Document Title:	Document Number:	ORAUT-TKBS-0006-6
Hanford Site – Occupational External Dose	Revision:	03
	Effective Date:	06/05/2007
	Type of Document	TBD
	Supersedes:	Revision 02

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☐ New ☐ Total Rewrite ☒ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
10/10/2003	00	First approved issue. Initiated by Edward D. Scalsky.
01/09/2004	01	Approved Issue of Revision 01. Initiated by Edward D. Scalsky.
10/05/2006	01 PC-1	Approved page change revision to add updated required language on page 8 in Section 6.1. Adds Purpose Section (6.1.1) and Scope Section (6.1.2) to page 9. Makes reference to ORAUT-OTIB-0017 on page 10 in Section 6.2 for guidance to be used. Adds two references to pages 56 and 58 in Reference Section. No changes occurred as a result formal internal review. Incorporates NIOSH formal review comments. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Edward D. Scalsky. Approval: Signature on File 09/02/2006 Edward D. Scalsky, Document Owner Signature on File 09/05/2006 John M. Byrne, Task 3 Manager Signature on File 09/29/2006 Edward F. Maher, Task 5 Manager Signature on File 10/03/2006 Kate Kimpan, Project Director Brant A. Ulsh Signature on File for 10/05/2006 James W. Neton, Associate Director for Science
11/21/2006	02	Approved Revision 02 to incorporate SC& A comments and responses to claimant concerns. Constitutes a total rewrite of document. Incorporates internal and NIOSH formal review comments. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Edward D. Scalsky.
06/05/2007	03	Approved revision initiated to include Attributions and Annotations. No further changes occurred as a result for formal internal review. Incorporates formal NIOSH review comments. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Edward D. Scalsky

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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.

- 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:

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.

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].

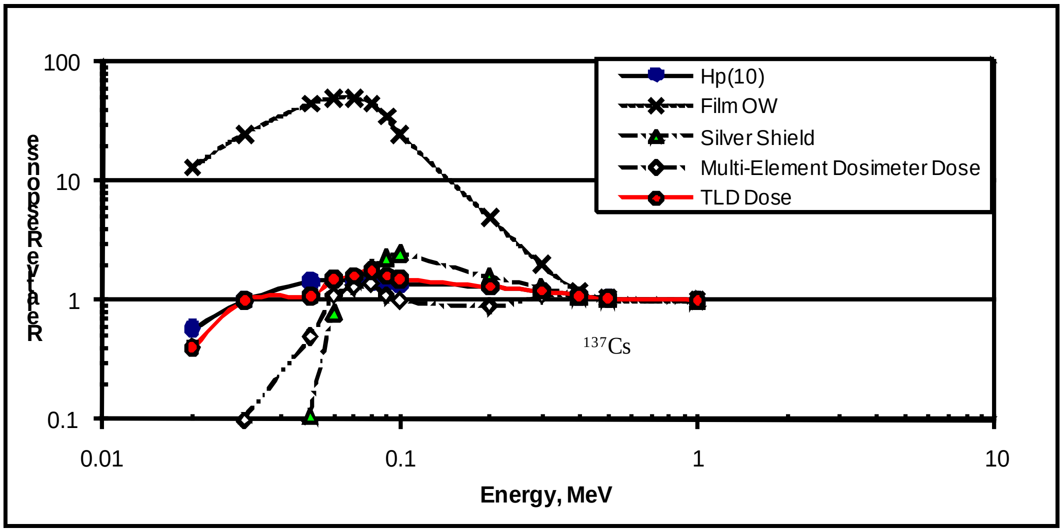

Figure 6-3. Measured Hanford dosimeter photon response characteristics (Wilson et al. 1990).

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		TLD 1972–present	Film dosimeters		TLD 1972–93
	Two-element 1944–56	Multielement 1957–71		Two-element 1944–56	Multielement 1957–71	
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

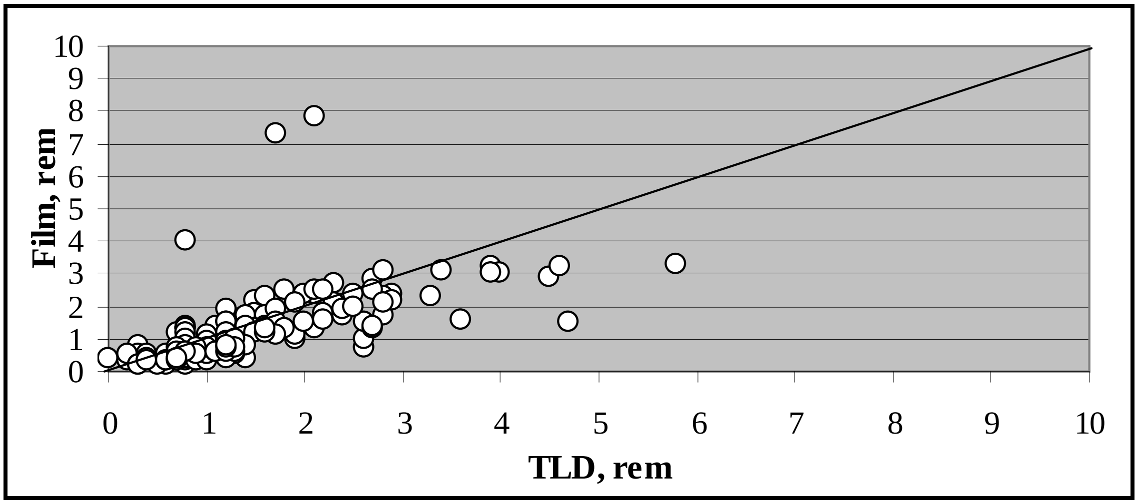

Figure 6-4. Comparison of Hanford film and TLD penetrating dose results (Nichols et al. 1972).

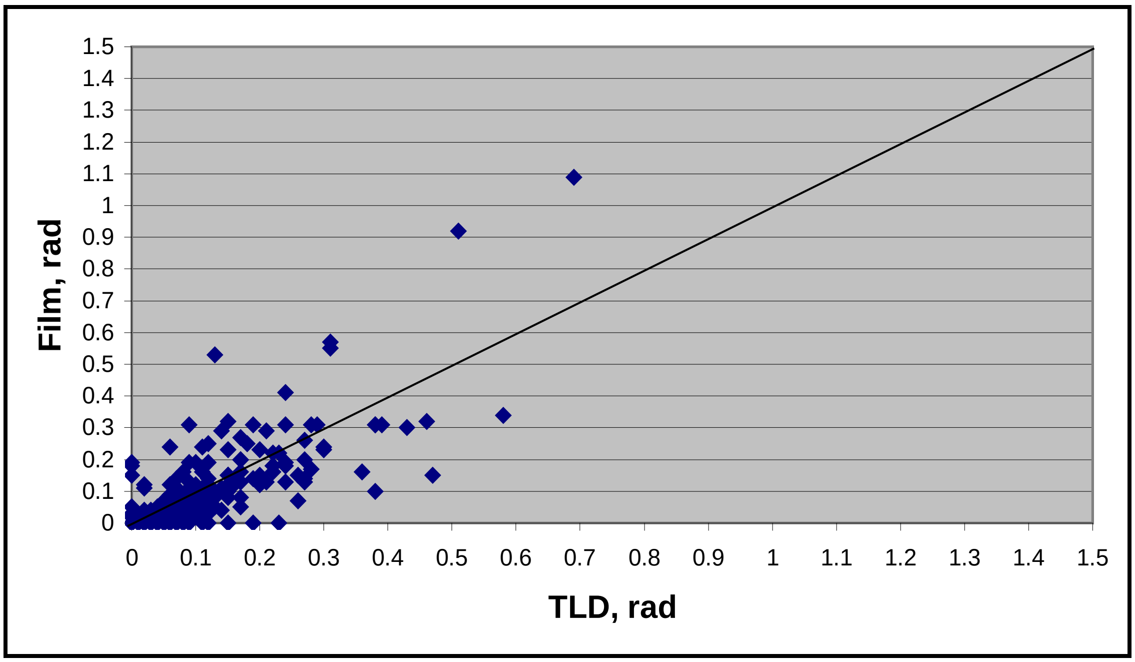

Figure 6-5. Comparison of Hanford film and TLD nonpenetrating dose results (Nichols et al. 1972).

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

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.

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

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

- 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	l	0.300	0.120	
Hanford Commercial TLD	1995-present	Monthly	30	10	l	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:

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

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 $D = \text{Log}_{10} (I_o/I)$.

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 2.58×10^{-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).

ATTACHMENT A
OCCUPATIONAL EXTERNAL DOSE FOR MONITORED WORKERS

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