. 2000), as well as portable neutron survey instruments (i.e., Snoopy, HMPDs, commercial TLDs, and TEDs). Energy spectrum measurements used multisphere (Bonner) sphere spectrometers, which are the primary system used, as well as ^{3}He spectrometers, and NE-213 liquid scintillation spectrometers. Table 6-17 summarizes Hanford reports that include measured neutron spectra.

Table 6-17. Hanford workplace neutron spectra measurements.[a]

Facility	Description	Measurements[a,b]	Reference
308 Bldg.	Fuel storage pit area	MS, TEPC, Rascal, HMPD	Fix et al. 1981
	Plutonium storage vault	MS, TEPC, Rascal	
	Fuel pin storage box area	MS, TEPC, Rascal	
	Bare fuel assembly	MS, TEPC, Rascal, HMPD	
234-5Z	Glovebox H-9A	MS, TEPC, Snoopy, HMPD	
	Glovebox HC-9B	MS, TEPC, Snoopy, HMPD	
2736-Z	Six locations in bldg.	MS, TEPC, Snoopy, HMPD	
324 Bldg	Pu storage vault	MS, ^{3}He, TEPC, HMPD	Fix et al. 1982
FFTF	Operating deck	MS, ^{3}He, TEPC, HMPD, Snoopy	
234-5Z	Hood HA-23 Area		
2736-Z	Storage vault, Room 1	MS, TEPC, HMPD	Roberson, Cummings and Fix 1985
	Storage vault, Room 4		
236-ZZ	Gloveboxes 5-6		
234-5Z	Process line C, Room B		
234-5Z	Pu metal, PuF_4 and PuO_2 with selected thicknesses of acrylic shielding	MS, TEPC, HMPD	Brackenbush et al. 1991
234-5Z	Frontside–storeroom	MS, TEPC, TLD, TED	Endres et al. 1996
	Frontside–near shops		
	Backside–glovebox		
	Backside–glovebox		
	Pu metal, PuF_4 and PuO_2 with selected thicknesses of acrylic shielding		

a. Only measurements that included neutron spectra are listed.
b. MS = multi-sphere, TEPC = Tissue Equivalent Proportional Counter.

100 and 400 Area Reactor Facilities

There is a potential for workers to be exposed to neutron radiation in the Hanford reactors. These facilities generally have extensive shielding to reduce worker neutron and photon radiation exposure in most work areas. Neutron radiation is significant only while a reactor is in operation and only in areas of a reactor that are typically closed to general worker access. Neutron exposure of workers is accompanied by photon radiation that is readily measured with Hanford portable instruments, pocket ionization chambers, personnel film dosimeters, and later thermoluminescent dosimeters. In general, there is relatively little information concerning measured Hanford worker neutron dose using the NTA dosimeter in the single-pass production reactor facilities (B, C, D, DR, F, H, KE, KW) although there are substantial laboratory studies (Wilson et al. 1990). Operations of these reactors terminated prior to the Hanford-wide implementation of the HMPD in 1972.

Worker exposure to neutron (and photon) radiation beams associated with instrument and test penetrations into the reactor core with the Hanford single-pass reactors that began operation in 1945 did occur. A report by Wilson (1956) summarizes the potential for significant neutron and photon dose rates for these beams and the concern for significant neutron dose to the eyes of workers conducting instrument measurements of the reactor core. In 1960, Peterson and Smalley (1960) evaluated the neutron dose rates on the face of the B reactor at Hanford. The purpose of this evaluation was to develop a shielding method to reduce the neutron dose rate resulting from leakage through empty fuel tubes. As part of this analysis, they reported existing neutron and photon dose rates for the various Hanford reactors and the estimated dose rates after adding external shielding. This information is summarized in Table 6-18.

As shown in Table 6-18, the neutron-to-photon dose ratios for reactor areas reported by Peterson and Smalley are considerably higher than the average neutron-to-photon dose estimates of approximately

Table 6-18. Estimated neutron and photon dose rates (mrem/hr) for Hanford reactor front face (Peterson and Smalley 1960).

Reactor	Prior to 1961			After adding external shielding			Ratio reduction factor
	Neutron	Photon	Ratio	Neutron	Photon	Ratio	
B	25	25	1.00	2	20	0.10	10.0
C	30	25	1.20	2	20	0.10	12.0
D	5	25	0.20	1	20	0.05	4.0
DR	10	20	0.50	1	16	0.06	8.3
F	15	25	0.60	2	20	0.10	6.0
H	5	25	0.20	1	20	0.05	4.0
KE	3	7	0.43	-	-	-	
KW	3	3	1.00	-	-	-	

5% reported in Wilson et al. (1990). This is likely the result of two competing factors. The first is that workers are typically only exposed to neutrons while working near the reactor core while the reactor is operating as in this example where measurements were made on the "front" face of the reactor and represent the maximum dose rate for "air" channels with minimal neutron shielding. The photon exposure occurs in multiple other locations and significantly during reactor maintenance when the reactor is shutdown and there is no neutron radiation. As a result, a reduced neutron-to-photon ratio is expected for workers in normal work activities compared to these measurements at the reactor front face only. The second factor is that the NTA film had an energy threshold of about 800 keV, whereas the measurements by Peterson and Smalley used the double moderator neutron dosimeter that has a BF3 detector. Fix, Wilson and Baumgartner (1997b) described this Hanford instrument and others as well as a study by Unruh in 1962 in which a comparison of NTA film with BF3 measurements on the B reactor face was conducted. The NTA film under-responded to the neutron field indicating considerable neutron exposure below the 800 keV. The range of the under-response was between 10% to 100%. Nichols (1972) reported a comparison of NTA and TEPC (and HMPD) measurements at the KE reactor (Table 6-14) and found that the NTA under-responded substantially.

Neutron Energy Spectra. No neutron spectra measurements for workplaces in Hanford single-pass reactors that operated from 1945 (100 B) through 1971 (100 KE) have been located. The measurements needed are during reactor operation. Field testing of HMPD and NTA film by Nichols et al. (1972) did include the 105-KE reactor. These results are shown in Table 6-14. Positive neutron dose was measured with the TLD and TEPC that was generally not recorded by the NTA film. Neutron spectrum measurements were made in the early 1980s at two locations at the FFTF in the 400 Area (Fix et al. 1982) as shown in Figure 6-9.

The data in Figure 6-9 may not be indicative of routine operations. At that time, a stainless-steel research thimble in one of the bundle tubes allowed neutrons to stream from the core to the head compartment. The neutron spectrum was highly scattered, resulting in significantly lower neutron energies. Highly scattered neutron fields are likely characteristic of Hanford single-pass reactor workplace fields and this resulted in the relatively low NTA measurements. The HMPD used in these measurements showed an over-response of about a factor of 6 compared to the multisphere measurements because of the highly degraded neutron spectrum. Although indirectly applicable, measurements of neutron spectra and dose, and personnel dosimeter performance in US nuclear power reactors reported by Endres et al. (1981) concluded that NTA emulsions are not sensitive to the leakage spectra that may be present in commercial power reactor plants.

200 and 300 Area Plutonium Facilities

Plutonium production at Hanford began January 16, 1945 (Freer and Conway 1997) in what is often called Z-Plant or the PFP 231-Z Plutonium Isolation Facility located in the Hanford 200 Area. At that

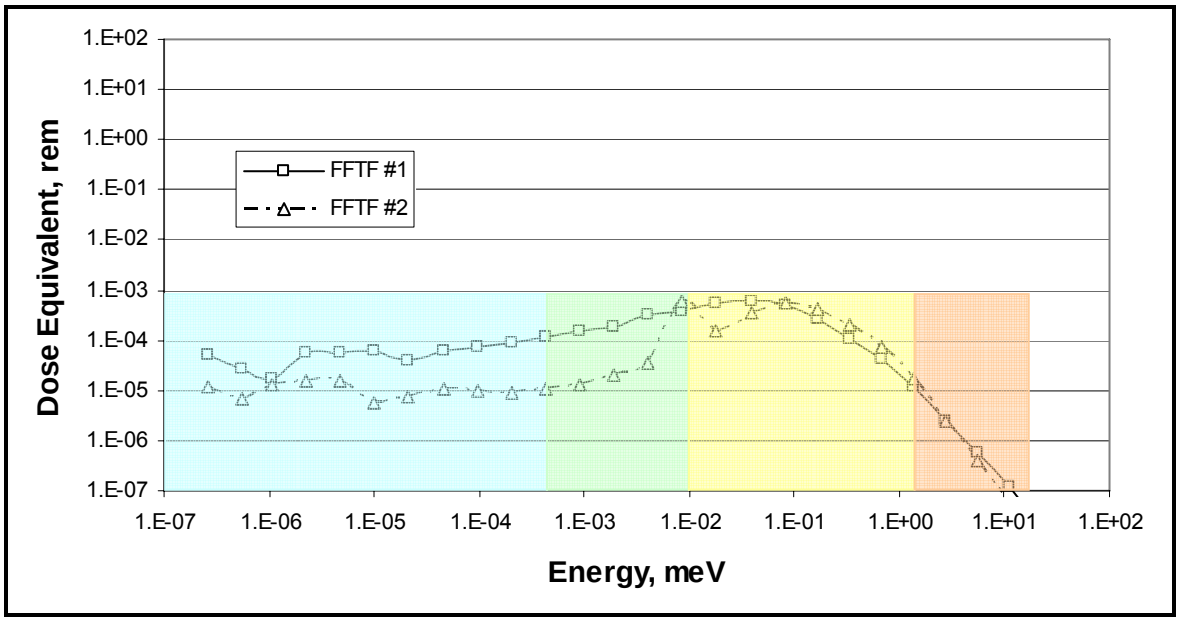

Figure 6-9. Neutron spectra for Hanford 400 Area FFTF (Fix et al 1982).

time, Hanford-produced plutonium nitrate was shipped to the Los Alamos National Laboratory for use in producing nuclear weapons. On July 5, 1949, the PFP 234-5Z facility provided the capability for Hanford to convert plutonium nitrate to metallic plutonium. The initial 234-5Z plutonium finishing equipment was termed the "Rubber Glove" line because it depended on personnel working with a series of 28 stainless-steel gloveboxes, 55 meters long, to move the plutonium mixtures manually through the finishing process (Fix, Wilson, and Baumgartner 1997b).

On March 18, 1952, a Remote Mechanical A (RMA) Line began operation. The RMA Line performed all the process steps in Pu metal production and fabrication except Task 1 (feed make-up and purification), which continued in the 231-Z facility. The RMA Line was in six rooms at 234-5Z. In mid-1957, the RMA Line was modified for a continuous calcination and hydrofluorination process that essentially handled the Task 1 activities previously done at 231Z (i.e., all processing tasks). Many projects were undertaken at PFP 234-5Z from 1957 to 1961 to accommodate the significant increase in throughput. The most significant of these were the construction of the remotely operated series of glove boxes (RMC) Button Line and the RMC Fabrication Line. Both of these began operation in the mid-1960s. The RMC Line (button and fabrication components) consisted of a completely self-contained, remotely operated series of glove boxes similar to the RMA Line areas (Fix, Wilson, and Baumgartner 1997b).

Neutron dose is associated with the overall Hanford plutonium production process in which plutonium from the respective processing facilities was brought into PFP as a liquid nitrate solution. At the PFP, plutonium was precipitated as an oxalate, converted to a fluoride, and reacted at high temperature with metallic calcium, forming the metal (Ballinger and Hall 1991). Neutron radiation was particularly enhanced during the fluorination step in the process because of plutonium fluoride (PuF_4) alpha neutron (α,n) reactions. The Hanford 200 Area plutonium facility is still in operation serving the primary purpose of maintaining and storing plutonium [35].

Research and development work with nuclear fuel has been done in the Hanford 300 Area particularly at the 308 bldg. PFPP, 309 bldg. PRTR, and in the 324 bldg. chemical and materials engineering hot cell laboratories. Pilot work was done in the 300 Area facilities in preparation for the 400 Area FFTF construction and operation [36].

Neutron Energy Spectra. PuF_4 is the most significant source, historically, of neutron exposure to workers in the Hanford 200 Area plutonium facilities. Figure 6-10 shows measurements by Brackenbush, Baumgartner, and Fix (1991) of a PuF_4 source with no shielding, 2.54 cm of acrylic plastic, and 5.08 cm of acrylic plastic shielding between the source and the detector system to illustrate the effect on the plutonium spectrum of increasing thicknesses of the acrylic in the glovebox sides. A PuF_4 source was used to calibrate Hanford personnel dosimeters beginning in 1958 (Fix, Wilson, and Baumgartner 1997b). This figure shows that, although different neutron spectra were measured, similarities were observed in the general shape of the degraded PuF_4 spectrum. The energy of the dose equivalent peak is centered at approximately 1 MeV. Similar plutonium source and acrylic shielding measurements were reported in Endres et al. (1996) in association with field evaluations of the Harshaw commercial TLD and TED system implemented on January 1, 1995. The results of these measurements led to the eventual elimination of the TED component in routine personnel monitoring because the TED substantially underestimated the neutron dose. This occurred because the TED did not respond to the substantial lower energy neutron spectrum from stored plutonium in the current Hanford PFP operation. There are many similarities between NTA film and TED characteristics, including physical size, direct neutron responding device, angular response, and a lower energy neutron response threshold. The TED has a significantly better energy threshold of about 100 keV compared to the NTA film threshold of about 700 keV, but showed unacceptable capabilities to measure neutron dose.

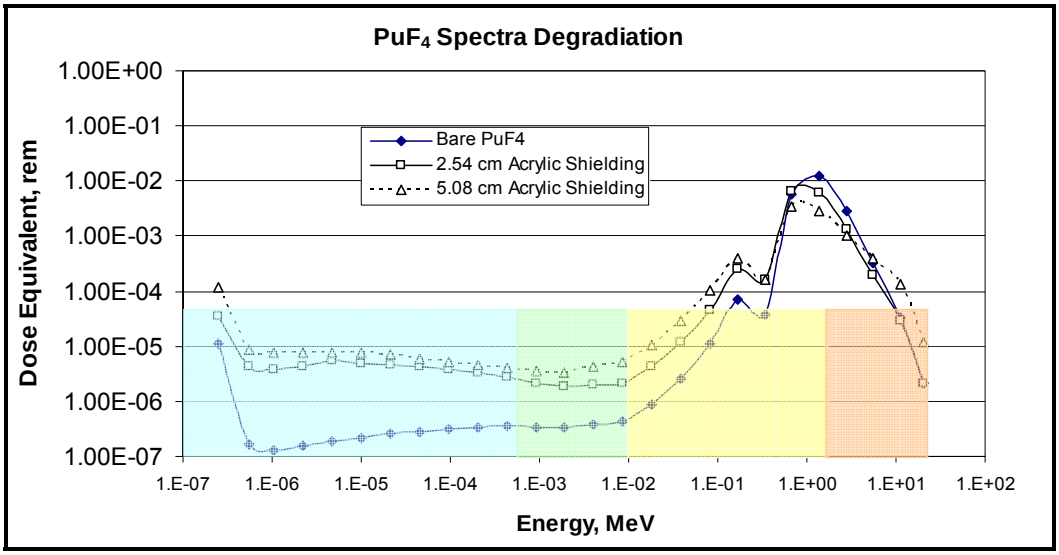

Figure 6-10. Degradation in neutron energy spectra for bare, 2.54 cm and 5.08 cm of acrylic plastic shielding with neutron energy groups overlay (Brackenbush, Baumgartner, and Fix 1991).

Neutron radiation spectra measurements in Figure 6-11 are documented in Fix et al. (1981, Study 4) and in Roberson, Cummings, and Fix (1985) at the PFP 234-5Z Building "C" Line, Room B, selected gloveboxes, and the 2736-Z plutonium vault. The 234-5Z locations are where plutonium nitrate was converted to plutonium fluoride with the associated high neutron flux rates. This location provided the highest neutron flux rates at Hanford. The original data were depicted as dose equivalent rates; however, for simplicity of calculation, a 1-hour exposure was assumed to use dose equivalent.

As noted in Roberson, Cummings, and Fix (1985), the HMPD was originally calibrated in neutron fields encountered in 234-5Z, and this calibration has been maintained over the years. As such, the estimate of personnel neutron dose equivalent has remained tied to the original measurements regardless of the neutron source used to calibrate the dosimeter. Table 6-19 lists the ratio between

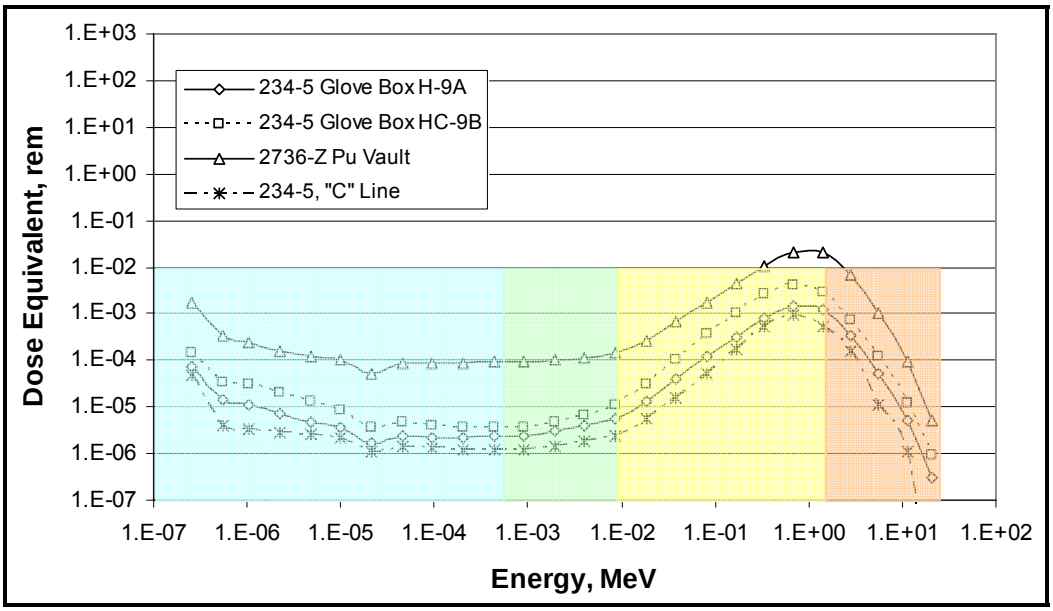

Figure 6-11. Neutron energy spectra recorded at Hanford PFP 234-5Z "C" line, glovebox, and plutonium storage vault (Fix et al. 1981, Study 4; Roberson, Cummings, and Fix 1985).

the HMPD measured dose and those measured with a Snoopy, TEPC, multisphere, and PNR-4 (i.e., common portable neutron instruments used to measure neutron dose based on 9-inch to 3-inch sphere ratio) as reported in Roberson, Cummings, and Fix (1985). In these measurements, the most significant observation is the generally close agreement in estimated dose between the HMPD and the respective instruments. In all of these measurements, the similarity in energy spectra with PuF_4 in Figure 6-10 is evident.

Table 6-19. 200 Area workplace measurement comparisons with HMPD (Roberson, Cummings and Fix 1985).

Location	Ratio of HMPD dose to instrument dose[a]			
	Snoopy	PNR-4[b]	TEPC	Multi-sphere
2736-Z, storage vault, Room 4	0.98 (0.37)	0.84 (0.18)	1.02 (0.18)	1.28 (0.24)
2736-Z, storage vault, Room 1	0.92 (0.14)	0.87 (0.56)	0.84 (0.10)	0.95 (0.13)
236-Z,gloveboxes 5-6	0.85 (0.18)	0.95 (0.43)	1.03 (0.41)	1.13 (0.41)
234-5Z, process line C, Room B	0.88 (0.28)	0.88 (0.21)	1.17 (0.26)	1.17 (0.25)
Average	0.90 (0.10)	0.87 (0.13)	0.92 (0.08)	1.05 (0.10)

a. Numbers in parentheses represent one-standard deviation.
b. Portable neutron REM instrument based on 9" to 3" sphere measurements.

Neutron spectrum measurements were made in the early 1980s at research and development laboratories in the 300 Area (Fix et al. 1982). Figure 6-12 shows measurements at selected locations including plutonium storage vaults in the 308 and 324 Buildings.

6.4.5.6 Neutron-to-Photon Ratio

Considering the uncertainty in the neutron recorded dose at Hanford reactor and plutonium facilities prior to implementation of the HMPD in 1972 and the recommendations of the 1972 AEC review (Biles 1972) of pre-1972 NTA neutron dose results in Hanford plutonium facilities, the recommended method to estimate dose to workers from neutron radiation is using a favorable to claimant neutron-to-photon ratio. The photon dose was reliably measured and essentially all significant Hanford neutron dose

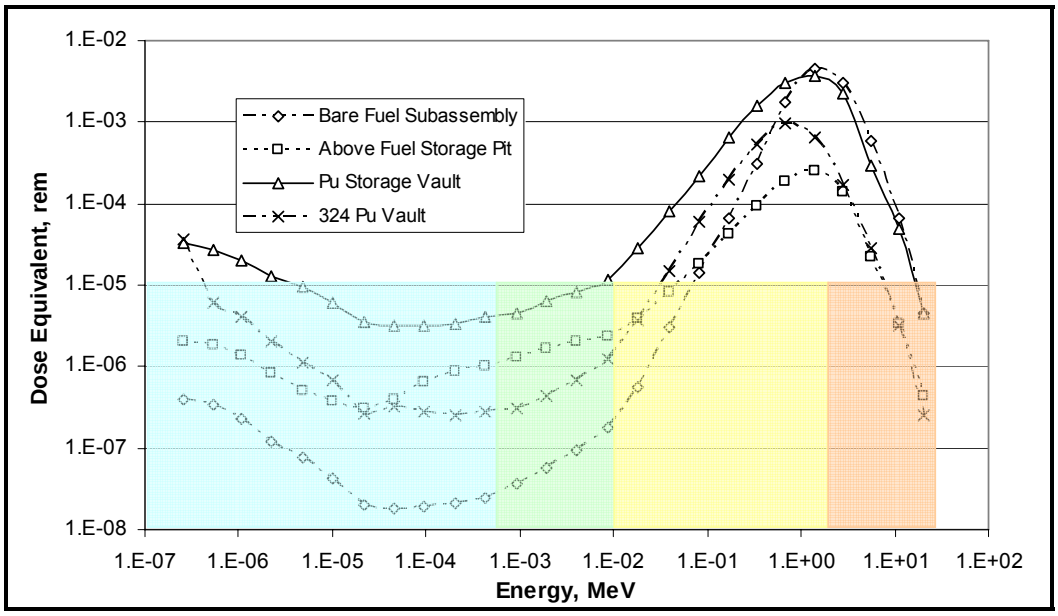

Figure 6-12. Neutron spectra for Hanford 308 and 324 facilities (Fix et al. 1982).

was accompanied by significant photon dose. Issues to be considered to arrive at a favorable to claimant ratio for pre-1972 Hanford facility operations with potential neutron exposure of workers are presented for each of the primary operating areas.

100 Area Reactors. All of the Hanford single pass through reactors were shutdown prior to the implementation of the HMPD in 1972. Neutron film dosimeter results for 14 workers between 1950 and 1961 are included in the retrospective analysis of Hanford personnel neutron dose discussed in Fix, Wilson and Baumgartner (1997b). Of these 14 workers, 7 primarily worked at the Hanford reactors. This analysis reevaluated the neutron dose using five different methods. Method 1 used a gross track count (i.e., no background subtraction) and resulted in the highest neutron doses and correspondingly the highest neutron/photon ratios. Method 5 was believed to be the most technically accurate employing a background subtraction based on the standard deviation of the number of neutron tracks on the blank films. Table 6-20 provides a summary of the seven 100 area reactor facility workers and the associated neutron photon ratios by method. Since it is not known which method is the most accurate, all of the data in Table 6-20 was used in this analysis. The data closely fit a lognormal distribution as shown in Figure 6-13 with a geometric mean of 0.11, a geometric standard deviation of 2.79, and an upper 95th percentile of 0.62.

Table 6-20. Neutron/photon ratios for reactor workers identified in PNNL-11196.

Worker #	Method 1	Method 2	Method 3	Method 4	Method 5
2	0.39	0.14	0.11	0.06	0.06
3	0.14	0.06	0.05	0.03	0.03
6	0.64	0.34	0.31	0.24	0.24
7	0.25	0.10	0.08	0.04	0.04
11	0.13	0.04	0.03	0.01	0.02
12	0.75	0.29	0.21	0.11	0.12
14	0.72	0.26	0.20	0.11	0.12

Neutron spectra measurements of the single pass Hanford reactors during operation have not been located. The under-response of the NTA film due to neutron energy can only be estimated. Nichols

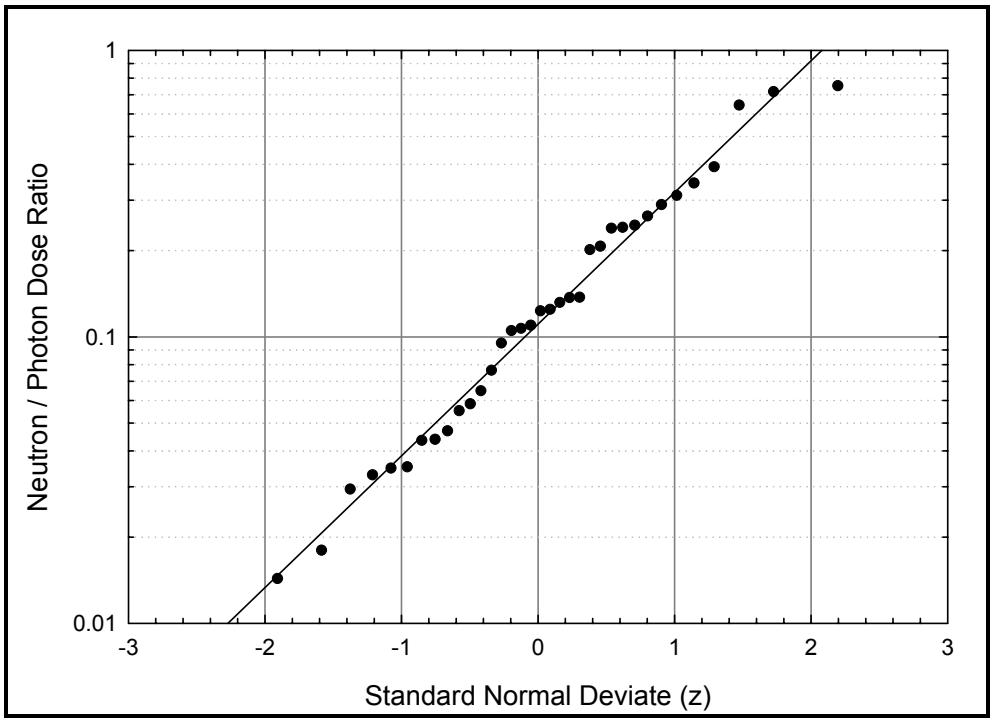

Figure 6-13. Lognormal plot of Table 6-20 data [37].

et al. (1972) showed that for the single 100 KE (Table 6-14) positive measured NTA dose measurement, the NTA film recorded 28% of the true neutron dose as measured by the TEPC. Most of the NTA measurements showed zero neutron dose, including the reactor front face measurement location used in measurements by Peterson and Smalley. To estimate the neutron-to-photon ratio, a factor of 28% was used to adjust the neutron-to-photon ratios from Table 6-20 to account for the unmeasured neutron dose. This resulted in a lognormal distribution as shown in Figure 6-14 with a geometric mean of 0.41, a geometric standard deviation of 2.79, and an upper 95th percentile of 2.22.

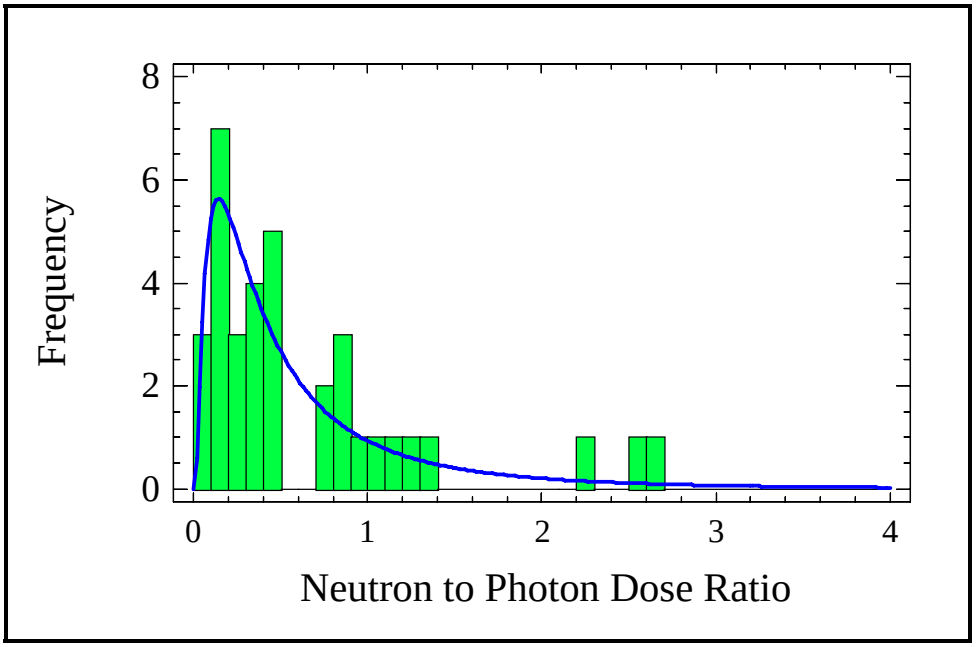

Figure 6-14. Adjusted neutron/photon ratio for Hanford reactors [38].

Worker dose reconstruction research is underway at the Russian Mayak facility that had a similar role in the development of Russian nuclear weapons as Hanford has performed in the US. Five Mayak graphite moderated reactors that first operated in 1948 have a design similar to Hanford's single-pass reactors with the exception that the fuel channels are placed vertically instead of horizontally and notably, fuel recharge is conducted while the reactors are operating. Estimates of the neutron-to-photon dose for these workers have been calculated by Smetanin et al. (2003) using Monte Carlo (i.e., Monte Carlo N-Particle radiation transport code) methods. The results are shown in Table 6-21 for exposure scenarios while the fuel channels were closed and open. Although the reactor design and operating practices were somewhat different, the data in Table 6-21 support the favorable to claimant conclusion of the analysis used to estimate the favorable to claimant neutron-to-photon ratio for Hanford workers. The values reported by Smetanin et al. (2003) are less-than the values reported by Peterson and Smalley in Table 6-18, however, there was substantial variability noted in the neutron dose rate among the respective Hanford reactors.

Table 6-21. Ratio of neutron-to-photon dose for graphite moderated reactor (Smetanin 2003).

Reactor plate	Ratio of neutron-to-photon dose	
	Measured	**Calculated**
Closed fuel channels	0.084	0.08
Open fuel channels	0.35	0.28

The purpose of the Peterson and Smalley report was to evaluate different shielding methods to reduce the neutron exposure on the face of the graphite reactors. It is not clear as to when the additional shielding recommendations identified in this report were implemented. Since the report was issued in July of 1960, and the first of the Hanford reactors were shutdown starting in 1964 with the last single pass reactor being shutdown in 1971, it is possible that the additional shielding was only installed in some reactors (later running reactors) and not installed in others. Until the installation time frame is identified, the favorable to claimant assumption that additional shielding was not installed prior to the reactor being shutdown is made [39].

Since the N-reactor involved a different design (non-single pass reactor) and was not started until December 1963, the neutron exposure problem would likely have been solved prior to startup. Thus, a reduced neutron-to-photon ratio is used for the N-Reactor. This reduction factor is based on the estimated reduction in neutron dose expected following the installation of additional shielding. The expected neutron photon reduction ratios are provided in Table 6-18. Since this resulted in a range of values, each of these factors were applied to the adjusted NTA film measurements and a combined data set was evaluated. Analysis of this combined data set also indicated a lognormal distribution with a geometric mean of 0.06, a geometric standard deviation of 3.00, and an upper 95th percentile of 0.37 [40].

200 and 300 Area Plutonium Facilities. To develop the neutron-to-photon ratio at Hanford's plutonium facilities, detailed dosimetry data between 1972 and 1991 from 15 long term workers was evaluated. This comprised a total of 303 dosimetry results spread over a total of 146 monitoring periods. Only instances where both a positive photon and neutron dose measurements were recorded and equal to or greater than 20 mrem, respectively, were used to develop the neutron-to-photon ratio. This was done to avoid the effects of low-dose variation. A total of 186 dosimeter results were analyzed. The frequency distribution of the neutron-to-photon ratios is provided in Figure 6-15. This analysis indicated a lognormal distribution resulted in the best statistical fit as shown in Figure 6-16. The geometric mean of the distribution is 0.73 and the geometric standard deviation is 2.10. This resulted in an upper 95th percentile of 2.47. There is little potential for significant unrecorded neutron dose in the 300 Area calibration (3745B) and accelerator (3745A) facilities

because these are the facilities used to develop, test, and calibrate Hanford dosimetry and instrumentation systems [41].

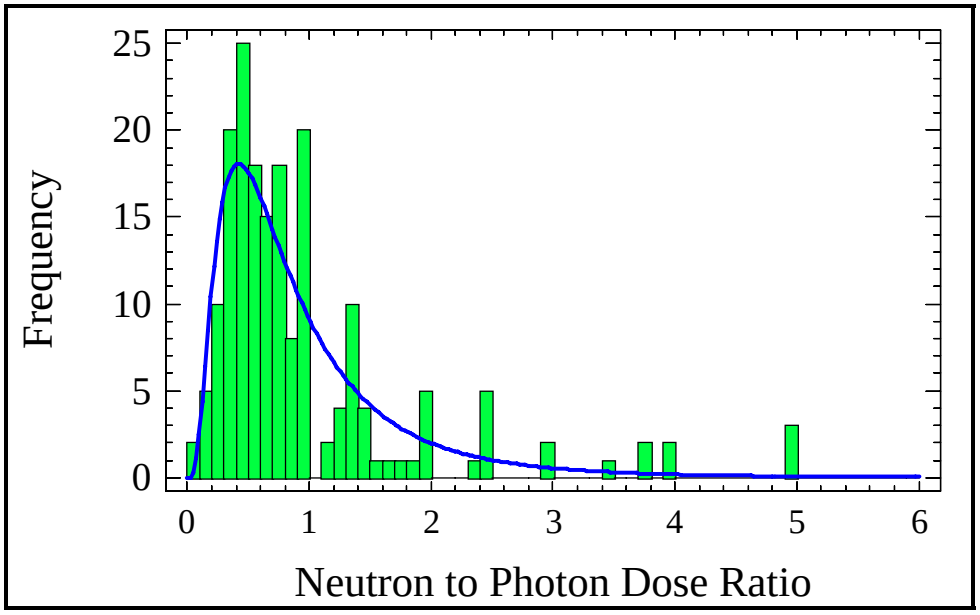

Figure 6-15. Neutron-to-photon dose ratio distribution of Hanford plutonium facility workers [42].

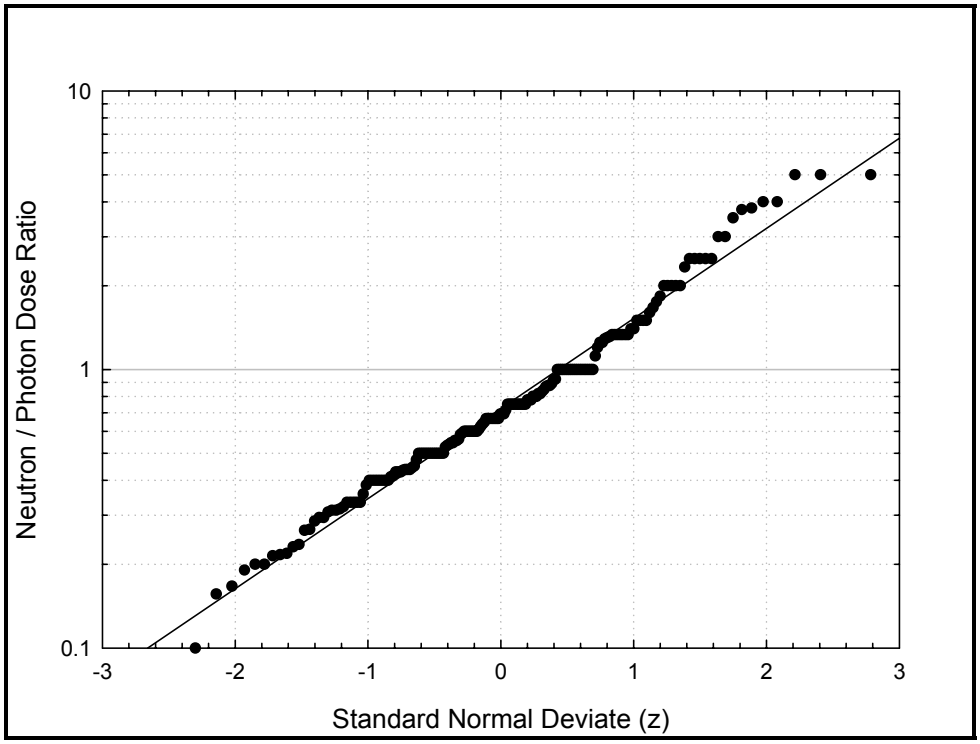

Figure 6-16. Lognormal distribution of data in Figure 6-15 [43].

Neutron-to-photon dose ratio distributions developed for Hanford reactor and plutonium facility workers are summarized in Table 6-22. These ratios should be applied after combining the recorded photon dose and the missed photon dose. It should be noted that if

the energy employee has measured neutron dose, the neutron photon ratio should be compared to the values in Table 6-22. If the measured neutron dose resulted in a higher neutron-to-photon ratio compared to the geometric mean in Table 6-22, the claim-specific ratio should be used [44].

Table 6-22. Hanford neutron-to-photon dose ratios.[a] [45].

Process	Description/buildings	Neutron-to-photon ratio		
		Geometric mean (GM)	Geometric standard deviation (GSD)	Upper 95th%
Reactors	During reactor operation: low level neutron exposure through shielding on the face of the reactors and through test ports.			
	B, D, F, H, DR, C, KW, KE Reactors	0.41	2.79	2.23
	N Reactor	0.06	3.00	0.37
Plutonium production	Plutonium finishing process: plutonium enters the process as PuF_4 and is then fired into production pucks. Work is primarily conducted in glove boxes with predominant close anterior exposure to workers. Radiation levels at the beginning of the process are fairly constant while levels at end of process are closely related to production levels.			
	Plutonium Facilities (200 Areas) (224-T, 231-Z, 232-Z, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U)	0.73	2.10	2.47
	Plutonium Laboratories (300 Area) (308, 309, 324)			

a. Applicable to facilities with significant potential for neutron exposure and prior to TLD use.

6.4.5.7 Neutron Dose Fraction

The fraction of the total dose in each neutron energy group shown in Figures 6-9, 6-10, 6-11, and 6-12 (see overlays in figures) was determined by subdividing the neutron spectra into the four lower neutron energy groups discussed in the External Dose Reconstruction Implementation Guideline (NIOSH 2006). The highest neutron energy group (>20 MeV) was not used because operations at Hanford did not produce a significant component of neutrons of this energy. The dose for each neutron energy group was calculated by multiplying the neutron flux (Ø) provided in the references by Roberson, Cummings, and Fix (1985) and Brackenbush, Baumgartner, and Fix (1991) by the corresponding flux to dose-rate conversion factors (DCF) found in National Council on Radiation Protection and Measurements (NCRP) Report 38 (NCRP 1971). The neutron doses in each NCRP 38 energy interval are summed to develop the four neutron group doses. The dose fraction (D_f) for each neutron energy group (n) was calculated by dividing the neutron group dose by the total dose (D_T).

$$D_f(E_n) = \frac{\sum_i \phi(E_i) DCF_i}{D_T} \qquad (6\text{-}1)$$

where:

$Ø(E_i)$ = Neutron flux of the ith energy bin;
DCF_i = NCRP 38 (1971) flux to dose-rate conversion factor for the ith energy bin;
D_T = Total dose.

Table 6-23 lists the neutron dose fractions by energy group using data measured by Roberson, Cummings, and Fix (1985).

Table 6-23. Laboratory-measured dose fractions from PuF_4.

Neutron energy group	Shielding of PuF_4 source[a]		
	0 cm (bare)	2.54 cm	5.08 cm
<10 keV	0.00	0.00	0.01
10–100 keV	0.00	0.00	0.00
0.1–2 MeV	0.06	0.85	0.89
2–20 MeV	0.94	0.15	0.10
	Favorable to claimant dose fractions		
0.1–2 MeV	0.1	0.9	0.9
2–20 MeV	0.9	0.1	0.1

a. Thickness of acrylic shielding between source and detector.

Table 6-24 lists selected neutron dose fractions by energy group using the measured neutron spectra or 200 Area PFP vault and glovebox locations presented in Fix et al. (1981) and Roberson, Cummings, and Fix (1985). The estimated default dose fractions for these PFP locations are similar to the 2.54- and 5.08-cm acrylic plastic shielded spectra shown in Figure 6-10.

Table 6-24. 200 Area measured dose fractions.

Energy group	Glovebox H-9B	Glovebox HC-9B	2736Z Vault	234-5Z C Room B
<10 keV	0.03	0.02	0.05	0.02
10–100 keV	0.04	0.04	0.04	0.03
0.1–2 MeV	0.84	0.87	0.80	0.88
2–20 MeV	0.09	0.07	0.11	0.07
	Favorable to claimant dose fraction default values			
0.1–2 MeV	0.9	0.9	0.9	0.9
2–20 MeV	0.1	0.1	0.1	0.1

Table 6-25 lists selected neutron dose fractions by energy group using the measured neutron spectra for 300 Area locations presented in Fix et al. (1982).

Table 6-25. 300 Area measured dose fractions.

Energy group	308–Bare fuel subassembly	308–Above fuel storage pit	308–Pu storage vault	324 Pu vault
<10 keV	0.00	0.02	0.01	0.02
10–100 keV	0.00	0.04	0.03	0.03
0.1–2 MeV	0.64	0.73	0.75	0.88
2–20 MeV	0.36	0.21	0.21	0.07
	Favorable to claimant dose fraction default values			
0.1–2 MeV	0.6	0.8	0.8	0.9
2–20 MeV	0.4	0.2	0.2	0.1

Table 6-26 lists selected neutron dose fractions by energy group using the measured neutron spectra for 400 Area FFTF locations presented in Fix et al. (1982). As reported in Fix et al. (1982), these measurements were taken at a time when a stainless steel research thimble was in one of the tubes and allowed neutrons to stream from the core to the head compartment. This is not a usual operating mode. Even with the streaming, the spectra show significantly reduced energy because of scatter.

The Radiation Effectiveness Factors used in the IREP to calculate the POC are less for the 10-100-keV category compared to the primary fission spectrum energy group (0.1 – 2 MeV) (Kocher, Apostoaei, and Hoffman 2002). Combining neutron energy groups into the primary 0.1 – 2 MeV fission spectrum group is a reasonable and favorable to claimant simplification of the dose calculation. The tables described above include the neutron energy favorable to claimant default values [46].

Table 6-26. 400 Area measured dose fractions.

Energy group	FFTF #1	FFTF #2
<10 keV	0.4	0.3
10–100 keV	0.5	0.4
0.1–2 MeV	0.1	0.3
2–20 MeV	0.0	0.0
	Favorable to claimant dose fraction default values	
10–100 keV	0.5	0.5
0.1–2 MeV	0.5	0.5

6.4.5.8 Uncertainty in Neutron Dose

Measurement of neutron dose in the workplace is difficult (Brackenbush, Baumgartner, and Fix 1991). Table 6-27 summarizes Hanford workplace neutron dosimeter performance characteristics. An evaluation of neutron dosimeter response in Hanford workplaces is presented in Fix, Wilson, and Baumgartner (1997b). The history is complicated, but the significant under-response in recorded dose with NTA dosimeters became evident in the late 1960s at several sites preparing to implement the TLD neutron dosimeters.

Table 6-27. Uncertainty in neutron $H_p(10)$ in Hanford facilities.

Parameter	Description	Workplace response
Workplace neutron energy spectra	NTA dosimeter response decreases and TLD response increases with decreasing neutron energy.	Depends on workplace neutron spectra. NTA recorded dose of record likely too low. Nichols et al. (1972) showed significant under-response.
Exposure geometry	NTA dosimeter response increases with increasing exposure angle (Kathren, Prevo, and Block 1964) and TLD response decreases with increasing exposure angle [47].	Effect is highly dependent on neutron energy. NTA recorded dose probably **too high** because dosimeter response is higher at angles other than AP. TLD recorded dose of record probably **too low** because dosimeter response is lower at angles other than AP.
Dosimeter Placement	Hanford instructed workers to wear neutron dosimeters close to body.	No effect noted for laboratory studies of NTA film irradiations in-air or on-phantom. However, there is significant dependence in HMPD response (Kocher et al. 1971) as a function of distance from worker body. Recorded dose of record probably **too low.**
Mixed low-energy photon and neutron radiation	NTA dosimeter responds significantly to lower-energy photons that can result in fogging NTA film [48].	NTA-recorded dose of record probably too low. HMPD five-chip TLDs have capability to remove photon dose contribution accurately. However, HMPD 4-chip TLD under-estimates total dose in plutonium facilities by about 25%.

6.5 ADJUSTMENTS TO RECORDED NEUTRON DOSE

Adjustments to the Hanford recorded neutron dose are necessary to arrive at a favorable to claimant dose considering the uncertainty associated with the recorded dose in the complex Hanford workplace radiation fields and the variability in exposure circumstances [49].

6.5.1 Neutron Dose Adjustments

Hanford incorporated the energy variation of the dose equivalent into its calibration methodology. As a result, the recorded dose equivalent (DE_R) is a combination of all neutron energies. To calculate the POC, the recorded neutron dose must be separated into neutron energy groups, as discussed in

Sections 6.3.4.6 and 6.3.4.7 and later converted to International Committee for Radiological Protection (ICRP) Publication 60 (ICRP 1990) methodology.

6.5.2 Neutron Weighting Factor

Adjustment to the neutron dose is necessary to account for the change in neutron quality factors between historical and current scientific guidance as described in NIOSH (2006). Hanford neutron calibration factors determined from National Institute of Standards and Technology (NIST)-calibrated sources are used directly without modification for field conditions (Brackenbush, Baumgartner, and Fix 1991). The quality factor is incorporated in the NIST calibration methodology, which used flux-to-dose-rate conversion factors for varying neutron energies for each calibration source. Flux-to-dose-rate conversion factors were based on NCRP Report 38 (NCRP 1971). The NCRP report lists both flux-to-dose-rate conversion factors and associated quality factors that vary from 2 at energies less than 1 keV to 11 at 1 MeV. To convert from NCRP 38 quality factors to ICRP Publication 60 (ICRP 1990) radiation weighting factors, a curve was fit describing the neutron quality factors as a function of neutron energy. The average quality factor for each neutron energy group was developed by integrating the area under the curve and dividing by the neutron energy range as shown in equation 6-2.

$$\overline{Q}(E_{n,0.1-2.0MeV}) = \frac{\int_{0.1}^{2.0} Q_f(E)dE}{Range(2.0-0.1)} \qquad (6\text{-}2)$$

Table 6-28 summarizes historical changes in the quality factors and the average NCRP 38 quality factor for the neutron energy groups used in dose reconstruction (See also ORAUT-OTIB-0055 [ORAUT 2006a]).

Table 6-28. Historical neutron quality or weighting factors.

Neutron energy (MeV)	Historical dosimetry guidelines[a]	NCRP Report 38 group averaged quality factor[b]	ICRP Publication 60 neutron weighting factor	Ratio[c]
Thermal	3	2.35	5	2.13
0.5 eV–10 keV	10			
10 keV–100 keV		5.38	10	1.86
100 keV–2 MeV		10.49	20	1.91
2 MeV–20 MeV		7.56	10	1.32
20 MeV–60 MeV		6.96[d]	5	1.00[e]

a. First Tripartite Conference at Chalk River in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994) and NCRP Report 17 (NCRP 1954; Taylor 1971).
b. See Figure 3-1.
c. Ratio of the ICRP 60 weighting factor to the group averaged NCRP38 quality factor each neutron energy group.
d. "Not applicable" is usually inserted here rather than the NCRP group averaged value of 6.96, which is larger than the ICRP 60 weighting factor of 5 for 20-to-60-MeV neutrons and results in a non favorable to claimant reduction in the corrected dose for this neutron energy group.
e. Ratio for adjusting neutron dose from NCRP 38 quality factor to ICRP 60 weighting factor is arbitrarily set equal to unity to avoid a non favorable to claimant reduction in the corrected dose for this neutron energy group.

6.5.3 Neutron Correction Factor

Table 6-28 lists the average quality factor for the four neutron energy groups that encompass Hanford neutron exposures. The neutron dose equivalent correction factor can be calculated by dividing the dose fractions from Section 6.3.4.4 for each neutron energy group ($D_f(E_n)$) by the corresponding energy specific average NCRP Report 38 (NCRP 1971) quality factor ($Q(E_n)$) and then multiplying by the ICRP Publication 60 (ICRP 1990) radiation weighting factor (w_R), as shown in equation 6-3.

$$C_f(E_n) = \frac{D_f(E_n)}{\overline{Q}(E_n)} \times w_R \qquad (6\text{-}3)$$

Table 6-29 summarizes the favorable to claimant default neutron dose fractions by energy for Hanford work areas where field measurements of neutron spectra were performed using the associated ICRP 60 correction factors. It should be noted that since a spectra was not available for the single pass reactors, the favorable to claimant assumption of 100% fission spectrum neutrons (0.1 -2 MeV) was used. The neutron dose equivalent is calculated by multiplying the recorded neutron dose by the area-specific correction factors. For example, consider a 1,000-millirem recorded neutron dose by a worker at the PFP, the corrected neutron dose is 1,710 millirem from neutrons between 0.1-2.0 MeV estimated to represent 90% of the dose fraction (i.e., 1,000 * 1.71) **and** 130 millirem from neutrons with energy between 2 and 20 MeV estimated to represent 10% of the dose fraction (i.e., 1,000 * 0.13). Thus, the corrected neutron dose is a total of 1,840 millirem. These adjustments should be applied to measured dose, missed dose, and dose determined based on a neutron-to-photon ratio [50].

Table 6-29. Hanford facility dose fractions and associated ICRP 60 correction factors [51].

Process	Description/buildings	Neutron energy (MeV)	Default dose fraction (%)	ICRP 60 correction factor
Reactors	During reactor operation: low level neutron exposure through shielding on the face of the reactors and through test ports.			
	B, D, F, H, DR, C, KW, KE, N	0.1-2	100	1.91
	FFTF	0.1-2 2-20	50 50	0.95 0.65
Plutonium production	Plutonium finishing process: plutonium enters the process as PuF_4 and is then fired into production pucks. Work is primarily conducted in glove boxes with predominant close anterior exposure to workers. Radiation levels at the beginning of the process are fairly constant while levels at end of process are closely related to production levels.			
	Plutonium facilities (200 Areas) (224-T, 231-Z, 232-Z, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U)	0.1-2 2-20	90 10	1.71 0.13
	Plutonium laboratories (300 Area) (308, 309, 324)			

6.6 MISSED DOSE

There is undoubtedly missed recorded dose for Hanford workers. The analysis has been separated according to photon and neutron missed dose [52].

6.6.1 Photon Missed Dose

Missed photon dose for Hanford workers would occur where (1) there is no recorded dose because workers were not monitored or the dose is otherwise unavailable, and (2) a zero dose is recorded for the dosimeter systems for any response less than the site dose recording threshold. Methods to be considered if there is no recorded dose for a period during a working career have been examined by Watson et al. (1994). In general, estimates of the missed dose can use dose results for coworkers or the recorded dose before and after the period of missed dose. However, these situations require careful examination. The missed dose for dosimeter results is particularly important for earlier years when recording thresholds were higher and dosimeter exchange was more frequent.

NIOSH (2006) describes options to calculate the missed dose. The recommended option is to estimate a favorable to claimant potential missed dose where MDL/2 is multiplied by the number of

zero or less-than MDL/2 dose results. The following sections describe potential missed photon dose adjustments according to year, facility/location, dosimeter type, and energy range.

6.6.1.1 Year

Analysis of the missed photon dose according to year (actually by period according to dosimeter type and exchange) is needed to evaluate the claim information, particularly if only annual dose data are available. The MDLs for the Hanford beta and photon dosimeters normally cited are based on laboratory irradiations. Actual MDLs are higher because of additional uncertainty in actual field use and the use of dose recording thresholds. Table 6-30 summarizes the potential missed dose. Reasonable MDLs are listed in this table for most applications for film dosimeters based on Wilson (1960b, 1987), NIOSH (1993), NRC (1989), and Wilson et al. (1990) and for TLDs from Fix et al. (1982) and Rathbone (2002).

Table 6-30. Hanford photon dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose.

Period of use[a]	Dosimeter	MDL[b] (rem)	Exchange frequency	Annual missed dose (rem)[c]
Hanford beta/photon dosimeters				
Prior to October 1944	PIC	0.005	Daily[d] (n=250)	0.625
October 1944–December 1950	Hanford two-element film	0.040	Weekly (n=52)	1.040
January 1951–March 1957		0.040	Biweekly (n=26)	0.520
April 1957–May 1957	Hanford multielement film	0.040	Biweekly (n=26)	0.520
May 1957–December 1971		0.040	Monthly (n=12)	0.240
January 1972–December 1994	Hanford TLD	0.020	Monthly (n=12)	0.120
		0.020	Quarterly (n=4)	0.040
January 1995 to 2003 (ongoing)	Harshaw TLD	0.010	Monthly (n=12)	0.060
		0.010	Quarterly (n=4)	0.020

a. For many years, Hanford workers had a dosimeter assigned to each operating area where they worked.
b. Estimated MDLs for each dosimeter technology in the workplace. Dose values were recorded at levels less-than the MDL
c. Annual missed dose calculated using MDL/2 from OCAS-IG-001 (NIOSH 2006).
d. Not routinely exchanged.

6.6.2 Neutron Missed Dose

Neutron radiation was present in the Hanford 100 Area reactors; 400 Area FFTF; 300 Area accelerator (3754B) and calibrations (3745A and 318 Buildings); and 200 and 300 Area plutonium facilities. There is potential for significant missed neutron dose among workers in the plutonium facilities where workers separated and finished plutonium (i.e., 224-T, 231-Z, 232-Z, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U, 308 Plutonium Fabrication Pilot Plan, 309 PRTR, and 324 laboratory) for use in nuclear weapons. Workers were in close proximity to the plutonium and in the early years actually physically moved the plutonium from one work location to the next. The approach recommended for use to calculate the neutron missed dose can be divided into two periods. The first period is prior to 1972 when ineffective PICs with ^{10}B enriched liners and NTA film dosimeters were used. In this case, the missed dose is calculated from the photon dosimeter MDL and, using a neutron-to-photon ratio, provided in Table 6-22. The second period is post 1971 when the HMPD was used. In this case, the missing dose is based on the MDL of the dosimeter. Table 6-31 summarizes the reported limits of detection or dose recording thresholds [53].

Table 6-31. Hanford neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose.

Period of use	Dosimeter	Exchange frequency	MDL (rem)[a]	Annual missed dose (rem)[b]
October 1944–December 1949	PICs with ^{10}B enriched liners	Daily[c] (n=250)	0.010	1.300
January 1950–December 1950	NTA	Weekly (n=52)	0.080	2.100
January 1951–March 1957		Biweekly (n=26)	0.080	1.000
April 1957–May 1957		Biweekly (n=26)	0.080	1.000
May 1957–December 1971		Monthly (n=12)	0.080	0.500
TLD Dosimeter				
January 1972–December 1994	HMPD – 4 or 5 chips	Monthly	0.050	0.300
January 1995–present	Harshaw TLD	Monthly	0.015	0.100

a. Estimated film dosimeter photon radiation detection levels before 1972 and neutron dosimeter MDLs after 1971.
b. Annual missed neutron dose calculated using: Prior to 1972, neutron-to-photon ratio after combining the recorded and missed photon dose. The actual estimate of annual missed dose will be the product of two lognormal distributions. After 1971, the lognormal distribution from the neutron dosimeter using a geometric mean of (n * MDL/2) and an upper 95% confidence interval of (n * MDL), where n is the number of missing dosimeter results [54].
c. Dosimeter not routinely assigned.

6.6.2.1 Year

Table 6-33 lists the potential missed dose for two distinct periods that are identified for correction to Hanford neutron dose results as described in the following paragraphs.

Before 1972. There is no recorded neutron dose prior to 1950 when ^{10}B-lined PICs were used. Recorded neutron dose using the NTA film will likely significantly underestimate the actual neutron dose (Fix, Wilson, and Baumgartner 1997b).

Due to the uncertainty in whether an employee's NTA badge would respond to the workplace neutron spectrum, using a ratio of the neutron-to-photon dose is a favorable to claimant option to reconstruct an individual worker neutron dose. This is based on the fact that routine neutron exposure is essentially always accompanied with measurable photon exposure (Watson 1959). The approach is illustrated as:

$$\text{Neutron dose} = \text{photon dose} * \text{neutron/photon dose ratio}$$

The 95th percentile neutron/photon dose ratio can be used to estimate the maximum missed neutron dose. The photon dose should be adjusted for any missed dose before an estimation of the missed neutron dose [55].

After 1971. The HMPD is sensitive to neutron radiation in Hanford workplaces with potential for neutron radiation. Estimates of the missed neutron dose for the HMPD dosimeter is based on the respective dosimeter exchange periods and MDL/2 [56].

6.6.2.2 Facility/Location

Table 6-31 lists the potential missed neutron dose for the MDL and exchange frequency using NIOSH (2006).

6.6.2.3 Dosimeter Type

The potential missed dose for neutron dosimeters depends strongly on the neutron radiation field in Hanford facilities. The MDLs are different for the Hanford neutron dosimeters cited based on

laboratory irradiations. The actual MDLs are greater than these values because of additional uncertainty in actual field use and the use of dose recording thresholds. Reasonable MDLs are shown in Table 6-31 for most applications for film dosimeters based on Wilson (1960b, 1987), NIOSH (1993), NRC (1989), and Wilson et al. (1990) and for TLDs from Fix et al. (1982) and Rathbone (2002).

6.6.2.4 Energy Range

An estimate of the missed neutron dose by energy range is possible based on the type of facility and predominant neutron energies measured during field measurements. The recorded neutron dose from the HMPD and commercial TLD response does not provide enough information to estimate discrete energy ranges. Based on workplace spectra measurements, the default values for Hanford plutonium facilities are assumed to be applicable to nonplutonium facilities, even though the actual measured spectra would be expected to be different. A favorable to claimant default is proposed because there are not sufficient workplace spectra measurements in the reactor facilities; this approach simplifies the dose calculation. The values are listed in Table 6-31 [57].

6.7 UNCERTAINTY

There is significant uncertainty in evaluating dose recorded decades into the past. Primary issues concern the missed dose for zero recorded doses and the uncertainty in the positive doses, particularly low values, as described in the following sections [58].

6.7.1 Missed Dose

Some considerations to evaluate dose to workers with low occupational exposure are examined in Wilson et al. (1990). The analysis of missed dose is typically based on the penetrating dosimeter response to a high energy calibration source such as ^{226}Ra or ^{137}Cs. For these energies, the nonpenetrating and penetrating dosimeter response is the same. In routine practice, the nonpenetrating dose response is typically higher because of its response to low energy photon and beta radiation. Hanford work areas have mixed fields of radiation particularly involving scattered photon radiation of high and low energies and in some areas, beta radiation. As such, the nonpenetrating dose recorded for workers provides a more sensitive means to determine if significant exposure has occurred. Also, the dosimeter response to low-energy photon radiation is significantly greater than for the high energy gamma radiation. There is concern for work performed close to sources of radiation such as repairing contaminated equipment, but typically workers would be assigned extremity dosimeters in addition to the whole-body dosimeters. The combination of the dose results measured by the extremity and whole-body dosimeter tend to lower the actual detection level in Hanford workplaces compared to an evaluation of the penetrating dose component only as described in the following paragraph. Figure 6-17 presents an illustration of the respective Hanford dose results for a single worker from 1948 through 1976. The tracking of the respective dose components is evident [59].

Wilson (1960b) conducted a detailed examination of the MDL for the Hanford dosimetry system used in 1960. The Hanford multielement film dosimeter implemented in 1957 included the OW and 1 mm Ag filtered regions of the two-element film dosimeter used at Hanford from 1944 to 1957 so studies of this dosimeter can be extrapolated to earlier results. Wilson described three changes in 1960 that led to a lower detection level of about 15 mrem at the 90% confidence level involving: (1) elimination of non-isotropic effect of calibration source, (2) automated film processing and (3) change to the more sensitive 508 film. He notes in this report a detection level of 40 mrem at the 95% confidence level for

the Hanford system (502 film) prior to these changes. An important consideration in this analysis concerned the level of potential missed dose. Wilson describes the analysis of 49 batches of Hanford

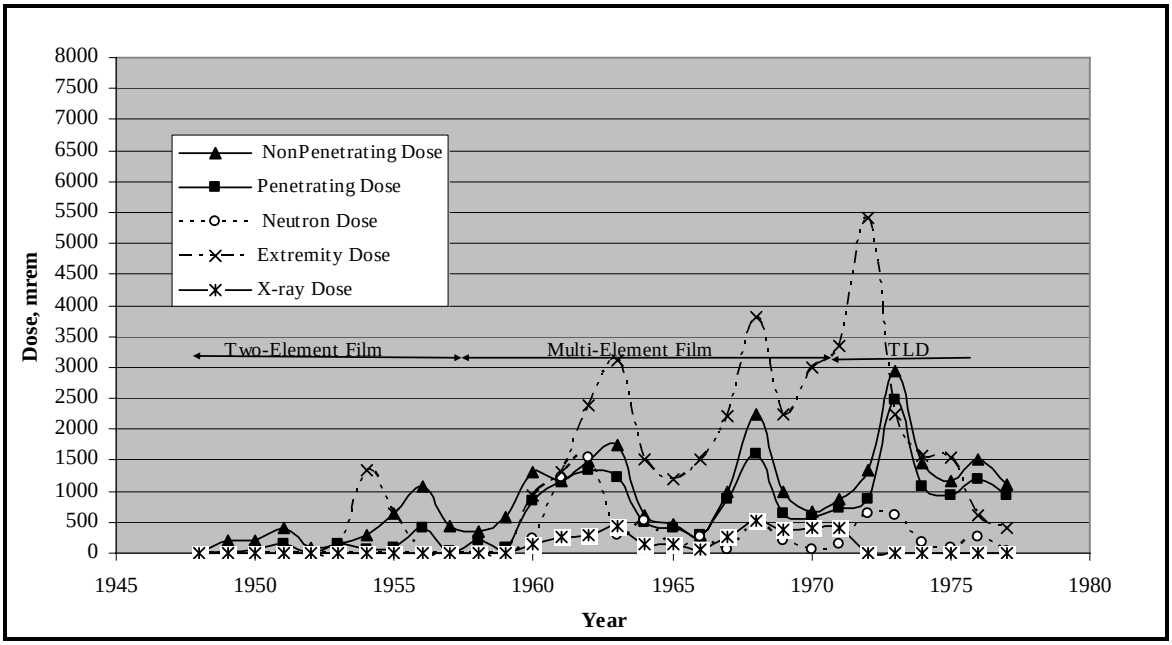

Figure 6-17. Annual dose components for a single Hanford worker, 1948–1976 [60].

routine calibration results that indicated a 25% standard deviation at the 30 mrem calibration level based on the optical density readings. Based on an analysis of the capabilities of the densitometer used to process the film, he estimated a likelihood of 0.33 (1/3) that a dose of 15 mrem would not be detected. The likelihood that this would occur for each successive monthly exchange for an entire year would be $(0.33)^{12}$ or about one in a million. Based on the 13 exchanges during the year at that time, he estimated a maximum potential missed dose of 195 mrem (i.e., 15 * 13). Conversely, Wilson estimated that about 8% of the time, a positive dose would be recorded for dosimeters that received no exposure. A similar analysis could be performed for the dosimeter used prior to 1960 with an estimate that about 30 mrem would be detected 1/3 of the time.

Assumptions favorable to claimants have been incorporated in the assessment of missed dose for zero recorded penetrating dose for the respective dosimeter exchange periods in this TBD. Hanford did use a practice of locating dosimeters at the badge control building for each operating area for each person expected to routinely enter. As such, some Hanford workers had dosimeters simultaneously located at several different Hanford areas. Dosimeters from each of these areas were processed and a dose assigned to the worker. In many cases, a zero dose was recorded for all the dosimeters. Assuming a worker had dosimeters at seven Hanford work areas and using the 40 mrem MDL as noted in the respective tables of this TBD, it is possible to calculate a maximum potential missed dose of 140 mrem (i.e., 7 * 40/2) using OCAS-IG-001 (NIOSH 2006) for each exchange period or, if this occurs throughout the year, a maximum potential missed dose of 1,680, 3,360 and 6,720 mrem, respectively, for monthly, biweekly, and weekly exchange periods. Often, the dose for a person with zero recorded dose will unrealistically exceed the dose for workers with recorded positive dose. It is recommended in this TBD that the guidance of OCAS-IG-001 (NIOSH 2006) be applied to the recorded dose for each exchange period regardless of the number of dosimeters assigned to a worker for each operating area. Using the analysis of Wilson (1990), the likelihood of all dosimeters reading zero for an exchange period when there is positive dose can be calculated as $(0.33)^y$ where y is the number of areas [61].

6.7.2 Positive Recorded Photon Dose

Uncertainty in the positive recorded photon dose for Hanford workers has been assessed in Wilson et al. (1990) and, for photon radiation >100 keV, by Fix, Gilbert and Baumgartner (1994). Results of these evaluations are noted in Tables 6-11 and 6-12. For the >100 keV photon radiation characteristic of all Hanford work areas with the exception of the plutonium handling facilities, the estimates of bias and uncertainty are primarily associated with the respective dosimeter systems as noted in Table 6-12.

Uncertainty in the positive recorded photon dose for Hanford workers in the low-energy photon fields characteristic of plutonium facilities is certainly larger than the values shown in Table 6-12. An estimate of the overall bias (defined as the ratio of the deep dose to the recorded whole body dose) is provided by Wilson et al. (1990) for the respective Hanford dosimeter types according to major facility categories as shown in Table 6-32.

Table 6-32. Estimate of overall photon and neutron radiation bias factor [62].

		Bias factor[a]									
		Fuel fabrication		Reactor		Fuel reprocessing		Plutonium finishing		Waste & laboratory	
Dosimeter	Period	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Two-element film	1944–1957	0.5	1.6	0.5	1.7	0.5	1.6	(b)	(b)	0.5	1.6
Multielement film	1958–1971	0.7	1.3	0.7	1.4	0.7	1.3	1.0	2.0	0.7	1.3
TLD	1972–1989	0.8	1.2	0.8	1.2	0.7	1.3	0.6	1.4	0.8	1.2

a. The bias factor is defined as the ratio of the deep dose to the recorded whole body dose.
b. Recorded photon and neutron dose known to be in error. Photon dose could be based on open window response of film dosimeter and neutron dose based on neutron-to-photon dose ratio of 1:1 (Wilson et al. 1990).

The Hanford film and thermoluminescent dosimeters easily respond to the predominant 17 keV (plutonium X-rays) and 60 keV (^{241}Am) photon radiation, particularly if the nonpenetrating and penetrating whole body and extremity dose components are analyzed (i.e., as shown in Figure 6-17) as was routine practice at Hanford. The ratio of the nonpenetrating and penetrating dose was routinely used in the analysis of dose (Larson and Roesch 1954). However, the variation in the recorded dose is highly effected by shielding, the worker's orientation in the field, etc. Evaluations of the dosimetry for Hanford plutonium workers have received more examination historically than any other area as shown by the letters, references, and bibliography noted in Wilson et al. (1990). In the early years, contamination of the plutonium by fission and activation problems undoubtedly occurred, which likely increased the energy of the radiation. DOELAP testing formally began in 1986 (DOE 1986) and included a 17 keV (k-fluorescent X-ray characteristic of plutonium) and 60 keV (^{241}Am) beams.

6.7.3 Neutron Dose

The technical inadequacy to measure the neutron dose with NTA film at Hanford prior to 1972 is well known. As such, the recommended option is to utilize a neutron-to-photon dose ratio. The uncertainty in this approach is a combination of the neutron-to-photon dose uncertainty and the uncertainty of the measured photon dose.

With the TL dosimeter methods beginning in 1972, comparisons of the Hanford thermoluminescent dosimeter photon and neutron dose measurements at the Hanford plutonium facilities have been conducted on several occasions with TEPCs and, in fact, the neutron dose calibration of Hanford TLDs is based on field measurements at the Hanford 234-5Z facility. The Hanford TLD and TEPC measurements compare on average (i.e., no change in dosimeter algorithm recommended), however

the variability is significant. A factor of 3 difference in closely placed dosimeters for a single many hour measurement is often observed [63].

6.8 ANALYSIS OF CLAIMS FILED BY HANFORD WORKERS

An analysis of external dose parameters reported in Hanford claims was done to better determine dose reconstruction recommendations. There are three primary sources of information in each claim that provide information of interest used to reconstruct external dose: (1) U.S. Department of Labor (DOL) claim documentation; (2) DOE medical X-ray, dosimetry, and incident archive records; and (3) records of interviews with claimant and coworkers, as available. This information is used to identify the employment period, job title and work activities, coworkers, supervisors, etc., for use in dose reconstruction. Analysis of the historical radiation monitoring and dose documentation for the respective claims provides insight into Hanford dosimetry practices, such as assignment of dosimeters, exchange periods, and dose recording levels.

For purposes of dose reconstruction, it is recognized that while “average” and “routine” activities are important and probably represent most exposure scenarios, there could be unusual circumstances in some claims that require special evaluation.

6.8.1 Years with a Claim

There were a total of 7,234 annual dose records for 2,495 claims filed with the DOL with positive reported external dose as of September 15, 2006. Doses for these claims were analyzed to examine trends in the data. These claims were assembled in a database with one record of annual dose data for each year of employment for each claimant. Overall, a total of 49,897 dose records were assembled for Hanford worker claims. The average period of employment for claimants was 10.9 years, the maximum was 48.9 years (~1949 to ~1997), and the distribution of the number of claims by years of employment is shown in Table 6-33. Figure 6-18 illustrates the frequency of the archive doses available for the 2,495 claims in each of the respective years. As would be expected, the very early years have relatively fewer dose records.

Table 6-33. Frequency of claims according to duration of Hanford employment.

Hanford employment (years)	Number of claims
<1	362
1-2	201
2-3	150
3-4	100
4-5	102
5-10	490
10-20	725
20-30	202
30-40	148
40-50	15
Total no. of claims	2,495

6.8.2 Analysis of Assigned Doses

Comparisons were made between the original measured penetrating dose (identified as archive hereafter) from penetrating photon radiation reported in Buschbom and Gilbert (1993) for years 1944 through 1989 and the assigned penetrating photon dose used in dose reconstruction. A comparison

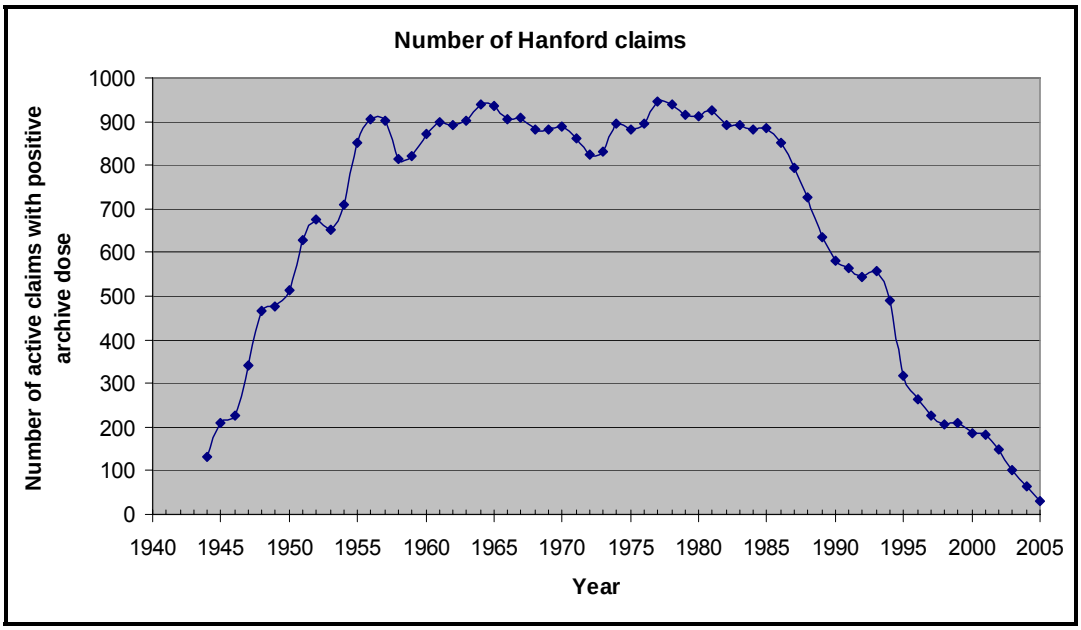

Figure 6-18. Frequency distribution of archive records for active Hanford claims within the respective years.

of the average and maximum doses for each year are presented in Figure 6-19. For the years when the maximum archive dose is equal to the assigned dose (e.g. 1963, 1977, etc.), this indicates a claim has been filed for the Energy Employees (EE) with the maximum archive dose. For all years, the assigned average and maximum annual doses are very similar with the exception being years prior to about 1954 when it is evident that some workers with the maximum archive dose have either not filed a claim or their claim information is not yet available for analysis (i.e., as of September 15, 2006). It is important to understand that these doses represent a comparison of the archive and assigned measured external radiation dose based on the DOE radiological records. The total assigned organ dose is not shown in Figure 6-19 that results from various elements of the NIOSH dose reconstruction (NIOSH 2006) process used to calculate a favorable to the claimant organ dose and to account for potential unmeasured dose arising from potential unrecorded (i.e., missed dose) occupational dose from photon or neutron external radiation, ambient environmental dose, medical X-ray dose, and internal intakes. These typically result in a highly significant increase to the original measured dose.

6.9 RECOMMENDATIONS FOR HANFORD WORKER EXTERNAL DOSE RECONSTRUCTION

Recommendations for dose reconstruction for Hanford workers is based on the foregoing information and the objective to provide an analysis that is favorable to claimants. Potential sources of additional dose to be assigned to the EE include:

- Adjustments to recorded occupational dose.
- Assignment of missed dose for monitored workers for low dose results (i.e., less than MDL/2 of the personnel dosimeter).
- Assignment of unmeasured neutron dose to monitored and unmonitored workers.

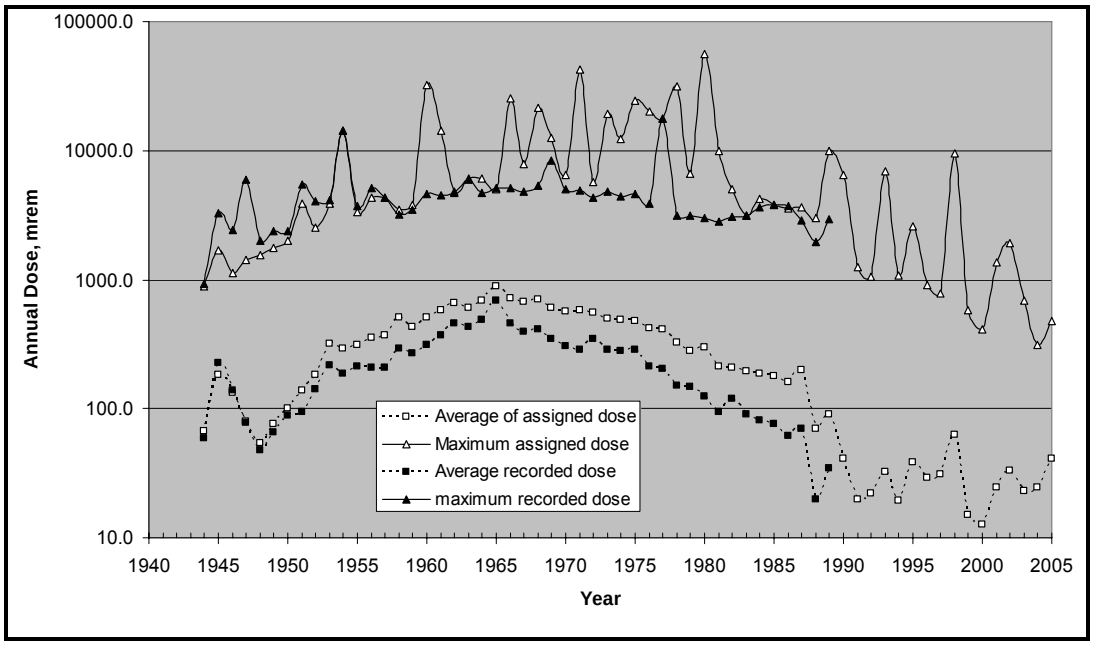

Figure 6-19. Comparison of average and maximum annual measured penetrating dose as originally recorded in Buschbom and Gilbert (1993) and as assigned in dose reconstruction prior to inclusion of missed occupational (external and internal radiation), medical X-ray, or ambient assigned dose.

- Adjustments to measured and missed dose associated with glovebox work activities for some workers and use as appropriate of the special plutonium dose conversion factors.

- Assignment of potential dose to unmonitored workers.

6.9.1 Adjustments to Recorded Occupational Dose

Hanford worker-recorded dose measurements are considered reasonably accurate from 1944 through the present with exceptions as follows:

- The low-energy photon dose component measured in Hanford plutonium facilities with the original two-element film dosimeter used prior to 1958 may be too low. Hanford practice was stated to include assignment to the penetrating dose of 20% of the measured nonpenetrating dose in plutonium facilities only. However, clear confirmation that this was indeed done for all years has not been possible to date. As such, if the early photon dose is significant to the dose reconstruction, the dose reconstructor may select to adjust the penetrating dose by using 20% of the nonpenetrating or shallow recorded dose to ensure a favorable assigned photon dose [64].

- Neutron doses determined prior 1/1/1972 with the NTA film dosimeter are likely too low and a neutron-to-photon dose ratio should be used to assign a favorable dose to the claimant [65].

- Neutron dose measurements with the workplace performance-validated TLD implemented in 1972 are considered accurate with the exception of a period from 1978 through 1983 when a 4-chip Hanford TLD was used. The recorded neutron dose during this period was too low. A factor of 1.35 times the recorded neutron dose should be used to ensure a favorable assigned neutron dose [66].

- An adjustment in recorded or assigned neutron dose for all years is needed to incorporate ICRP Publication 60 neutron weighting factors [67].

6.9.2 Determination of Missed External Dose for Low-Dose Results for Monitored Workers

Missed dose occurs when the dose of record is zero because the dosimeter response was less than the MDL or there is no dose of record for an assigned badge for a monitoring period. This kind of missed dose is most important for earlier years when MDLs were higher and dosimeter exchange was more frequent. Dose reconstructors should follow NIOSH (2006) guidance and use data in Table 6-34 to calculate the missed photon dose. The method recommended for estimating missed photon dose is to assign a missed photon dose based on the MDL/2 method and the number of exchange periods (NIOSH 2006) given in Table 6-34 for the respective dosimetry systems.

Table 6-34. Potential missed dose for low-dose values [68].

Dosimeter	Period	Exchange frequency[a]	MDL (mrem)			Missed annual mean dose (rem)		
			Skin	Deep	Neutron	Skin	Deep	Neutron
Pocket ionization chamber	Early 1940s	Daily	5	5	N.A.	0.625	0.625	(d)
Hanford two-element βγ film	1944–1950	Weekly	40[b]	40[b]	(c)	1.040	1.040	(d)
Hanford two-element βγ film and NTA film	1951–1957	Biweekly	40	40	(c)	0.520	0.520	(d)
Hanford two-element βγ film and NTA film	1958–1971	Monthly	40	40	(c)	0.240	0.240	(d)
Hanford TLD	1972-1994	Monthly	50	20	I	0.300	0.120	
Hanford Commercial TLD	1995-present	Monthly	30	10	I	240	0.060	

a. Exchange frequencies were established from dosimetry reports for routine exchange.
b. Estimated MDL typical of film dosimeter capabilities (Wilson 1960b, 1987; NRC 1989; Wilson et al. 1990).
c. The MDL for neutron doses estimated for years prior to 1972 was unreliable.
d. For years prior to 1972, the reconstructed neutron dose is calculated using the adjusted photon dose and a neutron-to-photon dose ratio.

6.9.3 Determination of Missed Neutron Dose for Monitored and Unmonitored Workers

Determination of the missed neutron dose for the period of NTA use prior to 1972 can be made using the values in Table 6-35.

Table 6-35. Potential missed neutron dose [69].

Facility	Neutron-to-photon dose ratio		
	GM	GSD	95th
Once through reactors: 100B, 100F, 100C, 100D, 100DR, 100KE, 100KW, and 100H	0.41	2.79	2.22
N-Reactor	0.06	3	0.37
FFTF	(a)	(a)	(a)
Plutonium Facilities	0.73	2.1	2.47
All others	0	0	0

a. FFTF operated only while TLND used to measured neutron dose.

The period of missed neutron dose with the Hanford TLD during 1978 through 1983 can be made using:

$$\text{Assigned neutron dose} = \text{recorded neutron dose} * 1.35$$

6.9.4 Adjustment for Glovebox Workers

Guidance in OCAS-TIB-0010 (NIOSH 2005) should be used to adjust the measured photon dose to Hanford workers in identified Hanford plutonium facilities.

6.9.5 Unmonitored Worker External Dose

For unmonitored Hanford workers, coworker doses from photon radiation for Hanford are presented in ORAUT-OTIB-0030 (ORAUT 2005b). This reference should be used to assign unmeasured photon radiation dose to Hanford workers. Typically, all significantly exposed Hanford workers should have been monitored with a recorded dose.

There should not, typically, be a significant neutron exposure to unmonitored workers. However, for an unmonitored worker with some evidence of potential neutron exposure, neutron doses can be conservatively estimated from the median photon doses for radiation workers listed in Table 6-35 by applying the median neutron-to-photon dose ratio (GM) listed for the respective facilities. Multiplying the median neutron-to-photon dose times the appropriate co-worker photon dose (50th or 95th percentile) for Hanford radiation workers for each year will yield a favorable to claimant assigned neutron dose to unmonitored workers.

6.9.6 Skin Dose

Hanford practice to assign the skin dose was to include the nonpenetrating and penetrating dose components as summarized in Table 6-36. Additional guidance on determining skin dose can be obtained from ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* ORAUT 2005a).

6.9.7 Extremity Dose

Ring extremity dosimeters have been assigned to Hanford radiation workers who directly handled plutonium or beta emitting nuclides with a significant potential to result in an extremity dose that was more limiting than the whole body dosimeter. A standard monitoring practice in operational health physics is to establish a factor between whole-body and extremity exposures to determine when extremity dosimeters should be assigned. The factor is typically based on radiation guidelines for the extremity, skin, and whole body, which have varied over the years. At the 1949 meeting in Chalk River, Canada, among U.S., UK, and Canadian nuclear weapon development organizations, several aspects of operational health physics were defined (Taylor 1971). The identified limits were:

Whole body – 0.3 rem/wk; skin – 0.5 rem/wk and extremity 1.5 R/wk.

Based only on the limits, it would not be necessary to monitor the extremity dose unless it was greater than a factor of about 5 multiplied times the whole body dose, otherwise the whole body dose would be limiting. To make certain that instances did not arise where in fact, the extremity dose limit could be exceeded, typically a lower factor is adopted, such as a factor of 3. As such, based on this analysis, it is recommended that the measured whole body dose be increased by a factor of 3 as a favorable to claimant assumption to assign a dose to the extremities based on the premise that monitoring to the extremity would have been performed if this was significant at the higher dose level [70].

Table 6-36. Historical Hanford recorded dose practices [71].

Year	Dosimeter measured quantities	Compliance dose quantities
Two-element beta/photon film dosimeter[a]		
1944–47	OW = open window, mrep S = "silver filter" dosimeter response, mR	Skin = OW + S WB = S
1948–50	Beta = open window, mrep Gamma = "silver filter" dosimeter response, mR	Skin = beta + WB WB = gamma
Two-element beta/photon film dosimeter + NTA neutron dosimeter		
1950–57	Beta = open window, mrep Gamma = "silver filter" dosimeter response, mR	Skin = beta + WB WB = gamma + neutron
Multielement beta/photon dosimeter + NTA neutron dosimeter		
1957–58	Beta Gamma X-ray Neutron	Skin = beta + gamma + 65% X-ray + neutron WB = gamma + 0.35% X-ray + neutron
1959–71	Beta (-B-) Gamma (-G-) X-ray (-X-) Fast neutron (F-N) Slow neutron (S-N)	Derma (skin) = beta + WB + 65% X-ray WB (penetrating) = gamma + neutron + 35% X-ray)
Thermoluminescent dosimeter		
1972–94	Nonpenetrating (NPEN) Penetrating (PEN) Slow neutron (SN) Fast neutron (FN)	Skin = NPEN + WB WB = PEN + SN + FN
1995–2003	Shallow (Sh Deep (Dp) Neutron (Nt)	Skin = Sh + Dp + Nt WB = Dp + Nt

a. From 1948-56, when dosimeter quantities for each period were noted as beta or gamma, the cumulative dosimeter dose quantities continued to be labeled as OW and S.

6.9.8 Radiation Dose Fraction

Tables 6-13 and 6-17 summarize the recommended radiation dose fractions for Hanford dose according to facility, worker occupational classification, and energy categories required by IREP.

These assumptions will generally result in favorable to claimant estimates of organ dose.

6.9.9 Organ Dose

Once the adjusted doses have been calculated for each year, the values are used to calculate organ doses of interest using the external dose reconstruction implementation guidelines (NIOSH 2006). Wilson et al. (1990) states "workers are typically facing the work being done, and for routine radiation exposure over long time periods, the front of the torso can be expected to receive the largest cumulative exposure." It is recommended that the 100% AP (front-to-back) geometry should be assumed for the irradiation geometry and for conversion to organ dose. The calculated neutron doses should be multiplied by the conversion factors from deep dose equivalent to organ dose for AP irradiation from Appendix B of NIOSH (2006). For photons (film badge and TLD era), the conversion factor from deep dose equivalent to organ dose should be used.

6.9.10 Claim Analysis Methods

The process of dose reconstruction follows three primary options [72] described as follows:

6.9.10.1 Minimizing Assumptions

When a claim is categorized as likely compensable, minimizing assumptions to assign a dose to the EE are used to process the dose assessment quickly and simply. Assumptions such as assigning no neutron dose or no missed dose are typical minimizing assumptions that can expedite processing. If the assigned dose corresponds to a POC exceeding a value identified by OCAS (i.e., currently 52%), even with minimizing assumptions, the claim is probably compensable.

6.9.10.2 Maximizing Assumptions

When a claim is categorized as likely noncompensable, maximizing assumptions to assign a dose to the EE are used to expedite claim processing. Assigning the maximum neutron dose, maximum missed dose, and maximum adjustment for uncertainty are typical maximizing assumptions. If the assigned dose with maximizing assumptions corresponds to a POC less-than a value identified by OCAS (i.e., currently 45%), the claim is probably noncompensable.

6.9.10.3 Best Estimate Assumptions

The resolution of claims that require a more realistic assessment to determine compensability should consider that the conversion of photon and neutron doses of record to organ doses requires careful evaluation without simplifying assumptions. Best available data for the claimant should be used, including actual dosimeter results, actual number of X-rays, and actual uptakes.

6.10 UNCERTAINTY IN PHOTON AND NEUTRON DOSES

For the usual analysis of measured film badge doses, MDLs in the literature range from about 30 to 50 mrem for beta/photon irradiation (Wilson et al. 1990). It is possible to read a photon dose of 100 mrem to within ±15 mrem if the exposure involved photons with energies between several keV and several MeV (Morgan 1961). The estimated standard error in recorded film badge doses from photons of any energy is ±30% [73].

The situation for neutrons was not as favorable as for photons. With NTA films used at Hanford before 1972, the estimated standard error was larger and varied significantly with the energy of the neutrons. Therefore, measured neutron doses to workers were very likely underestimated. The recommended approach is to use neutron-to-photon dose ratios to estimate the neutron dose using the reliably measured photon doses. For TLDs used at Hanford beginning in 1972 through 1987, the estimated standard errors for photon and neutron dose, respectively, of 100 mrem or more are approximately ±30% and ±50% based on actual DOELAP performance testing or preparations for testing.

6.11 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations to assist in the process of worker dose reconstruction. These callouts are listed in this section with information that identifies the source and justification for each item. Conventional references are provided in the next section that link data, quotations, and other information to documents available for review on the Oak Ridge Associated Universities Team servers.

Jack Fix served as the initial Subject Expert for this document. Mr. Fix was previously employed at the Hanford Site; his work involved management, direction, or implementation of radiation protection

and/or health physics program policies, procedures, or practices related to atomic weapons activities at the Site. This revision and earlier revisions have been overseen by a Document Owner who is fully responsible for the content, including all findings and conclusions. Mr. Fix continues to serve as a Site Expert for this document because he possesses or is aware of information relevant to the reconstruction of radiation doses experienced by claimants who worked at the Site. In all cases where such information or prior studies or writings are included or relied upon by Mr. Fix, those materials are fully attributed to the source. Mr. Fix's Disclosure Statement is available at www.oraucoc.org.

[1] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Hanford workers do have recorded nonpenetrating doses of record [see Buschbom and Gilbert (1993)], but analysis of these data was not included in this TBD.

[2] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This judgment is based on Mr. Fix's experience in occupational dose reconstruction.

[3] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This judgment is based on the dose reconstruction recommendation presented in later sections of this TBD to assign, as appropriate based on claimant work activities, an annual neutron dose for each year of Hanford employment prior to the use of the TLD beginning in 1972, using a distribution of the neutron-to-photon dose ratio.

[4] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This judgment is based on Mr. Fix's perspective on the historical development of personnel dosimetry systems and the respective performance studies conducted historically leading to the adoption of ANSI N13-11-1983 (ANSI 1983).

[5] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This judgment is based on Mr. Fix's experience in the preparation of Fix, Wilson and Baumgartner (1997b), during which a database of all Hanford NTA processing results from 1950 through about 1961 was developed from the paper records obtained from the Federal Record Center.

[6] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This list of administrative practices that could significantly affect the completeness of the historical recorded occupational dose is based on Mr. Fix's judgment.

[7] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data used to prepare this figure were obtained from statistical tables included in PNL-8909 (Buschbom and Gilbert 1993) of the Hanford Health and Mortality Study worker cohort.

[8] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data used to prepare this figure were obtained from statistical tables included PNL-8909 (Buschbom and Gilbert 1993) of the Hanford Health and Mortality Study worker cohort.

[9] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Mr. Fix was the Hanford External Dosimetry Program Project Manager in 1995. The commercial Harshaw dosimetry systems became effective with the January 1, 1995, dosimeter issue to Hanford workers.

[10] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Reference to the routine comparison of pocket ionization chamber and film dosimeter results is based on judgment of the information in the *Manual of Standard Procedures: Personnel Meters* (HEW 1946). Mr. Fix was the Hanford External Dosimetry Program Project Manager in 1995. The use of the commercial Harshaw dosimetry system became effective with the January 1, 1995, dosimeter issue to Hanford workers.

[11] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The first computer system for radiological records was introduced in 1958 as described in Wilson (1987). Before this, it was necessary to record the assigned dose manually on forms. Fix, Carbaugh, and MacLellan (2001) enables a person to view the forms used. In addition, DOE provided historical dose forms that provide a means to view these forms for the respective years.

[12] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The methods used to record dose at Hanford are described in Fix, Carbaugh, and MacLellan (2001).

[13] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The precise period of accreditation of the Hanford External Dosimetry Program is a matter of record available from the DOELAP. The stated year of 1989 is based on Mr. Fix's recollection as chair of the DOELAP Oversight Board.

[14] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment presented is based on Mr. Fix's assessment of the association of dosimeter error on dosimeter response and workplace radiation characteristics. For example, see Wilson et al. (1990).

[15] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment presented in this table is based on Mr. Fix's experience in dose reconstruction. The information is very similar to that presented in Chapter 8 of Wilson et al. (1990).

[16] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Consideration to assign 20% of the shallow dose to the deep dose is described in Hanford references and is noted in Chapter 7 of Fix, Wilson, and Baumgartner (1997b). The potential error in assigning this dose can be evaluated using Appendix D of Wilson et al. (1990).

[17] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The difference of about a factor of 2 in TLD shallow dose response between exposures to ^{90}Sr/Y and to uranium is described in Nichols et al. (1972) and Fix et al. (1981).

[18] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The complex history of radiation quantities used to measure and record dose from neutron radiation is well known to dosimetrists involved in dose reconstruction. Fix, Wilson, and Baumgartner (1997b) provides a description relevant to Hanford.

[19] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement and the judgment identified in this table by Mr. Fix of the effects of angular response on recorded dose is based on Mr. Fix's assessment of the complex interactions that involved dosimeter angular response and workplace radiation fields.

[20] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Statements in this table by Mr. Fix about effects of fading on recorded dose are based on Mr. Fix's assessment of Hanford calibration and control dosimeter procedures used to adjust for known fading. The procedures manuals [HEW (1946) and Hanford External Dosimetry Operating Procedures, July 22, 1963 (GE 1963)] describe fading and calibration practices adopted to adjust for effects on recorded dose.

[21] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment of complex radiation fields in the workplace is based on consideration of the types of processes and radionuclides at Hanford. The 10-year review by Parker (1954) could be consulted for a description.

[22] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is based on judgment by Mr. Fix on the challenge presented by mixed beta/ photon radiation fields and neutron radiation and on his experience in accurate measurements of these fields, his role on the DOELAP Oversight Board, and in the content of national dosimeter performance standards such as ANSI N13.11-1983 (ANSI 1983).

[23] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is supported in Nichols et al. (1972, pp. 3 and 7) and in Fix et al. (1981. Study 5).

[24] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
These statements are based on judgment by Mr. Fix and require knowledge of the gamma energies associated with the radionuclides in Table 6-9. The prevalent ^{60}Co (1.17 and 1.33 MeV) and ^{137}Cs (0.662 MeV) in several facilities are generally considered to be higher energy gamma radiation, whereas in Hanford plutonium facilities ^{241}Am (59 KeV) is considered to be of low to intermediate energy and the 17-keV radiation (prevalent X-ray from plutonium) is considered to be low-energy.

[25] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The Hanford Multipurpose TLD response to a ^{90}Sr/Y calibration source was about 2 times higher than the response to a uranium calibration source. This is noted in Kocher et al. (1972, p. 7) and Fix et al. (1981 pp. 2.3 and 3.2).

[26] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is based on the judgment by Mr. Fix about the penetrating dose filtration for the two-element film, multielement film, multipurpose TLD and commercial Harshaw dosimetry system used from 1944 through the current time. Fix, Gilbert, and Baumgartner (1994) contains relevant dosimeter deep dose response information for each of the pre-1995 Hanford (see Table 3.1). Rathbone (2002) states that the filtration of the deep dose responsive Harshaw 8825 dosimeter element is about 1,000 mg/cm^2.

[27] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The statements in this table are based on judgment by Mr. Fix of the effects of fading on recorded dose, based on Mr. Fix's assessment of Hanford calibration and control dosimeter procedures used to adjust for known fading. The procedures manuals [HEW (1946) and Hanford External Dosimetry Operating Procedures, July 22, 1963 (GE 1963)] describe fading and calibration practices adopted to adjust for effects on recorded dose.

[28] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The radiation dose fractions presented in Table 6-13 to segregate beta, photon, and neutron dose components into IREP input categories are based on judgment by Mr. Fix.

[29] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data in Table 6-14 were obtained from Table II of Nichols et al (1972).

[30] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data in Figure 6-7 were obtained from Appendix A of Nichols et al. (1972).

[31] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data in Figure 6-8 were determined from the annual collective Hanford recorded dose in Table A.5 of Buschbom and Gilbert (1993) normalized to the plutonium production annual rate in Table 2 of DOE (1996) (annual total in kilograms of plutonium).

[32] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data in Figure 6-8 were determined from the annual collective Hanford recorded dose in Table A.5 of Buschbom and Gilbert (1993) normalized to the plutonium production annual rate in Table 2 of DOE (1996) (annual total in kilograms of plutonium).

[33] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The list of Hanford facilities with a potential for neutron exposure was developed from Hanford Section 2 (ORAUT 2004), experience with Hanford facilities, and historical documentation. The early reactor facility 305 should be included in the 300 Area list.

[34] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The separation of Hanford facilities with neutron radiation into two general categories (i.e., plutonium and reactor facilities) is based on the judgment of Mr. Fix about the expected neutron energy spectra. It should be noted, as described in the next paragraph, that several field measurements of neutron dose and spectra have been performed in Hanford facilities.

[35] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The statement that the ongoing operation of the PFP has continued with the primary purpose to store plutonium is based on judgment by Mr. Fix.

[36] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The statement about research and development in Hanford 300 facilities in preparation for operation of the 400 Area FFTF is based on judgment by Mr. Fix.

[37] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The lognormal plot in Figure 6-13 of data in Table 6-20 was first prepared by Timothy Taulbee.

[38] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The histogram plot in Figure 6-14 was first prepared by Timothy Taulbee.

[39] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment to assume that the reactor front face measurements by Peterson and Smalley (1960) are applicable throughout the operational history of the eight once-through cooling reactors (i.e., no additional shielding added) was first made by Timothy Taulbee.

[40] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment to incorporate a reduced neutron-to-photon ratio for N-Reactor based on the estimated reduction in neutron dose expected following the installation of additional shielding was first made by Timothy Taulbee.

[41] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment to select positive neutron dose results from Hanford claims was originally made by Timothy Taulbee. This resulted in 2003 with the selection of 186 dosimeter results. The frequency distribution of these data was determined and resulted in the lognormal plot provided in Figure 6-15. The lognormal distribution statistical parameters were determined using Crystal Ball. The original analysis has been verified and an updated analysis with similar results conducted with positive neutron dose results available in 2006.

[42] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Figure 6-15 is a histogram plot of the 186 neutron-to-photon dose ratios associated with the positive neutron and photon dosimeter results, respectively, ≥20 mrem for the 186 dosimeter results.

[43] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
As described in the text, Figure 6-16 is the standard lognormal probability plot of the data in Figure 6-15.

[44] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The recommendation to use the claim-specific neutron-to-photon dose ratio if higher than the values in Table 6-22 is to ensure that the neutron dose of record for the claimant is not reduced.

[45] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The neutron-to-photon dose ratios in Table 6-22 are a summary of the values developed in the previous text.

[46] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Tables 6-23 through 6-26 summarize neutron spectral information from measurements described in the respective references. The 0.1- to 2-MeV category represents a substantial component in each workplace, and it alone could be used (i.e., assign 100%) as an analysis that is favorable to claimants.

[47] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The statement that the TLD response decreases with increasing angle is based on the experience and judgment of Mr. Fix. There are many documented studies (such as Rathbone 2002), and angular response documentation is required as part of the DOELAP accreditation of dosimetry systems.

[48] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The statement that the NTA film responds significantly to lower energy photons is based on knowledge of the atomic number (i.e., 47) of silver used in the NTA emulsion and the interaction probability (i.e., photoelectric interaction predominant at low photon energies increases as the 4th or 5th power of the atomic number) of low-energy photons with matter.

[49] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This represents the judgment of Mr. Fix and is substantially based on information in Fix, Wilson, and Baumgartner (1997b).

[50] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The example is intended to aid the dose reconstructor in the conversion of the neutron dose historically based on DOE/AEC recommended quality factors to ICRP Publication 60 weighting factors (ICRP 1990). OCAS-IG-001 (NIOSH 2006) describes the basic requirement to assign an ICRP Publication 60-equivalent neutron dose.

[51] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table 6-29 contains summaries of the neutron dose fractions for different facilities, the factor to transform the neutron dose of record to incorporate ICRP Publication 60 weighting factors (ICRP 1990), and the overall factor that can be used by the dose reconstructor. The process is explained in OCAS-IG-001 (NIOSH 2006) and in ORAUT-OTIB-0055 (ORAUT 2006a).

[52] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This represents the judgment of Mr. Fix and is substantially based on information in Fix, Wilson, and Baumgartner (1997b) and explained in the succeeding sections.

[53] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the method to be used to evaluate missed dose. The method requires that the minimum reportable level or MDL be specified. The values provided are based on the experience and judgment of Mr. Fix, based substantially on information in Wilson, Fix, Baumgartner and Nichols (1990).

[54] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the method to be used to evaluate missed dose. This footnote describes the precise method used to calculate the missed dose shown in Table 6-31.

[55] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the neutron-to-photon dose ratio method to evaluate missed neutron dose. This explanation describes the precise method to be used to calculate the missed neutron dose before 1972.

[56] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the detection level method to evaluate missed neutron dose. This explanation describes the precise method to be used to calculate the missed neutron dose after 1971.

[57] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table 6-31 summarizes for the dose reconstructor the annual missed dose value to be assigned based on the selected methods to assign pre-1972 and post-1971 missed neutron dose.

[58] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes considerations to account for uncertainty as noted in this statement and as further explained in the succeeding sections.

[59] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Hanford claims contain DOE-provided and -recorded dose information. Data for a single

claimant were selected and presented in Figure 6-17 to illustrate the type of data being used in the dose reconstruction process.

[60] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The data in Figure 6-17 for a single claimant were obtained from the DOE dose records for this person for employment at Hanford.

[61] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is originally provided in Wilson (1960b, p. 1) on the potential missed dose for Hanford workers with dosimeters located simultaneously at several Hanford area dosimeter exchange gatehouses.

[62] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The summary estimates of bias and uncertainty in Table 6-32 are based on the judgment of Mr. Fix.

[63] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Validation measurements of personnel neutron dosimeter performance in Hanford workplaces compared to instrument-measured dose have been performed by Scherpelz, Fix, and Rathbone (2000), Endres et al. (1996), and Brackenbush, Baumgartner and Fix (1991). Typically, multiple dosimeters are used in these measurements, such as by placement on the respective sides of a phantom placed in the workplace for an extended period of time. In the judgment of Mr. Fix, a factor of 3 in response is often observed, which illustrates the complexity of the workplace fields.

[64] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
There are several references to the measurement of low-energy photons in the plutonium facilities (see Wilson et al. 1990, Table 8.1 under plutonium finishing facilities). The challenge has been to determine whether the 20% of the open-window response was used in the calculation of the deep or penetrating dose assigned to workers during the period from 1944 to April 1957, when the multipurpose dosimeter was implemented. Because the practice to assign the additional dose has not been validated, the recommendation that is favorable to the claimant was to assign the additional dose, assuming it was not done.

[65] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The underestimate of the neutron dose component assigned to workers before use of the TLD beginning in January 1972 is extensively covered in Biles (1972) and Fix, Wilson, and Baumgartner (1997b).

[66] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The underestimate of the neutron dose component assigned to workers before use of the TLD beginning in January 1972 is extensively covered in Biles (1972) and Fix, Wilson, and Baumgartner (1997b).

[67] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the basic requirement to assign ICRP Publication 60-equivalent neutron dose.

[68] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS-IG-001 (NIOSH 2006) describes the method to be used to evaluate missed dose. The method requires that the minimum reportable level or MDL be specified. The MDL values in

Table 6-34 are based on the experience and judgment of Mr. Fix, based substantially on information in Wilson et al. (1990). The missed annual mean neutron dose before 1972 is based on the missed photon dose multiplied by the neutron-to-photon dose ratio (see Table 6-35) for the facility in which the person was employed.

[69] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table 6-35 summarizes the neutron-to-photon dose ratio to be applied by the dose reconstructor according to worker employment period and primary facility.

[70] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The information in this section is based on the judgment of Mr. Fix recommending to the dose reconstructor, depending on the target tissue, consideration to assign an extremity dose in the event that monitoring for extremity dose is not performed and an extremity dose is not reported by DOE.

[71] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table 6-36 summarizes the Hanford dosimeter dose calculations based on information in Fix, Carbaugh and MacLellan (2001).

[72] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The process of dose reconstruction according to minimizing, maximizing, or best estimate assumptions is described in ORAUT-PROC-0006, “External Dose Reconstruction” (ORAUT 2006b).

[73] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The expression of an estimated standard error of 30% in assigned doses is based on the judgment of Mr. Fix considering information in Appendix B, “Derivation of Performance Criteria” in ANSI (1983).

[74] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is based on Mr. Fix’s experience and judgment as the first DOELAP Oversight Board Chair (1986 to 1901) and continuing Board chair. The DOELAP standard is also available as noted in the references.

[75] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Input instructions in the use of IREP are described in NIOSH (2006). This is readily available from the Office of Compensation Analysis and Support (OCAS) Web site. All claim dose reconstruction uses IREP.

[76] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Input instructions in using IREP are described in NIOSH (2006). This is readily available from the OCAS Web site. All claim dose reconstruction uses IREP.

[77] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This statement is based on Mr. Fix’s experience and judgment in examining the history of dose records for Hanford workers as part of technical support for three combined epidemiologic studies of Hanford workers: Cardis et al. (1995), Cardis et al. (2005), and Gilbert, Cragle, and Wiggs (1993). As one example, a database of 100,000 NTA processing records from 1950 to 1961 was developed as described in Fix, Wilson, and Baumgartner (1997b).

[78] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
OCAS provides an IREP Users Software capability on its Web site for use by dose reconstructors.

[79] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The judgment of favorable to the claimant is based on the calculated highest target organ dose from realistic assumptions of the worker's exposures.

[80] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The radiation dose fractions presented in Table A-2 to segregate beta, photon and neutron dose components into IREP input categories are based on judgment by Mr. Fix.

[81] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The list of Hanford facilities with a potential for neutron exposure was developed from Hanford Section 2 (ORAUT 2004), experience with Hanford facilities, and historical documentation. The early reactor facility 305 should be included in the 300 Area list.

[82] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Potential neutron radiation exposure can be categorized generally according to the two primary reactor and plutonium workplaces based on judgment by Mr. Fix.

[83] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table A-3 contains summaries of the neutron dose fraction for different facilities, the factor to transform the neutron dose of record to incorporate ICRP Publication 60 weighting factors (ICRP 1990), and the overall factor that can be used by the dose reconstructor. The process is explained in OCAS-IG-001 (NIOSH 2006) and ORAUT-OTIB-0055 (ORAUT 2006a).

[84] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Input instructions in the use of IREP including assumptions of distribution type and exposure mode are described in NIOSH (2006). This is readily available from the OCAS Web site. All claim dose reconstruction uses IREP.

[85] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table A-3 summarizes information in Tables 6-23 through 6-26 of the text on neutron spectral information from measurements as described in the references. The 0.1- to 2-MeV category represents a substantial component in each workplace, and it alone could be used (i.e., assign 100%) as an analysis that is favorable to claimants.

[86] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
As noted above, IREP input instructions are described in NIOSH (2006). This is readily available from the OCAS Web site. All claim dose reconstruction uses IREP.

[87] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Hanford dosimeter assignment practices are based on the judgment of Mr. Fix in his experience with the examination of Hanford worker radiological records. DOE-provided claimant data can be examined for monitoring completeness. See also Wilson (1987) and Wilson, Fix, and Baumgartner (1990).

[88] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Hanford practice to record dosimeter processing results is based on the judgment of Mr. Fix in

his experience with the examination of Hanford worker radiological records. DOE-provided claimant data can be examined as well (see also Fix, Carbaugh, and MacLellan 2001).

[89] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Hanford practice to include 20% of the shallow dose in the assignment of a deep dose in plutonium facilities is described in Fix, Wilson, and Baumgartner (1997b, Table 3.1 in the row labeled 1952).

[90] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
This is based on the judgment by Mr. Fix. It is feasible to check this judgment using the dosimeter response data in Wilson et al. (1990, Appendix D).

[91] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The information in Table A-4 is based on the judgment of Mr. Fix as explained in Section 6.3.4.5.

[92] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The information in Table A-4 is based on the experience of Mr. Fix with the validation of the dose of record from individual dosimeter data. This is described in detail in Fix, Carbaugh, and MacLellan (2001). The process can be checked using the individual worker detailed dose information provided by DOE for claimants.

[93] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The information in this section is based on the judgment of Mr. Fix as explained in Fix, Wilson, and Baumgartner (1997b). The use of neutron-to-photon dose ratios to reconstruct dose was also used in the 1972 AEC retrospective evaluation of Hanford worker neutron dose described in Biles (1972).

[94] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The adjustment to the measured photon dose for any missed photon dose prior to application of the neutron-to-photon dose ratio to estimate the neutron dose is required by OCAS-IG-001, Section 2.2.2 (NIOSH 2006). The topic is the focus of ORAUT-OTIB-0023, “Assignment of Missed Neutron Doses Based on Dosimeter Records” (ORAUT 2005c).

[95] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
During the period of use at Hanford of the four-element dosimeter, there was an associated overestimate of the photon dose and an underestimate of the neutron dose. The Site Profile recommendation was to make favorable to claimant adjustments only (i.e., no adjustment to the overestimated photon dose and adjusting the underestimated neutron dose). This recommendation better ensures a dose assignment that is favorable to the claimant. The issue is described on page 6.5 of Fix, Wilson, and Baumgartner (1997b). The issue was extensively examined by the Hanford Personnel Dosimetry Advisory Committee and further documentation particularly during 1983 could be obtained from DOE/RL. See Fix (1983).

[96] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table A-5 provides a summary of the respective neutron-to-photon dose ratios to be used in dose reconstruction of the neutron dose for the respective Hanford facilities.

[97] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The example presented is intended to aid the dose reconstructor in conversion of the neutron dose historically based on DOE/AEC-recommended quality factors to ICRP Publication 60

(ICRP 1990) weighting factors. OCAS-IG-001 (NIOSH 2006) describes the basic requirement to assign ICRP Publication 60-equivalent neutron dose.

[98] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Guidance for dose reconstructors to assign an Energy Employee for employment periods without recorded dose (i.e., unmonitored dose) is a component of routine dose reconstruction. ORAUT-OTIB-0030, "External Dose Coworker Study Data for the Hanford Site" (ORAUT 2005b) provides the coworker data for Hanford.

[99] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table A-6 is a summary of missed photon dose estimates for the dosimeter exchange periods for the convenience of the dose reconstructor. The values implement the requirements of OCAS-IG-001 (NIOSH 2006).

[100] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The missed dose estimate is calculated from the detection level for each dosimeter and the exchange frequency. Because the same dosimeter and dosimeter exchange were used throughout Hanford facilities, the estimated missed dose is the same.

[101] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Data for each responsive element of a dosimeter are typically inadequate to evaluate the range of radiation field energy spectra in the workplace. Information on the source of radiation combined with the dosimeter response does allow an estimate.

[102] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The recommended approach to estimate the missed neutron dose estimates for the dosimeter exchange periods is: (1) for the period before 1972 to base the evaluation on the beta/photon dosimeter detection level and to use a neutron-to-photon dose ratio, and (2) to use the detection level of the TLD from 1972 through the present.

[103] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table A-7 is a summary of missed neutron dose estimates for the dosimeter exchange periods for the convenience of the dose reconstructor based on the beta/photon dosimeter before 1972 using a neutron-to-photon dose ratio and the TLD from 1972 through the present.

[104] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The Hanford TLD responds to neutron radiation; an analysis of the missed dose using the neutron dose detection level of this dosimeter is feasible for the period of its use beginning in 1972 through the present.

[105] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Options to evaluate missed neutron dose after 1971 with the four-chip dosimeter include using the neutron-to-photon dose ratio multiplied by the photon dose detection level or using the detection level of the TLD.

[106] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The missed neutron dose values in Table A-7 include the uncertainty associated with the neutron energy in the workplace.

[107] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
An analysis that is favorable to the claimant is better assured by using the energy range with the highest dose conversion factor.

[108] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
Table 6-8 provides the default dose fractions and associated ICRP 60 (ICRP 1990) correction factors for the respective Hanford facilities for the convenience of the dose reconstructor.

[109] Fix, Jack J. Dade Moeller & Associates. Senior Health Physicist. March 2007.
The approach used to prepare input to IREP is described in ORAUT-PROC-0006 (ORAUT 2006b).

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GLOSSARY

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

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

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

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

algorithm
A computational procedure.

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

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

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

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

Bonner Sphere
See Multi-Sphere neutron Spectrometer

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

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

curie
A special unit of activity. One curie exactly equals 3.7 x 1010 nuclear transitions per second.

Cutie Pie (CP)
A portable ion chamber survey meter with a pistol grip and a large cylindrical ionization chamber.

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

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

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

density reading
See optical density.

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

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

dose equivalent index
For many years, the dose equivalent used to calibrate neutron sources that were used to calibrate neutron dosimeters a concept of summing the maximum dose equivalent delivered in the International Commission on Radiological Units (ICRU) sphere at any depth for the respective neutron energies even though the maximum dose occurred at different depths.

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

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

DuPont 552
A film packet containing two pieces of film: (1) a 502 sensitive film and (2) a 510 insensitive film.

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

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

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

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

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

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

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

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

favorable to claimant
This term refers to the process of estimation based on technical considerations of the parameters significant to dose such that the estimated dose is not underestimated.

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

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

film density
See optical density.

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

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

First Collision Dose
The "first collision dose" can be determined for either photons or neutrons. For neutron radiation, perhaps the simplest calculation that can be made is one relating dose to flux through a thin layer of tissue. The resulting graph, sometimes referred to as the first-collision curve, is derived from the assumption that the probability of two or more interactions per neutron is negligible (Hine and Brownell 1956). Because of the short range of the charged secondary radiation from fast neutrons, the first collision dose in irradiated material is practically the same as the absorbed dose (NBS 1961).

free-field dose equivalent
The dose equivalent assigned for neutron irradiation as if it were performed in free space with no background from air and room scattering and no source asymmetry (Schwartz and Eisenhauer 1982).

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.

Geiger-Mueller (GM) counter
A radiation measuring device used to detect beta and gamma radiation.

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

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

3He Spectrometer
An instrument used to measure neutron energy spectra based on neutron interactions with ^{3}He atoms to produce a triton and a proton that are detected in a proportional counter.

induced radioactivity
Radioactivity produced in certain materials as a result of nuclear reactions particularly the capture of neutrons.

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

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

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

kilo-electron volt (keV)
An amount of energy equal to 1,000 electron volts.

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

Manhattan Engineer District (MED)
U.S. agency designated to develop nuclear weapons and a predecessor to the U.S. Department of Energy (DOE).

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

minimum recorded dose
Based on a policy decision, the minimum dose level that is routinely recorded. A closely related concept is the dose recording interval. Hanford has generally recorded minimum doses of 10 mrem and at intervals of 10 mrem (i.e., 10, 20, 30, etc.).

million-electron volt (MeV)
An amount of energy equal to 1,000,000 electron volts.

Multiple-Collision Neutron Dose
The “multiple collision dose” for neutron radiation relates the dose to flux through tissue based on the assumption that two or more interactions per neutron occurs resulting in greater energy deposition.

Multi-Sphere Neutron Spectrometer
The multi-sphere neutron spectrometer consists of a series of neutron moderating spheres of tissue equivalent material with a neutron detector positioned at the middle of the respective spheres. Algorithms are used to unfold the data to calculate the neutron spectra.

nuclear emulsion
Generally refers to NTA film.

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

neutron, fast
Neutrons with energy equal or greater than 10 keV.

neutron, intermediate
Neutrons with energy between 0.4 eV and 10 keV.

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

neutron–to-photon dose ratio
In this TBD, this term refers to a neutron-to-photon dose ratio that is used with the photon fraction to estimate the unmeasured neutron dose.

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

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

open window (OW)
Designation on Hanford film dosimeter reports for nonpenetrating dose based on film response in this region with little (i.e., no metallic filter, only security credential) shielding.

operating area
Designation of Hanford major operational work areas among the respective fuel fabrication (e.g., 300), reactor operations (e.g., 100B, 100C, 100D, 100DR, 100F, 100H, 100KE, 100KW, 100N), chemical separations (e.g., U-Plant, T-Plant, B-Plant, UO3 Plant, Reduction Oxidization [REDOX] Plant and PUREX Plant)), plutonium finishing (Z-plant), research and development (e.g. 300, 3000), and transportation, communication and general site support (e.g., 600, 700, 1100).

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

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

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

PuF_4 source
A neutron source with plutonium tetrafluoride activating material. The source was used to duplicate the neutron energies in Hanford's plutonium facilities generally referred to as the 200 Area Z-Plant or plutonium finishing plant.

Personal Dose Equivalent, $H_p(d)$

Radiation quantity recommended for use as the operational quantity to be recorded for radiological protection purposes by the International Commission on Radiological Units and Measurements (ICRU 1993). The Personal Dose Equivalent is represented by $H_p(d)$, where d identifies the depth (in mm) and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 mm and is noted as $H_p(0.07)$. For penetrating radiation of significance to “whole-body” dose, d = 10 mm and is noted as $H_p(10)$.

photon

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

photon dose fraction

In this TBD, this term has been used to identify the fraction of the measured photon dose used to estimate the unmeasured neutron dose by multiply this fraction times the neutron-to-photon dose ratio.

precision

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

quality factor, Q

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

rad

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

radiation

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

radiation monitoring

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

radioactivity

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

random errors

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

RBE

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

rem

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

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

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

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

shallow dose equivalent (Hs)
Dose equivalent at a depth of 0.07 mm in tissue.

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

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

sigma pile
A device used to obtain thermal neutrons for calibration purposes.

silver shield(s)
The 1-mm- and 0.13-µm-thick shields covering the film packet in the early Hanford personnel film dosimeters.

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

Snoopy
A portable neutron monitoring instrument with a moderated BF3 detector.

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

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

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

Tissue Equivalent Proportional Counter (TEPC)
This device is used to measure the absorbed dose from neutron radiation in near tissue equivalent materials and, through analysis of the counter data, determination of the effective quality factor and the dose equivalent.

TLD chip
A small block or crystal made of LiF used in the TLD.

TLD-600 - A TLD chip made from Li-6 (>95%) used to detect neutrons.

TLD-700 - A TLD chip made from Li-7 (>99.9%) used to detect photon and beta radiation.

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

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

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

X-ray
Ionizing electromagnetic radiation of extranuclear origin.

Z-Plant
A Hanford facility, composed of several buildings, where plutonium is processed (also known as 234-5-Z Building).

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A.0 DISTRIBUTION PARAMETERS

Several technical parameters of the U.S. Department of Energy (DOE)-provided dose of record information are considered in the evaluation of individual claims. The focus of this attachment is to ensure a favorable to claimant analysis that considers the uncertainty in historically recorded dose. These doses are often based on less capable technology than currently available. A basis of comparison for evaluation of dose is the *Personal Dose Equivalent,* $H_p(d)$, where d identifies the depth (in mm) and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 mm and is noted as $H_p(0.07)$. For penetrating radiation of significance to "whole-body" dose, d = 10 mm and is noted as $H_p(10)$. $H_p(0.07)$ and $H_p(10)$ are the radiation quantities recommended for use as the operational quantity to be recorded for radiological protection purposes by the International Commission on Radiological Units and Measurements (ICRU). These are the dose quantities used to accredit DOE dosimetry programs since the mid-1980s [74].

The primary Interactive RadioEpidemiological Program (IREP) screen used to input dose parameters is in Table A-1. Input to these fields is obtained from the Hanford dose of record. The claim provides the primary organ of interest and other worker information needed to run IREP. Guidance for the selection of the parameters in Table A-1 by the dose reconstruction analyst is presented in the following sections [75].

Table A-1. IREP dose parameter input screen [76].

Exposure				Distribution parameters			
#	Year	Rate	Radiation type	Type	1	2	3
1	1960	Acute	Photon, 30-250 keV	Normal	2	2	0
2	1961	Acute					

A.1 YEARS OF EXPOSURE

The years of exposure should be identified from the claim information and from the DOE radiation dose reports. For years with no recorded radiation dose, a missed dose as described later in this section is calculated for all zero or missing records. Hanford policies required monitoring of all workers who entered a radiological control area and radiological monitoring staff were present in all primary facilities with the responsibility to ensure radiation protection guidelines were followed. Valid reasons are expected for years in which there is no recorded dose (i.e., a blank entry) [77].

A.2 RATE

Acute is selected for all types of external beta and photon dose. Chronic is selected for neutron dose [78].

A.3 RADIATION TYPE

The evaluation is separated into beta/photon and neutron dose as described in the following sections.

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A.3.1 Beta/Photon

Assumptions favorable to claimants should be made using guidance in Table A-2 for beta and photon radiation. The values presented in this table are intended to provide a favorable to claimant estimate of parameters to be used to calculate the organ dose for long-term Hanford workers in the respective facilities [79].

Table A-2. Selection of beta and photon radiation energies and percentages [80].

Process/ buildings	Description	Operations Begin	Operations End	Radiation type	Energy selection, keV	Percentage
Fuel fabrication	Produced reactor fuel and target assemblies from uranium.			Beta	>15	100%
	313, 306, 333	1945	1972	photon	30–250	100%
Reactors	**During operation:** highly dispersed fields of higher energy photon radiation fields from fission process, activation and fission product nuclides. Potentially narrow beams of higher energy neutron radiation from test ports, etc., into reactor core. Potential for significant airborne nuclides, and there might be significant higher energy beta radiation.			Beta photon	>15 30–250 >250	100% 25% 75%
	Not in operation: highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides. No significant neutron radiation. There might be significant higher energy beta radiation during maintenance work resulting from fission products.					
	B-Reactor	9/26/44	1946			
		1948	2/12/68			
	D-Reactor	12/17/44	6/26/67			
	F-Reactor	2/23//45	6/25/65			
	H-Reactor	10/29/49	4/21/65			
	DR-Reactor	10/50	12/31/64			
	C-Reactor	11/18/52	4/25/69			
	KW-Reactor	12/54	2/1/70			
	KE-Reactor	2/55	1/28/71			
	N-Reactor	12/63	1/6/87			
	B-Reactor	9/44	2/68			
	D-Reactor	12/44	6/6/67			
	FFTF	2/9/80	12/93			
Processing plants	**Radiochemical operations:** highly dispersed fields of higher energy photon radiation fields from activation and fission product nuclides dominant to most exposure profiles. Potential for higher-energy beta radiation during sampling and maintenance work resulting from fission products.			Beta photon	>15 30–250 >250	100% 25% 75%
	T Plant	12/26/44	3/56			
	B Plant	4/13/45	1956			
	S Plant (Redox)	1/51	12/67			
	C Plant	7/52	7/67			
	A Plant (Purex)	1/56	6/72			
		1983	1988			
	U Plant	3/52	1/58			
	UO_3 Plant	56				

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Process/ buildings	Description	Operations		Radiation type	Energy selection, keV	Percentage
		Begin	End			
Plutonium production	**Plutonium component production:** plutonium is machined into weapon components using a glovebox assembly process with predominant close anterior exposure to workers. Radiation characteristics in this area involve significant lower energy photons and neutron radiation.			Photon	<30 30–250	25% 75%
	Plutonium storage: radiation characteristics in these areas generally involve dispersed lower energy scattered photons, including- 60 keV ^{241}Am- gamma ray and neutron radiation.					
	200 Area PFP, Z-Plant, 234-5Z, 231-Z, etc.	1945	2003			
	300 Area Plutonium Laboratories 308/309, 324		2003			
Calibrations	Hanford site calibration of instruments and dosimeters			Beta photon	>15 30 – 250 >250	100% 25% 75%
	3745-A, 318	1945	2003			
Waste handling	Radiation characteristics are highly dependent on source of waste, but typically fission product nuclides (Sr/Y-90, Cs-137) are dominant.			Beta photon	>15 30–250 >250	100% 50% 50%
	200East and West	1953	2003			

Neutron circumstances of neutron exposure at Hanford facilities is based on the facility of worker primary employment and separated generally according to [81]:

1. 200 and 300 Area plutonium facilities where neutron radiation is generated from plutonium either by spontaneous fission or, importantly, by alpha particle interaction with light elements such as oxygen, fluorine and beryllium.

2. 100 and 400 Area reactor facilities where neutron radiation is generated by fission of uranium and plutonium in the reactor core.

Potential neutron radiation in the 300 area facilities generally involved laboratory experiments related primarily to nuclear fuel development as well as neutron dose calibration of instruments and personnel dosimeters used throughout Hanford. These sources of neutron radiation exposure of workers should be evaluated according to the two general methods of neutron exposure (i.e., reactor or plutonium) that most closely fits the exposure pattern [82].

Simplified assumptions are presented in Table A-3 for neutron radiation. These values are intended to provide a favorable to claimant estimate of parameters to be used to calculate the organ dose for long-term Hanford workers in the respective facilities [83].

A.4 DISTRIBUTION PARAMETERS

The selection of the distribution parameters in Table A-1 is discussed in the following sections.

A.4.1 Type

The selection of a normal distribution for the type determines the definition of Parameters 1 and 2. For a normal distribution, Parameter 3 is not used [84].

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Table A-3. Hanford facility neutron radiation energies, percentages, and default neutron dose fractions International Commission on Radiological Protection (ICRP) 60 correction factors [85].

Process	Description/buildings	Neutron energy (MeV)	Default dose fraction (%)	ICRP 60 correction factor
Reactors	During reactor operation: low level neutron exposure through shielding on the face of the reactors and through test ports.			
	B, D, F, H, DR, C, KW, KE, N	0.1-2	100	1.91
	FFTF	0.1-2 2-20	50 50	0.95 0.65
Plutonium production	Plutonium finishing process: plutonium enters the process as PuF_4 and is then fired into production pucks. Work is primarily conducted in glove boxes with predominant close anterior exposure to workers. Radiation levels at the beginning of the process are fairly constant while levels at end of process are closely related to production levels.			
	Plutonium facilities (200 Areas) (224-T, 231-Z, 232-Z,, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U)	0.1-2 2-20	90 10	1.71 0.13
	Plutonium laboratories (300 Area) (308, 309, 324)			

A.4.2 Parameter 1

For a normal distribution, parameter 1 is the mean of the distribution of recorded dose for each year of monitoring. Before calculating this, it might be necessary to adjust the recorded dose to provide a favorable to claimant estimate of $H_p(10)$ in accordance with information in the following sections [86].

A.4.2.1 Resolution of Recorded Dose Components

Hanford radiation monitoring policies prior to the mid-1990s required workers to be assigned a dosimeter for any entry into a radiologically controlled area. Beta/photon personnel dosimeters were assigned to all personnel and, in some facilities, personnel were also assigned a neutron personnel dosimeter. All dosimeters were processed and the results recorded. For any missing dosimeter data, an investigation was conducted to assign a dose to the worker. As such, the recorded dose record should be complete. Any blank results (i.e., for neutron dosimeters) are expected to be represent situations where the worker did not enter a radiologically controlled area or the dosimeter (i.e., neutron) was not used. Since the mid-1990s, dosimeters are assigned only to workers anticipated to exceed a whole body dose of 100 mrem/year [87].

There are three major changes in the format of Hanford dosimeter processing results corresponding to the major changes in dosimeter types. This is clarified as follows [88]:

- **Before 1957** – This period is characterized by use of the two-element dosimeter with doses reported for the film response behind the open window (OW) and 1-mm silver filtration (S). The nonpenetrating dose is typically referred to OW on the processing forms, but it might be identified as beta. The penetrating dose is typically referred to as S (i.e., silver) on the processing forms but it might be identified as gamma. During this period, Hanford processing data were manually recorded. As such, these forms were updated each year to allow staff to directly record dosimeter results for each dosimeter exchange period and for each operating area. These forms were organized to allow the dosimeter results to be totaled to manually

calculate and record the annual dose for each worker. In the latter 1950s, the annual dose data were transferred to the newly implemented Hanford radiological computer system.

- **1957 through 1971** – This period is characterized by the use of multielement film dosimeters that included an X-ray component in addition to the beta and gamma identified doses. To calculate the whole-body dose, 35% of the X-ray dose was added to the gamma dose (plus any neutron dose). To calculate the skin dose, the X-ray dose was added to the gamma dose (plus any neutron dose). The tritium dose was added to the whole-body and skin dose components beginning in about 1964. During this period, the dose results were computerized providing easy to read summaries.

- **1972 to present** – This period is characterized by the use of thermoluminescent dosimeters (TLDs) that measured the beta, photon, and neutron dose. For the Hanford Multipurpose Dosimeter (HMPD), the doses were typically referred to as nonpenetrating, penetrating, slow neutron, and fast neutron. Later, the $H_p(d)$ dose quantities were used in DOE Laboratory Accreditation Program (DOELAP) performance testing. The whole-body dose was calculated as the sum of the penetrating [later $H_p(10)$], slow neutron and fast neutron doses. The skin dose was calculated as the sum of the nonpenetrating [later $H_p(0.07)$] plus the whole-body dose. Until about 1987, the tritium dose was also included in the whole-body and skin doses.

A summary of the respective Hanford recorded dosimeter recorded quantities and the compliance skin and whole body dose quantities based on the foregoing are shown in Table A-4.

A.4.2.2 Adjustments to Recorded Penetrating Dose

No adjustment in the recorded photon dose is recommended for multielement or thermoluminescent dosimeter recorded penetrating or gamma dose with the exception of the penetrating dose (i.e., identified as S dose in the early years) recorded for the two-element film dosimeter used prior to April 1957. For this dosimeter, the adjusted penetrating dose is calculated as follows [89]:

Adjusted penetrating dose = penetrating dose (i.e., S) + (0.2 * nonpenetrating dose (i.e.,OW)

The adjustment is <u>to be applied only</u> to workers in Hanford 200 Area plutonium facilities. Significant errors will occur if this adjustment is applied to nonplutonium facility exposure [90].

A.4.2.3 Adjustments to Recorded Neutron Dose

Studies have shown a significant potential for under-estimation of the neutron dose for Hanford workers exposed to neutron radiation <u>prior to</u> implementation of the HPMD on January 1, 1972. The vast majority of neutron dose to Hanford workers was received at the 200 West Area Plutonium Finishing Plant (PFP) facilities. There is potential for significant missed dose in Hanford 300 Area plutonium facilities (308, 309, 324). There is also evidence of missed neutron dose to workers in the Hanford 100 Area reactor facilities. There is potential missed dose in Hanford 300 Area accelerator (3754B) and calibrations (3745, 318) and 400 Area Fast Flux Test Reactor facilities [91].

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Table A-4. Historical Hanford recorded dose practices [92].

Year	Dosimeter measured quantities	Compliance dose quantities
Two-element beta/photon film dosimeter[a]		
1944–47	OW = open window, mrep S = "silver filter" dosimeter response, mR	Skin = OW + S WB = S
1948–50	Beta = open window, mrep gamma = "Silver filter" dosimeter response, mR	Skin = beta + WB WB = Gamma
Two-element beta/photon film dosimeter + Nuclear Track, Type A emulsion (NTA) neutron dosimeter		
1950–57	Beta = open window, mrep Gamma = "silver filter" dosimeter response, mR	Skin = beta + WB WB = Gamma + Neutron
Multielement beta/photon dosimeter + NTA neutron dosimeter		
1957–58	Beta Gamma X-ray Neutron	Skin = beta + gamma + 65% X-ray + neutron WB = gamma + 0.35% X-ray + Neutron
1959–71	Beta (-B-) Gamma (-G-) X-ray (-X-) Fast neutron (F-N) Slow neutron (S-N)	Derma (skin) = beta + WB + 65% X-ray WB (penetrating) = gamma + neutron + 35% X-ray)
Thermoluminescent dosimeter		
1972–94	Nonpenetrating (NPEN) Penetrating (PEN) Slow neutron (SN) Fast neutron (FN)	Skin = NPEN + WB WB= PEN + SN + FN
1995–2003	Shallow (Sh Deep (Dp) Neutron (Nt)	Skin = Sh + Dp + Nt WB = Dp + Nt

a. From 1948-56, when dosimeter quantities for each period were noted as beta or gamma, the cumulative dosimeter dose quantities continued to be labeled as OW and S.

Before 1972. The neutron dose recorded historically at Hanford prior to the January 1, 1972, implementation of the HMPD is not accurate and likely to be significantly under-estimated. The only option to arrive at a favorable to claimant estimate of neutron dose prior to 1972 is to utilize neutron-to-photon dose ratios. Essentially, all Hanford radiological work areas that involved significant neutron radiation also had significant photon radiation that was reliably measured [93].

To arrive at a favorable to claimant analysis, a neutron dose should be calculated in all Hanford facilities with any potential for neutron dose using a neutron-to-photon ratios listed in Table A-5. The photon dose should be adjusted for any missed dose before applying the neutron-to-photon ratio to estimate the neutron dose [94].

After 1971. Neutron dose measurements at Hanford after 1971 with the five-chip HMPD and Harshaw TLD provide reasonable agreement with published field measurements with one exception. The exception concerns use of the four-chip HMPD during the period of its use from July 1978 through December 31, 1983 in Hanford 200 and 300 Area plutonium facilities only. During this period, the adjusted neutron dose is calculated as follows [95]:

Table A-5. Hanford neutron-to-photon dose ratios [96].

Process	Description/buildings	Neutron-to-photon ratio		
		Geometric mean (GM)	**Geometric standard deviation (GSD)**	**Upper 95th%**
Reactors	During reactor operation: low level neutron exposure through shielding on the face of the reactors and through test ports.			
	B, D, F, H, DR, C, KW, KE Reactors	0.41	2.79	2.23
	N Reactor	0.06	3.00	0.37
	FFTF	1	1	1
Plutonium production	Plutonium finishing process: plutonium enters the process as PuF4 and is then fired into production pucks. Work is primarily conducted in glove boxes with predominant close anterior exposure to workers. Radiation levels at the beginning of the process are fairly constant while levels at end of process are closely related to production levels.			
	Plutonium facilities (200 Areas) (224-T, 231-Z, 232-Z,, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U)	0.73	2.10	2.47
	Plutonium laboratories (300 Area) (308, 309, 324)			

Adjusted neutron dose = 1.35 * recorded neutron dose

ICRP 60 Equivalent Neutron Dose. Historically, Hanford incorporated the energy variation of the dose equivalent into the calibration methodology. As a result, the recorded dose equivalent (DE_R) is a combination of all neutron energies. To calculate the probability of causation, the recorded neutron dose must be separated into neutron energy groups. Table A-3 summarizes favorable to claimant default neutron dose fractions by energy for work areas where field measurements of neutron spectra were performed and using the associated ICRP 60 correction factors. The neutron dose equivalent is calculated by multiplying the recorded neutron dose by the area-specific correction factors. For example, consider a 1,000-millirem recorded neutron dose by a worker at the PFP, the corrected neutron dose is 1,710 millirem from neutrons between 0.1-2.0 MeV estimated to represent 90% of the dose fraction (i.e., 1,000 * 1.71) **and** 130 millirem from neutrons with energy between 2 and 20 MeV estimated to represent 10% of the dose fraction (i.e., 1,000 * 0.13). Thus, the corrected neutron dose is a total of 1,840 millirem. These adjustments should be applied to measured dose, missed dose, and dose determined based on a neutron-to-photon ratio [97].

A.4.2.4 Unmonitored Photon Dose

Adjustments to the recorded annual dose can be made using dose results for coworkers or the recorded dose before and after the period of missed dose. These situations require careful examination since Hanford policy was to monitor all workers who entered a radiological controlled area, and to estimate and record the dose for any missing results [98].

A.4.2.5 Missed Photon Dose

Missed photon dose for Hanford workers can occur where (1) there is no recorded dose because workers were not monitored or the dose is otherwise unavailable, and (2) a zero dose is recorded for the dosimeter systems for any dosimeter response less than the Minimum Detection Level (MDL). Estimates of the missed dose can be made using dose results for coworkers or using the recorded

dose before and after the period of missed dose. However, these situations require careful examination. The missed dose for dosimeter results less than the MDL is particularly important for earlier years, when MDLs were higher and dosimeter exchange was more frequent. NIOSH (2006) describes options to calculate the missed dose. One option is to estimate a favorable to claimant maximum potential missed dose where the MDL/2 is multiplied by the number of zero dose results. Table A-6 summarizes the potential missed photon dose adjustments according to year, facility/location, dosimeter type, and energy range.

Table A-6. Missed photon dose adjustments to recorded deep dose [99].

Period		Dosimeter	MDL[b] (rem)	Exchange frequency	Annual missed dose (rem)[c]
Default year	**Period of use[a]**				
1944	Prior to October 1944	PIC	0.005	Daily (n=250)	0.625
1945–1950	October 1944–December 1950	Hanford two-element film	0.040	Weekly (n=52)	1.040
1951–1957	January 1951–March 1957		0.040	Biweekly (n=26)	0.520
1957	April 1957–May 1957	Hanford multielement film	0.040	Biweekly (n=26)	0.520
1958–1971	May 1957–December 1971		0.040	Monthly (n=12)	0.240
1972–1994	January 1972–December 1994	Hanford TLD	0.020	Monthly (n=12)	0.120
			0.020	Quarterly (n=4)	0.040
1995–2005	January 1995–2005 (ongoing)	Harshaw TLD	0.010	Monthly (n=12)	0.060
			0.010	Quarterly (n=4)	0.020

a. For many years, Hanford workers had a dosimeter assigned to each operating area where they worked.
b. Estimated MDLs for each dosimeter technology in the workplace.
c. Annual missed dose calculated from OCAS-IG-001 (NIOSH 2006).

Year. Table A-6 summarizes the potential maximum missed photon dose according to year using the default year shown in column 1.

Facility/Location. The potential missed photon dose for the respective Hanford facilities is similar and, as such, Table A-6 can be used based on the year [100].

Dosimeter Type. The potential missed photon dose for the respective periods of use, dosimeter types, MDL, and the exchange frequency is included in Table A-6.

Energy Range. An estimate of the missed photon dose by energy range is possible based on the type of facility and predominant radionuclides such as intermediate (>100 keV) energies for all

facilities handling activation and fission product nuclides, primarily lower energy (<100 keV) photons for plutonium facilities and for uranium fuel fabrication facilities. The recorded dose from the dosimeter response does not typically provide sufficient information to estimate discrete energy ranges. It is possible to examine the energy response characteristics of the respective multielement dosimeters, but this analysis does not recognize the substantial uncertainties present in the workplace associated with shielding, radiation scattering, and mixed radiation fields [101].

A.4.2.6 Missed Neutron Dose

Neutron radiation was present in the 100 Area reactors, 200 Area plutonium, 400 Area Fast Flux Test Reactor (FFTF), 300 Area accelerator (3754B), calibrations (3745A and 318 Buildings) calibration facilities. There is a potential for significant missed neutron dose only for workers in the 200 Area PFP facilities that separated and finished plutonium (i.e., 224-T, 231-Z, 232-Z,, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U) for use in nuclear weapons and some potential for significant missed neutron dose in

the 300 Area Building 308 Plutonium Fabrication Pilot Plant and at the Building 309 Plutonium Research Test Reactor. The missed dose is calculated using Table A-5 and the MDL information for the TLDs in Table A-7. Table A-7 summarizes the period of use for Hanford neutron dosimeters for plutonium and non-plutonium facilities [102].

Table A-7. Hanford neutron dosimeter period of use, type, MDL, exchange frequency, and potential annual missed dose [103].

Period of use	Dosimeter	Exchange frequency	MDL (rem)[a]	Max. annual missed dose (rem)[b]
October 1944–December 1949	PICs with 10B enriched liners	Daily[c] (n=250)	0.010	1.300
January 1950–December 1950	NTA	Weekly (n=52)	0.080	2.100
January 1951–March 1957		Biweekly (n=26)	0.080	1.000
April 1957–May 1957		Biweekly (n=26)	0.080	1.000
May 1957–December 1971		Monthly (n=12)	0.080	0.500
TLD Dosimeter				
January 1972–December 1994	HMPD	Monthly	0.050	0.300
January 1995–present	Harshaw TLD	Monthly	0.015	0.100

a. Estimated film dosimeter photon radiation detection levels before 1972 and neutron dosimeter MDLs after 1971.
b. Annual missed neutron dose calculated using: Prior to 1972, neutron-to-photon ratio after combining the recorded and missed photon dose. The actual maximum annual missed dose will be the product of two lognormal distributions. After 1971, the lognormal distribution from the neutron dosimeter using a geometric mean of (n * MDL/2) and an upper 95% confidence interval of (n * MDL), where n is the number of missing dosimeter results.
c. Dosimeter not routinely assigned.

Year. The approach used to calculate the neutron missed dose can be divided into two periods. The first period is before 1972 where the neutron dose is estimated from the measured and missed, respectively, photon dose using neutron-to-photon dose ratios. The second period is after 1971 using TLDs [104].

Before 1972. There is essentially no recorded neutron dose prior to 1950 when ^{10}B-lined PICs were used. Recorded neutron dose using the NTA film will likely underestimate significantly the actual neutron dose (Fix, Wilson, and Baumgartner 1997b).

Due to the uncertainty in whether an employee's NTA badge would respond to the workplace neutron spectrum, using a ratio of the neutron-to-photon dose is a favorable to claimant option to reconstruct an individual worker neutron dose. This is based on the fact that routine neutron exposure is essentially always accompanied with measurable photon exposure (Watson 1959). The approach is illustrated as:

$$\text{Missed Neutron dose} = \text{missed photon dose} * \text{neutron/photon dose ratio}$$

The 95th percentile neutron/photon dose ratio can be used to estimate the maximum missed neutron dose.

After 1971. Neutron dose assessment with the five-chip HMPD provides reasonable agreement with published field measurements. The potential missed neutron dose for the MDL and exchange frequency using NIOSH (2006) guidance is shown in Table A-5 for this time period [105].

Facility/Location. The potential missed neutron dose for the MDL and exchange frequency using NIOSH (2006) is shown in Table A-7.

Dosimeter Type. The potential missed dose for neutron dosimeters is strongly dependent on the neutron radiation field characteristics of the different Hanford facilities. This is also included in Table A-7 [106].

Energy Range. An estimate of the missed neutron dose by energy range is possible based on the type of facility and predominant neutron energies measured during the respective field measurements. The recorded neutron dose from the HMPD and Harshaw commercial TLD response does not provide sufficient information to estimate discrete energy ranges. Favorable to claimant defaults are proposed based on available workplace spectra measurements. The values are listed in Table A-8. Since spectra measurements were not available for the single-pass reactors, a favorable to claimant default value of 100% fission spectra neutrons is assumed. This assumption is the most favorable to claimants because the Radiation Effectiveness Factors in the probability of causation (POC) calculation are the greatest for this energy range [107].

Table A-8. Hanford facility dose fractions and associated ICRP 60 correction factors [108].

Process	Description/buildings	Neutron energy (MeV)	Default dose fraction (%)	ICRP 60 correction factor
Reactors	During reactor operation: low level neutron exposure through shielding on the face of the reactors and through test ports.			
	B, D, F, H, DR, C, KW, KE, N	0.1-2 MeV	100%	1.91
	FFTF	0.1-2 MeV 2-20 MeV	50% 50%	0.95 0.65
Plutonium production	Plutonium finishing process: plutonium enters the process as PuF_4 and is then fired into production pucks. Work is primarily conducted in glove boxes with predominant close anterior exposure to workers. Radiation levels at the beginning of the process are fairly constant while levels at end of process are closely related to production levels.			
	Plutonium facilities (200 Areas) (224-T, 231-Z, 232-Z,, 234-5Z, 236-Z, 242-Z, 2736-Z, 271-U)	0.1-2 MeV 2-20 MeV	90% 10%	1.71 0.13
	Plutonium laboratories (300 Area) (308, 309, 324)			

A.4.2.7 Organ Dose

Once the adjusted photon and neutron doses have been calculated for each year, the values are used to calculate the organ dose distribution for the primary organ of interest identified in the claim. The front of the worker's torso is expected to have received the greatest cumulative exposure and thus the AP orientation is typically selected. A comparison of dose conversion factors for the respective exposure geometries for the organ of interest can be made to determine a realistic option to perform a favorable to the claimant analysis.

A.4.3 Parameter 2

Parameter 2 is the standard deviation of the normal distribution for the organ dose. The individual dose result for each dosimeter exchange period will be available to calculate the mean and standard deviation for each year. If it is not available, the adjusted organ dose can be used for each year and a default standard deviation value used for parameter 2 [109].

A.4.3.1 Hanford Workplace Recorded Dose Uncertainty

Uncertainty in the recorded dose is an important consideration in favorable to claimant analyses. The overall uncertainty depends on (1) administrative practices, (2) dosimetry technology, (3) calibration, and (4) workplace radiation fields (Fix et al. 1997a). The potential effect of each of these parameters on the recorded dose is described in the proceeding sections.