ORAU TEAM
Dose Reconstruction
Project for NIOSH

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Document Title:	
A Standard Complex-Wide Methodology for Overestimating External Doses Measured with Film Badge Dosimeters	Document Number: ORAUT-OTIB-0010 Revision: 01 Effective Date: 06/05/2006 Type of Document: OTIB Supersedes: Revision 00

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Document Owner Approval:	Signature on File James P. Griffin, Deputy Project Director	Approval Date:	05/17/2006
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Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	06/05/2006

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/12/2004	00	New Technical Information Bulletin for a Standard Complex-Wide Correction Factor for Overestimating External Doses Measured with Film Badge Dosimeters. First approved issue. Initiated by Donald N. Stewart.
06/05/2006	01	Constitutes rewrite of document as a result of biennial review. Incorporates resolution of S. Cohen & Associates final draft comments contained in "The Review of NIOSH/ORAUT Procedures and Methods used for Dose Reconstruction" (ref: letter from John Mauro to David Staudt, dated January 17, 2005). Approved issue of Revision 01. 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 Jack J. Fix and Donald N. Stewart.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AP	anterior-posterior
CFR	Code of Federal Regulations
cm	centimeter
DCF	Dose Conversion Factor
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
INEEL	Idaho National Environmental and Engineering Laboratory
$H_p(d)$	Personal Dose Equivalent
keV	kilovolt-electron
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MDL	minimum detection level
MED	Manhattan Engineer District
MeV	megavolt-electron
mg	milligram
mm	millimeter
mR	milliroentgen
NTS	Nevada Test Site
NVLAP	National Voluntary Laboratory Accreditation Program
ORNL	Oak Ridge National Laboratory
ORAUT	Oak Ridge Associated Universities Team
OW	open window
PIC	Pocket Ionization Chamber
RFP	Rocky Flats Plant
SRS	Savannah River Site
TIB	technical information bulletin
TLD	thermoluminescent dosimeter
U.S.C.	United States Code

1.0 INTRODUCTION

Technical information bulletins (TIBs) 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. TIBs may be used to assist the NIOSH staff in the completion of individual dose reconstructions.

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.

The Manhattan Engineer District (MED) and later the U.S. Atomic Energy Commission (AEC) had early responsibility for processing nuclear weapons material. The AEC was superseded in this function briefly by the Energy Research and Development Agency, and then DOE. In this document, "DOE" is used as a term of convenience to mean the Department of Energy and its predecessor agencies.

Essentially all DOE sites followed a similar evolution in external dosimetry technology. Early two-element film dosimeter designs were followed by multielement film dosimeter designs; thermoluminescent dosimeters (TLDs) replaced film dosimeters from the late 1960s through the early 1980s. Information in this Oak Ridge Associated Universities Team (ORAUT) TIB supports radiation dose estimates for complex-wide cases over the period of photographic film dosimetry beginning in 1950. Uncertainties inherent in applying simplifying overestimating assumptions for film dosimeters are greater than during the later period of TLD use. The use of film dosimetry systems in DOE facilities continued generally through about 1980. Film systems are typically significantly more variable in response to photon radiation. For this reason, dose reconstructors must exercise care in the selection of cases that are processed under the assumptions in this TIB. Case selection will be based on the likelihood that the assumptions applied here provide a claimant-favorable overestimate of dose once site- and case-specific exposure conditions are taken into account. Do not use this TIB for sites at which significant personnel doses could result from the presence of elevated airborne levels of environmental radioactivity.

This TIB is based on the feasibility to formulate reasonable, overestimating, complex-wide assumptions for interpreting recorded photon dose for monitored employees with likely-non-compensable claims. This is due to the high degree of standardization of DOE film-based dosimeter programs. In accordance with the process efficiencies discussed in 42 CFR pt 82, the TIB analysis selected a reasonable overestimate of external radiation dose for cases that are judged likely-noncompensable. This overestimate of the actual dose enables the expeditious processing of likely-noncompensable cases. Accordingly, this TIB should only be used for monitored employees with likely non-compensable claims

1.1 OBJECTIVES

The objectives of this document are to (1) evaluate the degree of standardization of typical DOE film dosimeters and (2) develop a standard methodology for use by the dose reconstructor to assign a dose, based on the recorded dose, that will result in a reasonable overestimate of the organ dose. Information in this document examines the response of film to radiation, the performance of film dosimeters compared to TLDs, and the application of a standard methodology to overestimate doses and to address uncertainties from the following sources:

- Variation in workplace photon radiation fields
- Variation in workplace exposure geometries
- Variation in worker orientation in the workplace, the organ of concern, and the range of values for organ dose conversion factors presented in *External Dose Reconstruction Implementation Guidelines* (NIOSH 2002)

While accounting for these uncertainties, the methodology proposed here takes into account similarities among sites across the DOE complex in the following attributes:

- Similar dose response performance by photon energies among the dosimeters used
- Similar minimum detection levels (MDLs)
- A standard exchange frequency

The proposed methodology considers variability associated with a large number of program features. The methodology must admit a greater degree of error into any estimate it modifies. The error is permissible as long as it is in the claimant's favor. Specifically, any error must tend to assuredly overestimate rather than to reduce the claimant's probability of causation.

Because the intent is to overestimate the dose for a quick evaluation of the potential for compensability, the proposed methodology is useful only for claims that are judged to be likely-noncompensable. The latest revision of ORAUT-OTIB-0017 (ORAUT 2005) should be used for assignment of shallow doses.

2.0 COMPLEX-WIDE STANDARD OVERESTIMATING METHODOLOGY

The following sections describe three components of the standard methodology to overestimate the organ dose assigned to a claimant for a likely-noncompensable claim:

- Recorded dose
- Dose Conversion Factor
- Missed dose

Recommendations are provided in the following with supporting information presented in Appendix A.

2.1 OVERESTIMATING APPLIED TO RECORDED DOSE

This TIB recommends a standard overestimating approach that, with a single modifying value applied to the recorded dose, increases the assigned deep dose to claimants to overestimate the actual organ dose. Based on performance testing results described in Appendix A, dose reconstructors should use a modifying factor of 2. The purpose of this factor is to ensure claimant-favorable assigned deep dose by compensating for uncertainty from potential variance in site-specific exposure conditions and calibration practices that, without correction, could have resulted in an underestimated dose.

2.2 OVERESTIMATING APPLIED TO ORGAN DOSE CONVERSION FACTOR

This TIB recommends a standard overestimating approach to select the organ DCF. Use the exposure (R)-to-organ (H_T) DCF value for the AP geometry for photons of energies between 30 and 250 keV from Appendix B of NIOSH (2002) unless that value is less than 1.0, in which case the DCF will be 1.

2.3 OVERESTIMATING APPLIED TO MISSED DOSE

This TIB recommends a standard overestimating approach to determine the missed dose in accordance with NIOSH (2002) guidance by inputting into IREP, for a lognormal distribution, a parameter #1 value of 0.24 R based on a default limit of detection (LOD) of 0.04 R and a monthly exchange [i.e., 12 * 0.04)/2]. This recommendation is based on consideration that the sensitivity of the film determines the lowest level of dose that can be detected. A typical value of film sensitivity is 0.5 net optical density units per 400-mR exposure (NRC 1989). This translates to a LOD of between 10 and 20 mR for films with this sensitivity for photons above a few hundred keV (NRC 1989). A review of doses reported by individual site dosimetry programs was done and film badge readings recorded as "< 10 mrem" were noted. However, dose reconstructors should ignore these low values. This review of site dosimetry programs also showed that 1960 is significantly predated by the first year of monthly dosimeter exchange for most sites, and thus the selection of 1960 as the year of first applicability of these recommendations and a default of 12 dosimeter exchanges per year. However, if the dosimetry record indicates the number of "zero" results is greater than 12 exchanges in a year, (i.e., such as every 4 weeks = 13 or biweekly = 26, etc.) use the larger number of exchanges in the missed dose calculation.

2.4 APPLICATION OF STANDARD OVERESTIMATING ASSUMPTIONS

Table 2-1 lists standard values recommended in Sections 2.1 through 2.3. These values can be applied to recorded doses from film dosimeter data. The assumptions in Table 2-1 support complex-wide dose overestimates from 1960 and later for workplaces without significant low-energy photon contributions. Section 3.0 contains examples of such workplaces.

Application of the values in Table 2-1 is based on the period of applicability for the site in question from 1960 until the date of first use of TLDs, as noted in Appendix A, Table A-1. For TLDs, use the guidance in the latest revision of ORAUT (2006a). This guidance should not be applied prior to 1960 without justification because of the potential unreliability of the respective correction factors particularly the site dosimeter exchange frequency, which might have been as often as weekly or even daily in the late 1940s to early 1950s. The response characteristics of film dosimeter systems prior to 1960 are probably similar to the information in this TIB but require further evaluation.

Table 2-1. Standard overestimating approach.

Parameter	Analysis	Standard overestimating approach
Recorded dose	Film typically over-responds in workplaces other than noted in Section 6.0.	Multiply recorded dose by factor of 2, incorporate DCF as described below, and enter as constant value in IREP
DCF	AP geometry, 100% 30-250 keV photon radiation (exposure)	DCF = ≥ 1[a] (constant)
Missed dose	Zero recorded dose.	Lognormal distribution, IREP parameter #1 = 0.24[b] IREP parameter #2 = 1.52

a. From Appendix B of NIOSH (2002): a value of 1.0 or the table value (typically assume 100% AP geometry), whichever is greater.

b. Use TBD identified value, if available. Otherwise use this value based on $(n * 0.04)/2$,, where n = 12.

3.0 WORKPLACE CHARACTERISTICS THAT PRECLUDE UNSUPPORTED APPLICATION OF THE OVERESTIMATING ASSUMPTIONS IN THIS DOCUMENT

Workers in the DOE complex who had significant exposure to low-energy photons might have recorded doses that do not reliably represent actual photon doses in the film badge era. Application of the assumptions presented here is not appropriate unless individual dose reconstruction reports specifically support justification. Examples of workplaces that would typically have spectra with significant low-energy photons include:

- Weapons assembly and disassembly areas
- Plutonium machining areas
- Plutonium processing facilities in areas where the primary hazard is from the product
- Laboratories performing work with plutonium or americium

In addition, dose reconstructors might encounter specific situations where workplace characterization suggests exposure to photons in the lowest energy range (less than 30 keV) or to lower energy photons in the intermediate range, up to 100 keV, which comprise a significant proportion of the dose.

4.0 EVALUATION OF SHALLOW DOSES MEASURED WITH FILM BADGES

Dose reconstructors should not use this TIB for evaluation of shallow doses. (NOTE: For breast and testicular cancer cases, use this TIB only for calculating the deep dose component.) ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (ORAUT 2005) and ORAUT-PROC-0006, *External Dose Reconstruction* (ORAUT 2006b), provides guidance for estimating shallow doses.

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ATTACHMENT A
TECHNICAL BASIS FOR RECOMMENDATIONS
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A.1 DOSIMETRY DEVELOPMENT AND BASIS OF COMPARISON

A.1.1 Dosimetry Development

DOE sites followed a similar evolution in photon film dosimetry technology to measure photon dose to workers. Two-element film dosimeters were commonly used in the 1940s and were replaced by multielement film dosimeters. Film dosimeters were gradually replaced by thermoluminescent dosimeters (TLDs) in the late 1960s, 1970s, and 1980s. Pocket Ionization Chambers (PICs) have typically been used in addition to personnel dosimeters throughout the years of DOE operations and results from PICs compared with those from TLDs. Table A-1 lists this pattern for DOE sites. These sites, and probably others, basically have equivalent dosimetry technology capabilities for photon radiation. The adequacy of the respective photon dosimetry methods to measure radiation photon dose accurately is determined from response characteristics of the dosimetry technology according to the radiation type, energy, exposure geometry, etc., as described in this section.

Table A-1. Evolution in DOE site photon dosimetry capabilities.

		Year of first use			
		Photographic film dosimeter		TLD	
Site	Site profile reference	Two-element	Multielement	Site-specific	Commercial
Fernald	ORAUT-TKBS-0017-6	1952	1954	N.A.[a]	1985
Hanford	ORAUT-TKBS-0006-6	1944	1957	1972	1995
INEEL	ORAUT-TKBS-0007-6	1951	1957	1966	1986
K-25	ORAUT-TKBS-0009-6	1944	1953	1980	1988
LLNL	ORAUT-TKBS-0035-6	1952[b]	N.A.	1969	1985
LANL	ORAUT-TKBS-0010-6	(c)	1950	1978	1999
Mound	ORAUT-TKBS-0016-6	1943[d]	N.A.	N.A.	1977
NTS	ORAUT-TKBS-0008-6	1951[e]	1966	1970	1987
ORNL	ORAUT-TKBS-0012-6	1944	1953	1974	1988
Pantex	ORAUT-TKBS-0013-6	1951[f]	(c)	1973	1980
Portsmouth	ORAUT-TKBS-0015-6	1954	N.A.	1981	1999
RFP	ORAUT-TKBS-0011-6	1951[g]	1954	1969	1983
SRS	ORAUT-TKBS-0003	1951[h]	1959	1970	1982
Y-12	ORAUT-TKBS-0014-6	1948	1961	1980	1988

a. N.A. – not applicable
b. LLNL used dosimeter capabilities from Lawrence Berkley Laboratory during 1952–1955 prior to implementing its site-specific system.
c. LANL used other dosimeter designs prior to 1950.
d. Mound used dental film initially and then began using the ORNL dosimeter design in February 1949.
e. LANL was responsible for external dosimetry at NTS in the beginning (1951). Reynolds Electrical & Engineering Company assumed responsibility in 1955.
f. Pantex used a commercial film service that probably used a multielement film dosimeter after the initial two-element dosimeter; the precise date of change has not been determined.
g. RFP used dosimeter capabilities from LANL until it implemented a site-specific system.
h. SRS used dosimeter capabilities from ORNL until it implemented a site-specific system.

Table A-2 lists a more detailed example of the evolution in dosimetry technology for Hanford, INEEL, ORNL, and SRS. This level of detail in the dosimetry design is an important consideration in evaluating the adequacy of the dosimetry technology. Dosimetry technology capabilities that can be inferred from this information include the following:

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Table A-2. Chronology of DOE site improvements to personnel dosimetry systems.

Facility	Period Start	Period End	Dosimeter material	Type	Filters	Density[(a)] (mg/cm^2)	Thickness (mm)
Hanford	1944	1944	PIC				
	1944	1952	Film	DuPont 552	OW, Ag	~0, Ag = 1,050	0, Ag = 1
	1953	1956	Film	DuPont 552	OW, Ag	~0, Ag = 1,050	0, Ag = 1
	1957	1962	Film	DuPont 552	OW, Al, Ag#1, Ag#2	~0; Al = 132; Ag#1 = 137; Ag#2 = 1,050	0
	1963	1971	Film	DuPont 558	OW, Fe, Ta	~0; Fe = 20; Ta = 843	0, 0.025, 0.5
	1972	1995	TLD	Five/four chips	OW, Al, Cd, Sn, Sn	~0;379; 912; 980; 912	0.05
	1995	-	TLD	Harshaw 8825	OW, pl, Sn, Cu	~0; 1,000,	0.64
INEEL	1951	1956	Film	DuPont 552	OW, Cd	~0; ~1,000	0; 1
	1957	1965	Film	DuPont 552	OW, Al, Ag, Cd	~0; 175, 203, 950	
	1966	1985	TLD	Two chips	OW, Al (Cd)	~0; 203 (0; 950)	
	1986	-	TLD	Panasonic 814/ 808	Al/plastic (4)	~16; 58; 600; 600	
ORNL	1943	1944	PICs				
	1944	1952	Film	DuPont 552	OW, Cd	~0; ~1,000	0; 1
	1953	1957	Film	DuPont 552	OW, Pb, Cd, Cu, plastic	~0; varies, ~1,000	
	1958	1979	Film	DuPont 552	OW, Al, Cd, plastic	~0; varies, ~1,000	
	1980	1988	TLD	Two chips	OW (plastic) , Al	~0; 430	
	1989	-	TLD	Harshaw 8805	OW, plastic, Cu, Teflon	~0; 300; 242; ~1,000	
SRS	1951	1958	Film	DuPont 552	OW, Cd	~0; ~1,000	Cd =1
	1958	1970	Film	DuPont 555	OW, Al, Ag	~0; 540; 1,050	Al = 2; Ag = 1
	1970	1982	TLD	Two chips	OW, Al	~0; 540	Al = 2
	1982	-	TLD	Panasonic, UD-802	Mylar, plastic+ mylar, plastic+ mylar, Pb	~0; 300; 300; ~1,000	Pb = 0.7

a. Density thickness of filtration in holder only. Total density thickness would also include filtration in the dosimeter card and responsive elements.

- Capabilities existed to measure the nonpenetrating or shallow [$H_p(0.07)$] and penetrating or deep [$H_p(10)$] dose with these dosimeter designs.

- The dosimeter designs ensured minimal effect on the penetrating dose component of typical beta radiation nuclides in the workplace because of the 1,000-mg/cm^2 density thickness of the metal filter. This thickness approximates the 1-cm depth in tissue [i.e., $H_p(10)$] such that any beta contribution to the dosimeter-calculated deep dose could be considered a true penetrating dose.

The most serious limitation of the two-element film dosimeter designs listed in Table A-2 concern mixed beta/photon radiation fields in which the shallow dose might be significantly in error (typically interpreted dose is too high for the usual uranium calibration and dosimeter over-response to lower energy photons) because of an inability to distinguish between beta and low-energy photon radiation.

Section A.2.1 describes this limitation, which was the motivating reason for the development of multielement film dosimeters.

A.1.2 Basis of Comparison

Since the initiation of the MED in the early 1940s, various radiation dose concepts and quantities have been used to measure and record occupational dose. A basis of comparison for reconstruction of dose 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 by the International Commission on Radiological Units and Measurements as the operational quantities to be recorded for radiological protection purposes (ICRU 1993). In addition, $H_p(0.07)$ and Hp(10) are the radiation quantities used in DOE Laboratory Accreditation Program (DOELAP) and National Voluntary Laboratory Accreditation Program (NVLAP) dosimeter performance testing (DOE 1986; Torres 2005).

A.2 DOSE RECONSTRUCTION PARAMETERS

Examinations of the beta and photon (X-ray, gamma ray) radiation type, energy, and geometry of exposure in the workplace, and the characteristics of the respective dosimeter response are relevant to the assessment of bias and uncertainty, respectively, of the original recorded dose in relation to the radiation quantity $H_p(10)$. The bias and uncertainty for current DOE dosimetry systems is well documented for $H_p(0.07)$ and $H_p(10)$ under DOELAP. The performance of current dosimeters can be compared with performance characteristics of historical dosimetry systems in the same, or highly similar, facilities or workplaces.

Overall, the accuracy and precision of original recorded individual worker doses and their comparability that dose reconstructors should consider in using NIOSH (2002) guidelines depend on the following (Fix, Wilson, and Baumgartner 1997):

- **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** at each site/facility, which can include mixed types of radiation, variations in exposure geometries, and environmental conditions

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

Each of these dependent factors must be evaluated. For cases requiring a detailed dose estimate, the evaluations must be based on an analysis of site-specific information, which is applied to formulate a realistic best dose estimate. For cases that are probably noncompensable, overestimating dose is appropriate, so dose reconstructors can use a modifying factor that increases the recorded deep dose to account sufficiently for variance in site practices. Identifying an appropriate value for this modifying factor is the goal of this document.

A.2.1 Dosimetry Technology

Personnel film dosimeters used to measure doses to workers from photon radiation were essentially identical at the MED Metallurgical, Clinton, and Hanford laboratories in the early to mid-1940s. Parker (1945) described results of an intercomparison study of dosimeter processing and exposure calculations between these laboratories prior to declaring the Hanford system capable of routine dosimeter processing. Ongoing comparisons of dose interpretation among these MED/AEC sites and other sites occurred through the years (Wilson et al. 1990). The dosimeter exchange frequency gradually lengthened, generally corresponding to the period of regulatory dose controls (GE 1954).

A.2.1.1 Two-Element Film Dosimeters

The two-element dosimeter was based on laboratory studies that identified the preferred element and thickness for a metallic filter to flatten the dosimeter photon energy response at lower energies (Pardue, Goldstein, and Wollan 1944). Pardue, Goldstein, and Wollan recommended selection of a filter of cadmium (Z = 47) about 1 mm thick to minimize the film energy response and still enable measurement of lower energy photons. The DOE sites used cadmium and other elements such as silver (Z = 48) or tin (Z = 50) in their designs with essentially the same photon response. The two-element dosimeter was first used at the University of Chicago (Thornton, Davis, and Gupton 1961). This dosimeter design was adopted for use at ORNL and referred to as the “tin” badge (Thornton, Davis, and Gupton 1961). There appear to have been some refinements in this basic design at ORNL where five design changes occurred (Thornton, Davis, and Gupton 1961) and at LANL by adding filters of lead (Z = 82) and brass (Cu = 29, Zn = 30) to obtain improved capabilities in beta/photon fields and in photon energy resolution. These refined dosimeter designs, using two or three metallic filters, provided improved capabilities for distinguishing between beta and photon radiation (primarily) and, with knowledge of the workplace radiation field, between beta and lower and higher energy photon radiation.

An important feature of the DOE site photon dosimeters was the selection of the type of film to be used. The available film had similar radiation energy response characteristics but its sensitivity to radiation varied (Thornton, Davis, and Gupton 1961). Many sites used film, such as the DuPont 502 type, with a sensitive (lower radiation dose response) and an insensitive (typically accident-level dose response) side to each film packet. In normal practice, only the sensitive side of the film was processed for personnel dose assessment. However, for higher doses and to confirm higher suspicious readings, the insensitive film response could be measured.

The two-element dosimeter design had an open window (OW) to measure nonpenetrating radiation in addition to the filter region with 1 mm of silver, cadmium, or tin. Each metallic filter had a density thickness of approximately 1,000 mg/cm^2. This selection minimizes the potential for beta radiation to contribute to the interpreted penetrating dose. Only beta radiation with energy greater than about 3 MeV can penetrate the filter and contribute to the interpreted penetrating dose.

Studies of film dosimeter performance, stability of latent image, etc., were performed during the 1950s (Wilson 1957, 1960). Numerous intercomparison and performance studies were done at the DOE laboratories (AEC 1955; Brodsky and Kathren 1963; Barber 1967; Wilson et al 1990). Figure A-1 shows the laboratory measured anterior-posterior (AP) photon energy response of the two-element dosimeter system in comparison with $H_p(10)$. As indicated in the figure, the film dosimeter OW response shows a significant over-response to lower energy photon radiation. The over-response was so significant operationally 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); there is reference to using a fraction (e.g., 20%) 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 1997; Taylor et al. 1995).

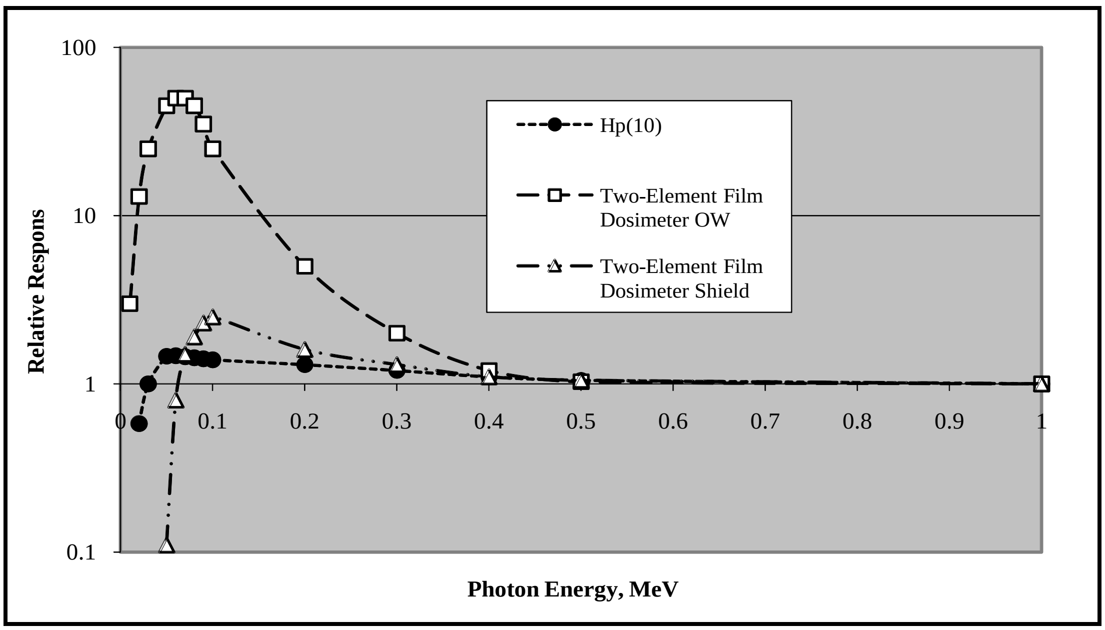

Figure A-1. Measured two-element dosimeter photon response for AP exposure geometry (Pardue, Goldstein, and Wollan 1944; Wilson et al. 1990).

A.2.1.2 Multielement Film Dosimeters

Multielement film dosimeters were developed to provide improved capabilities to measure beta and lower and higher energy photon radiation dose components, particularly in mixed beta and photon radiation fields. Most DOE sites used several site-specific designs. The basic design of the two-element dosimeter (i.e., open window and 1-mm silver, cadmium, or tin shield) was often incorporated by the sites in the design of the multielement dosimeters. Multielement beta/photon film dosimeters generally consisted of three or four shielded areas and provided substantially improved capabilities for measuring deep dose by flattening the overall response, as shown in Figure A-2. Processing results (i.e., optical density) were recorded for the film response behind each of these filters and an algorithm was used to calculate the dose components.

ATTACHMENT A
TECHNICAL BASIS FOR RECOMMENDATIONS

A.2.2 Dosimeter Performance Studies

Performance testing of personnel dosimetry systems is typically an ongoing activity by the dosimetry service provider and a routine component of dosimeter processing quality control. Well-documented independent performance studies of personnel film dosimeters have been conducted by the AEC (1955), Brodsky and Kathren (1963), Unruh et al. (1967), the U.S. Public Health Service (Barber 1967), the NVLAP, and Thierry-Chef et al. (2002). The combination of these studies involved many laboratories and dosimetry systems. For example, the Public Health Service study involved approximately 2,000 film badges from 25 organizations (Barber 1967). The NVLAP dosimeter performance testing program initiated in the mid-1980s involves essentially all commercial dosimeter service organizations in the United States. Performance testing is typically repeated every 2 years to maintain DOELAP or NVLAP accreditation.

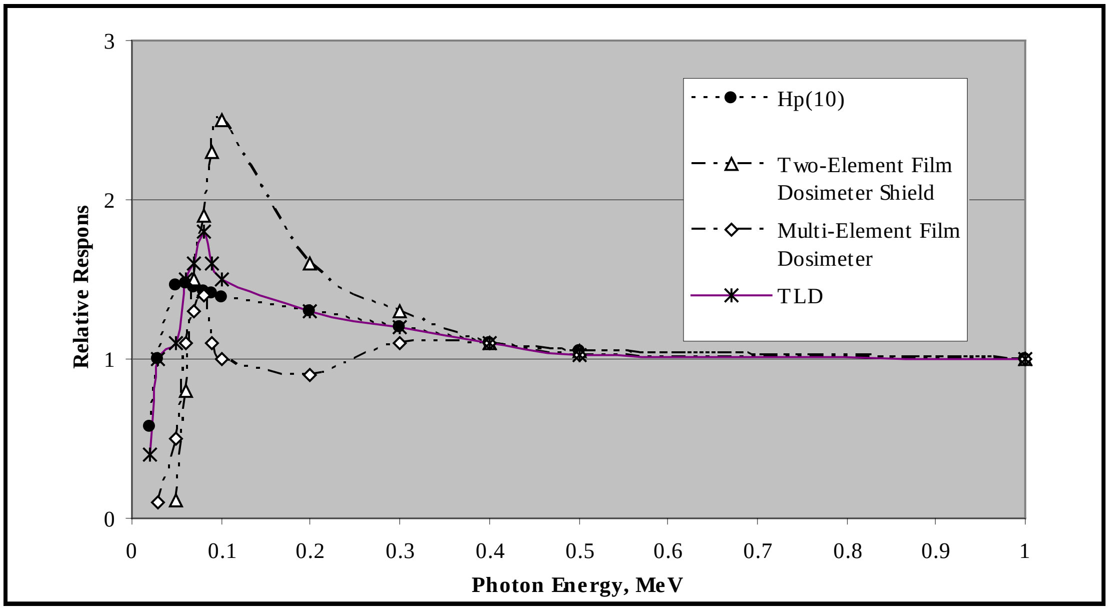

Figure A-2. Measured deep dose response for Hanford two-element film, multielement film, and thermoluminescent dosimeter compared to $H_p(10)$ (Wilson et al. 1990).

A simple representation of the measured performance in these studies of dosimeter systems, in the categories of testing, is probably not possible. In addition, it is not possible to represent generally the improved performance associated with the ongoing evolution in dosimetry technology. National Sanitation Foundation Standard No. 16 (Barber 1967) presented upper and lower error factor limits that ranged from about 30% low to about 100% high (i.e., an asymmetric interval that is biased high) for beta and photon (X-ray and gamma) fields, and mixtures of beta and photon radiation. NVLAP and DOELAP testing protocols have varied somewhat, but fundamentally contain a tolerance criterion of bias plus one standard deviation between 0.3 and 0.5 (relative error) in routine beta, photon, and mixed beta/photon test and accident categories determined for 15 test dosimeters submitted in monthly exchanges of five dosimeters per test category for a 3-month period.

ATTACHMENT A
TECHNICAL BASIS FOR RECOMMENDATIONS

A.2.2.1 Film Badge Response in Comparison with $H_p(10)$

As can be seen in Figures A-1 and A-2, the comparison of typical film badge deep dose performance to $H_p(10)$ dose demonstrates that the deep dose (1) generally under-responds to photons of energies less than about 60 keV, (2) generally over-responds to photons of higher energies to about 250 keV, and (3) compares well for energies greater than about 250 keV. Figure A-1 shows that for the shallow dose, the OW portion of the two-element film badges over-responds substantially at even very low energies in relation to energies greater than about 250 keV. This over-response is corrected with the compensating design of the multielement film badge as shown in Figure A-2, although somewhat overcompensated in that the deep dose is slightly under-responded to photons between about 100 and about 250 keV. The typical workplace radiation field will contain many different photon energies.

A.2.2.2 Interpretation of DOE Film Badge Records

The predominant concern with regard to interpreting film badge results is the potential deep dose under-response to photons of energies less than about 60 keV. For this reason, dose reconstructors should not apply the dose parameters in this TIB to workplaces with extensive exposure to low-energy photons. Workplace radiation fields that included photons in the less-than-30-keV energy range are probably underestimated by the two-element film badge dosimeter in particular; for this reason, the dose reconstruction report or an appropriate supporting document should discuss assumptions dealing with this dose component, such as with workers who worked directly with plutonium. An early practice was to assign a fraction (20%) of the nonpenetrating dose to the penetrating dose to compensate for the under-response. The dose reconstructor must be aware of site-specific protocols for adjusting OW dose when applying the provisions of this TIB to workplaces with the potential for low-energy photon exposure.

Another concern related to interpreting film badge results is the potential shallow dose over-response in the OW reading to photons of energies typically less than about 250 keV. This is not necessarily of concern for dose reconstruction. The error in this case occurs on the side of the claimant because the film badge result overestimates the shallow dose the energy employee might have received. Dose reconstructors can make adjustments to this overestimated dose component as necessary on a case-by-case basis. An example of a common adjustment, in accordance with ORAUT (2005) is to multiply the OW photon dose response of the two-element dosimeter shown in Figures A-1 and A-2 by 0.6.

The strategy for interpretation of documented film badge results from DOE records can be summarized by the following:

- Shallow or deep dose from photons in the standard energy range of greater than 250 keV can be interpreted as exposure without modification.

- Deep doses for multielement film dosimeter doses can be slightly underpredicted between about 100 keV and about 250 keV.

- Deep dose from photons is not reliably estimated in the lowest energy range, less than 30 keV, and performance around 60 keV is questionable. Workplaces with photons from plutonium are not adequately characterized by the assumptions in this document; therefore, deep dose reconstructions that involve exposure to plutonium and those that utilize dose from the lowest photon energy range must document assumptions on a case-by-case basis.

- Shallow dose from photon radiation for energies less than 250 keV can be substantially overestimated unless special precautions were taken. This can be a significant issue for mixed beta/photon radiation fields.

The pattern in recorded shallow and deep doses and general knowledge of workplace radiation fields allow judgment of the reasonableness of the recorded doses.

A.2.3 Site-Specific Information

Site-specific information is necessary to develop detailed dose estimates. This is done to evaluate the performance of the dosimetry technology in the actual workplace radiation fields and the site-specific administrative practices regarding use of the dosimeters and practices. This establishes a basis to calculate and record occupational dose for individual workers. For cases that are probably noncompensable, however, dose reconstructors can apply a standard overestimating methodology that overestimates dose to account for site-specific variations as described in Section 2.0.

A.2.3.1 Workplace Radiation Fields

Table A-3 summarizes common beta/photon personnel dosimeter parameters important to $H_p(10)$ performance in the workplace. Based on energy response characteristics, DOE film dosimeters are expected to reasonably measure the $H_p(10)$ dose in many workplace photon radiation fields, subject to limitations noted in OTIB Sections 3 and 4. This is particularly true for long-term workers with many dosimeter results, which tends to improve the accuracy of dose estimation because potential effects from extremes in workplace exposure geometries and radiation fields are minimized. Adjustments to dose measured by film dosimeters is not recommended. However, the biases listed in Table A-3 are of sufficient magnitude that the respective default factors in Section 2.0 of this OTIB must be sufficiently high to ensure claimant-favorable dose assignment

Table A-3. Common workplace photon dosimeter $H_p(10)$ performance.[a]

Parameter	Description	Workplace bias[b]
Exposure geometry	Dosimeter systems commonly calibrated using AP laboratory irradiations	Recorded dose of record probably **too low** because dosimeter response is often lower at angles other than AP. This assessment assumes calibration of the dosimetry system to Hp(10) in an AP exposure geometry, which is the common practice.” Effect is highly dependent upon radiation type and energy.
Missed dose	Doses less than MDL recorded as zero dose	Recorded dose of record probably **too low.**
Environmental effects	Workplace heat, humidity, etc., fade dosimeter signal.	Recorded dose of record probably **too low.**

a. Judgment based on common dosimeter response characteristics and workplace radiation fields.
b. Recorded dose compared to Hp(10).