
**Pacific Northwest
National Laboratory**

Operated by Battelle for the
U.S. Department of Energy

**Hanford External Dosimetry
Technical Basis Manual
PNL-MA-842**

B. A. Rathbone

March 12, 2007

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830



DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY

operated by

BATTELLE

for the

UNITED STATES DEPARTMENT OF ENERGY

under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>



This document was printed on recycled paper.

(9/2003)

Environmental Technology Directorate
Health Effects and Risk Sciences Division

HANFORD EXTERNAL DOSIMETRY TECHNICAL BASIS MANUAL

In case of termination or transfer, return this
Manual to Document Control, K3-70

Responsible Staff Member:



B. A. Rathbone, Technical Manager
Hanford External Dosimetry Program
Radiation & Health Technology

Approved for Use by:



J. R. Hilliard, Program Manager
Hanford External Dosimetry Program
Radiation & Health Technology



M. L. Johnson, Manager
Radiation & Health Technology

Pacific Northwest National Laboratory
Richland, Washington 99352

THIS PAGE INTENTIONALLY LEFT BLANK

Preface

The Hanford External Dosimetry Program (HEDP) provides support to the U.S. Department of Energy's Richland Operations Office (RL), Office of River Protection (ORP), Pacific Northwest Site Office (PNSO), and DOE contractor radiation protection organizations in determining doses-of-record from external sources of radiation. The Pacific Northwest National Laboratory (PNNL) ^(a) administers the HEDP in coordination with Hanford contractor radiation protection organizations to ensure consistent site-wide implementation of external dosimetry practices for Hanford workers and visitors. Coordination of dosimetry practices at Hanford is accomplished through the Hanford Personnel Dosimetry Advisory Committee (HPDAC). Technical services provided by the HEDP include personnel, area, nuclear accident, and environmental dosimetry capabilities that comply with DOE requirements in 10 CFR 835, the DOE Laboratory Accreditation Program (DOELAP) performance standard (DOE 1986a) and DOELAP handbook (DOE 1986b) as well as selected DOE guidance in the Radiological Control standard (DOE 1999a), and the External Dosimetry Program Guide (DOE 1999b).

The primary purposes of this *Hanford External Dosimetry Technical Basis Manual* are to document the design and implementation of the external dosimetry system used at Hanford, and to document the rationale for the methods used. This manual includes documentation of the technical basis for the dosimeter design, processing protocols, dose calculation methodology, and recommended dosimeter use in the field, in a manner intended to demonstrate compliance with 10 CFR 835 and Hanford requirements and to ensure the defensibility of the doses of record. A secondary purpose of this manual is to provide general information on dosimeter response characteristics and guidance on the proper use and limitations of Hanford dosimeters that are used by Hanford radiation protection organizations.

The primary users of this manual are DOE and DOE contractors at Hanford using the dosimetry services of HEDP. Development and maintenance of this manual is funded directly by DOE and DOE contractors. Its contents have been reviewed and approved by DOE and DOE contractors at Hanford through the HPDAC which is chartered and chaired by DOE. This manual supports the Radiation Protection Programs of Hanford contractors.

(a) Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DC-AC06-76RLO 1830.

THIS PAGE INTENTIONALLY LEFT BLANK

Glossary

absorbed dose, D	The energy absorbed per unit mass at a specific place in a material. The special unit of absorbed dose is the rad; the SI unit of absorbed dose is the gray (Gy), which has units of joules per kilogram (J/kg) where $1 \text{ J/kg} = 1 \text{ Gy} = 100 \text{ rad}$. As used in this document, "absorbed dose" stands for the absorbed dose in the material of interest, that is, soft tissue or in a phantom approximating soft tissue in composition.
accident dosimetry	Determination of high levels of deep absorbed dose resulting from uncontrolled conditions.
accreditation	The DOE process of granting accreditation based on onsite assessment against the DOELAP handbook (DOE 1986a) and dosimeter performance testing against the DOELAP standard (DOE 1986b). Accreditation must be updated every two years.
air kerma-to-dose-equivalent conversion factors (C_k factors)	The numerical quantity that relates the air kerma to the dose equivalent at a specified depth in a phantom of specified geometry and composition. Factors are a function of the photon energy and angular distribution.
ALARA	An acronym for "as low as reasonably achievable." It is the objective of current radiation protection efforts to maintain exposures of radiation as low as reasonably achievable, with limiting economic and social factors being taken into account.
albedo effect	As used in this document, the neutron dosimeter response caused by the moderating and backscattering properties of a phantom or the human thorax for neutron radiation.
alpha radiation	Alpha particles are defined as a helium nucleus with a plus-2 positive charge.
angular dependence	The response of a dosimeter as a function of the angle of incidence of the radiation detected compared with its response at normal incidence (nonperpendicular incidence).
background	In the 10 CFR 835 definition, background means radiation from (i) naturally occurring radioactive materials which have not been technologically enhanced; (ii) cosmic sources; (iii) global fallout as it exists in the environment (such as from the testing of nuclear explosive devices); (iv) radon and its progeny in concentrations or levels existing in buildings or the environment which have not been elevated as a result of current or prior activities; and (v) consumer products containing nominal amounts of radiation. In application in the HEDP, background for personnel dosimeters at Hanford was determined as an average of reader values on dosimeters that were prepared but not issued to personnel. Background for non-Hanford personnel dosimeters is based on readings from customer-selected locations and may include

adjustment for transit dose if necessary. Background for environmental dosimeters is based on dosimeters stored in a lead-walled cave in the 318 building.

beta particle An electron or positron emitted from a nucleus during beta decay.

beta radiation Radiation consisting of beta particles.

bias, B The average of the performance quotients, P_i for n dosimeters, for a specified radiation category and test depth

$$B \equiv \bar{P} = (1/n) \sum_{i=1}^n P_i$$

calibration To adjust or determine the response or reading of an instrument (e.g., readers, thermometers) relative to a standard or to a series of conventionally true values.

chip A TLD phosphor in solid form that allows reproducible readout. Typical chip dimensions for the Harshaw dosimetry system are approximately 0.32 cm x 0.32 cm with thicknesses ranging between 0.15 and 0.89 mm.

criticality In the context of this document, an unplanned situation in which fissionable material sustains a chain reaction.

declared pregnant worker A woman who has voluntarily declared to her employer, in writing, her pregnancy for the purpose of being subject to the occupational dose limits to the embryo/fetus as provided in 10 CFR 835.206. This declaration may be revoked, in writing, at any time by the declared pregnant worker.

deep dose, deep dose equivalent Denoted in this manual as H_d . The dose equivalent at a depth of 1 cm in the human body or in a phantom of ICRU tissue-equivalent material that results from external beta, photon *and* neutron radiation. As used in this manual, this term represents the same quantity referred to by the ICRU as “personal dose equivalent” at a depth of 10 mm ($H_p(10)$). This operational quantity is typically measured for specific radiation types by dosimeters placed on the front torso of the body and is used as an estimate of the effective dose equivalent received by the whole body, assuming the body was irradiated in a uniform radiation field. Hanford dosimeters measure and report the photon component (H_{dp}) and neutron component (H_n) of deep dose separately (see deep photon dose and neutron dose). Beta particles contribute a negligible amount to the deep dose received at Hanford. Any contribution to deep dose from beta radiation is measured and included in the dosimeter’s reported deep photon dose result.

deep photon dose Denoted in this manual as H_{dp} . Deep photon dose (or photon deep dose) refers to the dose equivalent at a depth of 1 cm in the human body or in a phantom of tissue equivalent material that results from external photon radiation.

DOELAP

Laboratory accreditation program administered by the U.S. Department of Energy (DOE 1986a, b).

dose

A general term for any of the following: absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, total effective dose equivalent, effective dose, or equivalent dose.

The term “dose” is often used to refer to one of several specific concepts in dosimetry. It is sometimes used to refer to “absorbed dose” which may be applied to any material. In common radiation protection usage, the term “dose” most often refers to “dose equivalent” which is applicable to human tissue and is the product of the absorbed dose D at a point in tissue, the radiation quality factor Q at the same point in tissue and any special modifying factors. The quality factor quantifies the relative biological damage to tissue. The quality factors used by HEDP are those specified in 10 CFR 835, which in turn are based on the Q -LET relationship given in ICRP 15, 21 and 26. To demonstrate compliance with the limits on protection quantities specified in 10 CFR 835, HEDP personnel dosimeters are designed and calibrated to measure the operational quantity *personal dose equivalent* at depths of 0.07 mm, 3 mm and 10 mm in soft tissue in the body. These are commonly referred to as the shallow dose, eye dose, and deep dose where the term “dose” refers to dose equivalent. These personal dose equivalent quantities have been denoted as $H_p(0.07)$, $H_p(3)$ and $H_p(10)$ respectively in national and international standards and are sometimes denoted as H_s , H_e , and H_d in this manual for convenience.

dose algorithm

A logic flow path or decision tree procedure for calculating dose equivalent from the response of individual TLD elements in a dosimeter. Sometimes referred to as just “algorithm”.

dose conversion coefficient

(or dose conversion factor) Dose conversion coefficients are factors for converting readily measurable physical quantities (such as exposure in air, absorbed dose in tissue, kerma in air or tissue, or particle fluence), to operational or protection quantities (such as shallow, eye, and deep dose equivalent, or effective dose equivalent or effective dose.) These conversion factors, which depend on both energy and geometry, are based on computer calculations of shallow, eye or deep dose equivalent in the ICRU 30-cm diameter sphere, or ICRU slab, or the effective dose equivalent in an anthropomorphic phantom corresponding to given particle fluences, energies and exposure geometries. Tables of conversion coefficients for monoenergetic radiations are available in ICRP 51, *Data for Use in Protection Against External Radiation* (ICRP 1987), ICRU 43, *Determination of Dose Equivalents from External Radiation Sources* (ICRU 1988), ICRU 47, *Measurement of Dose Equivalents from External Photon and Electron Radiations* (ICRU 1992), and ICRU 57, *Conversion Coefficients for use in Radiological Protection Against External Radiation* (ICRU 1998). HPS has prepared

a consensus standard for testing personnel dosimeters (HPS N13.11 2001) that uses these factors to determine conversion coefficients for the specific photon, beta and neutron energy spectra, irradiation geometries and phantoms used for dosimeter performance testing. DOELAP uses similar factors in their dosimeter performance test standard (DOE 1986a). HEDP dosimeters are calibrated against the DOELAP test standard to provide shallow, eye and deep dose equivalent measurements for Hanford personnel.

dose equivalent, H

The product of the absorbed dose (D), the quality factor (Q), and any other modifying factors (N), at the point of interest in tissue. The special unit of dose equivalent is the rem. When D is expressed in rad, H is expressed in rem. When D is expressed in gray, H is expressed in sievert (Sv), where 1 Sv = 100 rem.

dosimeter

The term dosimeter as used in this manual refers to a device used to assess external radiation exposure or dose to individuals or the environment. HEDP dosimeters are passive devices designed and calibrated to measure either exposure in air, absorbed dose, or personal dose equivalent $H_p(d)$. The HEDP uses thermoluminescent dosimeters (TLDs) to assess dose to personnel and the environment. A combination of TLDs and activation foils and pellets are used in nuclear accident dosimeters to assess absorbed dose in personnel in the event of a criticality. When used to refer to HEDP personnel, area and environmental dosimeters, the term “dosimeter” generally refers to the complete assembly consisting of a dosimeter card and dosimeter holder.

dosimeter card

An aluminum card containing one or more radiation responsive phosphors.

dosimeter holder

A plastic holder used to contain the dosimeter card. The holder typically has one or more metallic filters used to modify the response of the phosphor to radiation.

dosimetry system

A system used to assess dose equivalent from external radiation. This system includes the selection, placement, and processing of the dosimeters; interpretation and recording of results; and the means by which the quality of results is assured.

effective dose, E

The summation of the equivalent doses in tissues or organs, each multiplied by the appropriate tissue weighting factor (ICRP 60 methodology).

effective dose equivalent, H_E

The sum of the tissue weighted dose equivalents to all significantly irradiated organs and tissues. $H_E = \sum w_T H_T$ where w_T is the risk related tissue weighting factor for the organ or tissue of interest and H_T is the dose equivalent received by the specified tissue of interest. The units of effective dose equivalent are the same as those for dose equivalent. An effective dose equivalent of 1 Sv is deemed to pose the same stochastic

risk as a uniform whole body dose equivalent of 1 Sv. In the context of this manual, the term effective dose equivalent and the acronym EDE generally refer to the effective dose equivalent resulting from external radiation only.

equivalent dose, H_T

The absorbed dose in an organ or tissue multiplied by the relevant radiation weighting factor (ICRP 60 methodology).

element

A dosimeter detector that provides a single readout value. TLD elements may be solid chips or powdered phosphors bonded on substrates suitable for heating such as Kapton™. The terms “chip” and “element” are often used interchangeably in the context of the Harshaw dosimeters and TLD system described in this manual.

element correction coefficient (ECC)

Correction factors used to normalize the sensitivity of an individual dosimeter element, to the mean sensitivity of a reference population (calibration set) exposed to the same source. The ECC is determined as follows:

$$ECC_{ij} = \frac{RCF_i}{Q_{ij}} X$$

where

- ECC_{ij} = element correction coefficient for chip i on card j
- RCF_i = reader calibration factor for ith photomultiplier tube.
- Q_{ij} = reported charge from chip i on card j
- X = ^{60}Co exposure value.

exposure

The term “exposure” technically refers to a physical quantity used to define the strength of a photon radiation field in terms of the resulting ionization in air, in units of roentgen (R) or coulombs per kilogram. It is often used to describe the amount of radiation delivered to a dosimeter, typically during a laboratory source irradiation. For the purpose of specifying photon radiation fields to demonstrate traceability to national standards labs (e.g. NIST, PTB, NPL), the quantity exposure in air has been replaced with kerma in air. A common use of the term “exposure” is simply to indicate that a person or dosimeter has been exposed to radiation, to light, to heat, etc.

exposure-to-dose-equivalent conversion factors (C_x factors)

The numerical quantity that relates the exposure in air to the dose equivalent at a specified depth in a phantom of specified geometry and composition. Factors are a function of the photon energy, and angular distribution.

external dosimetry

Theory and application of the principles and techniques involved in the measurement and recording of radiation absorbed dose, dose equivalent and effective dose equivalent in personnel from external sources of radiation. The objective of external dosimetry is the assessment of personnel exposure to external radiation in terms of the operational and protection dosimetric quantities used to measure and limit personnel

dose.

extremities

The hand and arm below the elbow or feet and legs below the knee.

eye dose, eye dose equivalent

Denoted in this manual as H_e . Refers to dose equivalent at a depth of 0.3 cm in the human body, or in a phantom of tissue equivalent material. The depth of 0.3 cm corresponds to the depth of the lens of the eye. This operational quantity is typically measured by a dosimeter placed on the front torso of the body and is used as an estimate of the actual dose equivalent received by the lens of the eye, assuming the body was irradiated in a uniform radiation field (see lens of eye dose). Hanford dosimeters measure and report *only the eye dose resulting from beta and photon radiation*. Hanford dosimeters do not measure or report “eye dose” from neutrons (i.e. dose at a depth of 0.3 cm from neutrons). As used in this manual, the symbol H_e and the term “eye dose” generally refers only to the beta-photon component of eye dose. It should be noted however, that neutron dose to the lens of the eye is not unaccounted for. Neutron dose received by the lens of the eye is accounted for by including the dosimeter’s reported *neutron dose equivalent* in an individual’s recorded dose totals for the lens of the eye. (See “lens of eye dose.”)

facility specific calibration factor

The dosimeter calibration factor applicable to a particular occupational environment. These calibration factors are determined by comparing reference instrument measurements with dosimeter response measurements. Both measurements are performed in the workplace.

fissile materials

Uranium-233, uranium-235, plutonium-239, plutonium-241, americium-242m, californium-249, californium-251, curium-243, curium-245, and curium-247, or any material containing any of the foregoing, with the following exceptions: materials containing natural or depleted uranium are not considered to be fissile materials.

fluence, Φ

The quotient of dN by da where dN is the number of particles incident on a sphere of cross sectional area da

free field dose equivalent

The delivered dose equivalent at a point in space, based on the free field fluence at that point and the fluence to dose equivalent conversion factor used to convert fluence to dose equivalent in a phantom, for the given neutron spectrum.

free field fluence, Φ

The fluence at a point in space that would occur if the irradiation were performed in the absence of air, walls, phantoms, or other scattering materials – usually applied to neutron radiation.

general employee

An individual who is either a DOE or DOE contractor employee: an employee of a subcontractor to a DOE contractor; or an individual who performs work for or in conjunction with DOE or utilizes DOE facilities

H_d

Deep dose equivalent. As used in this manual, H_d is synonymous with the ICRU operational quantity $H_p(10)$. (See “dose.”)

H_{dp}	Deep photon dose equivalent. As used in this manual, H _{dp} is synonymous with the ICRU operational quantity H _p (10) when assessed for external photons only.
H_e	Eye dose equivalent. As used in this manual, H _e is synonymous with the ICRU operational quantity H _p (3) for beta and photons only. Contribution from neutrons is not measured directly.
H_n	Neutron dose equivalent (see <i>neutron dose equivalent</i>).
H_s	Shallow dose equivalent. As used in this manual, H _s is synonymous with the ICRU operational quantity H _p (0.07) for beta and photons only. Contribution from neutrons is not measured directly.
H_p(10)	Personal dose equivalent specified at a depth of 10 mm (see <i>personal dose equivalent</i>). As used in this manual, H _p (10) is synonymous with deep dose equivalent H_d .
H_p(3)	Personal dose equivalent specified at a depth of 3 mm (see <i>personal dose equivalent</i>). As used in this manual, H _p (3) is synonymous with eye dose equivalent H _e .
H_p(0.07)	Personal dose equivalent specified at a depth of 0.07 mm (see <i>personal dose equivalent</i>). As used in this manual, H _p (0.07) is synonymous with shallow dose equivalent H _s .
high dose range	A performance test range outside the normal operating range. DOELAP performance tests for accident dosimetry capability are conducted within the high dose range of 10 to 500 rad.
in-air exposure	As used in this document, exposure of a dosimeter without any phantom or other backscatter material nearby.
individual	Any human being
internal dosimetry	Theory and application of the principles and techniques involved in the measurement and recording of radiation dose from sources of radiation internal to the human body.
ionizing radiation	Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions.
irradiation category	DOELAP performance testing radiation types and energies (or mixtures) for which performance criteria are given.
kerma, K	the quotient of dE_{tr} by dm , where dE_{tr} is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a volume element of mass dm .

lens of the eye	An organ of concern from a dosimetric and regulatory point of view. The lens of the eye is located at a depth of approximately 300 mg/cm ² .
lens of eye dose	Lens of eye dose (or lens of eye dose equivalent) refers to the protection quantity representing the actual dose equivalent received by the lens of the eye. For radiological records purposes, the recorded lens of the eye dose is typically based on the beta-photon component of eye dose measured by the chest dosimeter (commonly referred to as “H _e ”) <i>plus</i> any neutron dose H _n , measured by the chest dosimeter. In the case of multiple dosimetry worn in non-uniform radiation fields, or a dosimeter worn on top of a lead vest, the actual value recorded as lens of eye dose may be based on an evaluation of the multipack dosimeter results, (e.g. a dosimeter located on the head), or an adjusted value from the chest dosimeter.
linear energy transfer, L	Linear energy transfer (or LET) is the quotient of dE by dL , where dE is the mean energy lost by the particle, owing to collisions with electrons, in traversing a distance dL . (also referred to as linear collision stopping power of a material for charged particles). The mathematical symbol commonly used for linear energy transfer is L
lower limit of detection (LLD)	The minimum evaluated dose equivalent for which the readout value of a dosimeter is significantly different (at the 95% confidence level) from the readout value at the detection threshold.
may	Denotes permission, rather than recommendation or requirement.
mil	Unit used to specify thickness of materials; equals 0.001 inch or 0.025 mm.
monitoring	From 10 CFR 835, actions intended to detect and quantify radiological conditions.
neutron activation	The process in which atomic nuclei become radioactive by absorption of neutrons.
neutron dose equivalent	Denoted in this manual by the symbol H_n . Neutron dose (or neutron dose equivalent) refers to the maximum dose equivalent (MADE) in a 30 cm diameter tissue equivalent cylindrical phantom when exposed with a broad parallel beam of neutron radiation. This concept is more closely related to the ICRU concept of dose equivalent index than personal dose equivalent. Unlike the personal dose equivalent quantities $H_p(10)$, $H_p(3)$, and $H_p(0.07)$, H_n is not pre-defined to be at a particular depth or location. For this reason, the term “deep” has not historically been used to describe this quantity. DOELAP performance testing assesses a dosimeter’s ability to accurately report neutron dose equivalent based on the fluence-to-dose-equivalent conversion factors given in <i>NCRP Report No. 38, Protection Against Neutron Radiation</i> (NCRP 1971). For the neutron energy spectra used in performance testing and most spectra found at Hanford, <i>neutron dose equivalent</i> is a close approximation to the <i>deep dose equivalent</i> resulting from

neutrons. For the purpose of demonstrating compliance with protection limits in 10 CFR 835.202(a)(1) and (2), the neutron dose equivalent H_n is summed with the deep photon dose equivalent H_{dp} to obtain total deep dose equivalent H_d . This practice is consistent with DOE guidance given in *DOE G 441.1-4 External Dosimetry Program Guide* (DOE 1999b) and DOE's discussion of quality factor tables in Section V of the Supplemental Information published with the 10 CFR 835 rulemaking (DOE 1993).

neutron radiation

Refers to one of the fundamental particles of the atomic nucleus with a neutral charge.

non-uniform fields (irradiation)

The condition when a portion of the body is expected to receive a radiation dose equivalent that varies by more than 50% from the dose equivalent expected at a reference location (e.g., the anterior torso).

on-phantom

As used in this document, exposure of dosimeters affixed to a phantom to simulate the dosimeter response while the dosimeter is being worn by a person.

operational quantities

Operational quantities are measurable quantities specified by the ICRU that are used to demonstrate compliance with dose limits expressed as protection quantities. Operational quantities are intended to provide a conservative estimate of their related protection quantities. Examples of operational quantities are personal dose equivalent $H_p(d)$, ambient dose equivalent $H^*(d)$ and directional dose equivalent $H'(d,\theta)$ where d is the tissue depth in millimeters and θ is the angle of incidence of the radiation (ICRU 43).

performance testing

Procedure with the following sequence:

1. Submission of dosimeters from a processor's current stock to a testing laboratory over a period of several months, in numbers sufficient for the specified irradiations in any one test category or subcategory covered by a processor's service.
2. Irradiation of the dosimeters by personnel of the testing laboratory using the type(s) of radiation specified for this test category or subcategory.
3. Evaluation by the processor of the response of the returned dosimeters in terms of shallow and deep dose equivalent for tests of protection monitoring, or in terms of deep absorbed dose for tests of accident monitoring.
4. Submission of these evaluations to the testing laboratory.
5. Analysis of the submitted evaluations by the testing laboratory.
6. Reporting of the results of this analysis (also referred to as "test results") to the processor.

performance testing category Each type of radiation (or of radiation mixtures) and range of irradiation level for which separate tests are performed.

performance testing laboratory (PTL) The DOELAP dosimeter performance testing laboratory.

performance quotient, P_i For tests of protection dosimetry, the performance quotient for the i th dosimeter is defined as:

$$P_i \equiv [H_i - H'_i] / H_i$$

where H_i is the dose equivalent assigned by the testing laboratory to the irradiated dosimeter and H'_i is the corresponding dose equivalent reported by the processor.

For tests of accident dosimetry, the same definition applies, with the absorbed dose, D , replacing the dose equivalent, H .

NOTE: In this definition, H stands for H_s or H_d , and D stands for D_d . No tests are performed for D_s .

performance testing subcategory A subset of a test category that includes only a limited portion of the energy range of the full category. A processor may select to participate in one or more of the subcategories in a given category as specified in the DOELAP standard.

personal dose equivalent An operational quantity defined by the ICRU at a specified depth in a body or tissue equivalent phantom (see operational quantities). Denoted as $H_p(d)$ where d is the specified depth in mm.

person Any human being. [Note: This definition is not entirely consistent with the definition provided in 10 CFR 835.2]

phantom A slab of plastic, typically measuring either 30-by-30 cm square by 15-cm deep or 40-x-40-cm by 15-cm deep, used to simulate the effect of the body on dosimeter response. May also be used to refer to an anthropomorphic phantom used for the same purpose.

phosphor As used in this report, a material with the characteristic of emitting light following irradiation. Thermoluminescent phosphors emit this light (luminesce) under heating (thermo).

photon radiation Refers to either x or gamma rays.

physical quantities Quantities used to measure the fundamental physical properties of radiation fields and radiation interaction in matter. Examples of physical quantities are: fluence Φ , air kerma free-in-air K_a , tissue absorbed dose D , linear energy transfer L . Relationships between physical quantities,

damage in tissue, and risk of stochastic effects are used to calculate the protection quantities and operational quantities used in radiation protection.

protection dosimetry

Routine estimation of the shallow and deep dose (shallow and deep absorbed dose, D_s and D_d , or shallow and deep dose equivalent, H_s and H_d) for the purpose of providing one of the parameters for assessing the radiation protection measures in a given radiation facility. In general, the absorbed dose or equivalent at the respective depths of 0.007 cm (shallow) and 1.0 cm (deep) in a slab phantom of ICRU tissue-equivalent material.

protection quantities

Dosimetric quantities specified in the human body by the ICRP. Examples of protection quantities are effective dose equivalent H_E (ICRP 26), and effective dose E (ICRP 60). Protection quantities are intended to serve as the basis for dose limitation adopted by regulators and other bodies. DOE and NRC currently use effective dose equivalent as the basis for dose limits. Protection quantities represent risk but are generally difficult to measure directly. Operational quantities are more readily measured.

quality factor, Q

The quality factor (Q) is the modifying factor used to calculate the dose equivalent from the absorbed dose; the absorbed dose (D) is multiplied by the quality factor.

quality assurance (QA)

All planned and periodic actions necessary to provide adequate confidence that an item or a service will satisfy given needs.

radiation

Unless otherwise specified, radiation refers to particulate or electromagnetic radiation that is ionizing. Examples of indirectly ionizing radiation significant at Hanford are gamma rays, x-rays, and neutrons. Examples of directly ionizing radiation encountered at Hanford are alpha particles and beta particles.

radiation weighting factor, W_R

A factor by which the tissue or organ absorbed dose is multiplied to reflect the higher RBE_M values for neutrons and alpha particles compared with low LET radiations

radiological worker

A general employee whose job assignment involves operation of radiation producing devices or working with radioactive materials, or who is likely to be routinely occupationally exposed above 0.1 rem per year total effective dose equivalent.

radioactivity

Unstable isotopes that release energy in the form of particles and/or electromagnetic radiation by a process of disintegration.

relative biological effectiveness, RBE_M

The ratio of the absorbed dose of a reference radiation to the absorbed dose of a given test radiation required to produce the same level of response, all other conditions being kept constant. The subscript M refers to a stochastic effect.

reporting threshold	The calculated dose level below which the dose result will be reported as zero.
roentgen (R)	A special unit of radiation used to quantify ionization in air from photon radiation. One R is equivalent to 2.58×10^{-4} coulomb/kg.
shall	Denotes a requirement.
shallow dose, shallow dose equivalent	Denoted in this manual as H_s . The dose equivalent at a depth of 0.07 mm (7 mg/cm^2) in soft tissue of the human body or in a tissue-equivalent phantom. As used in this manual, the terms shallow dose and shallow dose equivalent are synonymous with the ICRU operational quantity personal dose equivalent when specified at a depth of 0.07 mm $H_p(0.07)$. This operational quantity is typically measured by dosimeters placed on the front torso of the body or on the extremities of the body. Hanford dosimeters measure and report <i>only the shallow dose resulting from beta and photon radiation</i> . Shallow dose from neutrons is not measured or reported. As used in this manual, the symbol H_s generally refers to the beta-photon component of shallow dose.
should	Denotes a recommendation.
skin	The thickness of the skin varies considerably from one part of the body to another. The basal cell layer of the epidermis is taken to be the skin tissue most at risk. For dose assessment purposes, a depth of 70 μm is considered to be the mean depth of the basal cell layer.
skin dose	Refers to shallow dose equivalent to the skin of the whole body
standard deviation, S	The standard deviation of the performance quotient, P_i , is determined as follows: $S \equiv \left\{ \left[\sum_{i=1}^n (P_i - B)^2 \right] / (n-1) \right\}^{1/2}$ <p>where the sum is extended over all n values of P_i for a particular test in a given radiation category or subcategory, and for a particular phantom depth (shallow or deep) and</p> $B = (1/n) \sum_{i=1}^n P_i$
track-etch dosimeter (TED)	A type of dosimeter that relies on the production of tracks in a plastic to measure dose. In this document, TED refers to the CR-39 plastic in which radiation damage sites produce tracks or "pits," which when electrochemically etched, can be seen under a microscope. The formation of these tracks is primarily caused by hydrogen recoil with fast neutrons, but can also be caused by alpha particles, protons, and heavy charged particles.

thermoluminescent dosimeter (TLD)

A type of dosimeter that relies on excitation of the crystalline lattice by radiation of certain fluorescent materials which, upon heating, emit light. Various phosphors and chemical activators have led to several common types of thermoluminescent phosphors. In this document, reference is made primarily to lithium fluoride (LiF) and to calcium fluoride (CaF₂).

tissue weighting factor, W_T

The fraction of the overall health risk, resulting from uniform, whole body irradiation, attributable to specific tissue (T). The dose equivalent to a tissue H_T is multiplied by the appropriate weighting factor to obtain the effective dose equivalent contribution from that tissue. The weighting factors used for determining effective dose equivalent for DOE workers are given below.

Organ	Weighting Factor
Gonads	0.25
Red bone marrow	0.12
Bone surfaces	0.03
Breast	0.15
Lung	0.12
Thyroid	0.03
Remainder*	0.30

*Remainder means the five other organs or tissues with the highest dose (e.g., liver, kidney, spleen, thymus, adrenal, pancreas, stomach, small intestine, and upper large intestine). The weighting factor for each remaining organ or tissue is 0.06.

whole body dose equivalent

The dose equivalent that results when the whole body is irradiated. If the irradiation is uniform, whole body dose equivalent is the same as effective dose equivalent. Whole body dose equivalent is expressed in the same units as dose equivalent.

whole body irradiation

Uniform radiation exposure of the gonads, active blood-forming organs, head, trunk, lens of the eye, the arms above and including the elbow, and legs above and including the knee.

THIS PAGE INTENTIONALLY LEFT BLANK

Acronyms and Abbreviations

ABS	acrylonitrile-butadiene-styrene
ACL	administrative control level
AEDE	annual effective dose equivalent
ALARA	as low as reasonably achievable
AMH	AdvanceMed Hanford
ANSI	American National Standards Institute
AP	anterior-posterior (exposure geometry)
BCF	beta correction factor
CCS	computer control system
CFR	Code of Federal Regulations
CEDE	committed effective dose equivalent
CPE	charged particle equilibrium
CPM	counts per minute
CV	coefficient of variation
DOE	U.S. Department of Energy
DOE-RL	U.S. Department of Energy - Richland Operations Office
DOELAP	DOE Laboratory Accreditation Program
DRD	direct reading dosimeter
DU	depleted uranium
ECC	element correction coefficient
EDE	effective dose equivalent
FNAD	fixed nuclear accident dosimeter
GDS	Global Dosimetry Solutions (company name)
GM	Geiger-Müller (counter)
HCND	Hanford Combination Neutron Dosimeter

HEDP	Hanford External Dosimetry Program
HEPA	High Efficiency Particulate Air (filter)
HIDP	Hanford Internal Dosimetry Program
HPDAC	Hanford Personnel Dosimetry Advisory Committee
HPRR	Health Physics Research Reactor
HPS	Health Physics Society
HRCF	Hanford Radiological Control Forum
HRD	Hanford Ring Dosimeter
HRRP	Hanford Radiation Records Project
HSD	Hanford Standard Dosimeter
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Quantities and Units
ID	identification
IODR	investigation of dosimeter result
ISO	isotropic (exposure geometry)
ISO	International Standards Organization
LANL	Los Alamos National Laboratory
LAT	lateral (exposure geometry)
LET	linear energy transfer
LLD	lower level of detection
LOI	letter of instruction
MMD	minimum measurable dose
MOU	memorandum of understanding
NAD	nuclear accident dosimeter
NCRP	National Council on Radiation Protection and Measurements
NHC	Numatec Hanford Corporation

NIST	National Institute of Standards and Technology
NRC	U.S. Nuclear Regulatory Commission
NVLAP	National Voluntary Laboratory Accreditation Program
OCR	optical character reader
OJT	on-the-job-training
ORNL	Oak Ridge National Laboratory
ORP	DOE Office of River Protection
PA	posterior-anterior (exposure geometry)
PC	personal computer
PFP	Plutonium Finishing Plant
PMMA	polymethylmethacrylate
PMT	photomultiplier tube
PNAD	personnel nuclear accident dosimeter
PNNL	Pacific Northwest National Laboratory
PNSO	Pacific Northwest Site Office (DOE Office of Science)
PTB	Physikalisch-Technische Bundesanstalt
PTFE	polytetrafluorethylene
QA	quality assurance
QC	quality control
RCF	reader calibration factor
REMS	Radiation Evaluation and Management System (TLD reader system)
REX	Radiological Exposure (System)
R&HT	Radiation & Health Technology
RIDS	records inventory and disposition schedule
RL	DOE Richland Operations Office
ROT	rotational (exposure geometry)
RPP	radiation protection program

RRF	relative response factor
RWP	radiation work permit
SOW	statement of work
TEDE	total effective dose equivalent
TED	track-etch dosimeter
TEPC	tissue-equivalent proportional counter
TL	thermoluminescent
TLD	thermoluminescent dosimeter
TTP	time-temperature profile
UPS	uninterruptible power supply
UV	ultraviolet
VAX	Digital Equipment Corporation VAX Computer Operating Environment
WB	whole body
WHC	Westinghouse Hanford Company
YTD	year to date

CONTENTS

PREFACE.....	iii
GLOSSARY.....	v
ACRONYMS AND ABBREVIATIONS	xix
1.0 INTRODUCTION.....	1.1
1.1 HEDP's Role at Hanford.....	1.1
1.2 HEDP Objectives	1.1
2.0 HANFORD EXTERNAL DOSIMETRY PROGRAM.....	2.1
2.1 HEDP Position within PNNL.....	2.1
2.2 HEDP Organization and Staffing.....	2.2
2.2.1 Project Manager.....	2.2
2.2.2 Technical Manager	2.2
2.2.3 Quality Manager	2.2
2.2.4 Dosimetry Professional Staff.....	2.2
2.2.5 Dosimetry Technician Staff.....	2.3
2.3 HEDP Facilities and Equipment	2.3
2.3.1 Accommodation and Environmental Controls	2.3
2.3.2 Dosimetry Laboratories.....	2.3
2.3.3 Irradiation Laboratories.....	2.3
2.3.4 Equipment.....	2.4
2.4 HEDP Documentation	2.4
2.5 HEDP Functional Relationship with DOE and DOE Contractors.....	2.5
2.5.1 Hanford Personnel Dosimetry Advisory Committee.....	2.5
2.5.2 Hanford Radiological Control Forum.....	2.5
2.5.3 Hanford Contractor Work Agreements.....	2.6
2.5.4 Non-Hanford Contractor Work Agreements.....	2.6
2.5.5 DOE Programmatic Assessments and Oversight.....	2.6
2.6 Field Dosimetry Practices and Contractor Responsibilities.....	2.6
3.0 QUALITY ASSURANCE AND QUALITY CONTROL.....	3.1
3.1 Dosimetry Materials	3.1
3.2 Dosimetry Laboratories.....	3.2
3.3 Dosimetry Processing Equipment	3.3
3.4 Design Features of TLD Reader Systems.....	3.3
3.5 Dosimetry Issuance and Receipt.....	3.5
3.6 Dosimetry Processing	3.6
3.7 Data Screening	3.7
3.8 Group QC Statistics	3.8
3.9 Glow Curve Analysis	3.9
3.10 Element Ratio Analysis.....	3.9
3.11 Review and Reporting of Dose Results	3.9
3.12 Dose Results Accountability.....	3.10
3.13 Unreturned Dosimeters.....	3.10
3.14 Lost or Damaged Dosimeters	3.10
3.15 "High" Dose Results.....	3.11
3.16 Abnormal Dosimeter Results	3.11

3.17	Blind Audit Dosimeter Program.....	3.13
3.18	Dosimetry Processing Quality Assurance Reports.....	3.13
3.19	External Dosimetry Program Records.....	3.13
3.20	Records Disposition.....	3.14
3.21	Other Quality Assurance Topics.....	3.15
4.0	REGULATORY BASIS.....	4.1
4.1	DOE Rulemaking.....	4.1
4.2	DOE Guidance.....	4.2
4.3	DOE Laboratory Accreditation Program.....	4.3
5.0	TECHNICAL BASIS.....	5.1
5.1	Characteristics of TLD Phosphors.....	5.2
5.1.1	Lithium Fluoride.....	5.2
5.1.2	Calcium Fluoride.....	5.3
5.1.3	Physical Form.....	5.3
5.1.4	Linearity of Dose Response.....	5.4
5.1.5	Sensitivity.....	5.4
5.1.6	Fading.....	5.4
5.1.7	Annealing.....	5.5
5.1.8	Photon Energy Dependence.....	5.5
5.1.9	Batch Uniformity.....	5.5
5.1.10	Reproducibility.....	5.5
5.1.11	Residual TL.....	5.6
5.2	Characteristics of HEDP Dosimeter Cards.....	5.6
5.2.1	Physical Testing.....	5.6
5.2.2	Unique Permanent Identification Number.....	5.7
5.2.3	Testing for Phosphor Type.....	5.7
5.2.4	Light Testing.....	5.7
5.2.5	Time-Temperature Profile.....	5.7
5.3	HEDP Dosimetry System.....	5.8
5.3.1	Generating Calibration Cards.....	5.8
5.3.2	TLD Reader Calibration.....	5.10
5.3.3	Card Calibration.....	5.10
5.3.4	Dosimeter Calibration.....	5.11
5.3.5	Calibrated Element Readings.....	5.12
5.3.6	Adjusted Element Readings.....	5.12
5.3.6.1	Models for Environmental Background.....	5.13
5.3.6.2	Models for Fading.....	5.15
5.3.6.3	Models for Supralinearity.....	5.18
5.3.6.4	Calculation of Weighted Fading and Supralinearity Corrections F_i and S_i	5.20
5.3.7	Dose Algorithms.....	5.21
5.3.8	Facility Calibration Codes.....	5.22
5.4	Hanford Standard Dosimeter.....	5.24
5.4.1	General Features.....	5.24
5.4.2	Dosimeter Assignment and Processing Protocol.....	5.24
5.4.3	Algorithm.....	5.26
5.4.4	HSD Element Response to DOELAP Sources.....	5.27
5.4.5	Algorithm Bias.....	5.28
5.4.6	Angular Response.....	5.31
5.4.7	Lower Level of Detection.....	5.40
5.4.8	Environmental Sensitivity.....	5.41
5.4.9	Fading.....	5.41

5.5	Hanford Combination Neutron Dosimeter.....	5.42
5.5.1	General Features.....	5.44
5.5.2	Dosimeter Assignment and Processing Protocol.....	5.45
5.5.3	Algorithm.....	5.45
5.5.4	HCND Element Response to DOELAP Sources.....	5.46
5.5.5	Algorithm Bias.....	5.47
5.5.6	Albedo Response.....	5.48
5.5.7	Angular Response.....	5.49
5.5.8	Lower Level of Detection.....	5.52
5.5.9	Environmental Sensitivity.....	5.53
5.5.10	Fading.....	5.53
5.6	Area Dosimetry.....	5.53
5.6.1	HSD Area Dosimeter.....	5.54
5.6.2	HCND Area Dosimeter.....	5.57
5.7	HSD Extremity (Wrist/Ankle) Dosimeter.....	5.58
5.7.1	General Features.....	5.59
5.7.2	Dosimeter Assignment and Processing Protocol.....	5.59
5.7.3	Algorithm.....	5.59
5.7.4	Algorithm Performance.....	5.59
5.7.5	Angular Response.....	5.60
5.7.6	Lower Level of Detection.....	5.62
5.7.7	Fading.....	5.62
5.7.8	Environmental Sensitivity.....	5.63
5.8	Hanford Ring Dosimeter (HRD).....	5.63
5.8.1	Dosimeter Description.....	5.63
5.8.2	Reader Description.....	5.64
5.8.3	Dosimeter Use Cycle.....	5.65
5.8.3.1	Dosimeter Preparation.....	5.65
5.8.3.2	Dosimeter Issuance.....	5.65
5.8.3.3	Dosimeter Receipt.....	5.66
5.8.3.4	Dosimeter Readout.....	5.66
5.8.3.5	Dose Calculation.....	5.66
5.8.3.6	Dose Reporting.....	5.67
5.8.4	System Calibration.....	5.67
5.8.4.1	Reader Calibration.....	5.67
5.8.4.2	Chipstrate Calibration.....	5.67
5.8.4.3	Calibrated Chip Readings.....	5.68
5.8.4.4	Ring Dosimeter Calibration.....	5.68
5.8.5	Dose Algorithm for Ring Dosimeter.....	5.69
5.8.5.1	Shallow Dose Equivalent.....	5.69
5.8.5.2	Facility Calibration Factor.....	5.69
5.8.5.3	Adjusted Element Reading.....	5.69
5.8.5.4	Zero Dose Reading.....	5.70
5.8.5.5	Environmental Background Function.....	5.70
5.8.5.6	Fade Correction.....	5.70
5.8.5.7	Supralinearity Correction.....	5.72
5.8.6	Performance Data.....	5.72
5.8.6.1	Uniformity.....	5.72
5.8.6.2	Lower Limit of Detection.....	5.72
5.8.6.3	Linearity.....	5.73
5.8.6.4	Angular Response.....	5.73
5.8.6.5	Photon Energy Dependence.....	5.77
5.8.6.6	Beta Energy Dependence.....	5.78

5.8.7	Default Correction Factor for Hanford Ring	5.78
5.8.8	Ring Correction Factor for the Plutonium Finishing Plant.....	5.82
5.9	EXT-RAD Ring Dosimeter.....	5.82
5.9.1	Dosimeter Description	5.83
5.9.2	Reader Description	5.84
5.9.3	Dosimeter Use Cycle, System Calibration, and Dose Algorithm	5.84
5.9.4	Performance Data	5.84
5.9.4.1	Lower Limit of Detection	5.85
5.9.4.2	Linearity	5.86
5.9.4.3	Angular Response.....	5.86
5.10	Hanford Environmental Dosimeter.....	5.88
5.10.1	General Features.....	5.88
5.10.2	Algorithm.....	5.89
5.10.3	Processing Protocol	5.89
5.10.4	Energy Response	5.90
5.10.5	Minimum Measurable Dose	5.90
5.10.6	Fading.....	5.90
5.11	Hanford Nuclear Accident Dosimetry.....	5.91
5.11.1	Hanford Nuclear Accident Dosimeters.....	5.92
5.11.2	Performance and Placement Criteria.....	5.95
5.11.3	Quick-Sort Data Analysis.....	5.97
5.11.4	Analysis of Physical and Biological Samples	5.99
5.11.5	Interpretation of Personnel Dosimeter Results After a Criticality Event	5.100
5.11.6	Assessment of Dose After a Criticality Event	5.100
5.12	Useful Dose Range for Hanford Dosimeters	5.102
6.0	OPERATIONAL BASIS	6.1
6.1	Occupational Dose.....	6.1
6.2	Selection of Individuals to be Monitored.....	6.2
6.3	Selection of Dosimeter Types To Use	6.3
6.4	Dosimetry Limitations	6.4
6.5	Dose Reporting Threshold	6.4
6.6	Dosimeter Exchange and Selection of Frequency	6.7
6.7	Dosimeter Wearing Practices.....	6.8
6.7.1	Dosimeter Use with Protective Clothing.....	6.9
6.7.2	Dosimeter Use with Lead Aprons or Vests for work in Uniform External Fields	6.9
6.7.2.1	Use of a Single Dosimeter Outside the Lead Apron.....	6.10
6.7.2.2	Use of Multiple Dosimeters with Lead Aprons	6.14
6.8	Hanford Recorded Dose.....	6.16
6.9	Multiple Dosimeters for Work in Non-Uniform Fields.....	6.17
6.9.1	Evaluating Dose for Non-Routine Jobs with Multiple Whole Body Dosimeters	6.18
6.9.2	Evaluating Dose for Routine Jobs with Multiple Whole Body Dosimeters	6.21
6.9.3	Calculation of EDE	6.22
6.10	Fetal Dose.....	6.23
6.11	Operational Quantities and Dose Conversion Factors	6.23
6.12	Personnel Dosimeter Accreditation.....	6.25
6.13	DOELAP Accreditation Categories.....	6.26
6.14	Radiation Types Not Covered by DOELAP Performance Testing.....	6.28
6.15	Facility Calibration Codes	6.28
6.16	Uncertainty in Recorded Dose	6.29

7.0	FIELD MEASUREMENTS, ASSESSMENTS, AND INTERCOMPARISON STUDIES	7.1
7.1	Methodology	7.1
7.2	Measurement Systems.....	7.1
	7.2.1 Photon Radiation.....	7.2
	7.2.2 Beta Radiation.....	7.2
	7.2.3 Neutron Radiation.....	7.2
7.3	Hanford Beta Radiation Measurements.....	7.3
7.4	Hanford Photon Radiation Measurements.....	7.4
7.5	Hanford Neutron Radiation Measurements.....	7.5
7.6	Hanford Environs Radiation Measurements	7.7
7.7	Intercomparison Studies.....	7.8
7.8	Uncertainty Analyses.....	7.9
7.9	Summary	7.10
8.0	ASSESSMENT OF NON-UNIFORM EXPOSURE OF SKIN AND EXTREMITIES.....	8.1
8.1	Hot Particles	8.1
8.2	Contamination Screening Levels.....	8.2
8.3	Assessment of Dose to Skin or Extremities from Contamination.....	8.4
	8.3.1 Alpha Contamination.....	8.4
	8.3.2 VARSKIN MOD2.....	8.4
9.0	REFERENCES	9.1

FIGURES

5.1	Buildup of Environmental Background Signal in HSD Shallow dose Element	5.14
5.2	Buildup of Environmental Background Signal in HSD Deep Dose Element	5.14
5.3	Post Irradiation Fade Functions Used for Hanford Dosimetry Materials	5.17
5.4	Error In Default Fade Correction When Entire Exposure Occurs on First Day of Use Cycle.....	5.17
5.5	Error In Default Fade Correction When Entire Exposure Occurs on Last Day of Use Cycle	5.18
5.6	Supralinearity Correction for Beta-Gamma Signal in TLD 600 and 700	5.19
5.7	Hanford Standard Dosimeter.....	5.25
5.8	Irradiation Setup for dosimeter Angular Response Evaluation.....	5.33
5.9	HSD Angular Response –Horizontal Rotation.....	5.35
5.10	HSD Angular Response – Vertical Rotation	5.36
5.11	HSD Angular Response – Horizontal Rotation.....	5.37
5.12	HSD Angular Response – Vertical Rotation	5.38
5.13	HSD Neutron Angular Response – Horizontal Rotation	5.39
5.14	HSD Neutron Angular Response – Vertical Rotation.....	5.39
5.15	Hanford Standard Dosimeter Fading at 80°C.....	5.42
5.16	Hanford Combination Neutron Dosimeter with PNAD.....	5.43
5.17	Hanford Combination Neutron Dosimeter without PNAD	5.43
5.18	8816 Albedo Neutron Dosimeter.....	5.44
5.19	Measured Albedo Response of 8816 Neutron Dosimeter	5.48
5.20	Hanford Combination Neutron Dosimeter Angular Response – Horizontal Rotation.....	5.50
5.21	Hanford Combination Neutron dosimeter Angular Response – Vertical Rotation.....	5.51
5.22	HSD Extremity Shallow Dose Angular Response – Horizontal Rotation	5.61
5.23	HSD Extremity Shallow Dose Angular Response – Vertical Rotation.....	5.61
5.24	Chipstrate	5.63
5.25	Illustration of Hanford Ring Dosimeter.....	5.64
5.26	Fade Correction for the Hanford Ring.....	5.71
5.27	Hanford Ring Shallow Dose Angular Response – Horizontal Rotation.....	5.75
5.28	Hanford Ring Shallow Dose Angular Response – Vertical Rotation	5.75
5.29	Ring Orientation for Angular Dependence Irradiations	5.76
5.30	HRD Photon Response	5.77
5.31	Ring BCF vs. ⁹⁰ Sr/ ⁹⁰ Y Source Filtration.....	5.79
5.32	Ring BCF vs. Average Beta Energy.....	5.79
5.33	Ring Correction Factor as a Function of Glove Thickness for Large Area Source (on contact).....	5.81
5.34	Ring Correction Factor as a Function of Sr:Cs Ratio for Large Area Source (on contact).....	5.81
5.35	Chipstrate	5.83
5.36	Illustration of Chipstrate Sealed in Vinyl Pouch	5.83
5.37	EXT-RAD Extremity Dosimeter	5.84
5.38	EXT-RAD Ring Shallow Dose Angular Response – Horizontal Orientation.....	5.87
5.39	EXT-RAD Ring Shallow Dose Angular Response – Vertical Orientation	5.87
5.40	Hanford Environmental Dosimeter (Harshaw 8807)	5.89
5.41	Hanford Environmental Dosimeter Energy Response (TLD 700)	5.91
5.42	Hanford Fixed Nuclear Accident Dosimeter	5.93
5.43	Hanford Personal Nuclear Accident Dosimeter.....	5.95
6.1	Variation in Dose Equivalent for Beta Radiation	6.25

TABLES

3.1	Prompt Notification Levels	3.11
3.2	Change in Calculated Dose Requiring Contractor Concurrence	3.12
5.1	Trace Elements in Lithium Fluoride Thermoluminescent Dosimeters.....	5.2
5.2	Typical Parameters for Reader Processing Setup.....	5.8
5.3	Contents of the HEDP Dosimeters.....	5.9
5.4	Parameters for Background Functions	5.13
5.5	Parameters for use in Post Irradiation Fade Models	5.16
5.6	HSD Element Response to DOELAP Sources	5.29
5.7	HSD Shallow and Deep Dose Response	5.30
5.8	HSD Algorithm Eye Dose Response	5.30
5.9	HSD Algorithm Neutron Dose Response	5.31
5.10	HSD Shallow Dose Angular Response	5.34
5.11	HSD Deep Dose ^(a) Angular Response.....	5.34
5.12	Calculated LLDs (in mrem) for the HSD	5.40
5.13	8816 Neutron Dosimeter Element Response to DOELAP Sources	5.47
5.14	HCND Shallow Dose Angular Response	5.49
5.15	HCND Deep Dose ^(b) Angular Response	5.49
5.16	Calculated LLDs (in mrem) for the HCND	5.52
5.17	HSD Photon Response in Air.....	5.55
5.18	HSD Neutron Response in Air.....	5.56
5.19	HSD Extremity Algorithm Bias.....	5.59
5.20	HSD Extremity Dosimeter Angular Response	5.60
5.21	HSD Extremity Shallow Dose LLD	5.62
5.22	Parameters for use in Chipstrate Post Irradiation Fade Model	5.71
5.23	LLDs for Hanford Ring.....	5.73
5.24	HRD Angular Shallow Dose Response.....	5.74
5.25	HRD Beta Response.....	5.78
5.26	LLDs for EXT-RAD Ring Dosimeter	5.85
5.27	EXT-RAD Ring Angular Shallow Dose Response	5.87
5.28	Hanford Environmental Dosimeter Time-Temperature Profiles	5.90
5.29	Materials and Approximate Dimensions of Hanford Fixed Nuclear Accident Dosimeter.....	5.94
5.30	Hanford Personal Nuclear Accident Dosimeter	5.95
5.31	Survey Instrument Readings on the Body after an Accident	5.98
5.32	Maximum Measurable Dose for Hanford Dosimeters	5.102
5.33	Maximum Measurable Dose for HSD at Various Depths	5.103
6.1	Summary of Dosimeter Applications and Limitations.....	6.5
6.2	Dose Reporting Thresholds (mrem)	6.7
6.3	Multiple Dosimeter Location Codes	6.19
6.4	Whole Body Compartmentalization Factors	6.22
6.5	Photon Dose Conversion Factors (Grosswendt 1990).....	6.24
6.6	Whole Body Dosimeter Test Categories	6.27
6.7	Extremity Dosimeter Test Categories.....	6.28
8.1	Portable Survey Instrument Screening Levels for Skin Dose Assessment	8.2
8.2	Specification of Sources Used in Instrument Response Measurements and in VARSKIN MOD2 Dose Calculations.....	8.5
8.3	Measured Eberline Model 260 Pancake GM Probe Response and Calculated Dose for Small	

	(0.2 cm ²) Radiation Sources.....	8.6
8.4	Measured Eberline Model 260 Pancake GM Probe Response and Calculated Dose for Large (225 cm ²) Radiation Sources.....	8.6
8.5	Measured Eberline Model RO-2 Ionization Chamber Response and Calculated Dose for Small (0.2 cm ²) Radiation Sources.....	8.7
8.6	Measured Eberline Model RO-2 Ionization Chamber Response and Calculated Dose for Large (225 cm ²) Radiation Sources.....	8.7
8.7	Measured Eberline Model RO-3B Ionization Chamber Response and Calculated Dose for Small (0.2-cm ²) Radiation Sources.....	8.8
8.8	Measured Eberline Model RO-3B Ionization Chamber Response and Calculated Dose for Large (225-cm ²) Radiation Sources.....	8.8
8.9	Measured Eberline Model RO-2 and RO-3 Ionization Chamber Response and Calculated Dose for Point (<2 mm ²) Radiation Sources.....	8.9

1.0 Introduction

The Hanford External Dosimetry Program (HEDP) has been an integral component of radiation protection at Hanford since its inception in 1944 (Wilson 1987). Since 1944, a centralized site-wide dosimetry system operated by HEDP or its predecessor organizations has been used to measure dose to Hanford workers and the Hanford environment. The HEDP complies with the DOE Laboratory Accreditation Program (DOELAP) standard (DOE 1986a) and DOELAP handbook (DOE 1986b) requirements and has been accredited under DOELAP since 1988.

1.1 HEDP's Role at Hanford

The HEDP provides consistent personnel, area, environmental and nuclear accident dosimetry services and technical support to the DOE Richland Operations Office (RL), DOE Office of River Protection (ORP), DOE Pacific Northwest Site Office (PNSO), and DOE contractors under the management of these offices. [Program services are also made available to and currently used by DOE contractors at DOE sites other than Hanford.]

Funding for HEDP is currently provided through cost reimbursement contracts with the DOE site offices and prime contractors, plus separately funded technical support tasks performed on a cost reimbursement basis. HEDP objectives and scope of work are defined through DOE program oversight and statements of work (SOW) with each contractor. HEDP's mission is to provide accurate, technically defensible personnel dose results for DOE and DOE contractors at Hanford, and to support the Radiation Protection Program (RPP) of each contractor. HEDP supports the RPP of each contractor by providing DOELAP accredited dosimetry services, technical basis documentation, and technical support as requested. HEDP currently maintains DOELAP accreditation and technical basis documentation for a centralized external dosimetry program shared by all DOE contractors at the Hanford site.

1.2 HEDP Objectives

External dosimetry is an integral part of most radiation protection programs. Viewing radiation dosimetry as an essential part of radiation protection, the National Council on Radiation Protection and Measurements Report No. 114, *Maintaining Radiation Protection Records* (NCRP 1992) identifies four major reasons for a radiation dosimetry program as follows:

- provide information allowing evaluation of the radiation safety program to ensure effective program operation
- provide evidence for regulatory compliance
- provide data for epidemiological studies

- provide information for making or contesting claims for radiation-induced injury

HEDP objectives are consistent with these NCRP rationale. HEDP objectives are summarized as follows:

- Provide accurate and technically defensible personnel, area, environmental and nuclear accident dose results
- Conduct the external dosimetry program in a manner that is compliant with applicable DOE regulations and direction, and consistent with applicable guidance
- Document policies, procedures and technical bases in sufficient detail to ensure defensibility of the dose of record for Hanford workers and to *demonstrate* compliance with applicable DOE regulations and direction, and consistency with applicable standards and guidance
- Provide and document laboratory and field measurements that establish the accuracy of dosimeter response under field conditions
- Maintain DOELAP accreditation for the Hanford Site
- Develop and maintain technical basis documentation for the Hanford Site
- Coordinate a consistent, shared dosimetry program for Hanford Site contractors through participation in the Hanford Personnel Dosimetry Advisory Committee (HPDAC)
- Support the RPP of each Hanford contractor as specified in SOWs
- Provide services that are cost effective and meet the needs of all contractors
- Participate in intercomparison programs in personnel, extremity, and nuclear accident dosimetry to demonstrate competency in areas outside of DOELAP
- Develop and implement improved technology when benefits clearly outweigh costs, or existing technology is inadequate to provide accurate dose results or support contractor objectives
- Ensure program conformance with applicable recommendations of the Health Physics Society (HPS), American National Standards Institute (ANSI), NCRP, and the ICRP whenever feasible.

2.0 Hanford External Dosimetry Program

The HEDP provides personnel, area, environmental, and nuclear accident dosimetry services for DOE personnel and contractors at Hanford and other DOE sites. The HEDP staff is responsible for conducting these activities in compliance with applicable DOE requirements and standards of good professional practice. Major areas of effort in the conduct of the HEDP are as follows:

- routine and special dosimeter processing and dose reporting
- dosimeter tracking and accountability
- dosimetry materials procurement and acceptance testing
- dosimeter and dosimetry system calibration
- equipment maintenance and calibration
- dosimeter processing quality control and dose results quality assurance
- verification of dosimeter response in work environments
- procedure development and maintenance
- software development and maintenance
- algorithm development and supporting technical studies
- documentation
- performance testing and accreditation

2.1 HEDP Position within PNNL

HEDP is organized as a program within Radiation and Health Technology (R&HT) Technical Group which functions within the Health Effects and Risk Sciences (HE&RS) Division, which in turn functions within the Environmental Technology Directorate (ETD) at the Pacific Northwest National Laboratory (PNNL).

The R&HT technical group provides Hanford services for external dosimetry, internal dosimetry, in vivo and in vitro bioassay, instrument calibration, and radiological records. In addition, R&HT operates a National Institute of Standards and Technology (NIST) secondary calibration laboratory for ionizing radiation and a laboratory for type testing of radiation instruments and electronic dosimeters.

2.2 HEDP Organization and Staffing

PNL-MA-841 *Hanford External Dosimetry Program Procedures Manual* describes HEDP roles and respective responsibilities in detail. An overview of critical roles is provided in the following subsections.

2.2.1 Program Manager

The HEDP Program Manager is responsible for overall administration of the program within budgetary constraints and in a manner consistent with contractual obligations. The program manager conducts line management of HEDP staff members including annual competency reviews. The program manager assigns roles and responsibilities for each staff member, prioritizes and assigns tasks, tracks progress, manages the budget, and ensures work is conducted in compliance with DOE requirements and within the scope of service contracts with Hanford contractor and other clients.

2.2.2 Technical Manager

The HEDP Technical Manager is responsible for HEDP technical practices including maintenance of the Technical Basis and Procedures Manuals, and is responsible for ensuring compliance with the conditions and criteria for accreditation, and is authorized by the Manager, R&HT, to sign the DOELAP accreditation applications, as necessary. The Technical Manager is the point of contact for DOELAP correspondence, receives proficiency testing materials and reports, and is the contact for onsite assessments. The Technical Manager is a professional experienced in applied radiation dosimetry who is knowledgeable in the design and operation of the HEDP system. The Technical Manager has the technical competence and the supervisory capability to direct the work of professionals and technicians in the dosimetry area.

2.2.3 Quality Manager

The HEDP Quality Manager is responsible for the quality system, including the Quality Manual, and its implementation. The Quality Manager has access to the R&HT Technical Group manager, representing the highest level of management at which decisions are made regarding dosimetry laboratory policy or resources.

2.2.4 Dosimetry Professional Staff

HEDP professional staff members are assigned several quality affecting roles. These roles include Dosimetrist, Training Coordinator, Computer Systems Administrator, and Program Analyst, etc., as defined in PNL-MA-841 *Hanford External Dosimetry Program Procedures Manual*. Proper conduct of these roles is crucial to the HEDP quality system. Staff assignments are made based on HEDP needs and staffing resources. The HEDP Program Manager makes these assignments with concurrence from the R&HT Manager.

2.2.5 Dosimetry Technician Staff

HEDP dosimetry technicians are dedicated to external dosimetry activities. These technicians are qualified in the respective procedures contained in PNL-MA-841 *Hanford External Dosimetry Program Procedures Manual*, and work under the technical direction of the Technical Manager. Training and qualification of HEDP technicians consist of formal training sessions and on-the-job training (OJT).

2.3 HEDP Facilities and Equipment

The R&HT staff occupies the 318 Radiological Calibrations Facility in the Hanford 300 Area near Richland Washington. This facility contains laboratories for dosimeter irradiation, portable radiological instrument calibration and repair, instrument environmental and type testing, and the HEDP dosimetry laboratories, along with staff offices. These laboratories, equipment, and staff members support a wide range of Hanford, national and international client programs. The 318 facility includes a NVLAP accredited secondary calibrations laboratory for ionizing radiation. Irradiations for NVLAP and DOELAP personnel and extremity dosimetry performance testing, and for contracted dosimeter and instrument irradiation services are performed in this facility.

2.3.1 Accommodation and Environmental Controls

The 318 Facility, totaling about 30,000 square feet, contains the original three-story 318 Building, four additions to the original building, and an adjoining trailer addition. The 318 Facility is primarily a laboratory complex with controlled ventilation, heating, cooling, humidity, etc., in accordance with good professional practice. Laboratories can be broadly divided into dosimetry and irradiation laboratories as described in the following subsections.

2.3.2 Dosimetry Laboratories

HEDP dosimetry laboratories generally occupy approximately 7,000-square feet in the south end of the building, an area dedicated to non-radiological designated laboratories. The laboratory and office space in the end of the building was designed to house the HEDP with dedicated, uninterruptible power supply (UPS) supported, electrical circuits for five reader systems.

2.3.3 Irradiation Laboratories

Irradiation laboratories generally occupy the basement and first floor of the original 318 Building, and selected laboratories for portable instrument testing and calibrations of the 318 Facility. All high-level irradiation capabilities are located within the original 318 Building. Irradiation capabilities covering a broad range are available within the 318 Facility. These capabilities have been used to evaluate and document response characteristics of HEDP dosimeters. Thermoluminescent Dosimeter (TLD) area monitors throughout the building are used to ensure that the use of irradiation sources does not produce measurable dose in the dosimetry labs and other non-radiological areas.

2.3.4 Equipment

HEDP dosimetry equipment has been commercially procured and represents “state of the art” capabilities. Primary and backup equipment exists for all critical program activities including annealing, bar code scanning of dosimeters to track movement of dosimeters to or from clients, and processing. Measuring and Test Equipment (M&TE) is classified as “quality affecting” or “non-quality affecting.” Quality affecting M&TE can directly influence the quality of the reported dose. Quality-affecting M&TE is calibrated and records kept in a manner that shows traceability to recognized national or international standards organizations.

The Hanford dosimetry system was procured based on HEDP design specifications. These design specifications were based on the recognized need for dosimeter capabilities to handle the broad spectrum of potential exposure environments in Hanford facilities. Hanford radiation fields have the potential for low-energy beta radiation from unsealed radiation sources, x-ray and gamma energies over a broad energy range and neutron radiation. Prior to procurement, the design specifications were reviewed by the HPDAC with representation from all Hanford contractor dosimetry organizations at the time of the procurement to ensure that the system would be adequate for current and anticipated field conditions.

2.4 HEDP Documentation

The HEDP practices are described in several PNNL manuals. These practices are implemented to comply with applicable DOE requirements, response(s) to program and/or facility appraisals, the DOELAP assessments, and “Hanford Practices” adopted through the HPDAC. These manuals are reviewed every three years at a minimum. A description of HEDP manuals follows:

- *Hanford External Dosimetry Program Procedures Manual* (PNL-MA-841) -This manual provides the administrative and technical procedures for the HEDP, including those describing the organization and administration of the program, change control, and technical procedures. This manual contains all procedures used in the HEDP conduct of personnel, area, environmental, and nuclear accident dosimetry.
- *Hanford External Dosimetry Technical Basis Manual* (PNL-MA-842) – This manual provides the technical bases and rationale for the design and implementation of the personnel, area, environmental, and nuclear accident dosimetry systems used at Hanford.
- *Hanford External Dosimetry Program Data Management Manual* (PNL-MA-844) – This manual documents the design of the External Dosimetry Data Management System, a collection of programs used to process and manage dosimetry data. These programs were developed at PNNL specifically to support the Hanford dosimetry system and are not a commercial off-the-shelf product. In addition to screening and analysis of data from TLD readers, the programs calculate dose, implement

process QC, import data from the Radiological Exposure System (REX), track dosimeters through the issue cycle to ensure all dosimeters are returned, processed, and results are reported. In addition to documenting the design and function of the software, PNL-MA-844 also documents hardware architecture, operating system, configuration control practices and data security practices.

- *Radiation and Health Technology (R&HT) Administrative Processes* (PNL-MA-870) – This manual documents document control, document review and change control, variance reporting, contract review, internal assessment and management review, backup and maintenance of electronic records, and other practices that are common to all programs within R&HT.
- *R&HT Quality Assurance Program Plan*—This plan includes the basic quality assurance elements that are used by the HEDP staff when performing external dosimetry functions. The requirements contained in it were established and implemented in conformance with 10 CFR 830 Subpart A, *Quality Assurance Requirements* (DOE 2003).

2.5 HEDP Functional Relationship with DOE and DOE Contractors

In addition to consideration of regulatory drivers, HEDP practices are formulated based on direct input from DOE and DOE Contractors. The primary mechanisms for external oversight and direction of HEDP are through the Hanford Personnel Dosimetry Advisory Committee (HPDAC), the Hanford Radiological Control Forum (HRCF), DOE Programmatic Assessments of HEDP and Contractor RPPs, and work agreements with each contractor and the associated SOWs.

2.5.1 Hanford Personnel Dosimetry Advisory Committee

The HPDAC was established by DOE-RL to provide technical guidance and establish uniformity in the administration of dosimetry programs at Hanford. The HPDAC is chaired by an RL/ORP representative, with identified representatives from respective contractor dosimetry organizations. The HEDP participates in HPDAC. Minutes of the monthly meetings are recorded and maintained in Hanford's radiological records historical file maintained by the Hanford Radiological Records Program (HRRP). HEDP technical issues and practices are coordinated through the HPDAC.

2.5.2 Hanford Radiological Control Forum

The Hanford Radiological Control Forum consists of representatives of the Hanford Site prime contractor's radiological control organizations and representatives of the RL/ORP radiological control organization. The chairperson is selected on a rotating basis. The activities of the HRCF include, but are not limited to:

- review of radiological control consistency
- review of Hanford radiological problems and successes

- review of DOE radiological control guidelines.

Policy affecting issues developed through the HPDAC are occasionally presented to the HRCF for formal adoption. The HRCF is primarily a policy-setting organization, with one of its objectives to provide direction to all Hanford contractor organizations.

2.5.3 Hanford Contractor Work Agreements

The HEDP funding is provided by the respective Hanford contractor organizations. Letters of instruction and/or memoranda of understanding with associated SOWs are used to detail responsibilities, authority, and communication requirements of the respective organizations. Copies of these agreements are maintained in the HEDP Program files located in the 318 Building. In general, it is HEDP practice to incorporate primary responsibilities within the program objectives.

2.5.4 Non-Hanford Contractor Work Agreements

Non-Hanford contractors are responsible for establishing and documenting their practices for assigning, issuing, wearing, storing, and exchanging dosimeters. Generally, these practices are at the discretion of the customer, except where practices are constrained by the design of the dosimeter or by the limits of the accreditation. However, proper interpretation of the information stored in dosimeters requires that the processor have some knowledge of the radiation fields to which dosimeters are exposed and how dosimeters were worn, stored, and shipped. This information is conveyed in the SOW with the customer, through codes in files sent to HEDP at the start of processing of each batch, or through personal communication between customer and HEDP technical staff. The latter communication is kept in HEDP Program files.

2.5.5 DOE Programmatic Assessments and Oversight

HEDP is periodically assessed either directly or indirectly by DOE as part of DOE's programmatic assessments which include assessments of Hanford contractor Radiological Protection Programs. HEDP policies and practices are often shaped in response to these assessments.

2.6 Field Dosimetry Practices and Contractor Responsibilities

Each of the Hanford contractor organizations has radiation protection professionals who are responsible for field dosimetry practices and ultimately are responsible for approving the dose assigned to their personnel. Contractor responsibilities include the following:

- assignment of dosimeters to individuals through REX
- issuing multiple dosimetry when necessary
- distribution, collection and accountability of dosimeters

- comparison of TLD and direct reading dosimeter (DRD) results and resolution of discrepancies
- review of dose results assigned to individuals
- implementing work restrictions as needed
- assessing dose for individuals with lost or damaged dosimeters
- determining which individuals are to be monitored with dosimetry
- determining proper exchange frequencies for routinely monitored employees
- enforcing proper dosimetry wear practices
- establishing proper controls on dosimetry storage and handling in the field
- assessment of field conditions to ensure proper dosimeter response
- specifying appropriate facility calibration code when returning ring dosimeters to ensure field specific correction factors are applied when appropriate
- specifying appropriate facility calibration code when returning dosimeters to ensure application of proper neutron dose algorithm
- notification of HEDP when improper dosimeter response is suspected
- notification of HEDP when dosimeters are used outside the conditions for which they have been calibrated
- requesting technical support when appropriate
- assessment of skin dose from non uniform radiation fields
- assessment of whole body dose from non-uniform radiation fields
- occurrence reporting
- administering workplace and area monitoring programs
- establishing locations for fixed nuclear accident dosimetry and exchanging of dosimeters
- issue and assignment of personal nuclear accident dosimetry
- implementation of quick sort methods in the event of a criticality

THIS PAGE INTENTIONALLY LEFT BLANK

3.0 Quality Assurance and Quality Control

HEDP quality assurance (QA) and quality control (QC) practices are described in *R&HT Quality Assurance Program Plan (R&HT QAPP)*, PNL-MA-870 *R&HT Administrative Processes*, and in PNL-MA-841, *Hanford External Dosimetry Program Procedures Manual*. The R&HT QAPP contains specific quality assurance elements that ensure compliance with 10 CFR 830, *Energy/Nuclear Safety Management*, Subpart A, *Quality Assurance Requirements* (DOE 2003), DOE Order 414.1A, *Quality Assurance* (DOE 1999d), and 10 CFR 835, *Occupational Radiation Protection* (DOE 1998c). The objective of a quality assurance program is to ensure that equipment, software, and processes, perform as planned. This chapter focuses primarily on quality control and describes selected HEDP QC/QA implementing practices.

The principle objective of the HEDP is to provide high-quality dose measurement for Hanford workers, visitors, and the environment (Baumgartner, Endres, and Reese 1992). To attain this objective, the HEDP must

- maintain an effective, ongoing program to measure and verify process QC and dosimeter performance under controlled conditions and in the workplace
- recognize and promptly correct any factors that adversely affect quality
- maintain complete records of processing activities, program performance, and final reports and analyses to verify resulting data
- ensure that programmatic assessments and audits of HEDP (internal and external) are performed on a regular basis and identified deficiencies corrected

3.1 Dosimetry Materials

The HEDP staff examines all materials used in dosimeters. Because personnel and/or visitors are typically assigned only one dosimeter at a time, failure of any component of the dosimeter has the potential to jeopardize the quality of the recorded dose for the monitoring period in question. Therefore, HEDP conducts 100% acceptance testing of dosimeter cards and holders (every unit is tested prior to use) rather than random sampling of production lots. Acceptance testing of dosimeter cards involves tests of *each element* for:

- beta-photon sensitivity
- neutron sensitivity
- unwanted sensitivity to light
- glow curve structure
- reproducibility

and tests of *each card* for:

- mechanical integrity
- bar code readability and uniqueness
- proper color coding
- proper phosphor placement

Acceptance testing of holders involves tests of:

- Proper composition of each filter
- Proper thickness of each filter
- Opaqueness to light for Mylar[®] beta window
- Adequate tinting of rose colored bar code window
- Integrity of gaskets and hinges

Acceptance testing of disposable components such as plastic ring casings, and Mylar windows is conducted on a production lot basis using sampling criteria from *ANSI/ASQC Z1.4-1993 Sampling Procedures and Tables for Inspection by Attributes*. Testing consists of 1) visual inspection for physical defects, 2) measurement of window thickness to verify within tolerance.

Each whole body dosimeter card and holder is uniquely labeled so that their entire history of dosimeter assignment and calculated dose can be tracked throughout their lifetime. Each reader system has a unique identifier that becomes a part of the permanent processing record. These unique, permanent identification numbers provide the capability to retroactively evaluate the quality of reported dose.

3.2 Dosimetry Laboratories

The HEDP dosimetry laboratory is designed and equipped to the extent practicable to minimize uncertainties in the TLD measurement process. Dosimetry laboratories and equipment are dedicated to dosimetry purposes only. To reduce electronic noise and to prevent loss of data from power failure, dedicated electrical circuits, with an installed UPS system, are used to power TLD reader systems. The laboratory spaces used by HEDP are temperature controlled and continuously monitored for temperature and humidity. Radiation levels are monitored monthly using area monitoring TLDs. Radiation and contamination levels are checked monthly using hand held survey instruments as part of a routine radiological survey. Incoming dosimeters are surveyed for contamination in a separate room using an automated contamination survey table. Laboratory lighting is provided by UV filtered warm white fluorescent tubes with

low emissions in the blue and ultraviolet regions so as to reduce spurious light induced signals on TL elements. Nitrogen gas used by the TLD reader systems is obtained from a liquid nitrogen source to ensure a low level of impurities such as moisture. Instrument quality air is provided for pneumatic devices and compressed inert gas is used for cleaning of TLD cards, and holders. HEPA filtered vacuum systems are used for cleaning of TLD readers and other laboratory equipment so as to minimize unnecessary spread of dust and chemical contaminants. Laboratory measurement and test equipment (M&TE) used in quality affecting processes is controlled, calibrated and maintained as part of an ongoing M&TE program.

Radiochemical analysis of NAD and PNAD components, personal items, and biological samples collected after a criticality accident are performed by the PNNL Analytical Chemistry Laboratory (ACL) under a work agreement with HEDP. The ACL primary laboratory is currently located in the 325 Building in the 300 area.

3.3 Dosimetry Processing Equipment

HEDP dosimetry handling and processing equipment includes the following:

- Harshaw 2000D, 6600, and 8800 TLD reader systems and associated computers and software
- TLD annealing ovens
- Automated holder openers
- Dosimeter contamination survey table
- Ultrasonic welder for sealing of rings
- Bar code scanning stations
- Label printers

3.4 Design Features of TLD Reader Systems

The heating system in all HEDP TLD reader systems consists, in principle, of two parts: 1) a heat-supplying medium, and 2) electronics for the control of temperature. The Harshaw Model 8800 and Model 6600 card readers use independent temperature-controlled streams of hot nitrogen gas to heat the individual TLD elements. Heating with nitrogen gas has been shown to have several advantages: the heat transfer from the gas to the dosimeter card is efficient and results in rapid readout, incandescent light emission is greatly reduced, and oxygen-induced background signals are easily suppressed. While these advantages are most pronounced for instruments in which the individual TLD phosphors are removed from their holder, the HEDP system has the following additional benefits even though the individual phosphors remain encased in cards during the heating cycle:

- increased number of reuses without significant degradation in performance
- improved reproducibility of glow curve shape and integral TL signal
- simplified maintenance (Harshaw 1988)

The light-measuring equipment in the Harshaw TLD readers consist of a photomultiplier tube (PMT) in which light is converted into an electrical charge, an amplifier for this electric signal, and a signal registration unit that quantifies and stores the signal. In the Model 8800, four 1.27 cm diameter PMTs in a thermoelectrically cooled housing independently convert the emitted light from each of the four TLD elements in a card to electrical signals that are transmitted to the data acquisition system. In the Model 6600, two 1.27 cm diameter PMTs in a thermoelectrically cooled housing are used. In the Model 2000D, a two inch PMT in a water cooled housing is used.

The mechanical portion of the Model 8800 TLD reader consists of two carousels for holding cartridges of dosimeter cards, a readout station with PMTs, and a transport mechanism. In addition, the system is equipped with an internal ^{14}C light source for use in monitoring changes in the PMT sensitivity. The Model 6600 TLD reader has no carousels and accommodates only one load and one unload cartridge. The Model 8800 is capable of reading 1400 cards with a single loading. The Model 6600 is capable of reading 200 cards with a single loading. Details of reader design are contained in the manufacturer's literature kept in HEDP files.

The following are manufacturer specifications for the HEDP 8800 and 6600 reader systems (from Harshaw 1988):

- Electrical linearity: The electrical linearity of the system is $\pm 2\%$, or ± 2 mrem, whichever is greater, in the range from 1 mrem to 2000 rem.
- Linearity with exposure: The TLD response is linear with exposure in the range of 0.001 to 100 rem to within 5%.
- Dark current randomness: The standard deviation from the mean of 10 readings taken without heating and without a dosimeter in the instrument is less than 1 mrem.
- System zero randomness: The standard deviation from the mean of ten readings taken with heating and with an unexposed dosimeter in the instrument is less than 5 mrem.
- Residual reading: The readings from dosimeters, that have been initially irradiated to 500 mR, read, and then re-read without any annealing, are less than 2 mR.
- Reproducibility of heating: The reproducibility of the heating assembly is such that the same percentage of the total signal is extracted during the

readout to within $\pm 1\%$.

- Background stability: Over time intervals from one read-cycle up to 8 hours, the reader background (dark current) is reproducible to within $\pm 10\%$ of a given threshold signal.
- Reproducibility of reader: Over a period of 8 hours, the readout value does not vary by more than 0.05% at a readout value corresponding to 100 times a given threshold signal.
- Card identification number: In conjunction with dosimeter assemblies, there are fewer than 1 in 10,000 erroneous dosimeter identifications, including dosimeter type and serial number. Each card can endure 500 readout cycles without any decrease in its mechanical performance, including dosimeter type and serial number identification/reading.

3.5 Dosimetry Issuance and Receipt

Daily activities within HEDP are directed toward processing dosimeters and interpreting results. However, other activities that precede and follow processing on the readers are necessary to ensure the quality of results. Process QC begins with preparing dosimeters for issuance. Once the dosimeter cards have been reader-annealed and oven-annealed and have been loaded into holders, the dosimeter (card and holder) barcodes are scanned to record the issued card/holder configuration. If the card/holder pairing is different upon return to the laboratory, an error message is generated when the dosimeter is scanned into the processing laboratory. When scanning the dosimeter for issue, the scanning software checks the status of several parameters within the HEDP database to establish eligibility of the dosimeter holder and card for issuance. The following are examples of conditions that will prevent the issuance of a dosimeter:

- The card has not passed one or more acceptance tests.
- The card has an invalid status (e.g. broken, lost, issued, or any status other than “annealed for issue.”)
- The card anneal date is more than 30 days old.
- The card is due for recalibration.
- The holder has not passed acceptance testing.
- The holder has an invalid status (e.g. broken, lost, issued, or any status other than “returned”).
- The card type and holder type are incompatible.

Dosimeters are scanned upon receipt for processing. The scanning software compares the issued configuration with the returned configuration and notifies the operator if changes have occurred. If the scanning transaction is successful,

the dosimeters are inspected for damage and opened to remove the cards for processing.

3.6 Dosimetry Processing

Before processing TLD cards, an electronic QC check is performed on the TLD reader to be used. This check assesses several operating parameters, such as the mean and standard deviation of PMT noise (dark current), reference light (REF) readings, PMT high voltage, digital-to-analog converter voltage, 5- and 15-volt power supply voltages, and gas jet temperatures. The results are compared with user-determined limits and, if not acceptable, flagged for user evaluation.

Additionally, either a reader calibration or a reader functional check are performed. This check involves processing several cards exposed to 500-mR radiation and verifies the function of the heating mechanism and the accuracy of the reader calibration factors to be applied.

After successful completion of the electronics and reader functional checks, TLD cards may be read. Field cards are stacked into reader cartridges with a QC card and a blank card inserted at the beginning and after every 50 field cards. During readout, the reader applies real-time process QC by continuously monitoring the QC card readings, blank card readings, reference light readings, and PMT noise readings. If any single reading falls outside user prescribed limits, the reader stops processing. Typically, the prescribed limits are as follows:

- QC card readings – 450 to 550 mR
- blank card readings – 0 to 20 mR
- PMT noise limit – 5 mR equivalent.

Reference light limits are set at approximately $\pm 10\%$ of their nominal (long-term mean) value. If the reader stops, a number of evaluations are required by procedure before the reader can be put back into use for dosimetric readout of dosimeters. The reader also monitors the frequency of QC and blank card readings. If a QC and/or blank card is not processed within the user-prescribed number of field card readings, the reader stops. The PMT and reference light readings are automatically conducted by the reader at the user-prescribed frequency. During the read process, parameters such as gas pressure, gas temperature, and the PMT cooler temperature are continuously monitored. If they exceed the internal limits of the reader, they cause an orderly shutdown of the system. Finally, if a card cannot be successfully identified by the reader's barcode scanner, if there is no valid element correction coefficient (ECC) on file, or if the time temperature profile (TTP) to be applied by the reader during processing does not have a valid calibration, the card is rejected without being processed.

3.7 Data Screening

The TLD cards are read in groups and the resulting electronic files produced by the reader are called group files. These group files are uploaded to the HEDP Alpha system for consolidation with other group files and data analysis. After reading the data into temporary files, the data are screened to ensure that they were acquired under the proper reader configuration. In addition to the card IDs and raw element readings, each group file contains information regarding the TTPs and reader calibration factors (RCFs) applied during readout, the type of card being processed (e.g., field, QC, blank, calibration), the reading type (e.g., field reading, annealing, card calibration, etc.), the reader number and reader environment, data acquisition setup, and other information, which is compared with the configuration prescribed in the procedures. The data are also compared with other data in the HEDP database for consistency. Cards not in the HEDP database are flagged. Cards showing no record of being returned to the HEDP processing laboratory are also flagged. The following are examples of the types of data checks performed by HEDP QC software:

- invalid reader number
- invalid group number
- invalid reader environment descriptor
- group file already imported
- dosimeter type inconsistent with reader environment
- External Dosimetry database key violation (record already in database based on reader number and date and time of reading)
- missing temperature information
- missing glow information
- duplicate card identification ID number in same group
- card not in database
- invalid reading date/time (i.e. subsequent to current system date/time, or of impossible value)
- TTP number inconsistent with reading type
- calibration option inconsistent with reading type
- invalid ECC (outside allowed range)
- invalid RCF (outside allowed range)

- invalid instrument type
- group number in record inconsistent with user input
- REMS environment in record inconsistent with user input
- card ID number invalid for REMS environment used
- card ID number inconsistent with dosimeter type used
- reading type inconsistent with group purpose
- card ID number inconsistent with reading type

If any record in the group file fails the above data-screening parameters, the group file is flagged for evaluation. In either case, a data screen report is generated to provide a summary of error conditions.

3.8 Group QC Statistics

After the data in the group file are incorporated into the HEDP database system, the PMT, reference light, QC card and blank card readings, and other QC-related information in the group are analyzed. A group QC statistics report is generated, summarizing the analysis. This report provides timely feedback on the stability of the reader and the acceptability of the process QC implemented at the reader level. By calculating the mean, and standard deviation of PMT dark current, reference light, and QC and blank dosimeter readings in each group file, a tighter level of QC can be maintained on dosimeter processing. Limits are established at the HEDP Alpha level for the minimum number of QC readings of each type (i.e., PMT dark current, reference light, QC, and blank readings) that must be contained in each group file, as well as limits for the minimum, maximum, mean and standard deviation for each of these reading types. Typically, the limits for the QC card mean in each group is $\pm 5\%$ of the delivered exposure. The limits for the other reading means are $\pm 5\%$ around their nominal values, as well. If all of the group file statistics are within an acceptable range, the group file is judged to have acceptable QC. A database record is kept of the QC statistics associated with each group file. If any QC result in a group file does not have acceptable QC statistics, each dose result record generated from the group file is flagged for evaluation and prevented from being reported until resolution.

3.9 Glow Curve Analysis

Glow curves for each chip on each card are analyzed for acceptable peak centroid and full-width at half-maximum and for the presence of single-channel spikes that contribute significantly to the total glow integral. Four regions of interest in each glow curve are analyzed. If the glow curve data do not conform to an expected pattern, the curve is flagged as having abnormal processing characteristics. Dose result records based on flagged glow curves are also flagged. Flagged dose records are evaluated by a dosimetrist to determine if adjustments to data are necessary and prevented from being reported until resolution.

3.10 Element Ratio Analysis

One of the first steps in the dose calculation process is the analysis of chip readings relative to each other. Three independent element ratios result from the four-chip dosimeter cards. If any one of these ratios is outside the pre-established range expected from the radiation types to which the dosimeter could have been exposed, the dosimeter record is flagged for evaluation. In addition to tests of element ratios, numerous other tests are performed on raw element readings, intermediate results and final results by the dose calculation software. If any of these tests are failed, an algorithm flag is set on the individual dose result record which prevents reporting of the dose result until the anomaly is investigated and resolved.

3.11 Review and Reporting of Dose Results

By procedure, every calculated dose result must be reviewed by a qualified dosimetrist before reporting. For those calculated dose results that have one or more software generated QC flags, the dosimetrist must clear the flag before dose results can be reported. To clear the flag, the dosimetrist must determine the cause of the flag, assess whether the result is accurate as is, or needs to be adjusted, make adjustments if necessary, and document the basis for the adjustments. In most cases, the adjustment is made to one or more raw chip readings on the basis of glow curve structure, and dose is recalculated using the adjusted readings. In addition to the individual results in a process group, the dosimetrist must verify that the process QC parameters associated with the group (e.g. group QC statistics) are within the allowed tolerances before dose results can be reported. Because dosimeters must be processed and dose results reported on a daily basis, process QC is designed such that a sufficient level of confidence in the accuracy of dose results can be achieved to allow reporting of dose results on a daily (i.e. on a group basis) rather than at the end of a pre determined time period (e.g. monthly). As such, reporting of dose results is not contingent upon availability of audit dosimeter results and the role of audit dosimeters is more closely related to quality assurance rather than quality control. The requirements for reporting of dose results are resolution of all flags, verification of adequate process QC, and dosimetrist review and signature on hardcopy dose calculation reports.

3.12 Dose Results Accountability

For every dosimeter returned for processing, the HEDP must ensure that a dose result is reported, or in the case of damaged dosimeters, notify the customer that a dose result cannot be determined. For each dosimeter issued to a customer, the status of the card and holder is tracked on the Alpha from the time of issue through final reporting of dose results. This status tracking ensures that all issued dosimeters will be accounted for and that dose results will be reported in a timely manner for all dosimeters returned to the lab for processing. The following listings are routinely generated from the Alpha database and acted upon by the HEDP staff:

- Dosimeters issued but not returned within allotted time frame (overdue)
- Dosimeters returned (according to the customer) but not scanned in (to the Lab) within allotted time frame
- Dosimeters scanned in but not processed within allotted time frame
- Dosimeters processed but not reported within allotted time frame

3.13 Unreturned Dosimeters

Dosimeters that have not been returned to the lab within the expected time frame for each exchange frequency will appear on an “over due” dosimeter report that is provided to contractor dosimetry organizations each quarter. Monthly, quarterly, and annual dosimeters that have not been returned to the lab within 60, 180 and 465 days respectively of their scan out date will be listed. Dosimeters issued without an exchange frequency (e.g. temporary dosimeters) are treated as annual dosimeters for this purpose.

3.14 Lost or Damaged Dosimeters

In cases where a dosimeter has been lost or has been returned in a condition too damaged for processing, the client is expected to conduct an investigation to determine the dose to be assigned. For Hanford clients, the results of the investigation are documented on an Investigation of Dosimeter Result (IODR) form. The form is used by the HRRP staff to enter the estimated dose into the individual’s exposure history file. Non-Hanford clients are responsible for review and input of the assessed dose into their own radiological records database. Hanford and Non-Hanford clients are notified by HEDP of dosimeters too damaged to be successfully processed and dosimeters over due for processing.

3.15 “High” Dose Results

The HEDP system is capable of flagging dose results during dosimeter processing, that exceed agreed-upon dose levels requiring prompt notification of the client dosimetry organization. For Hanford clients, prompt notification is made when a dosimeter result contains a dose component exceeding one of the following:

Table 3.1. Prompt Notification Levels

Dosimeter Type	Dose Equivalent Type	Notification Level (mrem)
HSD, 8825BP	Shallow	2000
HSD, 8825BP	Eye	1000
HSD, 8825BP	Deep Photon	300
HSD, 8816	Neutron	200
HSD	Deep Photon + Neutron	500
Ring	Shallow	3000

Note: The prompt notification levels for an HSD dosimeter worn on an extremity (e.g. HSD Wrist dosimeter) are the same as for an HSD worn as a whole body dosimeter.

These records are automatically flagged as “high” in the HEDP database system. Following review and approval by HEDP dosimetrists applying a knowledge of the algorithms and processing equipment, these results are reported on a priority basis to the respective clients’ dosimetry organizations. For Hanford clients, dose results are electronically reported to REX by 10:00 AM the morning following determination of dose and the contractor dosimetry representative is notified by e-mail or by phone at the same time. The dosimeter result records sent to REX are individually flagged in a manner that REX recognizes as a “high” dose. It should be noted that the notification levels above apply to individual dosimeters. The HCND is actually two dosimeters (8825BP + 8816) and the dose calculation/flagging software applies limits to their deep photon and neutron results independently.

3.16 Abnormal Dosimeter Results

Whenever a dosimeter result is suspected of being in error based on the raw glow or heat curve data, or dose algorithm flags, or detection of unanticipated radiation types based on the work environment in which the dosimeter was used, HEDP notifies the respective client in one or more ways. The results are identified with “notecodes” of 50, 53, or 59 in the notecode field of the dose results file provided for input to REX or the non-Hanford customer’s radiological records database. Notecode 50 identifies results for which HEDP is unable to confidently estimate a dose based on observed processing data and for which the client is expected to perform an investigation to determine the dose to be recorded. Dosimeter results with a notecode of 50 are generally reported as 0 mrem when no estimate of dose is possible. Notecode 53 results represent results for which HEDP has revised one or more chip readings because of abnormalities in the glow curve or other

raw processing data, then recalculated dose. Notecode 59 results are results that include a positive neutron dose for dosimeters for which no neutron dose is expected based on the facility calibration code under which the dosimeter was submitted for processing. For Hanford clients, notecode 53 and 59 dose results, as reported in the dose results file, are automatically entered into REX whereas notecode 50 results are not. For notecode 50 results, an investigation must be performed by the client to determine the correct dose to enter into REX. Practices for non-Hanford clients regarding incorporation of HEDP dose results into their radiological exposure records databases varies from client to client. Non-Hanford clients are instructed to treat notecode 50 results as non-results requiring investigation to determine dose in the same manner as a lost or damaged dosimeter that could not be processed.

For all notecode 50 and 59 records and selected notecode 53 records (see paragraph below); the HEDP database system automatically produces a "Suspect Dosimeter Results Evaluation Form." This form is mailed from HEDP to the respective Hanford client dosimetry representative for notification of the suspect result. For note code 53 and 59 results, the Hanford client provides a concurrence signature and returns the form to HRRP for inclusion in the individual's exposure history record. In rare cases, if the client does not agree with the reported dose they may elect to complete an IODR form assigning the dose to be recorded. For notecode 50 results, the Hanford client must document the dose to be assigned on an IODR form. In either case, the IODR form is sent to the HRRP for inclusion in the individual's exposure history files and for use by HRRP staff members in updating REX. Similar arrangements are available to all users of HEDP services.

HEDP has latitude to make corrections to chip readings as appropriate to improve accuracy of reported dose and reduce false positive results. Such changes are typically based on clearly identified noise or other abnormalities in the glow curve and are made on a regular basis. Changes of this type are always identified with a notecode of 53 in the electronic dose record used to update REX. However, "Suspect Dosimeter Results Evaluation Forms" are generated and forwarded to contractor dosimetry organizations for concurrence only when there is a change in calculated dose (increase or decrease) that exceeds established thresholds. The current thresholds requiring contractor notification and concurrence are shown in Table 3.2. These thresholds have been agreed to by the HPDAC and apply to all dosimeter types.

Table 3.2 Change in Calculated Dose Requiring Contractor Concurrence

Dose Equivalent Quantity	Change in Calculated Dose (mrem)
Shallow	1,500
Eye	450
Deep photon	50
Neutron	50

3.17 Blind Audit Dosimeter Program

In addition to the above QC methods, the HEDP maintains an ongoing blind audit dosimeter program as a quality assurance measure. This is an in-house (R&HT) blind test of HEDP. Each month, the R&HT Quality Manager arranges for exposure of blind audit dosimeters to radiation sources and doses unknown to HEDP dosimetrists or processing staff. The dosimeters used as audit dosimeters are labeled for and assigned to fake individuals in REX and are indistinguishable to HEDP staff members from other assigned dosimeters. On a quarterly basis, audit dosimeter results are evaluated against the delivered doses and performance is determined according to the methodology in the DOELAP performance test standard (DOE 1986a). The results of these performance evaluations are reported to DOE-RL, Hanford contractor dosimetry organizations and are retained in HEDP records.

3.18 Dosimetry Processing Quality Assurance Reports

Quality assurance of dose results is provided by the HEDP on a quarterly basis by plotting and statistical evaluation of PMT readings, REF readings, QC card readings, and Blank card readings, as well as analysis of monthly blind audit dosimeter performance against DOELAP criteria. On an annual basis, PMT readings, REF readings, QC card readings, and Blank card readings and RCFs are plotted and statistically evaluated over a period representing a calendar year. The performance of quarterly and annual blind audit dosimeters is also evaluated against DOELAP criteria. The results of all these analyses are documented in HEDP files in dosimeter processing quality assurance reports generated by a HEDP Dosimetrist.

3.19 External Dosimetry Program Records

The HEDP maintains comprehensive records of all processing data, including the following:

- electronic records of all processing data
- electronic records of all QC data to include qualification testing of dosimeter cards and holders
- electronic records of the digitized glow curves
- hard-copy records of dose evaluation for abnormal circumstances
- electronic records of the use history of all HEDP personnel dosimeter cards and holders
- hard-copy records of procedures
- hard-copy records of QA requirements
- hard-copy records of letters of instruction, memoranda of understanding, or contracts

- hard-copy records of training and staff qualifications
- hard-copy records of DOELAP and NVLAP certificates and letters of instruction, accreditation status, responses to DOELAP onsite assessments
- electronic records to retroactively evaluate dose
- hard-copy records of technical studies or documentation.

The foregoing records are an important element of the HEDP. They provide the detailed information necessary to technically validate the calculation of reported dose, the capability to retroactively evaluate dose upon request, and the information needed to meet regulatory, technical and QA requirements.

3.20 Records Disposition

DOE has prescribed requirements for the orderly disposition of records at DOE facilities. External dosimetry records are considered to be under the general heading of medical, health, and safety records. The requirements for records disposition separate dosimetry information into program records and exposure histories. HEDP record requirements include the following four categories:

Results of equipment calibration establishing the authenticity of the dose results must be held for 75 years.

Automatic data processing system programs, codes, instructions, tapes, and discs, if used for the retrieval of dosimetry data, must be held for 75 years.

Worksheets, requests for analysis, charts containing information that must be interpreted or further modified before use, automatic data processing system input records, information used in interim calculations, and information used to verify that the recorded data are correct, must be held until the exposure record has been verified and approved or for a period of 1 year, whichever is earlier.

Historical files of standards, guides, and procedures (including revisions) must be retained permanently.

Individual exposure records require a 75-year retention period for the following types of information: records of contamination incidents, results of dose assessments, and documentation on any investigations undertaken.

3.21 Other Quality Assurance Topics

The following QA topics are described in greater detail in the *R&HT QAPP*, *PNL-MA-870 R&HT Administrative Processes*, and *PNL-MA-841 Hanford External Dosimetry Procedures Manual*:

- R&HT Quality Policy
- R&HT Organization and Personnel
- Personnel Training and Qualification
- Document Control
- Review of Work Requests
- Subcontracting
- Purchasing of Services and Supplies
- Reviewing Client Service Requirements
- Handling of Client Complaints
- Control of Non-Conforming Work or Items
- Variance Reporting
- Change Control
- Records Control
- Internal and External Assessments
- Management Reviews
- Confidentiality and Proprietary Rights
- Preventive Action
- Corrective Action
- Action Tracking

THIS PAGE INTENTIONALLY LEFT BLANK

4.0 Regulatory Basis

DOE requirements applicable to the HEDP are defined in the DOE Occupational Radiation Protection 10 CFR 835 rulemaking (DOE 1998c), DOE Quality Assurance Requirements 10 CFR 830 Subpart A rulemaking (DOE 2003), DOE Quality Assurance Order, DOE O 414.1A (DOE 1999d), DOELAP Technical Standard (DOE 1995), DOELAP Administrative Standard (DOE 1998a), DOELAP Performance Testing standard (DOE 1986a) and DOELAP Handbook (DOE 1986b). Some or all of these requirements may be applicable to Hanford contractors using the services of HEDP, to the extent that they are stipulated in the individual contracts with DOE. The DOE Richland Operations Office (RL) and Office of River Protection (ORP) define additional requirements for HEDP and Hanford contractors in the *Hanford Radiological Health and Safety Document* (DOE 2001), to the extent that this document is referenced by contract. Technical guidance is given by DOE in the *DOE Standard - Radiological Control; DOE-STD-1098-99* (DOE 1999a), and in the DOE program guides for external dosimetry and fetal dose (DOE 1999b,1999a). The HEDP also implements specific clarifications, agreements or directives identified through the HPDAC that do not conflict with regulatory requirements or contractor SOWs. This hierarchy of DOE radiation protection requirements and guidance pertaining to external dosimetry as well as the basic provisions of these documents pertaining to external dosimetry, are summarized in this chapter.

4.1 DOE Rulemaking

The primary DOE requirements for occupational radiation protection are provided in 10 CFR 835 (DOE 1998c). This rule codifies DOE radiation protection requirements pertaining to external dosimetry. The primary DOE requirements for quality assurance are provided in 10 CFR 830 Subpart A (DOE 2003). Basic requirements pertaining to external dosimetry in 10 CFR 835 and 10 CFR 830, Subpart A, include:

- for stochastic effects, annual limit of 5-rem total effective dose equivalent (including both internal and external sources)
- for non-stochastic effects, annual limits of 15-rem dose equivalent to the lens of the eye and 50-rem dose equivalent to the extremities, or to any organ or tissue
- for protection of unborn children, a limit of 0.5-rem dose equivalent to the fetus/embryo over the entire gestation period
- for members of the public/occupationally exposed minors, annual limit of 0.1-rem total effective dose equivalent
- for personnel monitoring, a DOELAP accredited dosimetry program
- for nuclear accident dosimetry, a system of personal and fixed units with associated analytical capabilities

- for retroactively calculating dose, necessary processing and calibration records
- for QA, documented QA plan, procedures, and training records.

4.2 DOE Guidance

DOE technical guidance is contained in the DOE technical standard *Radiological Control* (DOE 1999c). This standard identifies several provisions which HEDP has adopted as standard practice. In addition, DOE has provided a series of technical implementation guides. Two of these guides, (DOE G 441.1-4; DOE1999b) *External Dosimetry Program Guide* and (DOE G 441.1-6; DOE1999a) *Evaluation and Control of Radiation Dose to the Embryo/Fetus Guide* also contain several provisions which HEDP has adopted as standard practice. DOE guidance implemented by HEDP includes the following:

- preparation and maintenance of a technical basis manual providing scientific information and other rationale explaining each element of the external dosimetry program
- maintenance of historical records of personnel dosimeter measurement results and dose assessments
- conduct of an internal audit program no less frequently than every three years
- personnel dosimeter measurement methods and frequencies appropriate for the specific dosimetry applications at Hanford.
- methods for control, accountability, and safe handling of dosimeters
- appropriate action level and investigation level guidelines
- historical records of the external dosimetry program and procedures, as well as changes in the programs and procedures
- QA program covering all aspects of activities that determine worker dose
- methods for the use of multiple dosimetry and a defined methodology for dose calculation
- performance criteria for nuclear accident dosimetry, to include a system of fixed and personal dosimeters, documentation of placement criteria and analytical methods
- methods for assessment of dose to extremities or skin from non-uniform irradiation
- methods for evaluating the various doses from external radiation

4.3 DOE Laboratory Accreditation Program

10 CFR 835 requires the accreditation of dosimetry programs. Three documents describe the DOE program for accrediting dosimetry programs at DOE facilities: *The Department of Energy Laboratory Accreditation Program Administration* DOE-STD-1111-98 (DOE 1998a), the *Standard for the Performance Testing of Personnel Dosimetry Systems* DOE/EH-0027 (DOE 1986a) which contains performance criteria for dosimetry systems similar to that of HPS N 13.11 (HPS 1993) and the *Handbook for the Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems* DOE/EH-0026 (DOE 1986b), which contains requirements for Personnel Training and Qualification, Materials and Equipment, Procedures, Quality Assurance, Documentation, and Dose Reporting. These standards establish required dosimeter testing and performance testing in several categories, described generally as follows:

- accident dose test categories extending from 10 to 500 rad
- personnel dose test categories for photon, beta, and neutron radiation
- subcategories of testing involving only one source of irradiation and testing involving mixed (i.e., beta/photon, beta/neutron photon/neutron sources)
- performance criteria for photon radiation testing at protection dose levels include an exposure category of monoenergetic x-rays (16 keV and 59 keV), which are used to simulate plutonium environments. The criteria also permit the use of an ^{241}Am source in lieu of the 59-keV x-ray category
- documentation of dosimeter angular response typically to include evaluations of angular response for exposure angles of $0^\circ \pm 30^\circ$, $\pm 60^\circ$, and $\pm 85^\circ$, for both vertical and horizontal planes of rotation
- documentation of lower level of detection (LLD) for each protection dose level category
- performance criteria for unmoderated and moderated ^{252}Cf in the neutron exposure category
- criteria for mixed radiation field tests between low-energy photons and beta particles, low-energy and high-energy photons, and low-energy photons and neutrons
- the maximum allowed values for precision and bias are 30% or 40% for the various exposure categories.

THIS PAGE INTENTIONALLY LEFT BLANK

5.0 Technical Basis

To the extent possible, the technical bases of HEDP dosimetry practices are determined from laboratory studies, field measurements and data available in the scientific literature. The 318 Building calibrations facility is a National Institute of Standards and Technology (NIST) accredited calibration laboratory for ionizing radiation with the capability to provide dosimeter irradiations under a variety of conditions. Essentially all source irradiations are traceable to NIST. Performance of HEDP dosimetry systems is tested under a range of radiation and environmental conditions expected in Hanford work environments. In addition, HEDP is required to meet DOELAP requirements as described in, *Standard for the Performance Testing of Personnel Dosimetry Systems* DOE/EH-0027 (DOE 1986a); and *Handbook for the Department of Energy Accreditation Program for Personnel Dosimetry System* DOE/EH-0026 (DOE 1986b).

To meet Hanford external dosimetry objectives, the HEDP provides centralized dosimetry services and technical support to all Hanford contractors. These services include personnel, nuclear accident, and environmental dosimetry support. A TLD-based system has been selected as the primary dosimetry method because of the TLDs demonstrated performance during approximately three decades of use and its advantages over other types of currently available dosimeter technology.

The HEDP provides several types of dosimeters, processing service, and technical support. These can be combined into five general areas as follows:

- whole body dosimetry
- extremity dosimetry
- area dosimetry
- environmental dosimetry
- nuclear accident dosimetry

Each of these areas employs thermoluminescent dosimetry capabilities. Other HEDP dosimetry techniques include neutron activation analysis to evaluate components of Hanford nuclear accident dosimeters. The TLD systems may be considered to involve five functional components:

- TLD phosphors
- TLD cards or Chipstrates[®]
- TLD holders
- TLD processing systems
- data storage, data analysis, data reporting and record systems.

5.1 Characteristics Of TLD Phosphors Used in HEDP Dosimeters

The successful use of thermoluminescence as a means of measuring radiation dose has been demonstrated for many years (ICRU 1992). Hanford has used TLDs for personnel dosimetry since 1971 (Wilson 1987), for environmental dosimetry since 1972 (Denham et al. 1972), and for nuclear accident dosimetry since 1977 (Glenn and Bramson 1977).

5.1.1 Lithium Fluoride

Lithium fluoride (LiF), with its low atomic number and simple cubic lattice, was one of the first phosphors to become commercially available for personnel dosimetry applications. This phosphor has many good performance characteristics including near-tissue-equivalent response, unaffected (relatively) by environmental conditions (i.e., humidity, normal working temperatures, etc.), and linear dose response at occupational dose levels. The phosphor also has some undesirable performance characteristics such as supralinearity at higher dose levels, complicated annealing behavior, response to light, and relatively poor sensitivity (Horowitz 1984). These issues require sophisticated evaluation of the dosimeter processing data to determine personnel dose.

The original LiF was made by the Harshaw Chemical Company before 1954. However, systematic studies of various activators and activator combinations led to the material that is now widely used. Various types of LiF phosphors are available, covering a wide variety of lithium enrichments. These include TLD-600 (approximately 95.6% ^6Li and 4.4% ^7Li) and TLD-700 (approximately 99.99% ^7Li and approximately 0.01% ^6Li). The natural isotopic abundance of lithium fluoride is 7.5% ^6Li and 92.5% ^7Li . Both TLD-600 and TLD-700 contain trace elements shown in Table 5.1 (Becker et al. 1970).

Table 5.1. Trace Elements in Lithium Fluoride Thermoluminescent Dosimeters

Contaminant	Approximate Contents, ppm
Aluminum	20
Calcium	6
Magnesium	300
Silicon	40
Titanium	5

In general, magnesium and titanium are believed to be the trace elements of primary dosimetric importance in LiF TLD (Robertson and Gilboy 1971), and for this reason the phosphor is typically noted as LiF:Mg,Ti.

Dosimetry technology has evolved using LiF phosphors for beta, photon, and neutron radiation dose measurement. LiF has an additional advantage. The isotope ${}^6\text{Li}$ has a relatively large capture cross-section (approximately 953 barns) for thermal neutrons, and because this isotope is present in natural lithium (i.e., approximately 7%), LiF makes an excellent detector of thermal neutrons. In contrast, ${}^7\text{Li}$ has an extremely small capture cross-section (approximately 0.037 barns). Natural lithium can be made more sensitive by enriching it in the isotope ${}^6\text{Li}$. Likewise, it can be made almost insensitive to thermal neutrons by depleting the lithium of ${}^6\text{Li}$.

When a radiation worker is irradiated with fast neutrons, there is little probability that the ${}^6\text{Li}$ in the personnel dosimeter will capture an incident neutron. It is more likely that some fraction of the fast neutrons will be moderated (slowed) by the worker's body, recoil backwards, and be captured by the ${}^6\text{Li}$ in the TLD. This "albedo effect" is the basis for neutron dosimetry in the HEDP TLD system.

The following Hanford dosimeters use the LiF phosphor:

- Hanford Standard Dosimeter (HSD)
- Hanford Combination Neutron Dosimeter (HCND)
- Hanford Ring Dosimeter (HRD)
- EXT-RAD Ring Dosimeter
- Hanford Environmental Dosimeter
- Hanford Nuclear Accident Dosimeters.

All of the LiF phosphors contained in these dosimeters are 3.2-mm (1/8-in.) squares in the form of hot pressed chips. Three different thicknesses of LiF phosphors are used: 0.15 mm (0.006 in.), 0.38 mm (0.015 in.), and 0.89 mm (0.035 in.). The phosphors used in each dosimeter type are given in Sections 5.3 through 5.11.

5.1.2 Calcium Fluoride

Calcium fluoride, $\text{CaF}_2:\text{Dy}$, (known commercially as TLD-200) is used in the Hanford environmental dosimeter. The TLD 200 phosphors used by HEDP are 3.2-mm (1/8-in.) squares in the form of hot pressed chips. Only one thickness of phosphor is used: 0.89 mm (0.035 in.). Unacceptable fading, as much as 10% per month, can occur without a post irradiation annealing. HEDP TLD readers are programmed to apply a pre-heat anneal as part of the readout process to minimize fading.

5.1.3 Physical Form

The hot pressed form of the TLD phosphors is produced by the vendor through compression of blended polycrystalline material into a slug at an elevated temperature. Blending of source material from different crystal growths with different glow curve structure and sensitivity results in uniform glow curve structure and sensitivity within the chips produced. The fused polycrystalline slug is sliced and diced to produce individual chips, which are then polished. While loose chips may be annealed at high temperature and are easily handled and washed, careful handling is necessary to avoid mechanical effects (e.g., triboluminescence). Because most HEDP dosimeters use chips mounted on a

substrate (card or chipstrate), physical handling of the individual chips is currently necessary only in nuclear accident dosimeter fabrication, disassembly, and processing.

5.1.4 Linearity of Dose Response

The dose-response curve is the function of TL output versus dose. The dose-response curves for these TLD phosphors are linear in the dose range for routine results, followed in the case of LiF by a supra-linear range for doses greater than 100 rad. Maximum over response occurs at about 50,000 rad, above which TL yield decreases. Within an absorbed dose range of 10 mrad to 100 rad, there is an average deviation of 4.5% from linearity for all TLD phosphors. The linear dose-response curves from 10 mrad to 10 rad have linear regression coefficients of 0.9993 or greater for all phosphors tested (Harshaw 1988).

5.1.5 Sensitivity

Sensitivity, defined as the TL output per unit mass and unit absorbed dose, is influenced by many factors (e.g., type of phosphor, the type and features of the reader, heat treatment, etc.). Typically, only the relative sensitivity is quantified. As used within the HEDP, (i.e. HEDP annealing and readout protocols), the sensitivity of CaF₂:Dy relative to LiF:Mg,Ti when irradiated with gamma radiation from ⁶⁰Co, is approximately a factor of 18 on a per unit mass basis (Rathbone, Endres, and Antonio, 1994).

In general, there is a decrease in sensitivity for TLD phosphors after many reuses. For all TLD phosphors contained in HEDP dosimeters, a loss of sensitivity of less than 2% is expected during as many as 500 re-uses. In addition, all phosphors exhibit less than 0.8% degradation for every 100 re-uses, up to a total of 2000 reads (Harshaw 1988).

5.1.6 Fading

Fading is defined as a loss of TL signal with time since exposure. Fading may be due to thermally or optically stimulated release of trapped electrons, or a combination of both. Marked thermal fading is observed when the glow curve contains one or more low-temperature peaks. The LiF phosphors without 80°C oven annealing exhibit <10% loss of signal per month at 25°C (Harshaw 1988), after an initial 24-hour fading period, following exposure to gamma rays from ¹³⁷Cs. Use of a pre-irradiation oven anneal for 16 hours at 80°C reduces fade in LiF phosphors used by HEDP to less than 15% per year.^(a) CaF₂:Dy exhibits a much larger fading rate.

(a) W. V. Baumgartner, "Study of Environmental Buildup and Fade for 8825 Card," October 11, 1994, letter to HEDP file.

5.1.7 Annealing

Various types of thermal annealing are conducted to minimize the effect of fading. For hot pressed LiF phosphors, a high-temperature oven annealing for two hours at 400°C followed by a cool-down annealing at 100°C for a stated number of hours is commonly used to minimize fading. For cards, where the temperature cannot exceed 312°C without destroying the Teflon[®], several other types of annealing are conducted. These types include pre-irradiation reader annealing, a long-term (i.e., HEDP uses 16 hours), low-temperature 80°C oven annealing, or post-exposure annealing at reduced temperature before actual readout to 300°C. All of these annealing options reduce the influence of low-temperature peak(s) to the final TLD result. The post-irradiation annealing "cleans out" the low-temperature electron traps without a significant effect on the main dosimetry peak(s). The long-term oven annealing is used to eliminate lower-temperature peaks in LiF. A reader pre-read annealing is used to eliminate the lower-temperature peaks, which greatly reduces the fading rate in CaF₂:Dy. The HEDP uses all of these annealing options to achieve greatly reduced fading rates and associated uncertainty in dose results for personnel and environmental dosimeters.

5.1.8 Photon Energy Dependence

The photon energy response of a TL phosphor depends primarily on its effective atomic number. The TL response of a phosphor is usually normalized to a particular photon energy. The theoretical energy response of LiF shows an over response (relative to ¹³⁷Cs) in the 20 to 100 keV range with a maximum of about 40% between 20 and 30 keV. This may be due to one or more factors, including absorption of the soft x-rays in the material or grain size effects (Horowitz 1984). For most applications, LiF elements are considered to be approximately tissue equivalent, with little energy dependence for photon energies greater than 100 keV. For CaF₂, a much higher photon energy dependence is observed because of the relatively high atomic number (16.3), compared with tissue (7.4) (McKinlay 1981). Energy dependence studies of TL phosphors have been published by several authors (ICRU 1992).

5.1.9 Batch Uniformity

The basic design of the HEDP dosimeters, which includes collection and storage of element-specific correction coefficients, does not require strict uniformity in response for all TLD elements. However, upon testing by the vendor, the raw response of 3600 randomly selected elements from the vendor inventory varied by less than 30% (Harshaw 1988). Typical standard deviations for raw response in 15 mil LiF chips being calibrated and acceptance tested for individual sensitivity are about 10%

5.1.10 Reproducibility

The average reproducibility of 80 TLD elements randomly selected from production inventory and repeatedly exposed to 100 mR from a ¹³⁷Cs source is better than 1.3% of the mean reading, as determined by vendor testing (Harshaw 1988). To avoid the need for frequent re-calibration of cards and chipstrates, it is critical that each dosimeter element maintain its initial readout characteristics for

a reasonable life span of exposure/readout cycles. The average change in sensitivity over 500 re-uses is less than 2% as determined from vendor testing (Harshaw 1988).

5.1.11 Residual TL

The residual TL was determined by the vendor for 80 randomly selected TLD elements, after giving them a dose of 500 mrad from ^{137}Cs gamma radiation. The ratio of the re-read responses to the read responses for all elements was less than 0.5% (Harshaw 1988).

5.2 Characteristics of HEDP Dosimeter Cards

The TLD phosphors contained in HEDP dosimeters are mounted in aluminum dosimeter cards and encapsulated between two sheets of Teflon[®] that are each 0.05-mm thick. Each card is marked with a seven-digit identification (ID) number in both human-readable and bar-coded format. The first digit of the ID number is used to identify the dosimeter type (i.e., standard, neutron, environmental, etc.). Because the dosimeter cards may contain one or more types of TLD phosphors (e.g., TLD-200, TLD-600, or TLD-700), this unique ID number is necessary to maintain card-specific read cycle parameters (i.e., calibration values, time-temperature profiles, etc.).

Processing of HEDP cards is expected to result in less than one in 10,000 erroneous dosimeter identifications, including both the dosimeter type and serial number (Harshaw 1988). Each card is designed to withstand a minimum of 500 readout cycles without decrease in its mechanical performance, including identification and reading of dosimeter type and serial number. Acceptance tests are conducted of all HEDP dosimeter cards and holders to ensure proper construction and performance under operational conditions. These tests are described in the following sections.

5.2.1 Physical Testing

Both dosimeter cards and holders are tested. For cards, the general appearance of the card is visually inspected, the integrity of the Teflon[®] is examined, and the first digit of the card ID number is compared to ensure that it corresponds to the type of dosimeter cards procured. For holders, each one is examined for physical damage, for proper clearances to allow insertion of the card in only one orientation, and for the quality of the "O-ring" gasket, which minimizes moisture and dust penetration. An eddy current meter is used to check the type and thickness of each of the metallic filters. Once these tests are completed, a visual test to detect light penetration of the Mylar[®] window on the Hanford standard holders is performed.

5.2.2 Unique Permanent Identification Number

Before any irradiation testing, each card is processed through the reader system to determine if the card barcode label can be read and the card processed. The file of processed cards is uploaded to the HEDP Alpha computer system where checks are made to ensure that the card's permanent ID number is unique.

5.2.3 Testing for Phosphor Type

Following reader- and oven-annealing preparation steps, cards are exposed to a ^{252}Cf neutron source centered in a stainless steel-lined sphere (30-cm diameter) containing D_2O . This source provides an abundance of thermalized neutrons sufficient to distinguish among TLD-100, TLD-600, and TLD-700 phosphors. To distinguish between the neutron-insensitive TLD-200 and TLD-700 phosphors which have vastly different beta-gamma sensitivities, the sensitivity factors or element correction coefficients (ECC's) obtained during card calibration (Section 5.3.3) are evaluated. The combination of these tests ensures that the correct phosphors are contained in each position of HEDP cards and that these phosphors demonstrate acceptable performance.

5.2.4 Light Testing

The LiF TLD phosphors and Teflon[®] substrates generally have some degree of sensitivity to light. However, some individual phosphors and or Teflon[®] enclosures are significantly more sensitive than others, and demonstrate unacceptable sensitivity to light. For this reason, all HEDP cards are tested for light sensitivity. Following reader- and oven-annealing preparation steps, cards are exposed for two hours under routine laboratory lighting conditions (fluorescent light with ultraviolet filter) and then processed. The data are screened to detect any unacceptable results.

5.2.5 Time-Temperature Profile (TTP)

During automated processing with the Harshaw 8800 reader system, each TLD card type has its own specific processing protocol because of the differences in heating and annealing characteristics of the different phosphors. Typical reader processing setup parameters are listed in Table 5.2. These time temperature parameters, along with specific information pertaining to the regions of the glow curve to be used for dose calculation and quality control, are referred to as the time temperature profile (TTP). Specification of correct TTP parameters and consistency of the temperature applied to all cards are very important to achieving quality performance. The automated reader system maintains a data file showing the TTP used for processing each card. TTPs are specified for each type of card. In addition, the reader system maintains a history of changes made to the configuration of each TTP. This is described further under subsequent sections for each type of dosimeter card.

Table 5.2. Typical Parameters for Reader Processing Setup

Description	Setting
Preheat temperature	50°C
Preheat time	0 seconds
Temperature rate	25°C/second
Maximum temperature	300°C
Acquire time	13-1/3 seconds
Annealing temperature	300°C
Annealing time	10 seconds

5.3 HEDP Dosimetry System

A dosimetry system consists of dosimeters, dosimeter readers, and a methodology for calibration and dose calculation as embodied in the processing procedures and software. The design features and performance characteristics of the Harshaw TLD readers used in the HEDP dosimetry system are described in Chapter 3. The dosimeters and calibration / dose calculation methodology are described in this section.

An HEDP dosimeter consists of a TLD card, complete with the appropriate complement of TLD phosphors, and a holder, used to maintain the card in a protected and light-sealed environment. The card holder is sealed with a gasket to prevent liquids from entering. The card cavity is keyed such that an improperly inserted TLD card will prevent the two halves of the card holder from closing. The cards are removed from their holders during processing. Individual TLD chips are used in the HEDP extremity and nuclear accident dosimeters. Table 5.3 describes the phosphors used in each of the HEDP dosimeters.

Table 5.3 also describes the holder for each dosimeter type, each of which contains specific design features and/or filtration to control the types of radiation admitted to the respective dosimeter phosphors. Holders for whole body dosimeters and environmental dosimeters are black to minimize light penetration to the card. Typically, the personnel dosimeters are mounted on a strap and coupled to the DOE security credential in a fashion that prevents visual obstruction of the picture and name on the badge but orients the dosimeter with the front facing "out." The environmental dosimeter is mounted vertically in air. Extremity dosimeters include the four element HSD used as a wrist dosimeter, and a single chip finger ring dosimeter. The HSD and HCND area dosimeters have the same specifications given for the HSD and HCND personnel dosimeters in Table 5.3. The nuclear accident dosimeter is available in two forms described in greater detail in Section 5.11.

5.3.1 Generating Calibration Cards

Before a TLD system can be calibrated, it is necessary to establish a set of reference cards that will be used for purpose of calibrating the reader and calibrating other cards. This set of cards is exposed and read together as a group. For each element position on the TLD card, the mean light output of all chips in the same position is determined and the output of individual chips in that position

compared against this. A sensitivity factor known as an element correction coefficient (ECC) is determined for each chip such that the response of the chip after correction with the ECC is equivalent to the mean response of all reference chips in the same position on the card. Thus the ECC corrected responses of all chips in the calibration set are theoretically the same for any given dose (Plato et. al. 1985, Moscovitch 1993, Tawil 1996).

Table 5.3. HEDP Dosimeter Specifications

Dosimeter Type (Card Type)	Card/Holder ID#	Description of Active Elements ^(a)	Description of Holder ^(b,c)
Standard Dosimeter (8825)	00xxxxx / 000xxxxx	Element 1: TLD-700 of 0.38-mm thickness (100 mg/cm ²) Element 2: TLD-700 of 0.38-mm thickness (100 mg/cm ²) Element 3: TLD-700 of 0.15-mm thickness (40 mg/cm ²) Element 4: TLD-600 of 0.38-mm thickness (100 mg/cm ²)	Front: ABS 242 mg/cm ² , Cu 91 mg/cm ² Back: ABS 173 mg/cm ² Front: PTFE+ABS 1000 mg/cm ² Back: ABS 173 mg/cm ² Front: Mylar [®] window 9 mg/cm ² Back: ABS 173 mg/cm ² Front: ABS 240 mg/cm ² , Sn 463 mg/cm ² Back: ABS 173 mg/cm ²
Combination Neutron Dosimeter (8816)	40xxxxx / 040xxxxx	Element 1: TLD-700 of 0.38-mm thickness (100 mg/cm ²) Element 2: TLD-600 of 0.38-mm thickness (100 mg/cm ²) Element 3: TLD-600 of 0.38-mm thickness (100 mg/cm ²) Element 4: TLD-600 of 0.38-mm thickness (100 mg/cm ²)	Front: Sn 464 mg/cm ² + ABS 80 mg/cm ² Back: Sn 464 mg/cm ² + ABS 80 mg/cm ² Front: Cd 461 mg/cm ² + ABS 80 mg/cm ² Back: Sn 464 mg/cm ² + ABS 80 mg/cm ² Front: Sn 464 mg/cm ² + ABS 80 mg/cm ² Back: Cd 461 mg/cm ² + ABS 80 mg/cm ² Front: Sn 464 mg/cm ² + ABS 80 mg/cm ² Back: Sn 464 mg/cm ² + ABS 80 mg/cm ²
Hanford Ring Dosimeter (XD740)	00001 – 29999 / 30000 – 99999	Elements 1: TLD-700 of 0.15-mm thickness (40 mg/cm ²)	Density thickness of ring window and label is approximately 52 mg/cm ² .
EXT-RAD Ring Dosimeter (XD740)	00001 – 29999 / 30000 – 99999	Elements 1: TLD-700 of 0.15-mm thickness (40 mg/cm ²)	Density thickness of ring window is approximately 7 mg/cm ² .
Environmental Dosimeter (8807)	90xxxxx / 090xxxxx	Elements 1 and 2: TLD-200 of 0.89-mm thickness (235 mg/cm ²) Elements 3 and 4: TLD-700 of 0.89-mm thickness (235 mg/cm ²)	Front and Back: Ta (422 mg/cm ²), Pb (58 mg/cm ²), 80 mg/cm ² ABS plastic Front and Back: 80 mg/cm ² ABS plastic
Nuclear Accident Dosimeter	N/A	Pairs of TLD-700 and TLD-600 chips are contained in outer and inner dosimetry capsules.	Plastic capsules are used to contain chips.

a. Elements on 8825, 8816 and 8807 card types consist of a TLD chip encapsulated in a PTFE (i.e. Teflon[®]) film having a density thickness of 8 mg/cm². The XD740 chip has no such encapsulation.

b. PTFE = polytetrafluorethylene

c. ABS = acrylonitrile-butadiene-styrene plastic

5.3.2 TLD Reader Calibration

Calibration of each reader is accomplished by exposing a representative sample of reader calibration cards in air without a holder to a known amount of radiation (typically ^{60}Co) and then processing on the reader. The cards used to calibrate the reader are typically exposed to 500 mR and a reader calibration factor (RCF) expressed in units of nC/mR is calculated for each of the four PMT channels according to the following relationships:

$$RCF_i = \frac{\bar{Q}_i}{X} \quad (5.1)$$

$$\bar{Q}_i = \frac{\sum_{j=1}^k Q_{ij} * ECC_{ij}}{k} \quad (5.2)$$

where: RCF_i = reader calibration factor for ith PMT (nC/mR)
X = exposure value (mR)
Q_{ij} = raw reading for chip i of card j (nC)
ECC_{ij} = element correction coefficient for chip i of card j
k = number of calibration cards used.

The reader calibration cards used for this purpose have been previously calibrated, and the resulting ECC for each chip is applied to its raw reading to correct for variations in chip sensitivity. This approach allows for a more precise measure of PMT sensitivity to be obtained in the reader calibration process with fewer cards. Reader calibration is performed prior to, and as an independent process from, the read-out of personnel cards for dose determination. The RCFs obtained in the reader calibration process are then applied to the subsequent field and QC card readings on a real-time basis as the cards are read. When RCFs are applied, chip readings are reported from the reader in units of ^{60}Co mR equivalent (in free air).

5.3.3 Card Calibration

The ECC of a given TLD element is a measure of how the phosphor responds to a source of radiation relative to the response of other similar elements in a reference population (calibration card set). The ECC for a given chip corrects that chip's sensitivity to the mean sensitivity of chips in the same position *in the population of cards used to calibrate the reader*. The process of card calibration entails calibrating the reader with a sample of reader calibration cards exposed to a known amount of radiation and applying the resulting RCFs to subsequent readings of cards being calibrated (which have been exposed to the same source). The ECC for each chip is determined according to the following relationship:

$$ECC_{ij} = \frac{RCF_i}{Q_{ij}} X \quad (5.3)$$

where: ECC_{ij} = element correction coefficient for chip i on card j
 RCF_i = reader calibration factor for PMT $_i$ (nC/mR)
 Q_{ij} = raw reading from chip i on card j (nC)
 X = delivered ^{60}Co exposure value (mR).

The ECCs are determined for a group of cards by annealing all cards, including "calibration cards," as a group (i.e. at the same time), followed by irradiation as a group and readout on the same day. Because of the demonstrated good reproducibility of response for TL elements in HEDP cards, only one exposure and readout are necessary to accurately determine the initial ECC for an element.^(a) Subsequent calibrations of the card entail a comparison of the old ECC with the new ECC and rejections of the new ECC if it is not within 20% of the old. Cards are re-calibrated on approximately a five (5 ± 1) year cycle.^(b) Cards with ECCs six or more years old are prevented from being issued by the External Dosimetry Data Management System.

5.3.4 Dosimeter Calibration

HEDP calibrates TLD readers with cards exposed in air to a local source (^{60}Co). When field cards used in dosimeter holders are read on a reader calibrated in this manner, the readings are given in units of mR (^{60}Co mR equivalent). It is necessary for the dose algorithm to convert these readings to the equivalent readings that would be obtained with reference geometry and reference source (e.g. in holder, on-phantom, at 1 meter, to a reference source described in the DOELAP standard). For the HEDP system, dosimeter calibration consists of determining the relationship between each chip's response to ^{60}Co in air without a holder, to its response to ^{137}Cs when irradiated in a holder, on a phantom in reference geometry. The resulting factor is called the ^{137}Cs relative response factor (RRF) and is expressed in units of mR/rem for each chip position. The RRF is a function of the chip thickness, the radiation types and energies for reference and local geometry, and the composition and thickness of filtration over the chip for the reference and local geometry. In the HEDP system, conditions of charged particle equilibrium (CPE) are satisfied for both the local and reference geometries. RRFs vary with dosimeter type and chip position.

(a) "Model 8800 Automatic TLD Card Reader with TLD-REMS User's Manual" Publication No. 8800-R-U-1188-001, release date November 15, 1992, Bicron (copy retained in HEDP files).

W. V. Baumgartner, "Comparison of ECCs Obtained From Calibration Cards," August 5, 1993, letter to HEDP file.

(b) B. A. Rathbone, "ECC Stability Study," June 8, 1998, letter to HEDP file.

For each dosimeter design, the RRF is determined by exposing a set of cards to ^{60}Co in air and a set of cards to the ^{137}Cs source on-phantom, and then reading the cards together in a single processing on a stable reader with ECCs applied. For each chip position, the ratio of the average response to the ^{137}Cs source on phantom (nC/rem) to the average response to the ^{60}Co source in air (nC/mR) is calculated. This ratio (mR/rem) is the ^{137}Cs RRF for that chip position in that dosimeter design. Dividing the calibrated reading (mR) for a given chip by the RRF for that position provides a ^{137}Cs rem-equivalent reading for that chip. This is the same reading that would have been obtained if the reader had been calibrated directly with cards exposed in holders and on-phantom to the calibration standard. Establishing and using RRFs allows for accurate system calibration without the need for costly routine irradiations with a calibration standard. It also allows flexibility to use a variety of local sources as backup sources for calibration and still obtain equally valid dose results. For the HEDP dosimetry system, RRFs have been determined for a primary ^{60}Co source and irradiation jig, and a backup ^{90}Sr card irradiator located in one of the TLD readers.^(a) RRFs have been determined for each chip position in each of the dosimeter types used at Hanford.

5.3.5 Calibrated Element Readings

When TLD cards are read, the reader applies ECCs and RCFs to the raw light output expressed as charge collected on the PMT (nC), to obtain calibrated element readings as follows:

$$X_i = Q_i * ECC_i / RCF_i \quad (5.4)$$

where X_i = calibrated reading for element i (mR)
 Q_i = raw reading from element i (nC)
 ECC_i = element correction coefficient for element i
 RCF_i = reader calibration factor for position i (nC/mR).

5.3.6 Adjusted Element Readings

When TLD card readings are processed on the Alpha, environmental background is subtracted, then supralinearity and fade corrections are made to the calibrated element readings to obtain “adjusted” element readings in ^{137}Cs mrem equivalent, as follows:

$$X_{net_i} = (X_i - E_i) \quad (5.5)$$

$$D_i = X_{net_i} / (RRF_i * F_i * S_i) \quad (5.6)$$

where D_i = adjusted element reading for element i (^{137}Cs mrem equivalent)
 X_i = calibrated element reading for element i (^{60}Co mR equivalent)
 E_i = estimated background signal for element i (^{60}Co mR equivalent)
 RRF_i = ^{137}Cs relative response factor for element i (mR/mrem)
 F_i = fade factor for element i

(a) B. A. Rathbone, “Re-evaluation of RRF Data for HSD and HCND,” October 6, 1999, letter to HEDP file.

S_i = supralinearity factor for element i .

Correction of individual element readings for supralinearity and fade prior to use by the algorithm allows the algorithm to provide valid results based on element ratios over a wide range of doses and wear periods. Because supralinearity and fading vary depending on the radiation type (McKeever, Moscovitch, and Townsend 1995; Horowitz;1984) the values of S_i and F_i in equation 5.6 are weighted averages calculated on the basis of the estimated fraction of the TL signal due to neutron radiation and the fraction due to beta-gamma radiation, as described below.

5.3.6.1 Models for Environmental Background

The total background that is subtracted from each calibrated chip reading is calculated from an empirically derived background function E_i for each chip position i in each dosimeter type as follows:

$$E_i = G_i * FD + B_i \quad (5.7)$$

where: G_i = background growth rate (mR/d)
 FD = field cycle days (days between previous and current processing date for the card)
 B_i = intrinsic background signal (mR)

The slope and intercept for the environmental background function E_i vary by chip position and dosimeter type. The slope and intercept measured for the Hanford site are given in Table 5.4.

Table 5.4 Parameters for Background Functions

Parameter	HSD	HCND	
	8825 BPN	8825 BP	8816 N
G_1	0.145	0.145	0.163
G_2	0.140	0.140	0.171
G_3	0.148	0.148	0.169
G_4	0.195	0.145	0.192
B_1	1.42	1.42	1.89
B_2	1.32	1.32	2.09
B_3	2.95	2.95	2.23
B_4	1.97	1.37	2.50

Slightly different values have been established for use at sites other than Hanford. It should be noted that neither B_i nor G_i have been corrected for fade. Since E_i is therefore not corrected for fade, it is subtracted directly from X_i which is also not corrected for fade.

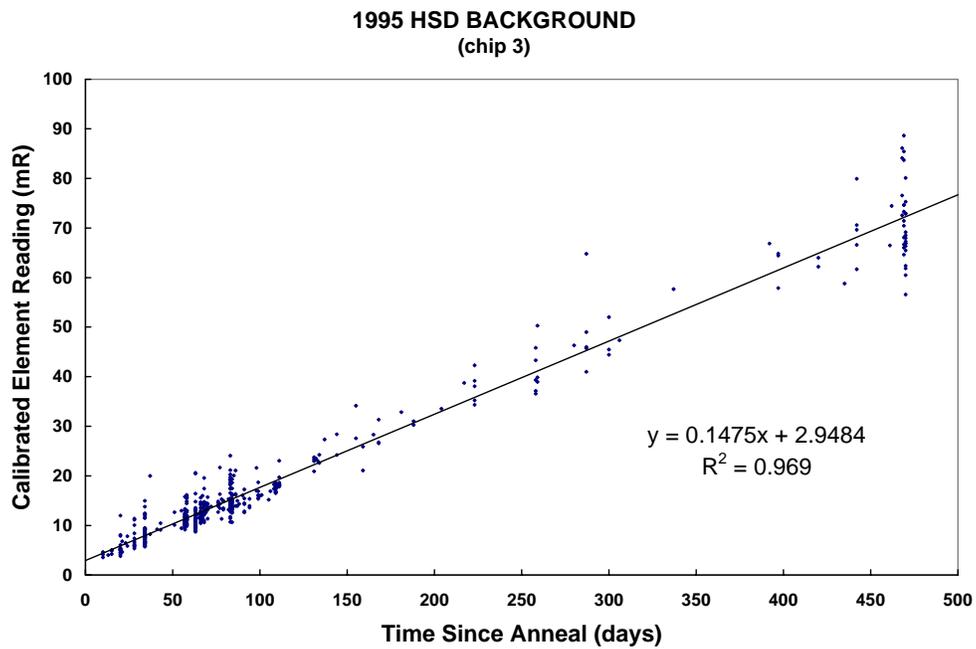


Figure 5.1 Buildup of Environmental Background Signal in HSD Shallow Dose Element

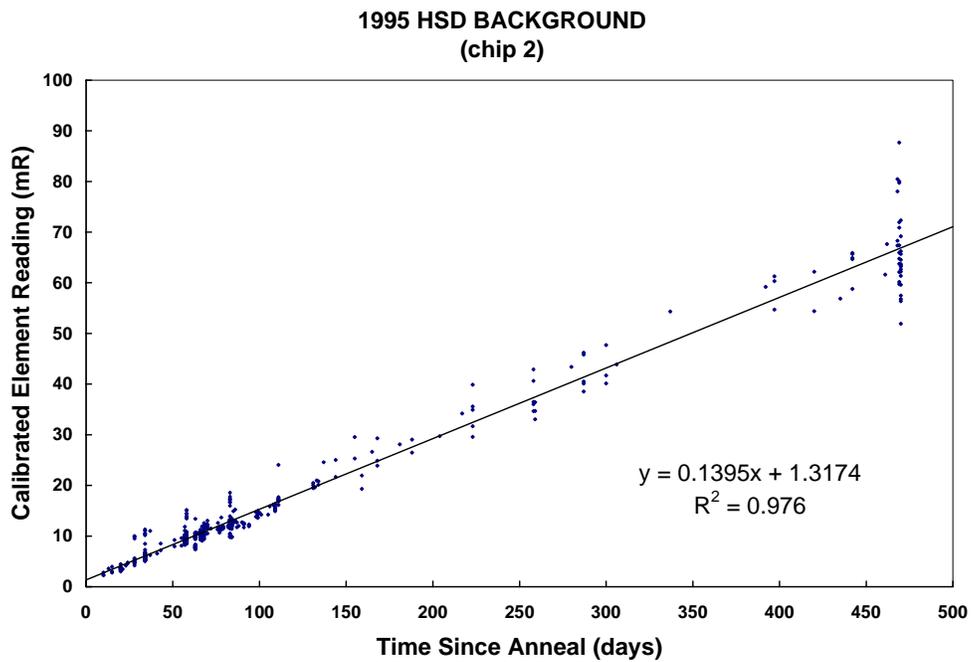


Figure 5.2 Buildup of Environmental Background Signal in HSD Deep Dose Element

The background functions established for Hanford ^(a) were determined from a least squares fit of a line to calibrated element readings from dosimeters that were stored at the 318 building and other Hanford facilities for varying periods up to 470 days. The storage locations were generally believed to be representative of natural background radiation levels at Hanford. Plots of the shallow dose element (chip 3) data and deep dose element (chip 2) data for the HSD are shown in Figures 5.1 and 5.2 respectively. The mR/d values used in all background functions are less than the yearly and five year average radiation levels measured at offsite locations (perimeter, community and distant locations) as part of the Hanford Environmental Surveillance Program (Antonio 1999, Antonio 2002). The background functions used for personnel and area dosimeters are therefore expected to provide a conservative measure of occupational dose.

Radiation measurement data from environmental surveillance reports indicate that the natural radiation background at Hanford and in nearby communities has varied by less than 5% from year to year over a seven year period from 1995-2002. Although in some regions seasonal variations can be as large as 25% due to changes in soil moisture and snow cover and as large as 10% due to changes in cosmic radiation (NCRP 1987), the data for Hanford indicate that quarterly variations during the time period from 1995 – 2002 are less than 10%. The above data suggest that personnel and area dosimeter background functions should not need to be changed from year to year. Analysis of HEDP annual audit dosimeter data for the same time period supports this conclusion. An analysis of potential errors in dose results that arise from use of a pre-determined background function indicates that relative to the DOE monitoring threshold of 100 mrem/y, the standard uncertainty of ± 20 mrem/y in recorded dose is acceptable.

5.3.6.2 Models For Fading

Fade corrections for each chip are based on empirical models of post irradiation fading for TLD 600 and 700 developed for routine dosimeter annealing and readout protocols at Hanford. ^(b) For each model, a non-linear least squares regression analysis was performed to fit a two compartment model to dosimeter response data. Because fading of *neutron* signal in TLD 600 is significantly more pronounced than fading of *beta-gamma* signal in TLD 600, (Johnson and Luersen, 1980; Horowitz, 1984; Doremus and Higgins, 1994; McKeever, Moscovitch and Townsend, 1995) separate models were necessary for beta-gamma and neutron fading in TLD 600. In addition, a model for beta-gamma fading in TLD 700 was developed. All three models have the form given in Equation 5.8.

-
- (a) B. A. Rathbone, "Re-evaluation of Background Functions for HSD and HCND Dosimeters," October 3, 1999, letter to HEDP file.
 - (b) B. A. Rathbone, "Re-evaluation of Post-irradiation Fading of Beta-Gamma Dose in TLD 600 and TLD 700, March 20, 2000, letter to HEDP file.

B. A. Rathbone, "Post Irradiation Fading of Neutron Signal in TLD 600", March 23, 2000, letter to HEDP file.

$$F(t) = R(t)/R_0 = a e^{-\lambda_1 t} + (1-a) e^{-\lambda_2 t} \quad (5.8)$$

where: t is the time since irradiation (days)
R(t) is the net chip response (mR) at time t
R₀ is the net chip response (mR) at time t = 0
a is the weighting factor for the short half-life compartment
λ₁ is the decay constant for the short half-life compartment
λ₂ is the decay constant for the long half-life compartment

For routine dosimetry, when the time since irradiation is generally not known, one half of the time between previous and current processing is used for t. The parameters to be used in the model for each phosphor and radiation type are shown in Table 5.5. The three models are shown graphically in Figure 5.3.

Table 5.5 Parameters for use in Post Irradiation Fade Models

Parameter	TLD 700 β-γ	TLD 600 β-γ	TLD 600 Neutron
a	0.0530	0.0851	0.1550
λ ₁	0.0179 d ⁻¹	0.0135 d ⁻¹	0.0286 d ⁻¹
λ ₂	0.000231 d ⁻¹	0.000135 d ⁻¹	0.000367 d ⁻¹

The fade models above were developed based on experiments in which single acute exposures are used, the pre-irradiation time interval is held small and constant, and only the post-irradiation interval is varied. Thus the model predicts post-irradiation fading. Models of this type are limited in actual use because the exposure time is seldom known, and exposure in the field is often chronic rather than acute. A comparison of fading from chronic exposure and fading from single acute exposure, was made in the referenced neutron fading study. The comparison showed that for neutron exposure in TLD 600, the default assumption for t [t = (T2-T1)/2 where T2 and T1 are readout date and anneal dates respectively] in the post irradiation fade model, results in a slight over estimate (F = 0.78) of the actual observed fading from chronic exposure (F = 0.82) by about 5% for an annual dosimeter. Because the magnitude of fading with beta-gamma exposure is smaller, the differences between model predictions and observed fading with chronic exposure are correspondingly smaller. The errors in fade correction incurred by assuming a mid cycle exposure for an actual exposure occurring at the beginning or end of a use cycle can be readily calculated and are shown Figures 5.4 and 5.5. Other errors involve uncertainty in the loss of sensitivity with time before irradiation (pre-irradiation fading). For a 407 day pre-irradiation fade interval, the loss of sensitivity for beta-gamma dose has been estimated to be about 6%. These and other sources of uncertainty in fade corrections are assessed in greater detail in an HEDP internal study.^(a)

The fading corrections for TLD 600 must be applied in a weighted manner based on the estimated fractions of the background corrected TL signal attributable to beta-gamma radiation and to neutron radiation as described in Section 5.3.6.4.

(a) B. A. Rathbone, "Potential Errors from Using a Post-Irradiation Model of Fading in TLD 600 and TLD 700", March 24, 2000, letter to HEDP file.

Post Irradiation Fading in TLD 600 and TLD 700

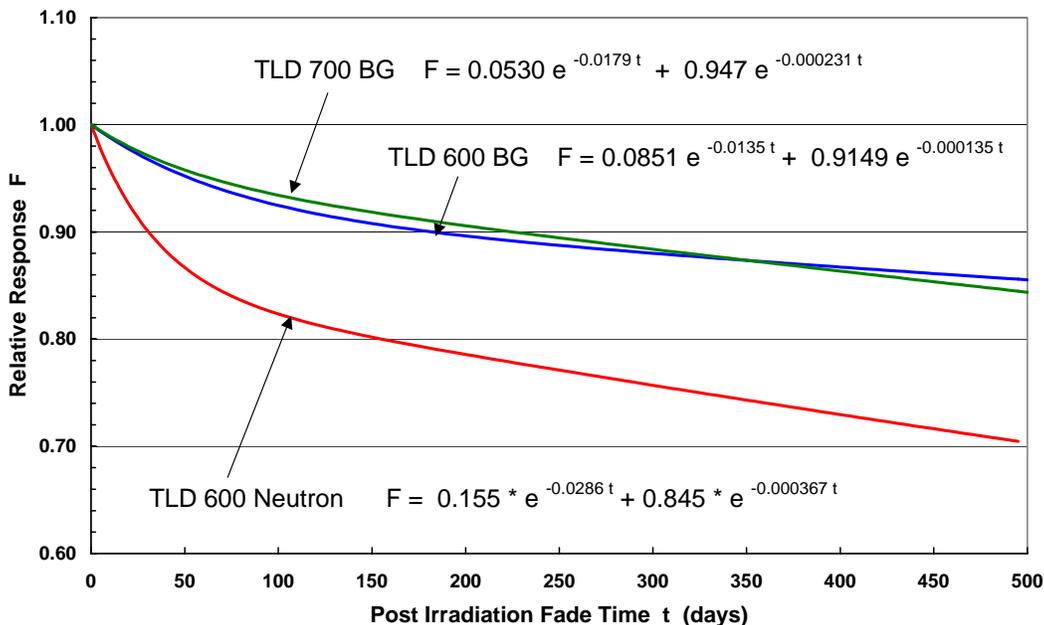


Figure 5.3 Post Irradiation Fade Functions Used for Hanford Dosimetry Materials

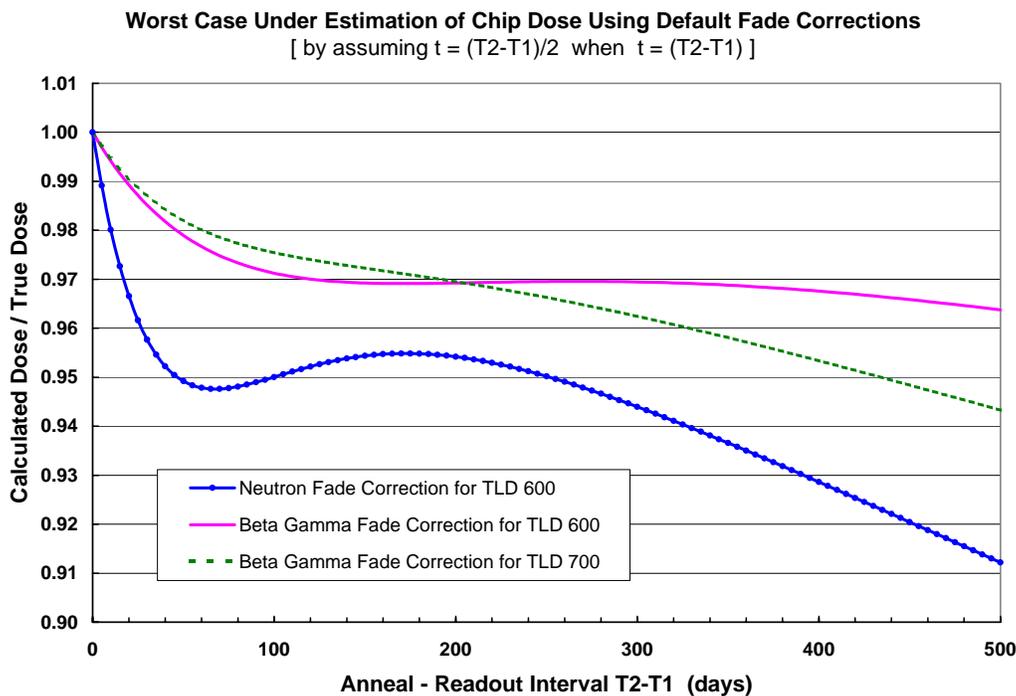


Figure 5.4 Error in default fade correction when entire exposure occurs on first day of use cycle.

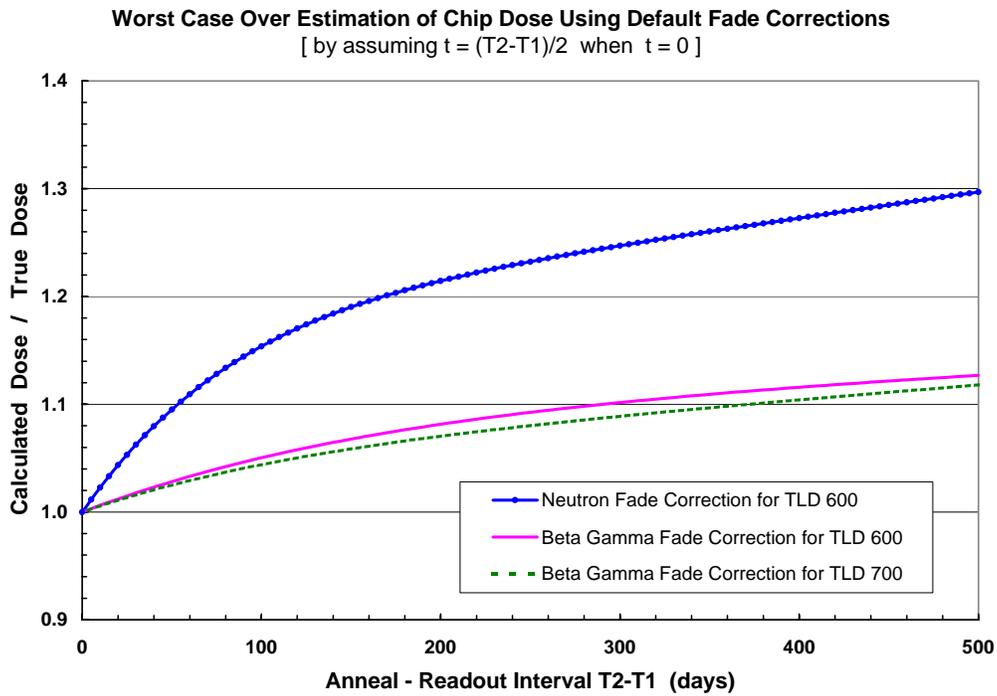


Figure 5.5 Error in default fade correction when entire exposure occurs on last day of use cycle.

5.3.6.3 Models for Supralinearity

The empirically derived model ^(a) for supralinearity of *beta-gamma* signal in TLD 600 and TLD 700 is as follows:

$$S_{\text{gamma}} = 1 + 3.411E-7 * X_{\text{net}} \quad (5.9)$$

where:

- S_{gamma} = net reading of chip (mR) / given exposure (mR)
- X_{net} = $X - E$ = background corrected chip reading (mR)
- E = estimated intrinsic + environmental background signal on chip (mR)
- X = calibrated chip reading for chip i (^{60}Co mR equivalent)

The data used to develop the model and a least squares fit of the model to the data are shown in Figure 5.6.

(a) B. A. Rathbone, "Supralinearity Corrections for TLD 600 and 700," April 3, 2000, letter to HEDP file.

**TLD 600/700 SUPRALINEARITY IN THE HSD
(all chips)**

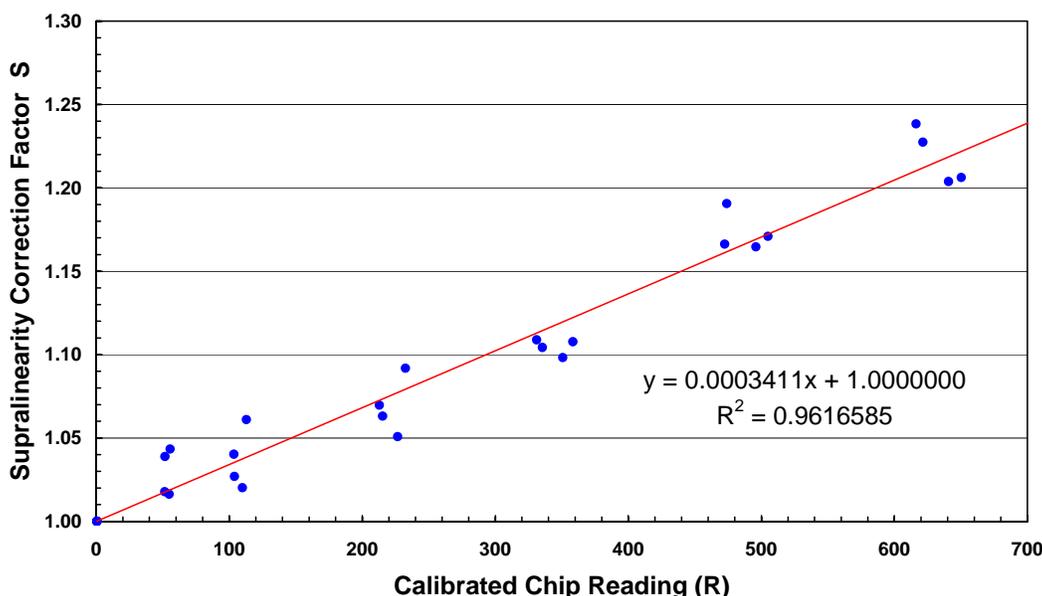


Figure 5.6. Supralinearity Correction for Beta-Gamma Signal in TLD 600 and 700.

This supralinearity model is not appropriate for high linear energy transfer (LET) radiations. In particular, it is not valid for *neutron* induced TL on the TLD 600 chip. The TL output from TLD 600 when exposed to thermal neutrons is due primarily to dose deposited in the chip from alpha particles and recoil tritons from the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ capture reaction. The scientific literature on TLD suggests that the response of TLD 600 to thermal neutron radiation shows considerably less supralinearity than the response of either TLD 600 or TLD 700 to high energy gamma radiation (Cameron, Suntharalingam, and Kenney 1968; Douglas 1981; Horowitz 1984). TLD 600 shows a maximum over response to neutrons between a factor of 1.2 and 1.5 at doses between 10,000 and 50,000 rad as reported by various authors (Horowitz 1984). Compared to this, the maximum over response of TLD 600 and 700 to high energy gamma radiation is between a factor of 3 and 4 in the same dose range. The over response to neutrons is essentially non-existent at Roentgen equivalent response levels less than 10,000 R (Douglas 1981). Therefore, a separate supralinearity model is used to correct the neutron portion of the TL signal. Based on data from Douglas (1981), the supralinearity correction is (conservatively) assumed to be equal to 1.0 for element readings up to 1000 R. The model for supralinearity of neutron signal in TLD 600 is as follows:

$$S_{neutron} = 1$$

The supralinearity corrections for TLD 600 must be applied in a weighted manner based on the estimated fractions of the background corrected TL signal attributable to beta-gamma radiation and to neutron radiation as described below. This assumes that the two types of supralinearity act independently.

5.3.6.4 Calculation of Weighted Fading and Supralinearity Corrections F_i and S_i

Weighted corrections for fading F_i and supralinearity S_i are calculated for each chip on each dosimeter based on the estimated fraction of TL signal due to beta-gamma radiation (W_{gamma}) as opposed to neutron radiation (W_{neutron}), and the fading and supralinearity corrections appropriate to each type of radiation. For TLD 600 elements, the estimated fraction of the TL signal due to neutron radiation is determined by comparing the TLD 600 element reading to that of a TLD 700 element reading (beta-gamma sensitive only) under similar filtration. For TLD 700 elements, the signal is assumed to be due entirely to beta-gamma radiation.

Do: $i = 1-4$

If: $X_{\text{net } i} > 0$,

If: card type = 0, 9, 10, or 60, and $i = 4$ (TLD 600 in 8825 card)

If: $X_{\text{net } i} > X_{\text{net } 2}$ (neutrons present)

$$\begin{aligned} W_{\text{gamma } i} &= X_{\text{net } 2} / X_{\text{net } i} \\ W_{\text{neutron } i} &= 1 - W_{\text{gamma } i} \\ F_{\text{gamma } i} &= 0.0851 \exp(-0.0135 t) + 0.9149 \exp(-0.000135 t) \\ F_{\text{neutron } i} &= 0.1550 \exp(-0.0286 t) + 0.8450 \exp(-0.000367 t) \\ S_{\text{gamma } i} &= 1 + 3.411\text{E-}7 * X_{\text{net } 2} \\ S_{\text{neutron } i} &= 1 \\ F_i &= (W_{\text{gamma } i} * F_{\text{gamma } i}) + (W_{\text{neutron } i} * F_{\text{neutron } i}) \\ S_i &= (W_{\text{gamma } i} * S_{\text{gamma } i}) + (W_{\text{neutron } i} * S_{\text{neutron } i}) \end{aligned}$$

Else: (neutrons not present)

$$\begin{aligned} F_i &= 0.0851 \exp(-0.0135 t) + 0.9149 \exp(-0.000135 t) \\ S_i &= 1 + 3.411\text{E-}7 * X_{\text{net } i} \end{aligned}$$

End If

Elseif: card type = 40, 46, 49 and $i = 2, 3$ or 4 (TLD 600 in 8816 card)

If: $X_{\text{net } i} > X_{\text{net } 1}$ (neutrons present)

$$\begin{aligned} W_{\text{gamma } i} &= X_{\text{net } 1} / X_{\text{net } i} \\ W_{\text{neutron } i} &= 1 - W_{\text{gamma } i} \\ F_{\text{gamma } i} &= 0.0851 \exp(-0.0135 t) + 0.9149 \exp(-0.000135 t) \\ F_{\text{neutron } i} &= 0.1550 \exp(-0.0286 t) + 0.8450 \exp(-0.000367 t) \\ S_{\text{gamma } i} &= 1 + 3.411\text{E-}7 * X_{\text{net } 1} \\ S_{\text{neutron } i} &= 1 \\ F_i &= (W_{\text{gamma } i} * F_{\text{gamma } i}) + (W_{\text{neutron } i} * F_{\text{neutron } i}) \\ S_i &= (W_{\text{gamma } i} * S_{\text{gamma } i}) + (W_{\text{neutron } i} * S_{\text{neutron } i}) \end{aligned}$$

Else: (neutrons not present)

$$\begin{aligned} F_i &= 0.0851 \exp(-0.0135 t) + 0.9149 \exp(-0.000135 t) \\ S_i &= 1 + 3.411\text{E-}7 * X_{\text{net } i} \end{aligned}$$

End If

Else: (TLD 700)

$$F_i = 0.0530 \exp(-0.0179 t) + 0.9470 \exp(-0.000231 t)$$
$$S_i = 1 + 3.411E-7 * X_{net_i}$$

End If (card type =)

End If ($X_{net_i} > 0$)

End Do (i=1-4)

5.3.7 Dose Algorithms

Each type of dosimeter has an algorithm that calculates dose based on the adjusted element readings of the dosimeter. The specific algorithms used for Hanford dosimeters are documented in HEDP files in sufficient detail to allow hand calculation of dose.^(a) The dose quantities calculated for personnel dosimeters are operational quantities generally accepted for use in demonstrating compliance with the protection quantities used by DOE in occupational radiation protection requirements (DOE 1998c). Dose algorithms for HEDP personnel dosimeter have been developed to calculate the beta-photon components of personal dose equivalent at specified depths, in units of mrem. Unless specified otherwise, the symbols below represent only the beta-photon component of personal dose equivalent.

- H_s = shallow dose, i.e., dose equivalent at 7 mg/cm², corresponding to the average depth of the skin's basal cell layer (0.007 cm)
- H_e = eye dose, i.e., dose equivalent at 300 mg/cm², corresponding to the depth of the lens of the eye (0.3 cm)
- H_{dp} = deep dose, i.e., dose equivalent at 1000 mg/cm², corresponding to measurement of the whole body dose equivalent at tissue depth of 1 cm.

In addition, for those dosimeters that are sensitive to neutrons, algorithms have been developed to calculate *neutron dose equivalent* H_n . Although strictly speaking this operational quantity is not personal dose equivalent and not defined at a particular depth, its use in conjunction with the beta-photon components of the personal dose equivalent quantities above is generally accepted for demonstrating compliance with 10 CFR 835 protection limits for the whole body, lens of the eye, skin and extremities (DOE 1999b).

The *External Dosimetry Program Guide* (DOE 1999b) lists the depths of interest in terms of linear distance and the density thickness equivalent for soft tissue as shown above. In principle, infinitely thin phosphors made of a tissue-equivalent material, imbedded at depths of 7, 300, and 1000 mg/cm² in a tissue-equivalent holder could be used to measure the skin, lens of the eye, and whole body

(a) B.A. Rathbone, "HEDP Dose Calculation Methodology," July 8, 2002, letter to HEDP file.

absorbed dose directly. These phosphors, together with the TLD reader system, could be calibrated with only one type of radiation (e.g., ^{137}Cs exposure on-phantom). When the dosimeter is irradiated by other types of radiation, such as low-energy photons or beta particles, the absorbed dose in the phosphors would change in the same manner as the absorbed dose in tissue. For radiation types having a quality factor of 1 (i.e. beta and gamma radiation), no adjustment would be required to convert absorbed dose to dose equivalent. For radiation having a quality factor greater than one (i.e. energetic neutron radiation), a knowledge of the energy spectrum at the point of interest in tissue would be required to calculate a spectrum weighted quality factor to apply to the absorbed dose to obtain dose equivalent.

In actual practice however, direct measurement of absorbed dose in tissue at a specific depth, is difficult with commonly available dosimeter technology. The TLD phosphors are not infinitely thin and are not exactly tissue equivalent. The TLD cards and holders are not composed of tissue-equivalent materials. Therefore, even for radiation types having a quality factor of 1, LiF phosphors require use of a mathematical algorithm to calculate shallow, eye, and deep absorbed doses based on the measured response of the dosimeter under a variety of exposure conditions. For neutron radiation, the energy spectrum must either be assumed (e.g. HSD) or must be inferred from element response ratios (e.g. HCND).

Algorithm development for personnel dosimeters is typically based on laboratory irradiations of dosimeters mounted on a tissue-equivalent phantom in an approximately parallel beam at normal incidence to the face of the phantom. This is the principal geometry specified in the DOELAP (DOE 1986a) and HPS (HPS 2001) performance testing standards against which dosimeter performance is evaluated. The phantom generally plays a significant role in the response of the dosimeter and is used to simulate the effect of a person's body on the dosimeter response. The backscatter factor may be defined as the ratio of tissue kerma at the surface of the phantom to that at the same point in space without the phantom present. For the standard polymethylmethacrylate (PMMA) slab phantom specified in HPS N 13.11, back scatter factors range from approximately 1.1 for 662 keV photons to approximately 1.8 for 50 keV photons (Bartlett et al 1990, Grosswendt 1990).

Similar algorithms are used to calculate dose for environmental and nuclear accident dosimeters. Procedures used to calculate dose are described in general terms under the respective dosimeter types in Sections 5.4 through 5.11. All algorithm development by the HEDP is based on radiation exposures traceable to the NIST.

5.3.8 Facility Calibration Codes

Contractor radiation dosimetry organizations provide a two digit calibration code to be used for calculating personnel dose for each type of personnel dosimeter returned for processing. This is a general capability that can be applied to the dose calculation for any dosimeter type. At present, facility calibration codes are used to specify one of two neutron algorithms for the 8816 neutron dosimeter (californium or plutonium), and to specify correction factors to be applied to the Hanford ring dosimeter result.

For Hanford users this two-digit calibration code, commonly referred to as the “facility calibration code” is part of each dosimeter record in the RETURN.TXT file transmitted electronically from the Radiological Exposure (REX) system to External Dosimetry (ED). Records are transmitted to ED for all dosimeters to be processed. Input to the RETURN.TXT file is prepared by Hanford field dosimetry staff using REX data entry screens and contains dosimeter assignment and wear information as well as the facility calibration code used in calculating and reporting personnel dose.

For the 8816 neutron TLD component of the HCND, the algorithm used to calculate neutron dose is determined from the facility calibration code. A facility calibration code = “00” results in use of the “californium” algorithm. A facility calibration code = “01” results in use of the “plutonium” algorithm. Individuals who receive the majority of their exposure at Hanford’s Plutonium Finishing Plant (PFP) should have their dosimeters returned for processing under facility calibration code = “01”. Individuals who receive a majority of their neutron dose from spent fuel, radioisotope sources (e.g. ^{252}Cf , AmBe) or other sources outside PFP should have their dosimeters returned for processing under facility calibration code = “00”. The 8816 neutron dose algorithms are described in greater detail in Section 5.5.3 and in HEDP files.

The extremity “ring” dose is also based on contractor input of the facility calibration code. For rings, the two-digit calibration code provided by the contractor is divided by 10 to obtain the calibration factor. The ^{137}Cs -based dose result is multiplied by the facility calibration factor to obtain the reported dose. Thus a code of 30 would result in the ^{137}Cs -based ring result being multiplied by 3.0. When a two-digit code of “00” is received, the algorithm interprets this as instruction to apply the default calibration factor of 2.0 established for general ring use in beta/photon fields. This factor is based on calculations and laboratory measurements conducted to measure ring response in attenuated beta radiation fields characteristic of Hanford work environments. The factor of 2.0 compensates for the under-response of the ring to low energy beta radiation. ^(a) For plutonium work environments that involve an over-response of the ring dosimeter to low-energy photon radiation and essentially no response to neutron radiation, a calibration factor of 2.0 is still appropriate. ^(b) This practice has been validated by field measurements (Scherpelz, Fix, and Rathbone 2000).

The use of facility-specific calibration factors is important to compensate for technological shortfalls in dosimetry technology for neutron and/or low-energy beta radiation fields. Accurate assessment of dose for these radiation fields must be based on a combination of laboratory and field measurements to ensure that the dose of record is not underestimated.

(a) B. A. Rathbone, “Attenuation Study for Lead Lined Gloves,” July 10, 1997, letter to J. M. Hammack, Lockheed Martin Hanford Corporation.

B. A. Rathbone, “Assessment of Ring Correction Factors for Use at Hanford,” November 30, 1998, letter to HEDP file.

(b) J. J. Fix, “Extremity Dosimetry: Neutron to Photon Ratio,” August, 1997, letter to HEDP file.

5.4 Hanford Standard Dosimeter

The HSD is designed to measure shallow, eye, and deep dose equivalent in mixtures of beta and photon radiation fields. In addition, the dosimeter has a neutron-sensitive TLD-600 phosphor for neutron detection. Although not intended as the primary dosimeter for measuring neutron dose, the HSD has been DOELAP accredited in neutron exposure categories and may be used for limited monitoring of individuals who are *not likely* to receive more than 100 mrem of neutron dose per year.

5.4.1 General Features

The HSD holder was designed according to HEDP specifications and is commercially available as a Harshaw 8825. The dosimeter card contains TLD-700 phosphors in positions one, two, and three and a TLD-600 phosphor in position four. These phosphors have thicknesses of 0.38 mm (100 mg/cm²) in positions one, two, and four and 0.15 mm (40 mg/cm²) in position three. The holder filtration consists of 242-mg/cm² ABS plastic plus 91 mg/cm² copper over position one, 1000-mg/cm² ABS and polytetrafluorethylene (PTFE) plastic over position two, 8-mg/cm² Teflon[®] and 9-mg/cm² Mylar[®] over position three, and 240 mg/cm² ABS plastic plus 463-mg/cm² tin over position four.

This dosimeter is illustrated in Figure 5.7. The dosimeter holder is constructed of black ABS plastic. The filter type and thickness is identified for each position of the dosimeter holder for the front side (i.e., dosimeter side facing away from the body). There are no filters on the back side. The density thickness of the ABS plastic case on the backside is 173 mg/cm². A red-tinted viewing window is centered on the back side of the dosimeter holder. The viewing window is used to electronically read the permanent ID number of the card enclosed within the holder.

5.4.2 Dosimeter Assignment and Processing Protocol

The HSD cards and holders must routinely satisfy a number of QC checks to be eligible for issuance to Hanford contractor dosimetry organizations and, upon return, to be eligible for routine processing. Assuming that a dosimeter holder and card have been qualified for use within the HEDP, the following series of actions, tracked by computer, must be taken to issue them:

- Dosimeter cards are processed through one of the automated 8800 reader systems to conduct a pre-issue reader "annealing." This reader processing cycle ensures that any remaining residual signal from past occupational use of the card or environmental background radiation is removed. Processing results for each card must satisfy established tolerance limits as one step in the overall qualification of a card for assignment.

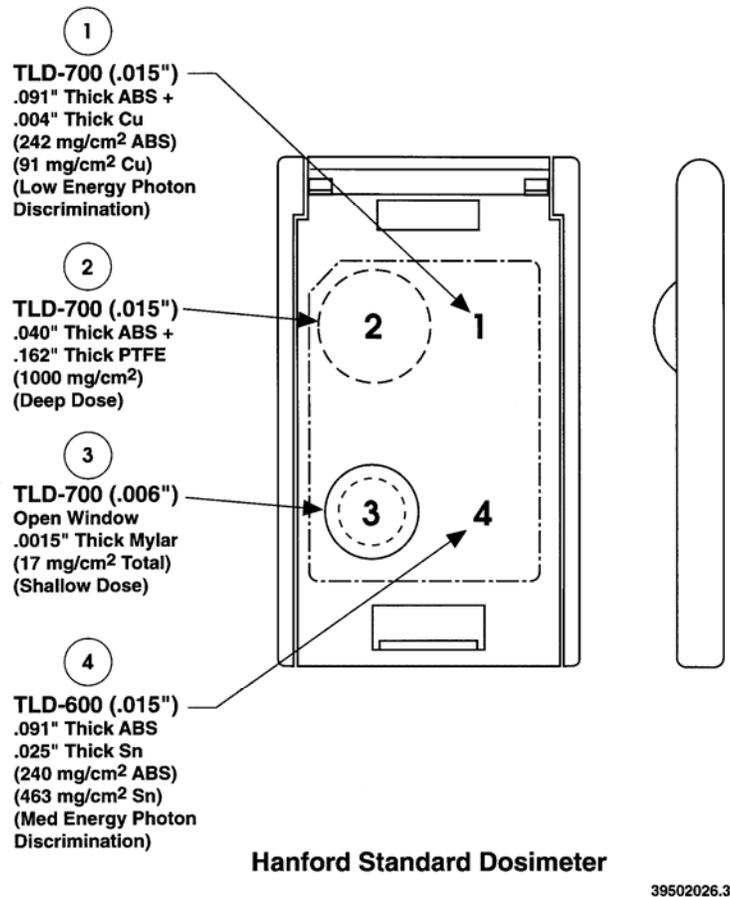


Figure 5.7 Hanford Standard Dosimeter

- All dosimeter cards are oven-annealed at 80°C for 16 hours before being loaded into a holder. This low temperature annealing process reduces the significance of signal fading by reducing the number of traps contributing to the lower-temperature peaks. It does not clear the higher temperature dosimetric traps to any significant extent. Use of this oven anneal reduces long-term fade to less than 15% per year. ^(a) Studies of various anneal treatment at Los Alamos National Laboratory have shown that this pre-irradiation oven-annealing technique provides improved reproducibility over other methods studied (Storm et al. 1981; Cortez, Storm, and Littlejohn, 1977).
- Card and holder assignments are electronically recorded when a dosimeter is issued.

(a) W. V. Baumgartner, "Study of Environmental Buildup and Fade for 8825 Card," October 11, 1994, letter to HEDP file.

- Upon return for processing, card and holder pairing is electronically checked to see if the dosimeter (i.e., card and holder) is being returned identically as issued.
- Cards are processed for a total read-out time of 13.3 seconds using the reader TTP parameters in Section 5.2.5.
- Throughout the processing, there are numerous reader parameters that must be satisfied for processing to continue. Selected portions of the glow curve, encompassing the dosimetric peaks, are used for dose calculation, thereby improving the signal-to-noise characteristics.
- Glow curves are electronically recorded for all personnel dosimeter processing. Plots of the TTP and the glow curve data visually demonstrate the rate at which light is being received by the PMT during processing of the dosimeter cards. These data are analyzed on the HEDP Alpha system to validate the quality of the processing data.

5.4.3 Algorithm

The HSD measures the dose equivalent at depths of 7, 300, and 1000 mg/cm² from beta and photon radiation. Primary calibration of the HSD algorithm is based on dosimeter response to ¹³⁷Cs when irradiated on a 30 x 30 x 15 cm³ (PMMA) phantom in the geometry specified in the *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems* DOE/EH-0027 (DOE 1986a). Algorithm response functions used for calculation of shallow and deep dose equivalent quantities from adjusted element readings were developed from the adjusted element responses to each source and source mixture specified in the standard and the delivered shallow and deep dose equivalents for those irradiations. The eye dose functions for photons were developed from irradiations to the NIST filtered x-ray sources specified in DOE/EH-0027 and HPS N 13.11-1993 and the NIST C_k factors for those sources. The eye dose function for beta radiation was developed using beta sources specified in the standards plus additional PNNL beta sources, and the measured dose rates at a depth of 300 mg/cm² for those sources.

The functions used to calculate shallow and deep dose when the radiation type is primarily low energy photons or mixtures of photons and beta particles were developed by Bicron/NE using a neural network (Moscovitch and Rotunda 1996). The application of neural networks in developing dose algorithms for multi-element dosimeters is described by Dr. Marko Moscovitch (Moscovitch 1999) and in Bicron/NE 8825 algorithm documentation (Bicron/NE 1999).

The algorithm has two major steps that must be completed in sequence to determine the correct dose equivalent (H_s, H_e, and H_{dp}). First, the algorithm identifies the type(s) of radiation to which a dosimeter was exposed by comparing adjusted element ratios with those established for known radiation types. The algorithm then uses dose response functions for the shallow, eye and deep dose elements, established for the identified radiation type, to calculate dose equivalent at the specified tissue depths. For mixtures of beta and photon radiation, the algorithm determines the shallow, eye, and deep dose and then

estimates the proportion due to beta or photon radiation. The functions used for calculating dose from mixtures of radiation are more complicated than for single sources.

The only information necessary to determine the radiation field composition is the adjusted chip readings. In the algorithm, the ratios of adjusted chip readings are used in a series of initial tests to determine the radiation composition and appropriate algorithm branch. The main branches of the algorithm are as follows:

- pure beta radiation
- low-energy photon radiation (< 50 keV)
- intermediate to high-energy photon radiation (≥ 50 keV)
- mixtures of beta and photon radiation.

Within each branch, the adjusted readings are used in response functions that calculate the appropriate "calibration factor" to convert the adjusted chip reading to the value of the measured quantity. The shallow and deep dose equivalent calibration factors r_3 and r_1 are applied to adjusted readings for the thin window and 1000-mg/cm² positions, respectively, to obtain shallow and deep dose. The eye dose equivalent calibration factor r_2 is applied to the adjusted reading in the copper-filtered position to obtain eye dose equivalent.

Although the HSD algorithm employs ratio tests to determine the radiation type and contains functions used to calculate the appropriate calibration factors to be applied to adjusted chip readings to obtain dose, there are some circumstances where it is desirable or necessary for the user to specify (either directly or indirectly) the radiation types and/or calibration factors to be used. Typically, these are situations where neutrons are detected and the TLD-600 chip behind tin filtration cannot be used for photon energy discrimination; they may also be situations where field conditions are well known and more accurate results can be obtained by the application of site-specific calibration factors.

5.4.4 HSD Element Response to DOELAP Sources

The relative element response of individual chips in the HSD to known amounts of shallow and deep dose from a variety of radiation sources is shown in Table 5.6. The values in this table were obtained from HSD irradiations to sources, geometry, and beam quality specifications contained in the DOELAP standard (DOE 1986a). The calibrated element response is the response of a chip when read with ECC and RCF applied. Five dosimeters were irradiated on-phantom to approximately 500 mrem (shallow dose) for each radiation type. The calibrated element response (mR) of each chip was divided by the applied shallow or deep dose equivalent (mrem) to obtain response factors (mR/mrem). For each radiation type, the mean response factor for each chip position was normalized to the response factor for ¹³⁷Cs to obtain the tabled relative values. The relatively good response of the position 3 phosphor to ²⁰⁴Tl is evident in the table. The TLD-600 phosphor (position 4) response to neutron radiation is shown, although it should be understood that neutron exposure will cause position four to be eliminated from consideration by the algorithm in beta/photon dose calculations.

The result is a reduction in the accuracy of beta/photon dose calculations due to the reduced information available to the algorithm.

5.4.5 Algorithm Bias

In general, the response of the HSD algorithm has been well documented in formal DOELAP and NVLAP performance test reports, as well as in studies documented in HEDP files.^(a) (HEDP no longer maintains NVLAP accreditation.) In preparation for initial DOELAP performance testing, groups of five HSDs each were irradiated to the sources in Table 5.7 according to the specifications contained in the DOELAP standard (DOE 1986a). The mean reported deep dose calculated by the algorithm was within $\pm 15\%$ of the given dose for each source used. The shallow and deep dose response of the algorithm for the various sources tested is shown in Table 5.7.

During calendar year 1996, several incidents involving the use of the HSD in high radiation fields with relatively large beta components, led to the identification of significant shortcomings in the “pure beta” branch of the vendor-supplied dose algorithm for the HSD. In particular, it was found that with pure or nearly pure beta radiation, eye dose was always under estimated and under certain circumstances, the algorithm would set the eye dose to zero. This occurred whenever the chip 3/chip 1 ratio was greater than 10 (indicative of soft beta radiation), even if the eye dose element (chip 1) may have had a significant reading. To evaluate the accuracy of the algorithm, heavily filtered beta sources were constructed using a nominal 50-mCi $^{90}\text{Sr}/^{90}\text{Y}$ Buchler beta source with Plexiglas™ filters such that none of the ^{90}Sr beta particles escaped and the ^{90}Y beta particles were degraded in energy. The eye dose rates from these sources were measured using an extrapolation chamber. The sources and filtrations are described in greater detail in Section 5.8.7. These sources provided degraded beta spectra having average energies between those of ^{90}Y (931 keV) and ^{204}Tl (267 keV). When the HSD was irradiated to known doses from these sources, it was found that the eye dose calculated in the beta branch of the algorithm was approximately 60% of the delivered eye dose from the unfiltered $^{90}\text{Sr}/^{90}\text{Y}$ Physikalisch-Technische Bundesanstalt (PTB) beta standard and 0% of the delivered eye dose for the filtered sources even when significant eye dose was delivered. The data obtained from these measurements were used to develop a new eye dose function for the beta branch of the algorithm. The response of the new algorithm to unfiltered ^{90}Y beta radiation is shown in Table 5.8.

(a) B. A. Rathbone, “HSD Performance Testing,” January 25, 1996, letter to HEDP file.

B. A. Rathbone, “HSD Performance Testing Using NVLAP Criteria and Ck”, September 30, 1997, letter to HEDP file.

In conjunction with verification of the new eye dose function for beta radiation, the HSD algorithm was also tested for photon radiation. The delivered eye dose for various NIST filtered X-ray techniques and for ^{137}Cs was based on C_k factors published by NIST. ^(a) The delivered eye dose for the K16 technique is based on C_k factors for monoenergetic photons and slab phantom (Grosswendt 1990). The algorithm's eye dose response for various sources is shown in Table 5.8. A complete evaluation of HSD bias and precision relative to delivered shallow, eye, and deep dose, from both pure sources and mixtures is documented in HEDP files. ^(b)

Table 5.6. HSD Element Response to DOELAP Sources

Beam Code	Element Response Per Unit Delivered Dose Equivalent Relative to ^{137}Cs Response							
	Shallow Dose Response ^a				Deep Dose Response ^b			
	chip1	chip2	chip3	chip4	chip1	chip2	chip3	chip4
M30	0.13	0.41	1.25	0.06	0.32	0.99	2.99	0.14
S60	1.09	1.32	1.57	0.48	1.17	1.41	1.69	0.52
M150	1.35	1.29	1.32	0.86	1.30	1.24	1.26	0.82
K16	0.07	0.46	1.32	0.04	0.21	1.32	3.74	0.13
K59	1.39	1.31	1.35	0.79	1.33	1.25	1.29	0.75
H150	1.15	1.06	1.12	0.91	1.15	1.06	1.12	0.91
$^{90}\text{Sr}/^{90}\text{Y}$	0.22	0.02	1.09	0.01	N/A	N/A	N/A	N/A
^{240}Tl	0.00	0.00	0.65	0.00	N/A	N/A	N/A	N/A
DU	0.09	0.02	0.57	0.02	N/A	N/A	N/A	N/A
^{137}Cs	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{241}Am	1.39	1.30	1.33	0.79	1.33	1.24	1.28	0.75
^{252}CfM	1.18 ^c	1.07 ^c	1.16 ^c	57.03 ^c	0.18 ^d	0.16 ^d	0.18 ^d	8.69 ^d
^{252}CfU	0.90 ^c	0.83 ^c	0.99 ^c	18.47 ^c	0.06 ^d	0.05 ^d	0.06 ^d	1.20 ^d

- a. Response of chips per unit of delivered shallow dose equivalent, normalized to the ^{137}Cs response.
b. Response of chips per unit of delivered deep dose equivalent, normalized to the ^{137}Cs response.
c. Delivered shallow dose equivalent from ^{252}Cf photons only was used to calculate these values.
d. Delivered deep dose equivalent from photons and neutrons was used to calculate these values.

(a) C. G. Soares and P. R. Martin, "A comprehensive Set of Conversion Coefficients for Photons," Proceedings of Bicron/NE TLD User's Symposium held in Las Vegas, NV; March 13-17, 1995.

(b) B. A. Rathbone, "HSD Performance Testing Using NVLAP Criteria and C_k ," September 30, 1997, HEDP file.

Table 5.7. HSD Algorithm Shallow and Deep Dose Response

Beam Code	Average Energy (keV)	Shallow Dose Response ^a	Deep Dose Response ^a
K16	16	1.03	1.09
M30	20	1.01	0.94
S60	36	1.11	1.03
K59	59	0.92	0.91
²⁴¹ Am	59	0.92	0.91
M150	70	0.94	0.93
H150	117	0.95	0.93
¹³⁷ Cs	662	1.00	1.00
⁹⁰ Sr/ ⁹⁰ Y ^b	931 ^c	1.04	n/a
²⁰⁴ Tl ^b	267 ^c	0.95	n/a

a. Reported/given dose equivalent. Normalized to ¹³⁷Cs value.

b. Source specifications described in DOELAP standard (DOE 1986a).

c. Nominal values. Actual energies are slightly less because of filtration inherent in encapsulation and beam flattener.

n/a = Not applicable.

Table 5.8 HSD Algorithm Eye Dose Response

Beam Code	Average Energy (keV)	Reported/Given ^a
K16	16	0.61
M30	20	1.06
M60	34	1.01
S60	38	1.11
M100	51	1.11
²⁴¹ Am	59	0.96
M150	70	0.95
H150	117	0.95
¹³⁷ Cs	662	1.00
⁹⁰ Sr/ ⁹⁰ Y ^b	931 ^c	1.02

a. Reported value normalized to reported ¹³⁷Cs value

b. Source specifications described in DOELAP standard (DOE 1986a)

c. Nominal values. Actual energies are slightly less because of filtration inherent in encapsulation and beam flattener

Table 5.9 HSD Algorithm Neutron Dose Response

Source or Field	Average Energy (keV)	Reported/Given ^a	Exposure Geometry ^{b,c,d}
AmBe (bare)	4160	0.70	AP @ 50 cm
²⁵² Cf (bare)	2130	1.00	AP @ 50 cm
²⁵² Cf (D ₂ O moderated with Cd)	550	8.17	AP @ 50 cm
²⁵² Cf (D ₂ O moderated w/o/Cd)	550	10.87	AP @ 50 cm
PWR fuel in NAC-1 shipping cask	n/a	4.31 ^e	AP @ 1.7 m
PWR fuel in NAC-1 shipping cask	n/a	6.17 ^e	AP @ 11.2 m
PFP “front side”	120 – 360 ^f	6 ^f	ISO, ROT
PFP “back side”	150 – 740 ^{f,g}	2 – 18 ^h	ISO, ROT

a. Given neutron dose equivalent based on TEPC measurement. R/G standard uncertainty = 10%

b. AP = anterior-posterior orientation (facing source)

c. ISO = isotropic radiation

d. ROT = rotational orientation with respect to source

e. B. A. Rathbone, “Neutron Response of HSD and HCND Personnel Dosimeters Near Spent Fuel Casks”, February 13, 2004, HEDP file

f. B. A. Rathbone, “Neutron Calibration Factors for HSD in Plutonium Environments”, August 20, 1997, HEDP file

g. R. I. Scherpelz and B. A. Rathbone, “Neutron Measurements at PFP August-September, 2003”, November 14, 2003, HEDP file

h. B. A. Rathbone, “Verification of 8816 Performance in PFP Neutron Fields”, March 3, 2004, HEDP file

The HSD does not have a true (energy compensating) neutron dose algorithm. Instead, it calculates neutron dose using a designated neutron calibration factor. When the dosimeter detects neutron dose and has been processed under facility calibration code = 00 (Hanford default), the neutron dose calculation will be based on a calibration of the dosimeter to an unmoderated ²⁵²Cf neutron energy spectrum. Most neutron dose detected by the HSD will likely be from scattered neutrons originating from distant or shielded sources. If this is the case, the HSD will over respond due to the moderation involved. An important exception where the HSD has the potential to under respond is exposure to an unshielded AmBe source (e.g. well logging source). The HSD’s neutron response (relative to TEPC) to various laboratory and field sources when processed using the default calibration code is shown in Table 5.9

5.4.6 Angular Response

The angular response of the HSD was measured as required by DOELAP (DOE 1986a), which require documentation of the angular response for each dosimeter design in irradiation categories III through VI. ^(a) The HPS had also identified angular response testing at ±40° (HPS 1993) in addition to the ±30°, ±60°, and ±85° angles already identified in the DOELAP standard so this angle was included as well.

(a) J. J. Fix, “Angular Response of Hanford Personnel Dosimeters,” October 18, 1994, HEDP file.

B. A. Rathbone, “Angular Dependence Study for Hanford Standard Dosimeter,” December 17, 1997, HEDP file.

J. J. Fix, “HSD Neutron Angular Response,” May 15, 1998, HEDP file.

Experimental Method

Measurement of angular response was conducted using irradiations from selected beta, photon, and neutron sources. Irradiation geometries are summarized as follows:

- Photon irradiations were performed using a phantom measuring 30 x 30 x 15 cm thick. Irradiations were performed using k-fluorescent K16, M30, S60, ²⁴¹Am, and ¹³⁷Cs sources. Irradiation distances from the source center to the front edge vertical centerline of the phantom were 50 cm for K16 ^(a) and ²⁴¹Am irradiations and 100 cm for ¹³⁷Cs irradiations.
- Beta exposures were made in a similar manner using a 30 x 30 x 5 cm phantom. A ⁹⁰Sr/⁹⁰Y source and a ²⁰⁴Tl source were used to irradiate dosimeters on the phantom located a distance of 35 cm from the source.
- Neutron measurements were made with bare and moderated ²⁵²Cf sources. A phantom measuring 40 x 40 x 15 cm was used at a distance of 50 cm from the source.

All source calibrations are traceable to NIST. Irradiations were timed to deliver an approximate dose of 5 mSv (500 mrem), in reference to the 0° angle (normal) exposure geometry, to each dosimeter.

To measure angular response, the phantom was rotated to each of the angles of 0°, 30°, 40°, 60°, and 85° clockwise and counter-clockwise as viewed from overhead. Dosimeters were mounted on thin Plexiglas™ sheets that were then mounted on the front of the phantom. Dosimeters were mounted upright with the beta window at the “top” to measure the vertical angular response and horizontally (i.e., dosimeter rotated 90° clockwise so that long axis is horizontal) to measure the horizontal angular response. Figure 5.8 illustrates the exposure setup. Two of the three dosimeters exposed at each angle were mounted on the phantom surface for one exposure while the third dosimeter was mounted in the center (similar to the HCND) and exposed separately. For all irradiations, distances of at least 7.5 and 10.0 cm between the outer edge of the dosimeters and the edge of the phantom, per HPS N13.11 (HPS 1993) and DOELAP (DOE 1986a) requirements, were maintained for beta and photon and for neutron irradiations, respectively.

(a) Surface of target to surface of phantom.

Results

The results of the study are shown in Tables 5.10 and 5.11, and shown graphically in Figures 5.9 - 5.14 for several sources of irradiation. These figures illustrate the ratio of the reported dose for each angle normalized to the dosimeter response at 0° for horizontal and vertical dosimeter rotation, respectively. In these plots, the angles for the clockwise rotation are considered to be negative; counter-clockwise rotations are positive.

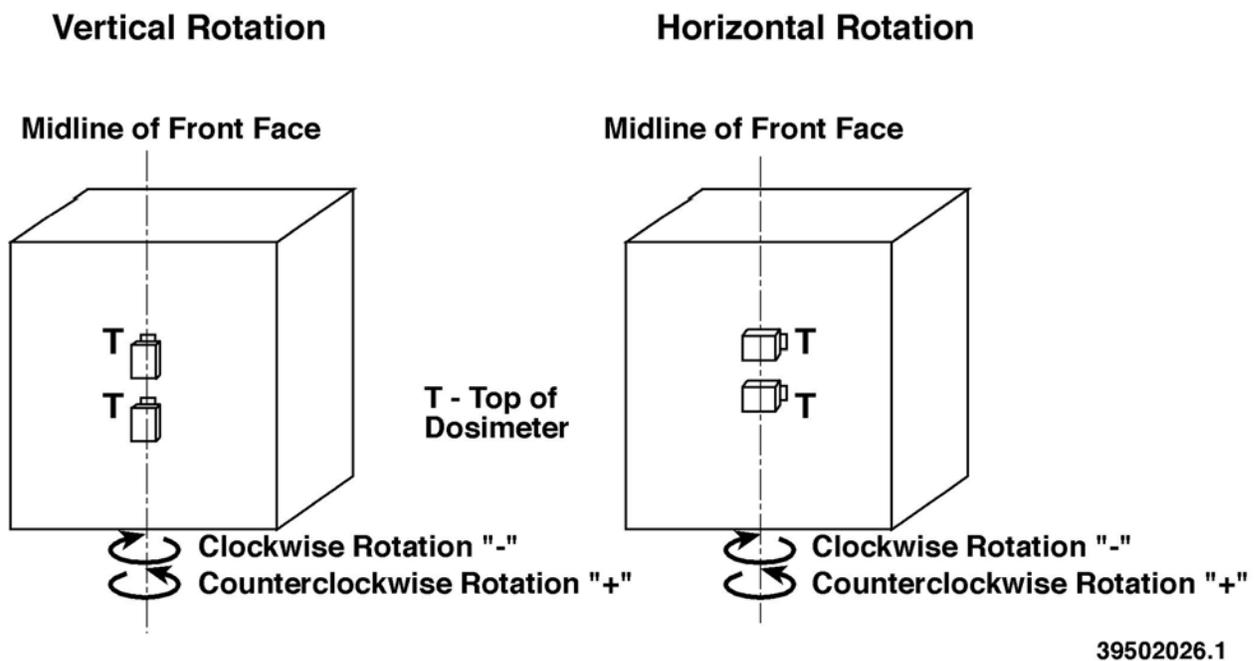


Figure 5.8. Irradiation Setup for Dosimeter Angular Response Evaluation

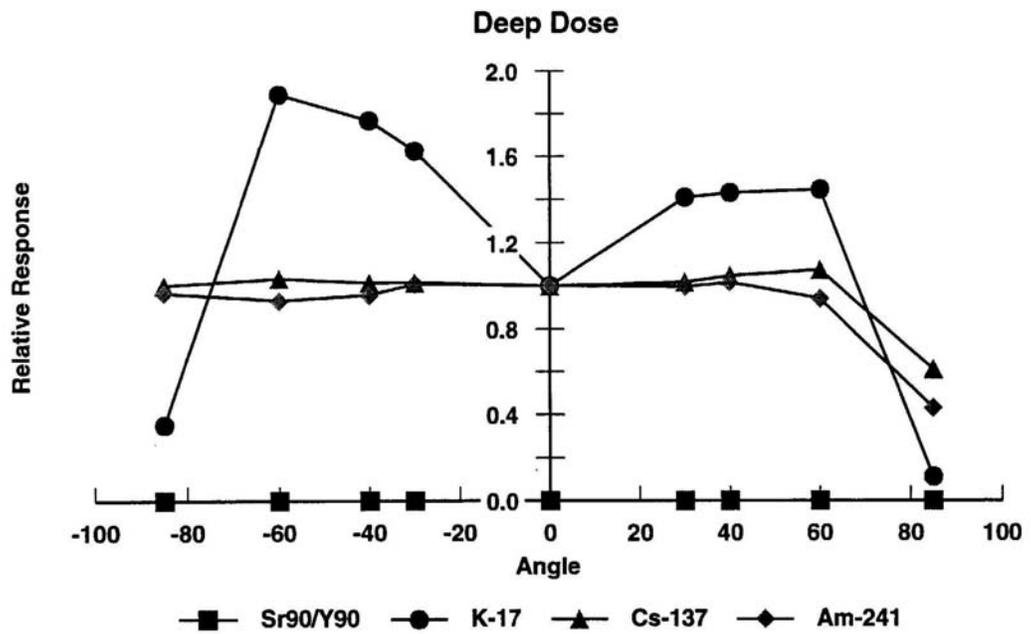
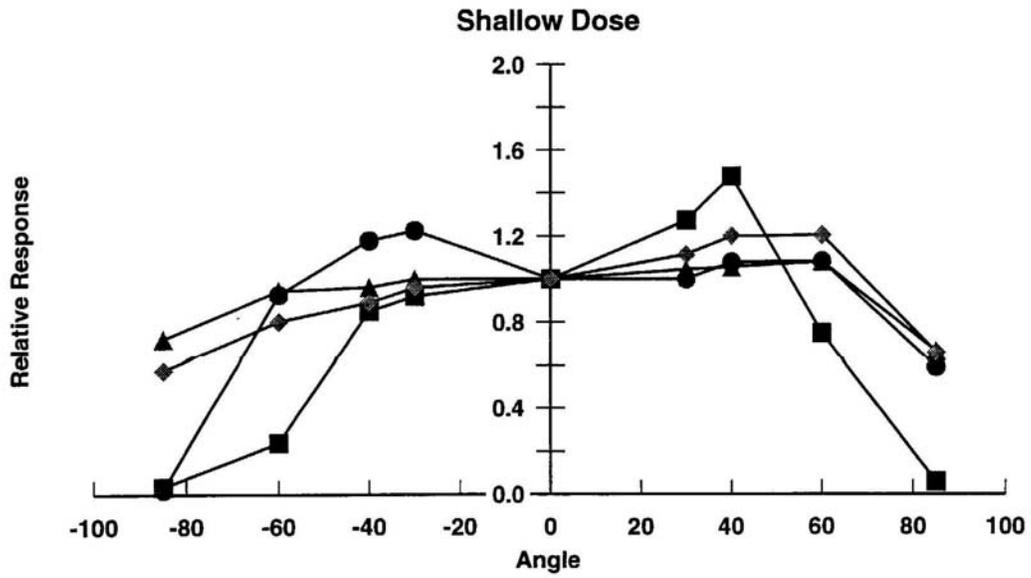
Table 5.10. HSD Shallow Dose Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K16	16	H	0.02	0.93	1.18	1.23	1.00	1.00	1.08	1.08	0.59
		V	0.04	1.00	1.24	1.23	1.00	1.28	1.27	1.04	0.10
M30	20	H	0.07	0.94	1.07	1.16	1.00	0.88	0.76	0.56	0.10
		V	0.12	0.83	0.89	0.95	1.00	0.92	0.96	0.64	0.04
S60	36	H	0.42	1.02	1.05	1.06	1.00	0.92	0.92	0.71	0.59
		V	0.47	0.89	1.02	0.99	1.00	0.97	1.01	0.87	0.20
²⁴¹ Am	59	H	0.58	0.80	0.89	0.96	1.00	1.11	1.20	1.20	0.66
		V	0.35	0.87	0.94	0.95	1.00	0.97	0.94	0.90	0.79
¹³⁷ Cs	662	H	0.72	0.95	0.96	1.00	1.00	1.05	1.06	1.08	0.66
		V	0.71	1.03	1.02	1.03	1.00	1.00	1.01	0.97	0.91
⁹⁰ Sr/ ⁹⁰ Y	931	H	0.04	0.24	0.85	0.92	1.00	1.27	1.48	0.75	0.06
		V	0.05	0.36	0.94	1.02	1.00	1.17	1.12	0.83	0.05
²⁰⁴ Tl	267	H	0.08	0.39	0.74	0.92	1.00	0.78	0.55	0.26	0.05
		V	0.07	0.33	0.66	0.86	1.00	0.81	0.57	0.31	0.07

Table 5.11. HSD Deep Dose ^(a) Angular Response

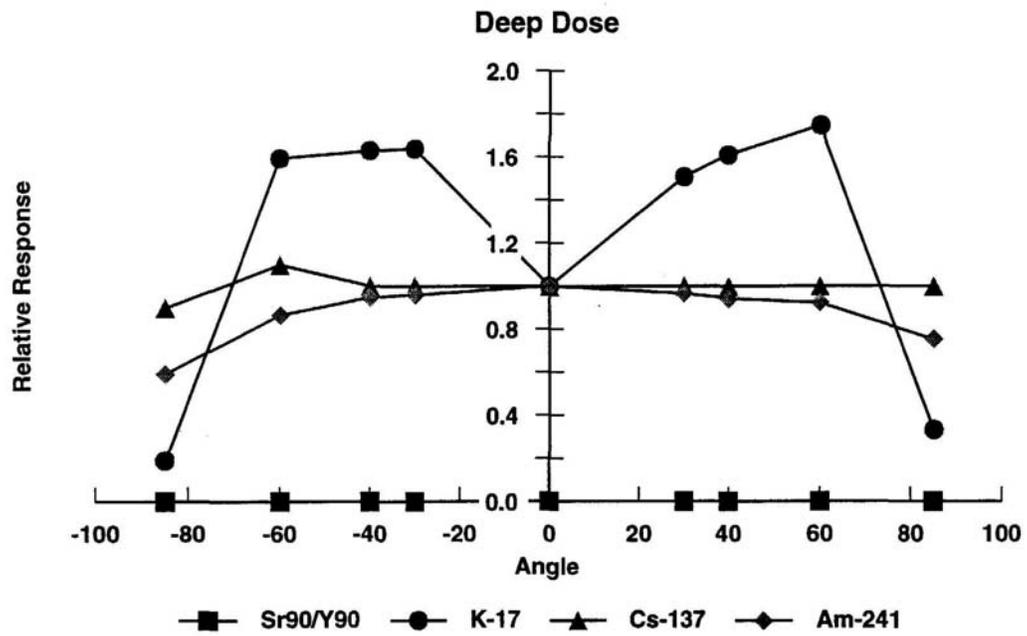
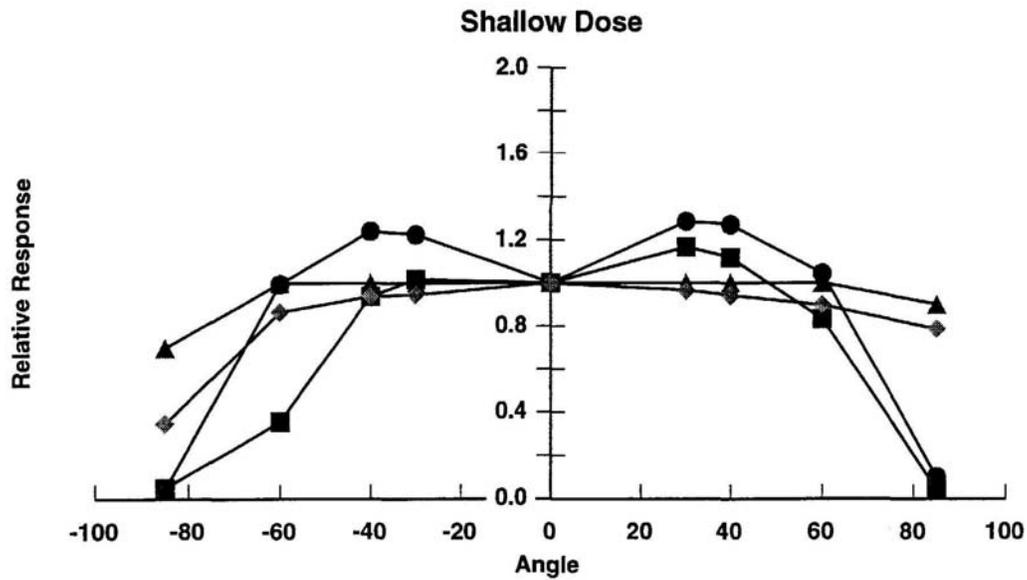
Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K16	16	H	0.35	1.89	1.77	1.63	1.00	1.41	1.43	1.45	0.11
		V	0.19	1.59	1.63	1.64	1.00	1.51	1.61	1.75	0.33
M30	20	H	0.09	1.20	1.00	1.01	1.00	0.98	0.93	0.92	0.30
		V	0.38	1.30	0.98	1.01	1.00	1.04	1.04	1.06	0.13
S60	36	H	0.33	0.89	0.95	0.99	1.00	1.00	1.00	0.92	0.80
		V	0.63	0.94	0.96	1.02	1.00	0.98	0.94	0.88	0.27
²⁴¹ Am	59	H	0.97	0.93	0.96	1.01	1.00	1.00	1.02	0.94	0.43
		V	0.59	0.89	0.95	0.96	1.00	0.97	0.94	0.92	0.75
¹³⁷ Cs	662	H	1.00	1.03	1.01	1.02	1.00	1.02	1.05	1.07	0.61
		V	0.91	1.06	1.04	1.03	1.00	1.00	1.03	1.02	0.98
²⁵² Cf U	2100	H	0.22	0.63	0.86	0.90	1.00	0.96	0.92	0.72	0.33
		V	0.28	0.70	0.93	0.91	1.00	0.90	0.86	0.65	0.26
²⁵² Cf M	550	H	0.16	0.53	0.78	0.84	1.00	0.96	0.90	0.65	0.22
		V	0.23	0.59	0.84	0.92	1.00	0.88	0.80	0.58	0.19

(a) For Cf-252 irradiations, neutron component only.



39502006.2

Figure 5.9. HSD Angular Response – Horizontal Rotation



39502006.1

Figure 5.10. HSD Angular Response – Vertical Rotation

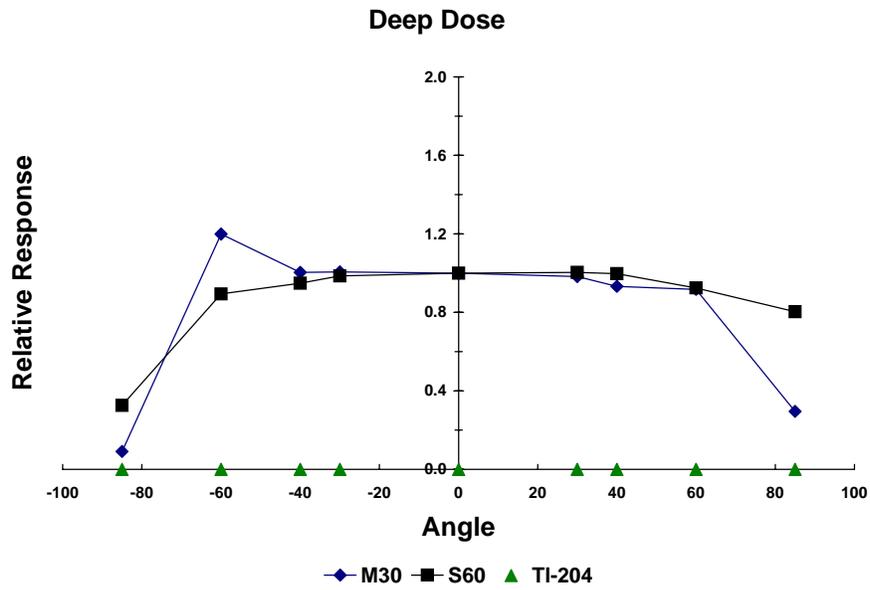
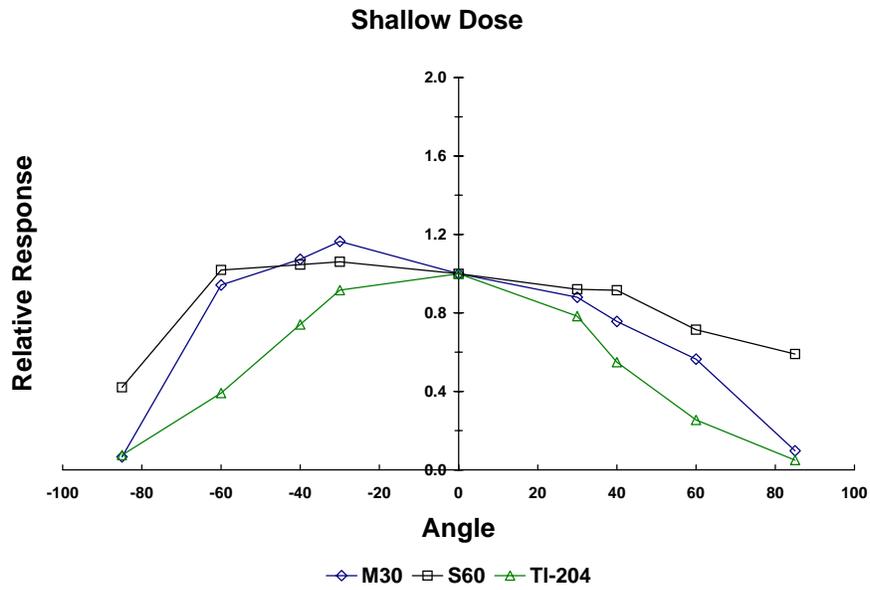


Figure 5.11. HSD Angular Response – Horizontal Rotation

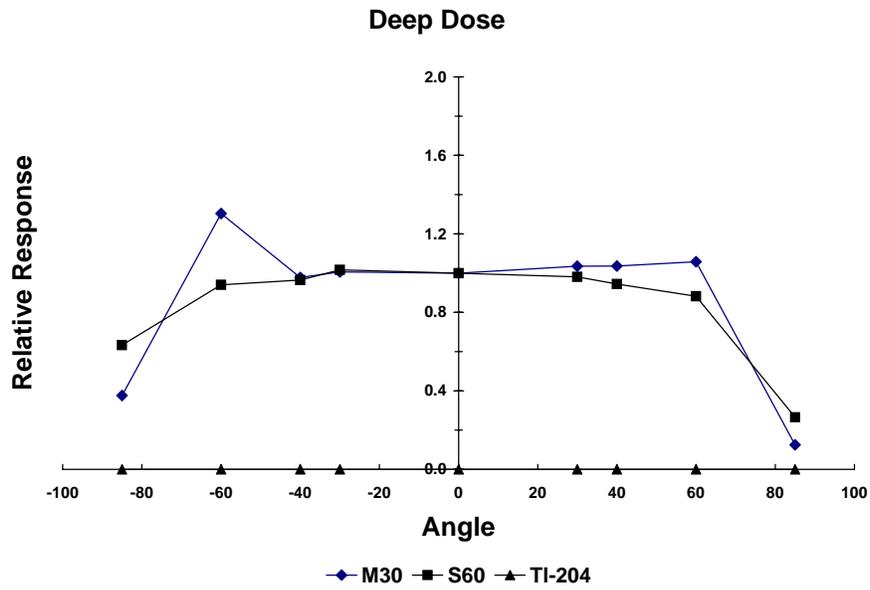
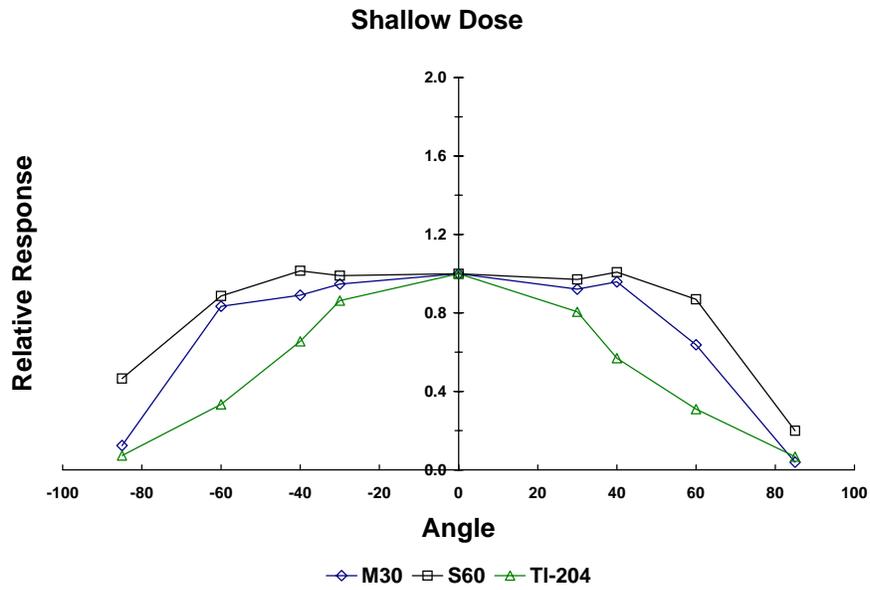


Figure 5.12. HSD Angular Response – Vertical Rotation

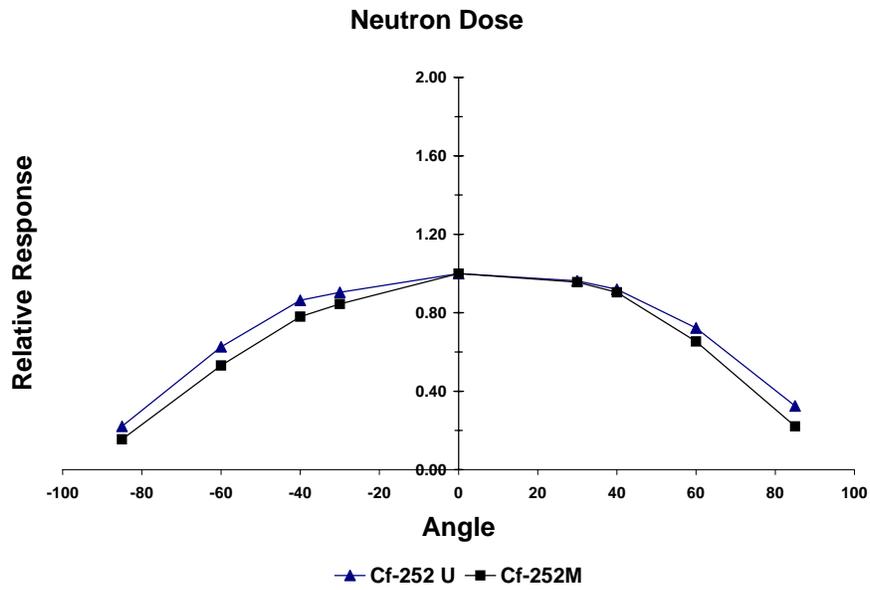


Figure 5.13. HSD Neutron Angular Response – Horizontal Rotation

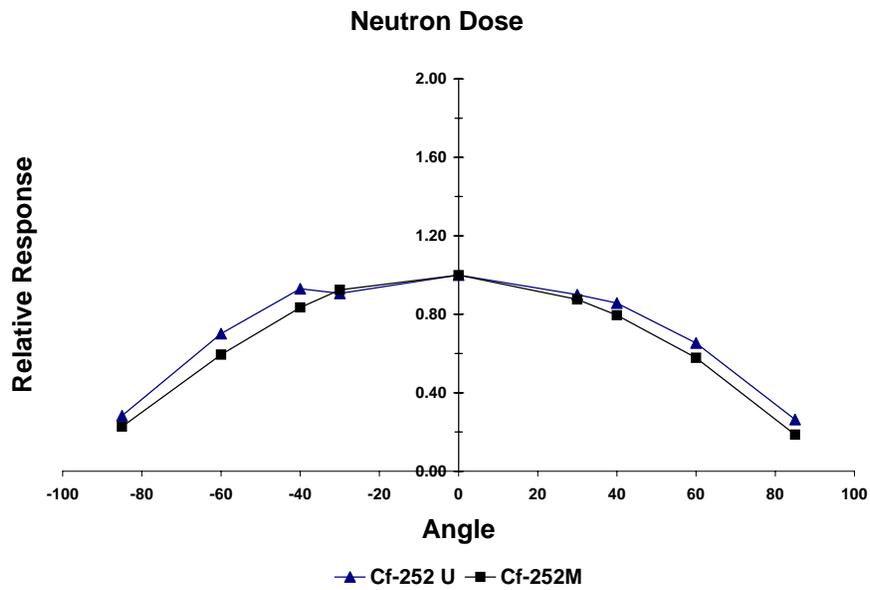


Figure 5.14. HSD Neutron Angular Response – Vertical Rotation

5.4.7 Lower Level of Detection

The lower level of detection (LLD) has been calculated for the HSD for monthly, quarterly and annual exchange periods in a variety of studies using either of the two methods given in the DOELAP performance test standard DOE/EH-0027 (DOE 1986a).^(a) These studies used open audit dosimeter data, DOELAP performance test data, and data from dosimeters prepared specifically for the purpose of conducting an LLD study. A composite of the results from these studies is presented in Table 5.12. The symbols H_s , H_e , H_{dp} and H_n represent the algorithm calculated *shallow* dose equivalent, *eye* dose equivalent, *deep photon* dose equivalent and *neutron* dose equivalent respectively. The LLDs for eye dose were not calculated because the delivered eye dose was not given in the irradiations used. However, LLDs for eye dose are expected to be similar to those calculated for deep dose because the variability in background readings and dosed readings of the eye dose element are similar to that of the deep dose element.

Table 5.12 Calculated LLDs (in mrem) for the HSD

Exchange Frequency	DOELAP Category	Parameter	H_s	H_e	H_{dp}	H_n (mod)	H_n (bare)
M	Controls	L_C	3.8	3.1	3.1	*	*
	III A (X-ray-general)	L_D	*	*	*	*	*
	IV (Cs-137)	L_D	7.6	*	6.2	*	*
	VC (beta-general))	L_D	*	*	*	*	*
	VI (neutron)	L_D	*	*	*	0.4	3.2
Q	Controls	L_C	3.4	3.0	3.0	0.3	2.3
	III A (X-ray-general)	L_D	8.3	*	7.3	*	*
	IV (Cs-137)	L_D	6.9	*	6.1	*	*
	VC (beta-general))	L_D	7.3	*	*	*	*
	VI (neutron)	L_D	*	*	*	0.6	4.8
A	Controls	L_C	8.5	7.1	7.1	0.9	7.1
	III A (X-ray-general)	L_D	22.2	*	18.5	*	*
	IV (Cs-137)	L_D	17.2	*	14.4	*	*
	VC (beta-general))	L_D	18.8	*	*	*	*
	VI (neutron)	L_D	*	*	*	1.8	14.8

(a) Letters to HEDP File:

- B. A. Rathbone, "LLD Calculations for HSD and HCND Dosimeters," July 9, 1996.
- J. J. Fix, "HSD Cf-252 Lower Level of Detection," June, 2, 1998
- B. A. Rathbone, "LLD Calculations for Quarterly HSD," May 20, 1999.
- B. A. Rathbone, "LLD Calculations for Annual HSD," May 20, 1999.

5.4.8 Environmental Sensitivity

The HSD is relatively unaffected by normal variations in heat, humidity, and light. The black ABS plastic construction of the holder was chosen to minimize effects of light. However, it is important to protect the dosimeter from environmental extremes because of the potential affect on the dosimeter response. Because the holder color is black, the dosimeter can reach temperatures in excess of 70°C when placed in direct sunlight in an unventilated area, such as the dashboard of a car. Data presented by E. Piesch (Oberhofer and Scharmann 1979) indicate fade can be as high as 60% for storage at 70°C for 100 days. Figure 5.15 illustrates results of a study that shows significant fade observed with the HSD from elevated temperatures. In this study, HSDs were prepared using routine procedures (i.e., reader and 80°C oven anneals), the cards were exposed to 500 mR of ⁶⁰Co gamma radiation, loaded into holders, and maintained at 80°C in an oven for selected time periods of up to 28 days. Fading in excess of 50% was observed.

While the HSD is unaffected by light, the bare card used in the dosimeter is sensitive to light. This sensitivity is due to the sensitivity of the TL phosphors and Teflon[®] encapsulation to visible and ultraviolet (UV) light. At ordinary indoor lighting levels, LiF:Mg,Ti response to light is negligible whereas the Teflon[®] encapsulation is unacceptably large for a small percentage of the elements. Acceptance testing of the 8825 and 8816 card types for production use shows a mean light-induced signal of less than 5 mR with batch-to-batch fluctuations evident when exposed for 2 hours to UV-filtered fluorescent room lighting at a level of 300 lux, which is representative of routine operating conditions. ^(a) Approximately 0.5% of the cards tested exhibit a response in excess of 20 mR on at least one chip when exposed under these conditions, with extremes greater than 200 mR having been observed. For this reason, the card should never be removed from the holder while in the field.

5.4.9 Fading

The fade corrections used for TLD 600 and TLD 700 elements in the HSD are described in Section 5.3.6.2. In general, fading is less than 15% per year for beta-gamma dose and less than 30% per year for neutron dose. Default fade corrections are applied, based on the assumption that a dosimeter was exposed mid cycle. This type of fade correction produces accurate results for acute exposures at mid cycle and for chronic exposures. However, when all of the exposure is received at the beginning or end of the exposure cycle, errors are introduced by use of default fade corrections. The worst case error in reported beta-gamma dose for a single acute exposure at the beginning or end of the exposure cycle is -5% and + 10% respectively for an annual badge. The worst case error in reported neutron dose for a single acute exposure at the beginning or end of the exposure cycle is -10% and + 30% respectively for an annual badge.

(a) Procedure 200.3.10. "Acceptance Testing of Type 8825 and 8816 Cards," PNL-MA-841, Hanford External Dosimetry Project Procedures Manual.

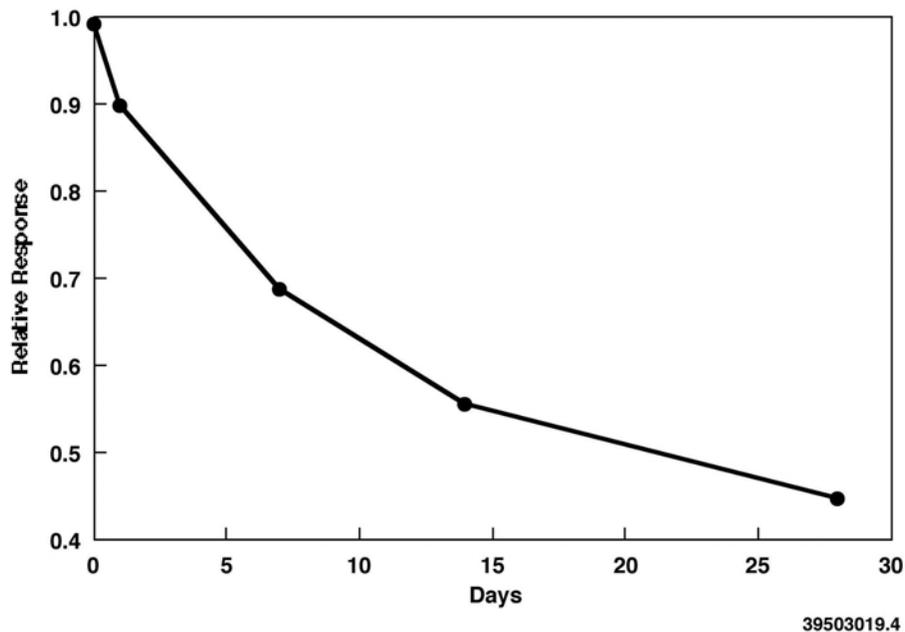


Figure 5.15. HSD Fading at 80°C

5.5 Hanford Combination Neutron Dosimeter

The HCND is used to record the shallow, eye, deep, and neutron dose of record for Hanford employees working in beta, photon, and neutron radiation fields. The dosimeter consists of the following components:

- a beta-photon 8825 TLD
- an albedo neutron 8816 TLD

The beta/photon TLD and the albedo neutron TLD are known commercially as the Harshaw 8825 and 8816 dosimeters, respectively. In addition to an 8816 card, the 8816 holder contains a pocket to hold two TED foils (CR-39). Because of cost considerations and performance issues at typically low dose levels, the CR-39 capability is no longer maintained or used at Hanford. Periodic field measurements have demonstrated adequate performance can be obtained with the 8816 TLD albedo neutron dosimeter. Detailed design considerations for the HCND are provided by Brackenbush, Baumgartner and Fix (1991) and Endres et al (1996). A clear plastic holder is used to retain the 8816 and 8825 TLDs, along with an optional Personnel Nuclear Accident Dosimeter (PNAD), as shown in Figure 5.16. The HCND without PNAD is shown in Figure 5.17. The PNAD is discussed in Section 5.11. The 8825 beta-photon dosimeter is identical to the HSD described in Section 5.4, with the single exception that a TLD-700 phosphor is used in position 4 instead of a neutron-sensitive TLD-600 phosphor. This is done to allow for better shallow, eye, and deep dose performance while in a neutron field. Characteristics of the albedo neutron 8816 TLD are described in this section. An illustration of the 8816 albedo neutron dosimeter is shown in Figure 5.18

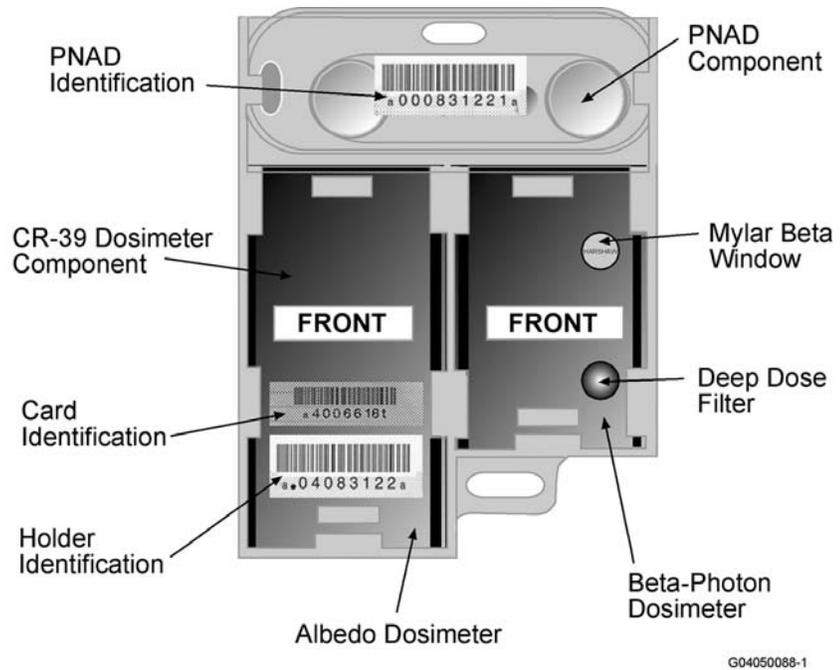


Figure 5.16 Hanford Combination Neutron Dosimeter with PNAD

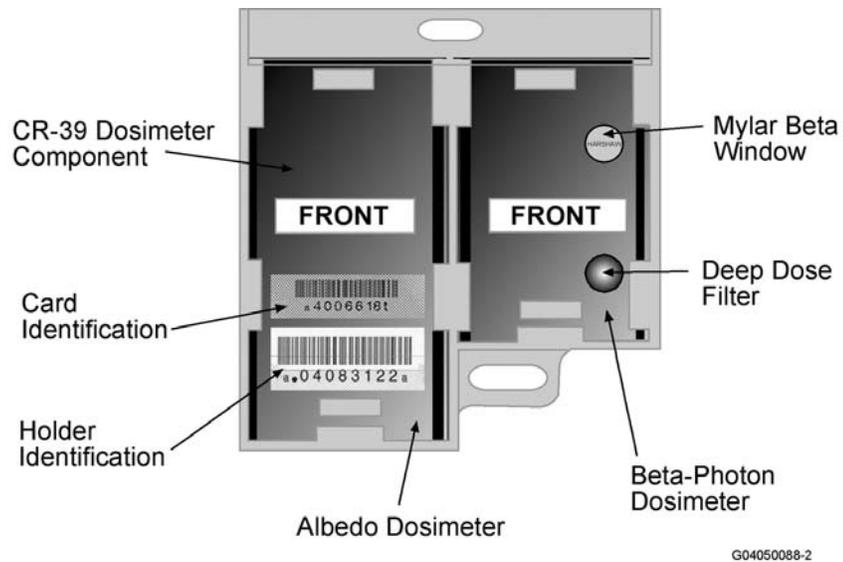


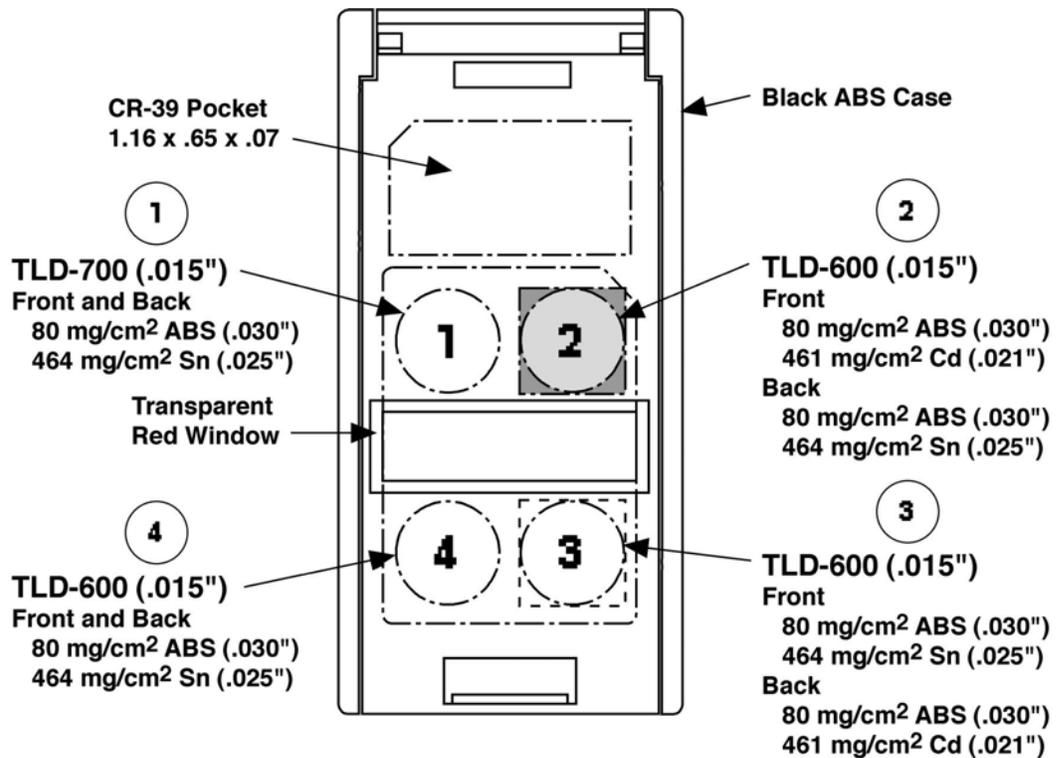
Figure 5.17 Hanford Combination Neutron Dosimeter without PNAD

5.5.1 General Features

The 8816 albedo neutron dosimeter contains three TLD-600 phosphors and one TLD-700. All four positions have nearly the same beta and photon radiation response because of the use of very similar (i.e., similar atomic number) filter materials and thicknesses over each dosimeter position. Three different filter configurations are used for each of the TLD-600 phosphors, as follows:

- cadmium filter on front and tin filter on the back
- tin filter on front and cadmium filter on the back
- tin filters on front and back.

For the single TLD-700 phosphor, tin filters are used on the front and the back. The dosimeter card has 0.38-mm phosphors in all four positions. The tin and cadmium filters have nearly equivalent mass density values of 464 mg/cm^2 and 461 mg/cm^2 , respectively, based on a density of 7.275 g/cm^3 for tin and 8.608 g/cm^3 for cadmium. An additional 80 mg/cm^2 of ABS plastic is present in all filter locations.



Hanford TL Albedo Neutron Dosimeter

39502026.4

Figure 5.18 8816 Albedo Neutron Dosimeter

5.5.2 Dosimeter Assignment and Processing Protocol

HCND cards and holders must routinely satisfy the same QC checks upon issue to, and receipt from, field dosimetry organizations as described in Section 5.4.2 for the HSD. Additional steps are involved to load the 8825 beta-photon and 8816 albedo neutron dosimeters together in the combination holder for issuance as a package. Because it is possible to successfully snap an 8816 holder shut with a TLD card loaded backward, 8816 holders are visually inspected after loading to verify proper loading. Otherwise, there are no differences between preparing this dosimeter for assignment and the subsequent TLD processing protocol.

5.5.3 Algorithm

The beta-photon 8825 algorithm is identical to the algorithm used with the HSD. The 8816 algorithm calculates only neutron dose equivalent. All positions of this dosimeter are photon equivalent (i.e., same signal on each phosphor from photon radiation). As such, the TLD-700 phosphor signal in position 1 is used to subtract any photon radiation caused signal from the other positions. There are currently four algorithms that can be used to calculate neutron dose with the 8816 TLD.^(a) These are:

- californium
- plutonium
- D₂O moderated ²⁵²Cf
- unmoderated ²⁵²Cf

The californium and plutonium algorithms are used to calculate dose to Hanford workers. The D₂O moderated ²⁵²Cf and unmoderated ²⁵²Cf algorithms are used for DOELAP performance testing. They are tailored to these two sources and do not have energy discriminating capabilities.

Energy discriminating response functions for the californium algorithm were derived from the response of the dosimeter on-phantom in AP exposure geometry, to a bare source and a source with varying thicknesses of Plexiglas™ moderator between the source and dosimeter. For the development of this algorithm, the reference or “delivered” dose was determined from tissue equivalent proportional counter (TEPC) and multisphere measurements of the neutron dose equivalent rate for each geometry (Endres et al 1996). Dosimeter irradiations and neutron measurements were performed with a ²⁵²Cf calibration source in the 318 Radiological Calibrations Facility. The californium algorithm has been shown to provide adequate response for moderated ²⁵²Cf neutron fields as well as neutron fields generated by spent reactor fuel in shipping casks.^(b)

(a) B. A. Rathbone, “HEDP Dose Calculation Methodology” July 8, 2002, letter to HEDP file.

(b) B. A. Rathbone, “Neutron Response of HSD and HCND Personnel Dosimeters Near Spent Fuel Casks” February 13, 2004, letter to HEDP file.

Energy discriminating response functions for the plutonium algorithm were derived from the response of the dosimeter in work locations at Hanford's plutonium finishing plant (PFP) representing a range of neutron energy spectra and scatter conditions (Scherpelz, Fix and Rathbone 2000). At each location, dosimeters were placed on four faces of a cubical water filled phantom. For the development of this algorithm, the TEPC measured dose rate at each location was used to calculate the reference or "delivered" neutron dose. ^(a) The response for each element was determined from the average reading from all four phantom faces. A comparison of the resulting algorithm's output against TEPC results shows that the algorithm provides results between -10% and +50% of the TEPC for the initial 10 locations used to develop the algorithm. Subsequent field measurements involving new source terms and geometries showed the response to be within $\pm 50\%$ of the TEPC. ^(b) Because the dosimeters are shielded by the phantom when exposed in isotropic or rotational geometries, whereas the dose algorithm simulates the isotropic response of the *unshielded* TEPC, the algorithm over estimates *effective* dose equivalent for individuals exposed in isotropic or rotational exposure geometries typical of the actual workplace. .

5.5.4 HCND Element Response to DOELAP Sources

The relative element response for the beta-photon 8825 TLD is identical to the information presented for the HSD in Table 5.6 except for the chip 4 response to bare and moderated ²⁵²Cf irradiations. The difference is due to the fact that chip 4 is TLD-700 in the beta-photon 8825 and TLD-600 in the HSD. For the beta-photon 8825, the shallow dose response and deep dose response of chip 4 to moderated ²⁵²Cf is 1.05 and 0.16, respectively. For unmoderated ²⁵²Cf the chip 4 shallow and deep dose responses are 0.77 and 0.05, respectively. For the 8816 albedo neutron dosimeter, the response for each chip position, for a variety of sources relative to the ¹³⁷Cs response, is shown in Table 5.13. As can be seen from the data, all four chip positions in the 8816 respond approximately the same when exposed to photon or beta radiation thus allowing the use of chip 1 (TLD-700) to subtract beta-photon signals from the chip 2, 3, and 4 readings (TLD-600) to obtain net neutron signal on these chips. Response values for neutron source radiation to bare and moderated ²⁵²Cf are also shown in Table 5.13.

-
- (a) B. A. Rathbone, "A New 8816 Algorithm for PFP," November 18, 2000, letter to HEDP file.
(b) R. I. Scherpelz and B. A. Rathbone, "Neutron Measurements at PFP August – September 2003," report, HEDP files.
B. A. Rathbone, "Verification of 8816 Performance in PFP Neutron Fields," March 3, 2004, letter to HEDP file.

Table 5.13 8816 Neutron Dosimeter Element Response to DOELAP Sources

Beam Code	Element Response Per Unit Delivered Dose Equivalent Relative to ^{137}Cs Response							
	Shallow Dose Response ^a				Deep Dose Response ^b			
	chip1	chip2	chip3	chip4	chip1	chip2	chip3	chip4
M30	0.03	0.02	0.02	0.02	0.06	0.06	0.06	0.06
S60	0.15	0.15	0.14	0.13	0.16	0.16	0.15	0.14
M150	0.39	0.41	0.38	0.39	0.37	0.39	0.37	0.37
K16	0.02	0.02	0.02	0.02	0.07	0.06	0.07	0.07
K59	0.28	0.28	0.26	0.26	0.27	0.26	0.25	0.25
H150	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
$^{90}\text{Sr}/^{90}\text{Y}$	0.06	0.04	0.06	0.06	N/A	N/A	N/A	N/A
^{240}Tl	0.00	0.00	0.00	-0.00	N/A	N/A	N/A	N/A
DU	0.05	0.04	0.05	0.05	N/A	N/A	N/A	N/A
^{137}Cs	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{241}Am	0.29	0.31	0.27	0.28	0.28	0.30	0.26	0.27
$^{252}\text{Cf M}$	1.16 ^c	40.46 ^c	17.15 ^c	44.97 ^c	0.18 ^d	6.16 ^d	2.61 ^d	6.85 ^d
$^{252}\text{Cf U}$	0.84 ^c	13.40 ^c	4.52 ^c	13.85 ^c	0.05 ^d	0.87 ^d	0.29 ^d	0.90 ^d

- a. Response of chips per unit of delivered shallow dose, relative to the ^{137}Cs response.
b. Response of chips per unit of delivered deep dose, relative to the ^{137}Cs response.
c. Delivered shallow dose from ^{252}Cf photons only, was used to calculate these values.
d. Delivered deep dose from ^{252}Cf photons and neutrons was used to calculate these values.

5.5.5 Algorithm Bias

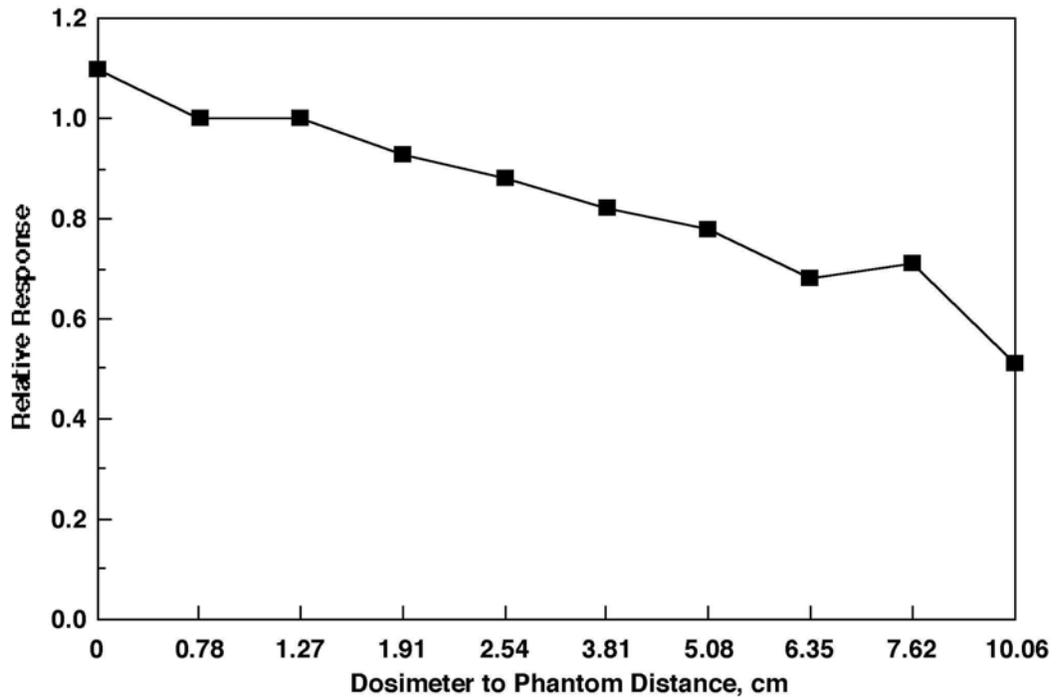
The dose equivalent response of the 8816 TLD albedo neutron dosimeter to different unmoderated sources of neutron radiation is similar to the response observed with the older Hanford multipurpose dosimeter (Fix et al. 1981) and albedo dosimeters used at other DOE facilities (Brackenbush et al. 1980). However, this dosimeter has substantially less over response when measuring scattered radiation. The neutron response of the default californium algorithm to spent reactor fuel in shipping casks is between 120% and 160% of delivered neutron dose equivalent depending on distance (1.7 meters and 11.2 meters respectively).^(a) The neutron response of the plutonium based TLD algorithm under all field conditions measured to date at Hanford's PFP is between 50% and 150% of the delivered neutron dose equivalent as determined from TEPC and Bonner sphere measurements. The response relative to delivered *effective* dose equivalent from neutrons in an isotropic or rotational geometry is between 100% and 200% of the delivered value. In general, instruments with isotropic response that are calibrated in AP geometry but used to measure dose in isotropic fields

(a) B. A. Rathbone, "Neutron Response of HSD and HCND Personnel Dosimeters Near Spent Fuel Casks" February 13, 2004, letter to HEDP file.

will over estimate effective dose equivalent by as much as a factor of two (DOE 1998b).

5.5.6 Albedo Response

Response characteristics of the 8816 TLD component are highly dependent upon the energy of the incident neutron radiation and the geometry of the exposure. An important consideration is the distance between the dosimeter and phantom. To measure this effect, 8816 TLDs on-phantom were irradiated with a bare ^{252}Cf source. The distance from the source to the front face of the phantom, which measured 40 cm x 40 cm x 15 cm in thickness, was 100 cm. The distance between the dosimeter and the face of the phantom varied from 0 to 10 cm. The measured response is shown in Figure 5.19 (a) At a distance of 10 cm, the albedo response is approximately 50% of the response measured at 1.27 cm.



39503019.1

Figure 5.19 Measured Albedo Response of 8816 Neutron Dosimeter

(a) W. V. Baumgartner, "New Badge Response at Different Distances from the Body," February 3, 1994, letter to HEDP file.

5.5.7 Angular Response

The method described for the HSD was also used to determine the angular response for the HCND except that only one HCND was placed on a phantom at a time to ensure that all active elements were within the central area of the phantom ^(a) The angular response for this dosimeter configured with PNAD, is shown in Tables 5.14 and 5.15, and Figures 5.20 and 5.21.

Table 5.14 HCND Shallow Dose Angular Response

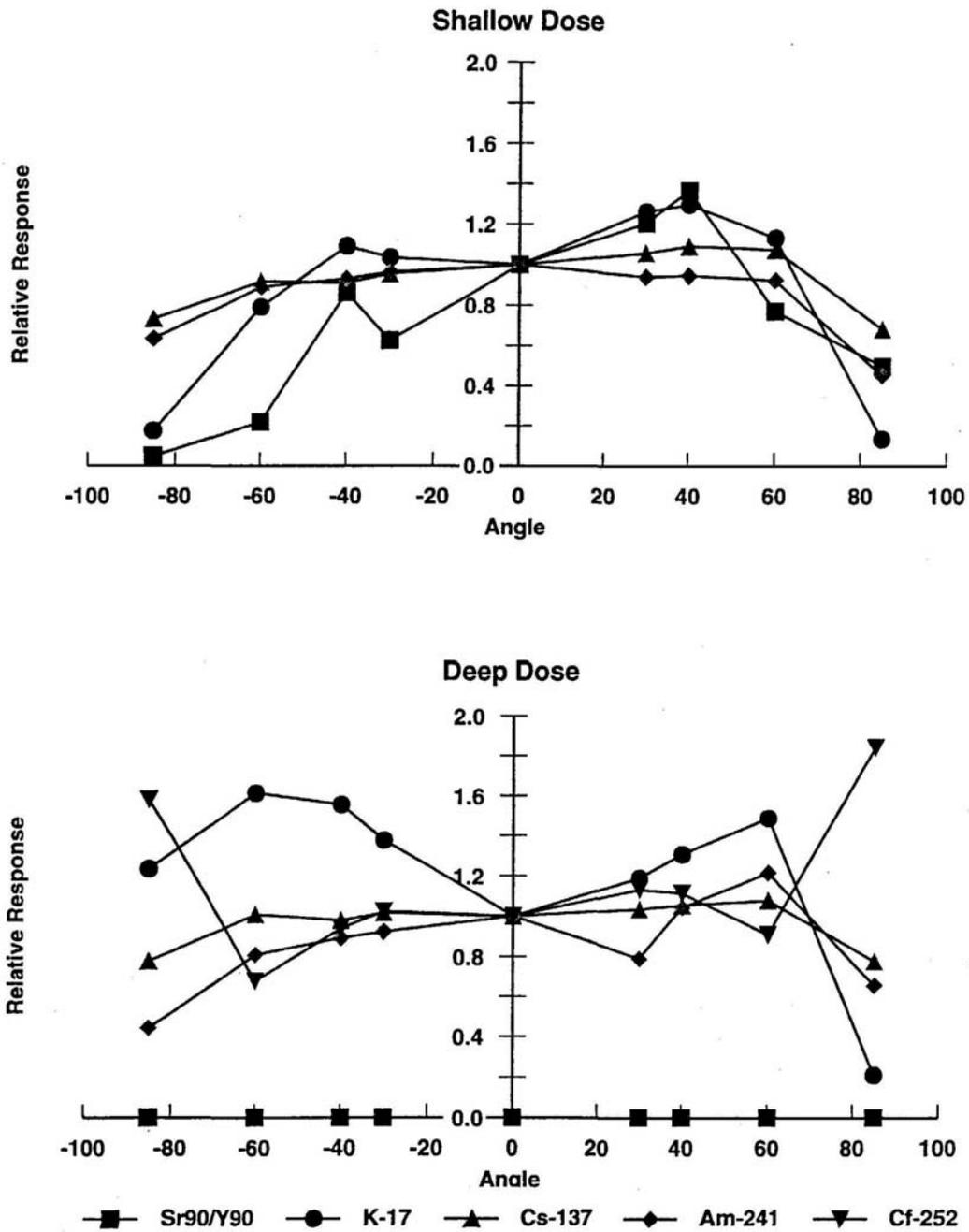
Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K16	16	H	0.17	0.79	1.09	1.04	1.00	1.26	1.30	1.13	0.13
		V	0.08	1.01	1.10	1.07	1.00	1.11	1.11	0.80	0.06
²⁴¹ Am	59	H	0.64	0.89	0.93	0.96	1.00	0.94	0.95	0.92	0.45
		V	0.92	1.40	1.45	1.48	1.00	1.36	1.30	1.24	0.71
¹³⁷ Cs	662	H	0.73	0.92	0.91	0.96	1.00	1.06	1.09	1.07	0.68
		V	0.94	1.23	1.05	1.17	1.00	1.16	0.75	0.98	0.57
⁹⁰ Sr/ ⁹⁰ Y	931	H	0.05	0.22	0.86	0.62	1.00	1.20	1.37	0.77	0.50
		V	0.16	0.55	1.11	1.03	1.00	1.02	0.66	0.22	0.03

Table 5.15 HCND Deep Dose ^(b) Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K16	16	H	1.24	1.61	1.55	1.38	1.00	1.19	1.31	1.49	0.21
		V	0.31	1.50	1.16	1.11	1.00	1.40	1.44	1.52	0.06
²⁴¹ Am	59	H	0.44	0.81	0.89	0.92	1.00	0.79	1.04	1.22	0.65
		V	0.62	1.37	1.49	1.46	1.00	1.39	1.32	1.27	0.58
¹³⁷ Cs	662	H	0.78	1.01	0.98	1.02	1.00	1.04	1.06	1.08	0.78
		V	0.93	1.06	1.05	1.01	1.00	0.99	0.65	1.00	0.48
²⁵² Cf U	2100	H	1.58	0.68	0.94	1.02	1.00	1.13	1.11	0.91	1.84
		V	0.11	0.57	0.89	0.94	1.00	1.12	1.08	0.89	0.37

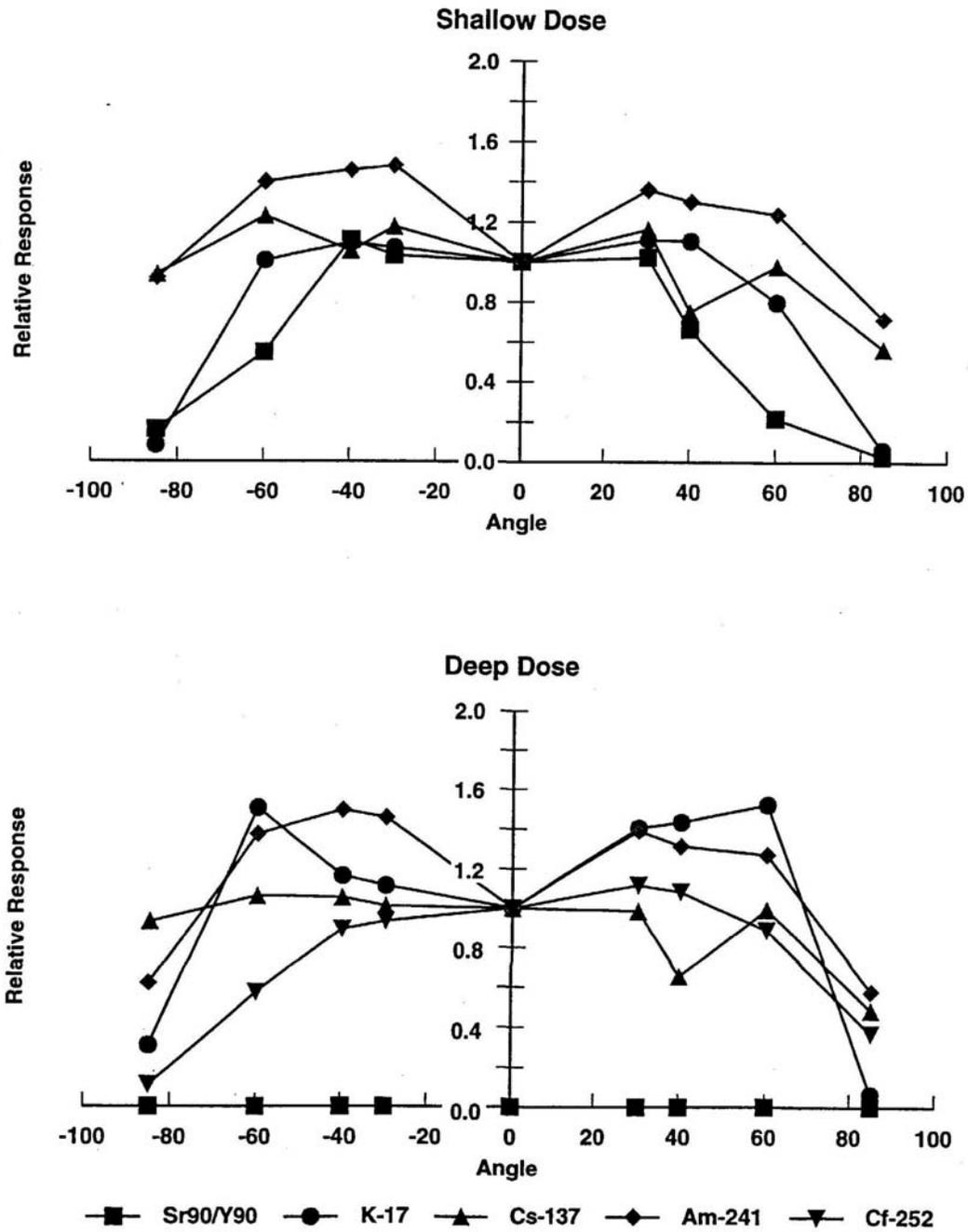
(a) J. J. Fix, "Angular Response of Hanford Personnel Dosimeters," October 18, 1994, letter to HEDP file.

(b) For ²⁵²Cf irradiations, neutron component only.



39502006.3

Figure 5.20 Hanford Combination Neutron Dosimeter Angular Response – Horizontal Rotation



39502006.4

Figure 5.21 Hanford Combination Neutron Dosimeter Angular Response - Vertical Rotation

5.5.8 Lower Level of Detection

The LLD has been calculated for the HCND for monthly, quarterly and annual exchange periods in a variety of studies using either of the two methods given in the DOELAP performance test standard DOE/EH-0027 (DOE 1986a).^(a) These studies used unexposed open audit dosimeter data and DOELAP performance test data. A composite of the results from these studies is presented in Table 5.16. The symbols H_s , H_e , H_{dp} and H_n represent the algorithm calculated *shallow* dose equivalent, *eye* dose equivalent, *deep photon* equivalent and *neutron* dose equivalent respectively. The LLDs for eye dose were not calculated because the delivered eye dose was not given in the irradiations used. However, LLDs for eye dose are expected to be similar to those calculated for deep photon dose because the variability in background readings and dosed readings of the eye dose element in the 8825 dosimeter is similar to that of the deep dose element.

Table 5.16 Calculated LLDs (in mrem) for the HCND

Exchange Frequency	DOELAP Category	Parameter	H_s	H_e	H_{dp}	H_n (mod)	H_n (bare)
M	Controls	L_C	3.8	3.1	3.1	0.2	1.2
	III A (X-ray-general)	L_D	*	*	*	*	*
	IV (Cs-137)	L_D	7.6	*	6.2	*	*
	VC (beta-general)	L_D	*	*	*	*	*
	VI (neutron)	L_D	*	*	*	0.4	2.5
Q	Controls	L_C	3.1	2.8	2.8	0.3	1.4
	III A (X-ray-general)	L_D	7.8	*	6.2	*	*
	IV (Cs-137)	L_D	6.4	*	5.7	*	*
	VC (beta-general)	L_D	6.5	*	*	*	*
	VI (neutron)	L_D	*	*	*	0.7	2.8
A	Controls	L_C	7.7	6.6	6.6	0.7	3.6
	III A (X-ray-general)	L_D	20.8	*	15.1	*	*
	IV (Cs-137)	L_D	15.7	*	13.3	*	*
	VC (beta-general)	L_D	16.1	*	*	*	*
	VI (neutron)	L_D	*	*	*	1.5	7.3

(a) Letters to HEDP file:

- B. A. Rathbone, "LLD Calculations for HSD and HCND Dosimeters," July 9, 1996.
- B. A. Rathbone, "LLD Calculations for Quarterly HCND," May 20, 1999.
- B. A. Rathbone, "LLD Calculations for Annual HCND," May, 1999.

5.5.9 Environmental Sensitivity

The HCND, similar to the HSD, is relatively unaffected by normal variations in heat, humidity, or light. The holder of black ABS plastic was constructed to minimize effects from light. However, it is important to protect the dosimeter from environmental extremes because of the potential effect on the dosimeter response. (See Section 5.4.8)

5.5.10 Fading

The fade corrections used for TLD 600 and TLD 700 elements in the HSD are described in Section 5.3.6.2. In general, post irradiation fading is less than 15% per year for beta-gamma dose and less than 30% per year for neutron dose. (See Section 5.4.9)

5.6 Area Dosimetry

Hanford contractors administer area monitoring programs for the DOE facilities for which they are contractually responsible. Area monitoring programs include routine workplace surveys for external radiation levels, surface contamination levels and airborne radioactivity levels. External radiation monitoring instruments and devices used in area monitoring programs include both fixed and portable instruments that provide real-time indication of radiation levels and passive monitoring devices such as TLDs that provide a retrospective indication of radiological conditions. The focus of this section is to describe the area TLDs used to support area monitoring programs at Hanford. Guidance on area monitoring programs in general is provided in the External Dosimetry Program Guide DOE G 441.1-4 (DOE 1999b) and the DOE Radiological Control Standard DOE-STD-1098-99 (DOE 1999c).

Area dosimeters are issued directly to Hanford contractors without tracking through REX and results are reported directly to Hanford contractors without the use of REX. Area dosimeter results are not stored in REX. Each contractor is responsible for maintaining records of area dosimeter results for their facilities.^(a) Each contractor's records inventory and disposition schedule (RIDS) should treat area dosimetry records in a manner consistent with other workplace surveillance records.

(a) D. E. Bihl, "Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held October 21, 1998." Copies of HPDAC minutes are retained in Hanford Radiological Records historical file

5.6.1 HSD Area Dosimeter

HSD area dosimeters are identified by an eight digit holder ID beginning with the digits 06. They are physically identical to, and use the same dose algorithms as HSDs used for personnel dosimetry. Therefore, the angular dependence data, LLD data, fade data, algorithm response data and other data provided for the HSD earlier in this chapter are generally applicable to the HSD area dosimeter as well. Important exceptions are discussed in the paragraphs below.

The LLDs determined for the HSD personnel dosimeter are based on dosimeter response on phantom. To the extent that HSD area dosimeters are used without phantom and under respond as a result (see Tables 5.17 and 5.18), the LLD is increased by a corresponding amount.

The angular dependence data for the HSD personnel dosimeter are based on dosimeter response on phantom. To the extent that HSD area dosimeters are used without phantom, the response at large angles, relative to response at normal incidence may differ from what has been determined for the HSD personnel dosimeter.

It is important to note that natural environmental background is subtracted from area dosimeters in the same manner as with personnel dosimeters. Area dosimeters are intended to measure only radiation from man made sources and provide an indication of potential occupational exposure as would be reported by a personnel dosimeter. Therefore, area dosimeters placed in areas with radiation levels no greater than the average natural background for the Hanford site would be expected to report doses at or near zero mrem.

Reporting thresholds are not applied to area dosimeter results (unlike Personnel dosimeter results). The 8825 algorithm does however apply implicit detection thresholds in its branching logic (e.g. for detection of neutrons, the neutron signal must be at least 20% of the total signal on chip 4).

Ideally, area dosimeters should be placed on phantoms for accurate dose results. However, in many locations where area dosimeters are used this is not practical. As long as the radiation environment consists primarily of beta particles and higher energy photons (>100 keV) the HSD will provide reasonable results even when used without phantom. However, if a substantial part of the exposure is from lower energy photons, the dosimeter may significantly under respond when used without a phantom.^(a) Table 5.17 shows the response when the dosimeter is exposed in air facing the source and facing away from the source. Similar errors can reasonably be expected for dosimeters mounted on gypsum wall board, because of the relatively small mass available for backscatter. The cognizant individual administering the area dosimetry program at each facility should evaluate the need for phantoms, based on a knowledge of the radiation environment being monitored, the potential errors involved, and the needed level of accuracy in results.

(a) B. A. Rathbone, "PIC/TLD Response Study," October, 4, 1995, letter to HEDP file

When mounting an HSD area dosimeter on a wall of any kind, the dosimeter should be facing the interior of the room or hallway in which the dosimeter is being placed. Dosimeters should not be mounted with the Mylar[®] window facing the wall. This is true even when the primary source of radiation contributing to area dose rates is on the other side of the wall. The rationale for this guidance is as follows: Beta radiation will not be transmitted through the wall; therefore it serves no purpose to have the Mylar[®] beta window facing the wall. The primary radiations transmitted will be photons > 50 keV and neutrons. In theory, having the metal filters facing the source allows the dosimeter to identify the presence of low energy photons and provide a more accurate result. When the source is in another room, it makes little difference since few low energy photons penetrate most walls. A dosimeter facing away from the wall will provide reasonably accurate shallow and deep dose results for the photons coming through the wall and the dosimeter's back side. To the extent that low energy photons do penetrate the wall, the results will actually be more accurate if the dosimeter has its backside to the wall (see Table 5.17). If the dosimeter is facing the interior of the room in which it is placed, it has the added advantage of being able to detect and measure any beta radiation or low energy photons that may have been present in the room. It can't do this when facing the wall. In the event of an unexplained high reading, or a suspected loss of radiological control, the ability to assess from dosimeter readings what radiation types may or may not have been present in the rooms in which the dosimeters are placed and to make some statement regarding the accuracy of the reported shallow, eye and deep dose results may be important. The HSD response to neutron radiation when used without phantom is basically independent of orientation.

Table 5.17 HSD Photon Response in Air

Source	Average Energy (keV)	Dosimeter Orientation	Reported/Given Shallow Dose	Reported/Given Deep Dose
¹³⁷ Cs	662	FWD	0.94	0.92
¹³⁷ Cs	662	BKWD	1.01	1.01
²⁴¹ Am	59	FWD	0.58	0.52
²⁴¹ Am	59	BKWD	0.87	0.83
S60	38	FWD	0.74	0.52
S60	38	BKWD	1.22	1.31

Although the HSD area dosimeter is not intended for use as a neutron monitoring device, it is sensitive to thermalized neutrons. If neutrons are detected, a neutron dose result will be calculated. However, the calibration factor used to calculate neutron dose is based on irradiation of the dosimeter on phantom to a bare ²⁵²Cf source (2100 keV avg). If the dosimeter is used with a phantom and exposed to unmoderated fission neutrons, the results will be reasonably accurate. If it is exposed on phantom to moderated (e.g. 550 keV average) neutrons as is typically the case when most neutrons reaching the dosimeter have been scattered several times in hydrogenous shielding and building materials, then the dosimeter may over respond by as much as a factor of 8. If significant scattering in intervening shielding materials (e.g. > 6 " of water, concrete, or polyethylene) can be shown to be the case, then application of a calibration factor based on moderated ²⁵²Cf will be more appropriate. If the dosimeter is not placed on a

phantom, and the neutron energy spectrum is unmoderated then the dosimeter may under respond by as much as a factor of 40. ^(a) If the dosimeter is not placed on a phantom, but the neutron energy spectrum is moderated by intervening shielding (e.g. > 6 inches of water, concrete or polyethylene), then the neutron dose calculated using the default calibration factor will be relatively accurate. If the dosimeter is exposed without a phantom to heavily moderated neutrons (e.g. average energies less than 100 keV), then the dosimeter may over respond by a factor of 5 or more. Table 5.18 shows the HSD neutron response (reported/given dose) without phantom when the default calibration factor (bare ²⁵²Cf) is used to calculate neutron dose.

Table 5.18 HSD Neutron Response in Air

Source	Average Energy (keV)	Neutron Response (R/G)
²⁵² Cf Bare	2130	0.027
²⁵² Cf D ₂ O (w/ Cd)	550	1.07
²⁵² Cf D ₂ O (w/o Cd)	550	2.66
Concrete Shielded PWR Fuel @ 51 m	50	7.5

As can be seen from the response of the HSD to the D₂O moderated source without Cd cover compared to its response to the source *with* Cd cover, the effect of neutrons below 0.4 eV (the Cd cutoff) on dosimeter response in the absence of a phantom is very large. In contrast to their effect on dosimeter response, the effect of neutrons below 0.4 eV on the delivered dose equivalent is quite small. The fluence below 0.4 eV constitutes about 11.5% of the total fluence emitted from a D₂O moderated ²⁵²Cf source without Cd cover (Schwartz and Eisenhaur, 1982). This same fluence produces only 1.5% of the total neutron dose equivalent rate. ^(b) This sensitivity of the HSD to thermal neutrons that do not contribute to dose equivalent is one of the reasons why it is not recommended for use as a neutron dosimeter.

The recommended dosimeter for area monitoring of neutron dose rates is the HCND area dosimeter (described below). The HSD area dosimeter is not recommended for routine monitoring of neutron dose rates unless location specific correction factors based on field measurements with suitable instruments can be applied to the area dosimeter's results and the scatter conditions on which the correction factors are based are not expected to change. An example of one such set of measurements is described below.

(a) B. A. Rathbone, "HSD Neutron Response in Air", May 30, 1999, letter to HEDP file.

(b) L. E. Myers, "HSD Irradiations in Air to Cf-252", May 11, 1999, letter to B. A. Rathbone (included as attachment to May 30, 1999 memo by B. A. Rathbone)

Measurements made in the vicinity of high burn up PWR fuel stored in NAC-1 casks on a concrete storage pad in the 200 West area before erection of a concrete shield wall indicate that at distances greater than 50 meters, a correction factor (reported/given) of 4 or more may be appropriate for HSD dosimeters used without phantom. ^(a) In this case, a large percentage of the neutrons reaching the dosimeter have been scattered one or more times in the shielding of the cask, in the concrete slab, in soil and in the air. Spectral measurements indicate that the fluence at these distances has an average energy well below 100 keV and a large thermal component. ^(b) Spectral measurements conducted after erection of a concrete shield wall around the fuel indicate an approximate 30% reduction in the average neutron energy. MCNP modeling of dose rates at selected locations 50 – 300 meters from the pad indicates that a large fraction of the fluence is from neutrons scattering in air. ^(c) A comparison of MCNP modeled dose rates with HSD area dosimeter results at nearby locations (50 meters and 80 meters) before and after erection of the wall indicates an approximate 50% increase to the HSD neutron correction factors as a result of the wall. Correction factors at distances greater than 50 meters with the wall in place varied between 5 and 15. ^(d) The size of correction factor was not always a direct function of distance, most likely because of intervening structures.

5.6.2 HCND Area Dosimeter

HCND area dosimeters are physically identical to HCND personnel dosimeters. The 8825 beta-gamma TLD component is identified by an eight digit holder ID beginning with the digits 036. The 8816 neutron TLD component is identified by an eight digit holder ID beginning with the digits 046.

HCND area dosimeters have the same response characteristics as, and use the same dose algorithms as HCND personnel dosimeter. Therefore, the angular dependence data, LLD data, fade data, algorithm response data and other data provided for the HCND earlier in this chapter are generally applicable to the HCND area dosimeters as well. Important exceptions are discussed in the paragraphs below.

It is important to note that natural environmental background is subtracted from area dosimeters in the same manner as with personnel dosimeters. Area dosimeters are intended to measure only radiation from man made sources and provide an indication of potential occupational exposure as would be reported by a personnel dosimeter. Therefore, area dosimeters placed in areas with radiation levels no greater than the average natural background for the Hanford site would be expected to report doses at or near zero mrem.

Reporting thresholds are not applied to calculated area dosimeter results (unlike personnel dosimeter results). The 8816 algorithm does however apply implicit

-
- (a) B. A. Rathbone, "Correction Factors for Neutron Dose Results on Area Dosimeters", December 31, 2003, Letter to R. L. Hill.
 - (b) R. I. Scherpelz, "Neutron Measurements on the ISA Pad", December 9, 2003. Letter report to R. L. Hill.
 - (c) R. J. McConn and R. I. Scherpelz, "MCNP Estimate of Dose Rates Surrounding the ISA Pad" January 23, 2004, Letter report to R. L. Hill.
 - (d) B. A. Rathbone, "Correction Factors for Neutron Dose Results on Area Dosimeters Near ISA", February 12, 2004, Letter report to R. L. Hill.

detection thresholds in its branching logic (e.g. for detection of neutrons, the neutron signal must be greater than 10 mR equivalent and be at least 10% of the total signal on each of the TLD 600 chips 2,3,and 4). For the neutron/gamma ratios and moderated neutron energy spectra typically encountered by HCND area dosimeters, this equates to a reporting threshold of 1-2 mrem.

For accurate dose results, the HCND must be placed on a phantom of adequate size and composition. Although current standards in the U.S. specify use of a 40 cm x 40 cm x 15 cm PMMA phantom for neutron dosimeter calibrations and performance testing, recent investigations have shown minimal differences in albedo dosimeter response between this and the 30 cm x 30 cm x 15 cm PMMA phantom. (McDonald et. al, 1995). Other studies indicate that acceptable phantoms include 9x9 inch polyethylene cylinders, and polyethylene slabs with minimum dimensions of 20 cm x 30 cm x 5 cm, and five gallon water containers (Hankins 1980b). The same study indicates that a one gallon water filled container provides marginal response. Studies conducted by HEDP indicate that 25 cm x 25 cm x 34 cm five gallon water containers provide excellent response (97%) and PMMA phantoms as small as 20 cm x 20 cm x 15 cm provide adequate response (83%).^(a) Although concrete provides some degree of moderation and backscatter, some studies indicate that concrete may not be a suitable phantom material. Albedo neutron dosimeters were shown to significantly under respond when placed on solid concrete walls as thick as eight inches (Hankins 1981). The HCND should be centered on the front surface of the phantom. No part of the 8816 dosimeter should be within 10 cm of the edge of the phantom.

5.7 HSD Extremity (Wrist/Ankle) Dosimeter

The HSD Extremity dosimeter is physically identical to the HSD personnel dosimeter. Its intended use is measurement of shallow dose to the upper or lower extremities. It is intended to be worn just above the wrists or ankles with the long axis of the dosimeter parallel to the axis of the forearm or lower leg and has been accredited under DOELAP in this configuration. For accurate results, the dosimeter must be secured to the forearm or lower leg in a manner that leaves as little air space as possible between the dosimeter and the extremity being monitored.

The HSD Extremity dosimeter is labeled in the same manner as the HSD personnel dosimeter and is indistinguishable on the basis of holder ID number (leading digits 00 same as HSD personnel dosimeter). Unlike the Hanford ring dosimeter, it cannot be automatically assigned to individuals on a routine frequency and is therefore used exclusively as a part of multipacks. About 1000 HSD Extremity dosimeters are used each year at Hanford.

(a) B. A. Rathbone, "Impact of Phantom Size and Orientation on 8816 Neutron TLD Response" September 6, 2001, Letter to HEDP file.

5.7.1 General Features

The HSD Extremity dosimeter is identical to the HSD personnel dosimeter and has the same general features described in Section 5.4.1.

5.7.2 Dosimeter Assignment and Processing Protocol

The HSD Extremity dosimeter uses the same assignment and processing protocol as the HSD personnel dosimeter. The description provided in Section 5.4.2 is applicable to the HSD Extremity dosimeter as well.

5.7.3 Algorithm

The HSD Extremity dosimeter uses the same algorithm as the HSD personnel dosimeter described in Section 5.4.3 – 5.4.5. Only the shallow dose results are used for extremity dose of record. The HSD personnel dosimeter algorithm was developed from dosimeter response data from irradiations on a 30 cm x 30 cm x 15 cm slab phantom and delivered dose data based on DOELAP C_x factors for that phantom. However, PNNL performance testing of the HSD in extremity configuration on a pillar phantom using C_x factors from the extremity performance test standard HPS N13.32 (HPS, 1996a) indicates acceptable performance as a wrist/ankle extremity dosimeter.^(a) Subsequent DOELAP performance testing has also shown acceptable performance and has led to DOELAP accreditation of the HSD as an extremity dosimeter.

5.7.4 Algorithm Performance

The results of PNNL performance testing of the HSD as an extremity dosimeter are shown in Table 5.19. Performance is expressed in terms of the bias (B) and standard deviation (S) of performance quotients (P_i) for individual dosimeter results (see glossary). The results indicate algorithm biases for individual filtered X-ray techniques, but the overall bias is well within the N13.32 criteria of $B < 0.35$.

Table 5.19 HSD Extremity Algorithm Bias

Source	Average Energy (keV)	B	S
M30	20	-0.124	0.012
M60	34	0.085	0.021
M100	51	-0.125	0.021
M150	70	-0.154	0.020
H150	117	-0.069	0.033
¹³⁷ Cs	662	0.007	0.003
²⁰⁴ Tl	267	0.051	0.014
⁹⁰ Sr/ ⁹⁰ Y	931	0.013	0.039

(a) B. A. Rathbone, "HSD Response on Wrist Phantom," October 20, 1997, letter to HEDP file.

5.7.5 Angular Response

The angular response of the HSD Extremity dosimeter was measured using the sources, geometry, and method specified in HPS N 13.32 (HPS, 1996a) at the specified angles of 0°, ±30°, ±60°, ±85° and 180°. ^(a) The standard specifies that at least one source from each category II through IV should be used. For the purpose of this study, two sources from category II (M30 and M100), one source from category III (¹³⁷Cs), and two sources from category IV (⁹⁰Sr/⁹⁰Y and ²⁰⁴Tl) were used. A delivered shallow dose of 1 rem was used for all irradiations. During the irradiations, the HSD was oriented with the Mylar[®] window at the “top” (see Figure 5.29). With the exception of the 180° irradiations with beta sources, four dosimeters were used for each angle in vertical rotation and three dosimeters were used for each angle in horizontal rotation. For the 180° angle no irradiations were performed with the beta sources since the thickness of the extremity phantom exceeds the range of any of the beta particles emitted from the reference sources. The results are shown in Table 5.20 and Figure 5.22 and Figure 5.23.

Table 5.20 HSD Extremity Dosimeter Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-30°	0°	30°	60°	85°	180°
M30	20	H	0.09	0.67	0.94	1.00	1.09	1.07	0.15	0.01
		V	0.09	0.73	1.01	1.00	0.98	0.96	0.15	0.00
M100	51	H	0.73	0.78	0.93	1.00	1.04	0.99	0.59	0.05
		V	0.54	0.76	0.93	1.00	0.99	0.91	0.68	0.05
¹³⁷ Cs	662	H	0.89	1.02	0.99	1.00	1.00	0.98	0.79	0.42
		V	0.89	0.96	0.98	1.00	0.97	0.96	0.93	0.39
⁹⁰ Sr/ ⁹⁰ Y	931	H	0.01	0.14	0.84	1.00	1.01	0.25	0.02	0.00
		V	0.02	0.18	0.90	1.00	0.93	0.19	0.05	0.00
²⁰⁴ Tl	267	H	0.03	0.15	0.69	1.00	0.76	0.28	0.03	0.00
		V	0.02	0.15	0.65	1.00	0.74	0.18	0.02	0.00

(a) J. J. Fix, “HSD Extremity Angular Response,” August 4, 1999, letter to HEDP file.

HSD Extremity Shallow Dose Response (horizontal rotation)

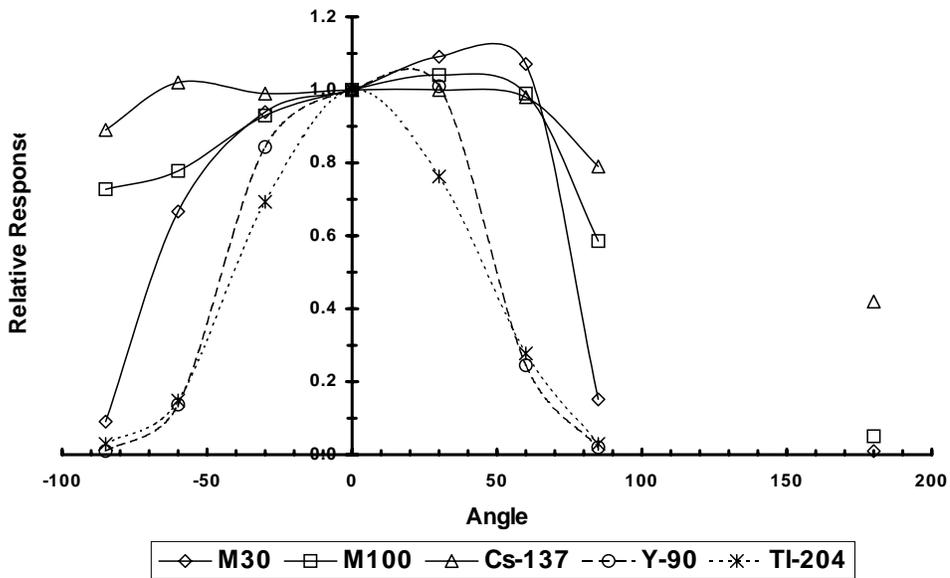


Figure 5.22 HSD Extremity Shallow Dose Angular Response – Horizontal Rotation

HSD Extremity Shallow Dose Response (vertical rotation)

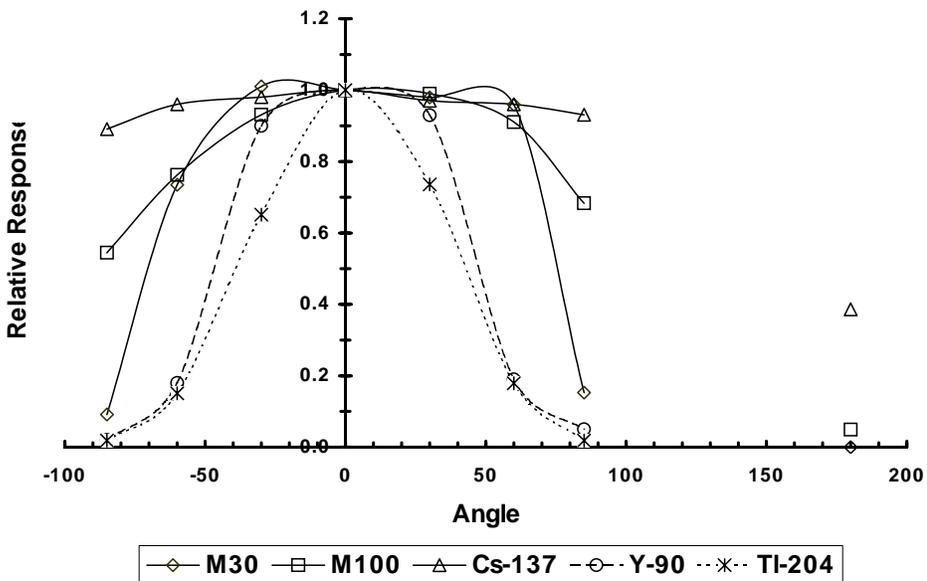


Figure 5.23 HSD Extremity Shallow Dose Angular Response – Vertical Rotation

5.7.6 Lower Level of Detection

The lower level of detection for the HSD Extremity dosimeter was calculated from exposure data from several beta and photon sources.^(a) The analysis was conducted using the procedure described in the Extremity Dosimetry performance standard HPS N 13.32 (HPS, 1996a). The analysis was conducted for the algorithm calculated shallow dose that would be reported and used as the basis for extremity dose of record when the HSD is used as an extremity dosimeter. The dosimeters used for the test had a cycle time of 68 days between anneal and readout which is considered representative of a monthly exchange. Because the HSD Extremity dosimeter's use is limited to multipacks, its exchange frequency is limited to monthly or shorter. The same set of control dosimeters was used for all irradiated dosimeter groups. The results are shown in Table 5.21. Because the variability of the control dosimeters is the dominant contributor to the calculated LLD in the equations provided in the test standard, similar values for LLD are expected for each source.

Table 5.21 HSD Extremity Shallow Dose LLD

Source	Average Energy (keV)	Shallow Dose LLD (mrem)
²⁰⁴ Tl	267*	3
⁹⁰ Sr/ ⁹⁰ Y	931*	3
M30	20	3
M60	34	3
M100	51	3
M150	70	3
H150	117	3
¹³⁷ Cs	662	3
⁶⁰ Co	1252	3

5.7.7 Fading

The fading properties of the HSD are not impacted by the body location on which the dosimeter is worn. Therefore, the fade characteristics described for the HSD Personnel dosimeter in Section 5.4.9 above are applicable for the HSD Extremity dosimeter as well. A single algorithm is used for the HSD whether used as an extremity or whole body badge. The fade corrections are applied in the algorithm on the basis of phosphor type, radiation type and number of days between anneal and readout.

(a) J. Fix, "HSD (Wrist) Lower Level of Detection," June 8, 1998, letter to HEDP file.

5.7.8 Environmental Sensitivity

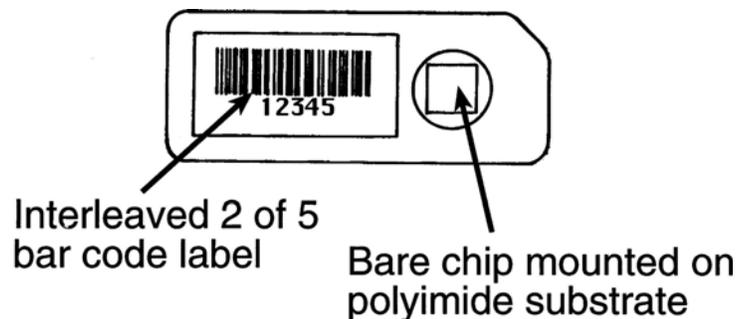
The description of environmental influences on the HSD as a personnel dosimeter given in Section 5.4.8 applies to the HSD when used as an extremity dosimeter as well. Precautions should be taken to avoid puncture of the beta window when the dosimeter is subject to contact with sharp objects.

5.8 Hanford Ring Dosimeter (HRD)

The primary dosimeter used for measuring extremity dose at Hanford is the Hanford Ring Dosimeter. This is a hard plastic ring dosimeter worn on the index finger of both hands. On a much less frequent basis, HSD dosimeters are worn on wrists or ankles as extremity dosimeters (see description above).

5.8.1 Dosimeter Description

The Hanford ring dosimeter contains a single $^7\text{LiF:Mg,Ti}$ (TLD-700) chip mounted on a thin polyamide (Kapton[®]) substrate with a permanent 5-digit barcode chip ID number. The Kapton[®] and chip assembly is commercially available from Harshaw under the product name Chipstrate[®], and is shown in Figure 5.24. The Harshaw product code for the specific chipstrate used by HEDP is "XD740." The chip consists of an active layer of TLD-700 phosphor in hot-pressed chip form, adhesively bonded to a dosimetrically inert ^7LiF base. The dimensions of the TLD-700 chip are 3.2 mm x 3.2 mm x 0.15 mm and the dimensions of the inert base are approximately the same. The laminated chip is adhesively bonded to the Kapton[®] substrate.

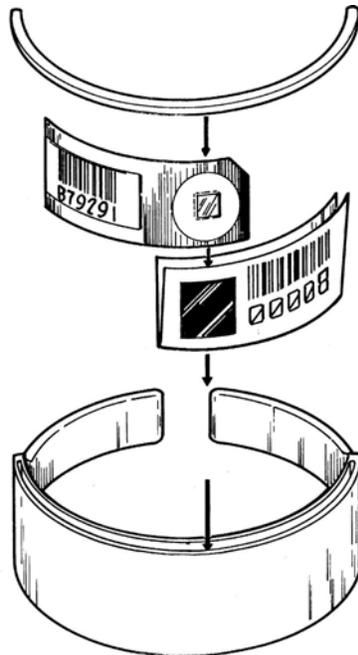


G00040106.2

Figure 5.24 Chipstrate

The chipstrate is wrapped in a barcode label, then inserted into the plastic ring and hermetically sealed with a C-shaped cap as shown in Figure 5.25. The label serves two purposes: 1) it protects the chip from light, and 2) it provides a sequential ring ID number that meets the needs of the user as follows:

Rings are assigned to individuals in sequentially numbered pairs. Hanford practice is to wear odd-numbered rings on the left hand and even numbered rings on the right. The rings are made of tinted transparent amorphous k-resin[®] plastic that can be ultrasonically welded. Rings are prepared in two colors. Blue is worn during odd-numbered months and gold is worn during even-numbered months of the calendar year. Three sizes are available. The ring has a plastic window with a density thickness of 36 mg/cm². The density thickness of the label is approximately 16 mg/cm². The density thickness of the active layer of the chip is 40 mg/cm². The permanent chipstrate ID number allows application of a chip-specific sensitivity factor to the dose result.



G00040106.3

Figure 5.25 Illustration of Hanford Ring Dosimeter

5.8.2 Reader Description

Chipstrates are read on one of two Harshaw Model 6600E hot gas readers. This reader contains two PMTs and two hot-gas heating jets. Prior to readout, chipstrates are inserted in aluminum carrier cards, two per card, which are then stacked in reader cartridges similar to those used on the Harshaw 8800 TLD readers. Hot nitrogen is used to heat the TLD chips according to a user-specified TTP. Nitrogen temperature is controlled to within $\pm 2^{\circ}\text{C}$ of the programmed value. The nitrogen gas stream is directed at the underside of the chipstrate and heat transfer occurs through the Kapton[®] substrate. The use of nitrogen provides an inert atmosphere in the readout chamber, which reduces spurious readings caused by chemoluminescence of contaminants on the chip. Nitrogen also provides optimal heat transfer and uniform heating via a "non-contact" method of heating which allows for repeated readout of the chipstrate without the wear and deformation common to contact methods of heat transfer.

The Harshaw 6600E reader sensitivity for the XD740 chipstrate, using the standard TTP described below, is typically 0.060 nC/mR. The gain on both 6600E readers has been adjusted to achieve a sensitivity in this range for each PMT. Average PMT dark current readings are less than 0.060 nC which is the equivalent of a 1-mR reading for the XD740 chipstrate.

5.8.3 Dosimeter Use Cycle

The following sections briefly describe the processes involved in the ring dosimeter use cycle from preparation to dose reporting.

5.8.3.1 Dosimeter Preparation

Chipstrates are annealed in the 6600E reader using a TTP that starts at 50°C and ramps to 300°C at the rate of 25°C/sec then holds at 300°C for six seconds. Chipstrates with an initial reading exceeding 100 mR are re-read by the reader. After reader annealing, the chipstrates (in carrier cards and reader cartridges) are oven annealed at 80°C for 16 hours. The reader annealing clears the primary longer-lived dosimetric traps, while the 80°C oven annealing reduces the number of short half-life traps, thereby reducing the fade of the overall TL signal.

After oven annealing, chipstrates are removed from the carrier cards, wrapped with the ring ID number label and inserted into the plastic ring. The ring cap is then ultrasonically welded to the ring to produce a hermetically sealed ring.

5.8.3.2 Dosimeter Issuance

After preparation, the barcodes on both the chipstrate and the ring ID label are scanned and the information stored in the External Dosimetry (ED) database. The chipstrate and ring number pairing, the date and time of scanning, contractor code, and other information are stored in a dosimeter TRACKING file in the same manner as for personnel dosimeters. Before a ring can be successfully scanned out to a contractor, the SCAN program checks the ED database to verify that the chipstrate has successfully passed all required acceptance tests, that it has been annealed within the past 30 days, and that it is available for issuance (i.e., not listed as damaged, or currently assigned). The TRACKING file is used to generate an ISSUE file which is used to update the REX database to make the dosimeters available for assignment to individuals.

5.8.3.3 Dosimeter Receipt

When the dosimeters are through being worn, they are physically returned to HEDP along with an electronic RETURN file of wearer/assignment information generated by REX. In addition to wear dates, wearer ID number, processing note code, and other pertinent information, this file also contains a facility calibration code. This code contains information about what correction factor should be applied to the ring dose result. The dosimeters are then scanned by HEDP staff to update the dosimeter TRACKING file showing the dosimeters as have been received. The scanning programs check to see if the dosimeter is returned with the same chipstrate ID number/ring ID number pairing as when issued as well as the dosimeter's last status in ED (i.e., last status = issued). This is a general feature of the SCAN code implemented primarily for use with personnel dosimeters.

5.8.3.4 Dosimeter Readout

After being successfully scanned in, each dosimeter is opened and the chipstrate is removed and cleaned as necessary. The chipstrates are then inserted in carrier cards, two per card, which are loaded into reader cartridges along with carrier cards containing QC and blank chipstrates. These chipstrates are then read as a group on one of the 6600 readers using a TTP specified for dosimetric readout. As the chipstrates are read, the TLD reader applies an RCF and an ECC to each chipstrate to obtain a reading in mR. Chipstrates for which no ECC is available, will be ejected to the reject bin unread and a message as to why this occurred is placed in the reader log. Likewise, the reader will not read chipstrates with a TTP for which no current RCF is available. While processing chipstrates, the reader applies real-time process QC in the form of upper and lower limits on PMT noise readings, reference light readings, QC chipstrate readings, and blank chipstrate readings. Any reading that exceeds the programmed limit will cause the reader to stop reading. Process QC limits for QC chipstrates are $\pm 10\%$ of the given exposure value (i.e., 450 mR to 550 mR).

5.8.3.5 Dose Calculation

After being processed by the reader, the chipstrate readings are transferred to the Alpha computer where wearer/assignment information from the RETURN file provided by REX is matched with the individual ring ID number/chipstrate ID number, and doses calculated. The facility calibration code provided in the RETURN file is used by the dose calculation algorithm to calculate dose. The quantity calculated (and reported to REX) is shallow dose equivalent in units of mrem.

5.8.3.6 Dose Reporting

After wearer information is matched with the dosimeter and dose results calculated, any QC-related flags placed on the dose record must be investigated and cleared, and doses recalculated as necessary. When a dose record is eligible for reporting, a dose results file (REXDOSE) is generated. For Hanford users, the file is transmitted to REX where the results are incorporated into the REX database. For each monitored individual, REX determines the value to assign as dose equivalent to the extremities for the monitoring period based on the higher of the two shallow dose equivalent ring results for the individual for the given monitoring period. Dose results for extremity dosimeters are reported on a daily basis when available, as are results for personnel dosimeters.

5.8.4 System Calibration

The following sections briefly describe the methods used to calibrate various elements of the extremity dosimetry system. These methods are very similar to those used for the personnel dosimetry system.

5.8.4.1 Reader Calibration

The Harshaw Model 6600 TLD reader is calibrated by reading calibration cards that have been exposed to 500 mR with a ^{60}Co source located in the 318 calibration facility's high-exposure room. The calibration cards consist of chipstrates which have been calibrated for individual chip sensitivity and permanently loaded into carrier cards. Annealed calibration cards are placed on a Plexiglas™ rack approximately 1/8 inch thick, at a distance of approximately 7 meters from the source. Exposure rates at this distance have been established using NIST-traceable ionization chambers and electrometers, and are re-evaluated annually. The calibration cards are read with ECCs applied, using a defined TTP, and the reader calibration program run to establish a RCF for that TTP, expressed in nC/mR. This RCF can then be applied on a real-time basis to all chipstrates subsequently read using the given TTP. The reader calibration process and RCF calculation methodology are the same as described for personnel dosimeters in Section 5.3.2. Reader calibrations are performed weekly using a set of calibration cards that are prepared on a monthly basis and may be used up to 45 days after irradiation. Fade and background effects attributed to the 45-day use window are relatively small (less than 5% and 7 mR respectively).

5.8.4.2 Chipstrate Calibration

Individual chipstrates are calibrated by exposing them to 500 mR from a ^{60}Co source, reading them on a calibrated reader, and comparing the individual chip response with the mean response of the chipstrate population (estimated by the mean response of the sample of calibration cards used to calibrate the reader). The resulting chip sensitivity correction factor is referred to as an ECC, and is applied by the reader on a real time basis to all subsequent readings of the

chipstrate. When the ECC is applied to raw chipstrate readings, a uniform response among chipstrates is achieved, with a standard deviation typically less than 3% for a 500 mR exposure. The ECC calculation methodology used for chipstrates is the same as that described in Section 5.3.3.

5.8.4.3 Calibrated Chip Readings

When field, QC or blank chipstrates are processed for measurement of dose or process QC, the reader software applies the ECC and RCF to the raw chip reading to obtain a "calibrated chip reading", X , in ^{60}Co mR-equivalent as follows:

$$X = Q * ECC / RCF \quad (5.10)$$

where X = calibrated chip reading (mR)
 Q = PMT charge collected (nC)
ECC = element correction coefficient
RCF = reader calibration factor (nC/mR).

The file of chipstrate readings created by the reader (Group File) includes the calibrated chip reading, the ECC applied, and the RCF applied.

5.8.4.4 Ring Dosimeter Calibration

Dosimeter calibration consists of determining the relationship between a chip's response to the local source and geometry (^{60}Co in air outside holder), and its response to the calibration standard (^{137}Cs in ring holder, on-phantom). The resulting factor is called the ^{137}Cs RRF and is expressed in units of mR/mrem. The RRF is a function of the local and standard sources used, the chip thickness, and the filtration over the chip when in the holder. Therefore, the RRF varies with chip position and dosimeter type for the personnel dosimetry system. For the extremity dosimetry system, there is a single chip position and dosimeter type at present. The RRF is determined by exposing a set of chipstrates to the local source and a set of chipstrates to the calibration standard and reading them interleaved together in a single group on a stable reader with ECCs applied. The ratio of the average response to the calibration standard (nC/mrem) to the average response to the local source (nC/mR) is calculated. This ratio is the RRF for the Hanford ring dosimeter. Dividing the calibrated reading (mR) for a given chipstrate by the RRF for the ring dosimeter, provides a ^{137}Cs mrem-equivalent reading for that chip. This is the same reading that would have been obtained if the reader had been calibrated directly with chipstrates exposed in-holder on-phantom to the calibration standard. The use of local sources in conjunction with RRFs results in more cost effective and reproducible calibration of the TLD system. The phantom, geometry, and source used as the calibration standard are as specified in HPS N13.32 (HPS 1996a)

5.8.5 Dose Algorithm for Ring Dosimeter

Because the ring dosimeter currently in use at Hanford is a single element dosimeter, the dose calculation algorithm is relatively simple compared with the algorithms used for the four-element HSD and HCND dosimeters. The following formulae describe the dose calculation methodology in sufficient detail to allow calculation by hand for verification of results if necessary.

5.8.5.1 Shallow Dose Equivalent

$$H_s = D * CF \quad (5.11)$$

where:

H_s	=	shallow dose equivalent (mrem)
D	=	adjusted reading (mrem)
CF	=	facility correction factor (dimensionless).

5.8.5.2 Facility Calibration Factor

A facility-specific calibration factor CF is determined from the two-digit facility calibration code FCC provided by the field dosimetry organizations in the RETURN file from REX as follows:

If	FCC	=	00
Then	CF	=	2.0
Else	CF	=	FCC / 10

Where	CF	=	facility specific calibration <i>factor</i> .
-------	----	---	---

5.8.5.3 Adjusted Element Reading

The method of calculating adjusted element readings for chipstrates is essentially the same as the one used for the 8816 and 8825 TLD cards that are used in the HCNDs and HSDs. Adjusted readings for chipstrates are calculated as follows:

$$D = (X - E) / (RRF * F * S) \quad (5.12)$$

where: D	=	adjusted chip reading (^{137}Cs mrem equivalent)
X	=	calibrated chip reading (^{60}Co mR equivalent)
E	=	estimated environmental background for chipstrate (^{60}Co mR equivalent)
RRF	=	^{137}Cs RRF for ring (mR/mrem)
F	=	fade correction factor for chipstrate
S	=	supralinearity correction factor.

The empirically determined RRF is verified periodically and is typically found to be close to unity.

5.8.5.4 Zero Dose Reading

The zero dose reading for unexposed chipstrates averages approximately 10 mR and this value is used as a constant (B) in Equation 5.13. The zero dose reading was determined by annealing 100 chipstrates and reading them on a calibrated reader two days later. This value accounts for both reader background and intrinsic chip background.

5.8.5.5 Environmental Background Function

The variable E, represents the portion of the chipstrate reading accumulated during the field cycle that is due to natural background radiation plus typical reader background and intrinsic chip background. E is calculated from an empirically determined background function based on the number of days in the field. For chipstrates, E is calculated as follows:

$$E = G * FD + B \quad (5.13)$$

where: G = background growth rate (0.145 mR/d)
FD = field days (days between previous and current processing date).
B = zero dose reading (10 mR)

5.8.5.6 Fade Correction

Fade corrections for the chipstrate are based on an empirically determined two compartment exponential post-irradiation fade model for TLD 700 as used at Hanford.^(a) Although the model is based on fading in TLD 700 chips in 8825 cards, it is considered valid for chipstrates as well because the same annealing and readout techniques are used for chipstrates. The model is as follows:

$$F(t) = R(t)/R_0 = a e^{(-\lambda_1 t)} + (1 - a) e^{(-\lambda_2 t)} \quad (5.14)$$

where: t is the time since irradiation (days)
R(t) is the net chip response (mR) at time t
R₀ is the net chip response (mR) at time t = 0
a is the weighting factor for the short half-life compartment
 λ_1 is the decay constant for the short half-life compartment
 λ_2 is the decay constant for the long half-life compartment

For routine dosimetry, when the time since irradiation is generally not known, one half of the time between previous and current processing date is used for t. The parameters to be used in the model are shown in Table 5.22 . The model is shown graphically in Figure 5.26.

(a) B. A. Rathbone, "Re-evaluation of Post Irradiation Fading of Beta-Gamma Dose in TLD 600 and TLD 700," March 20, 2000, letter to HEDP file.

Table 5.22 Parameters for use in Chipstrate Post Irradiation Fade Model

Parameter	TLD 700 β - γ
a	0.0530
λ_1	0.0179 d ⁻¹
λ_2	0.000231 d ⁻¹

Post Irradiation Fading of Beta-Gamma Signal in TLD 700

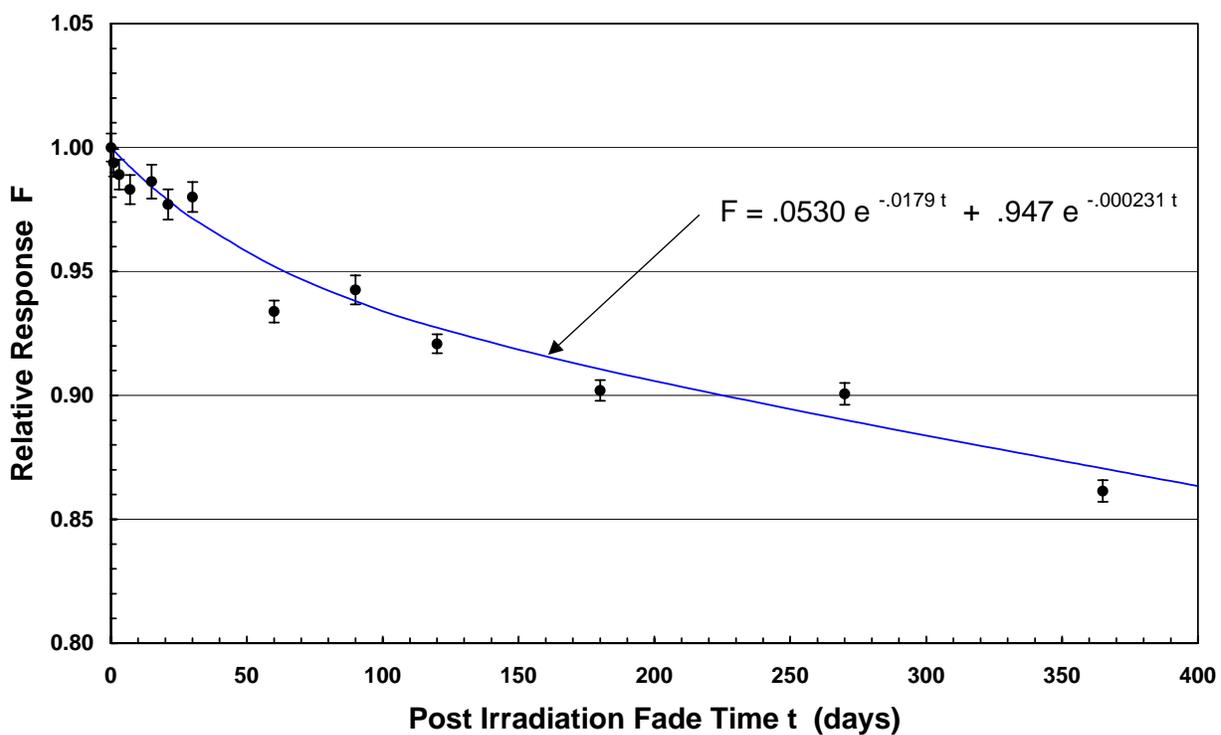


Figure 5.26 Fade Correction for the Hanford Ring

5.8.5.7 Supralinearity Correction

Supralinearity correction for the chipstrate is taken to be the same as for other TLD-700 chips because supralinearity is a function of the phosphor type, radiation type, and annealing/readout protocol in addition to absorbed dose. Based on the supralinearity correction established for TLD 700 in personnel dosimeters the supralinearity correction used for chipstrates is as follows:

$$S = (1.0 + 3.411 * 10^{-7} * X_{net}) \quad (5.15)$$

where:

$$X_{net} = X - E = \text{background corrected chip reading (mR)}$$

5.8.6 Performance Data

The following sections briefly describe the basic performance characteristics of the Hanford ring dosimeter. The results of formal DOELAP and NVLAP performance testing are available in HEDP files.

5.8.6.1 Uniformity

Uniformity of response is defined as the coefficient of variation of response for many dosimeters given the same dose. Uniformity of response for the Hanford ring dosimeter was determined by irradiating 10 dosimeters on a Plexiglas™ extremity phantom to 1000 mrem of ¹³⁷Cs radiation and reading the dosimeters after 30 days of fade. The % C.V. of the 10 reported doses was 2.5%. Uniformity of response for the XD740 chipstrate response in mR as reported by the TLD reader was determined by exposing 20 chipstrates in carrier cards to a ⁶⁰Co source in air at a distance of 7 meters. The % C.V. of the 20 calibrated readings was 1.5%.

5.8.6.2 Lower Limit of Detection

Initial determination of the LLD for the Hanford ring dosimeter was made using the method described in HPS N13.32 (1996a). Twenty dosimeters were prepared using standard procedures and read out 69 days later. Ten of these dosimeters were exposed to 1 rem of ¹³⁷Cs radiation on Plexiglas™ extremity phantom and ten dosimeters were used as background controls. The mean and standard deviation of the reported shallow dose equivalent (without background subtraction) from both groups were calculated and used to calculate LLD. The LLD thus calculated was 8 mrem. A reporting threshold of 10 mrem was adopted for use at Hanford.

To support issue of the Hanford Ring on a quarterly exchange frequency, a subsequent study was performed according to the alternate method in HPS N13.32-1995 *Performance Testing of Extremity Dosimeters* (HPS 1996a). DOELAP performance test data was used for the exposed dosimeter set and readings from unused dosimeters exchanged to and from field locations were

used for the unexposed dosimeter set. The unused dosimeter data set was chosen such that the time between anneal and readout was about 120 days, typical for a quarterly exchanged dosimeter.^(a) The results are shown in Table 5.23.

Table 5.23 LLDs for Hanford Ring

Source	Ring CF	Quarterly Field LLD (mrem)
M30	0.710	13
M60	0.660	12
M100	0.676	13
M150	0.742	14
H150	0.836	16
¹³⁷ Cs	1.000	18
⁹⁰ Sr/ ⁹⁰ Y	0.916	19
²⁰⁴ Tl	4.281	91

5.8.6.3 Linearity

Because linearity is a function of the TL phosphor and annealing/readout protocol, it is assumed that this characteristic for the personnel dosimeters and chipstrates will be essentially the same. Based on the response of Teflon[®] encapsulated TLD-700 chips using the same readout and annealing protocols as used for chipstrates, linearity for chipstrates is within $\pm 5\%$ of the given dose from 10 mrad to 100 rad. Above 100 rad, supralinearity corrections become significant. Supralinearity corrections are automatically applied to all ring readings using the relationship in equation 5.15.

5.8.6.4 Angular Response

A study was conducted to measure the angular response of the Hanford Ring dosimeter to photons and beta particles of various energies.^(b) The study was performed using the sources and protocol described in HPS N13.32 (1995) *Performance Testing of Extremity Dosimeters*. Documentation of angular dependence for extremity dosimeters according to this standard is a requirement for both NVLAP and DOELAP accreditation. The standard states that at least one source from each category II through IV should be used. For the purpose of this study, two sources from category II (M30 and M100), one source from category III (¹³⁷Cs), and two sources from category IV (⁹⁰Sr/⁹⁰Y and ²⁰⁴Tl) were used. The delivered shallow dose for all sources was approximately 5 rem except for the ²⁰⁴Tl source for which the delivered shallow dose was 3600 mrem due to time constraints. The extremity phantom was rotated on horizontal and vertical axes as shown in Figure 5.29. Exposures were made at angles of 0°, $\pm 30^\circ$, $\pm 60^\circ$,

(a) B. A. Rathbone, "LLD Calculations for Quarterly Ring Dosimeter," May 20, 1999, letter to HEDP file.

(b) B. A. Rathbone, "Angular Dependence Study for Hanford Ring Dosimeter," August 18, 1997, letter to HEDP file.

$\pm 85^\circ$, and 180° . The negative angles refer to rotation in the counter-clockwise direction on the axis in question. Irradiations with the photon sources were made at a distance of 100 cm. Irradiations with the beta sources were made at a distance of 30 cm. The irradiations were conducted by the Battelle Calibration Research and Accreditation group using the sources, phantoms, geometry, and C_x factors specified in HPS N13.32 (1995).

For each data point in the horizontal orientation, five rings were irradiated on the phantom together in one shot, and the average reported/given value used for calculation of the angular response. For each data point in the vertical orientation, three rings were irradiated on the phantom together in one shot, and the average reported/given value used for calculation of the angular response. The results are summarized in Table 5.24 and shown graphically in Figures 5.27 and 5.28. The raw data are included in HEDP files. As expected, significant under-response is evident at extreme angles with beta radiation and low energy (20-keV) photon radiation.

Table 5.24 HRD Angular Shallow Dose Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-30°	0°	30°	60°	85°	180°
M30	20	H	0.49	0.83	0.93	1.00	0.94	0.80	0.61	0.20
		V	0.50	0.83	1.00	1.00	0.99	0.90	0.73	0.21
M100	51	H	0.76	0.95	1.02	1.00	1.00	0.98	0.81	0.60
		V	0.87	0.94	1.04	1.00	1.01	0.98	0.94	0.65
^{137}Cs	662	H	0.98	0.99	1.02	1.00	1.01	1.01	0.99	0.89
		V	0.94	0.96	0.98	1.00	1.00	0.97	0.97	0.85
$^{90}\text{Sr}/^{90}\text{Y}$	931*	H	0.15	0.58	0.93	1.00	0.93	0.60	0.24	0.01
		V	0.23	0.55	0.93	1.00	0.97	0.71	0.32	0.01
^{204}Tl	267*	H	0.09	0.30	0.71	1.00	0.78	0.40	0.07	0.07
		V	0.05	0.23	0.70	1.00	0.81	0.36	0.16	0.04

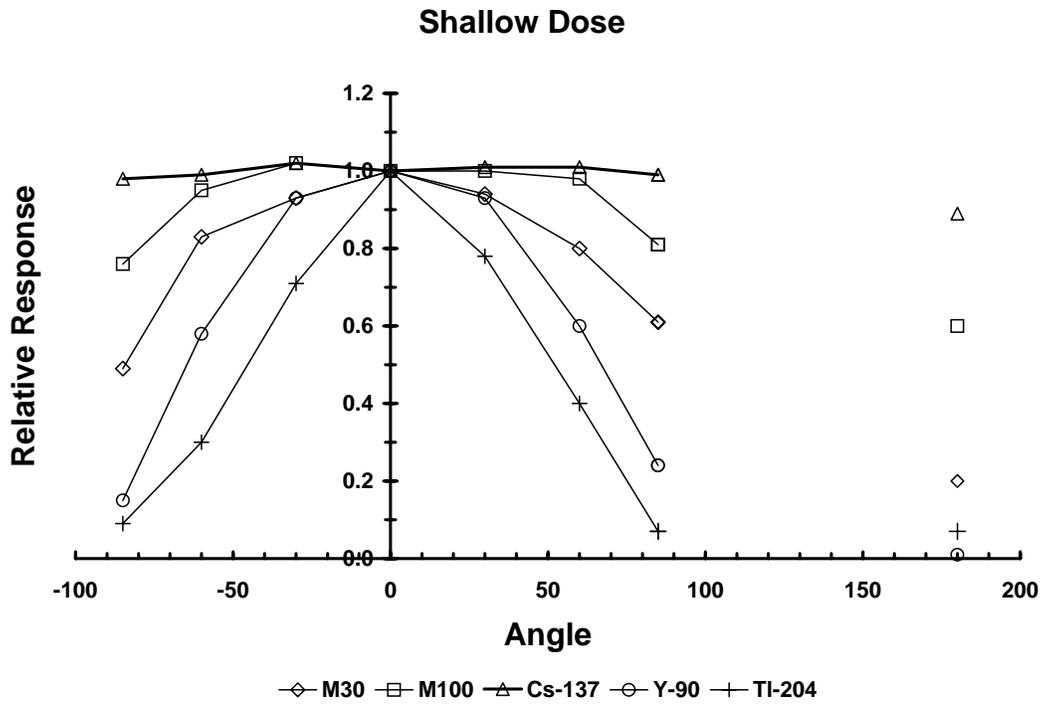


Figure 5.27 Hanford Ring Shallow Dose Angular Response – Horizontal Rotation

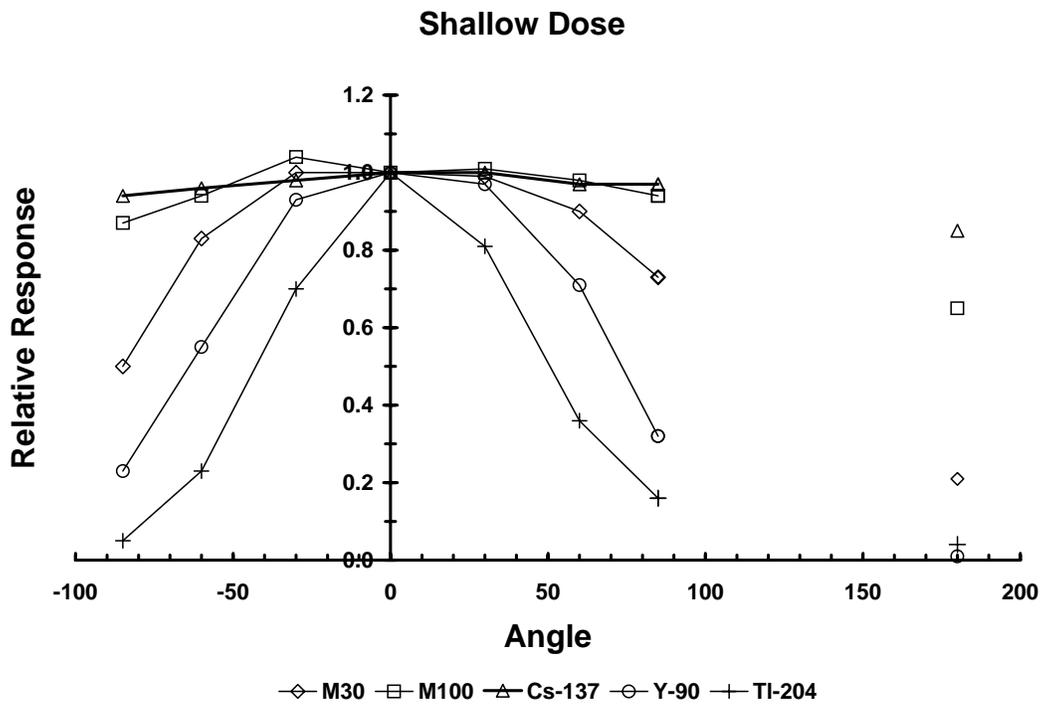


Figure 5.28 Hanford Ring Shallow Dose Angular Response – Vertical Rotation

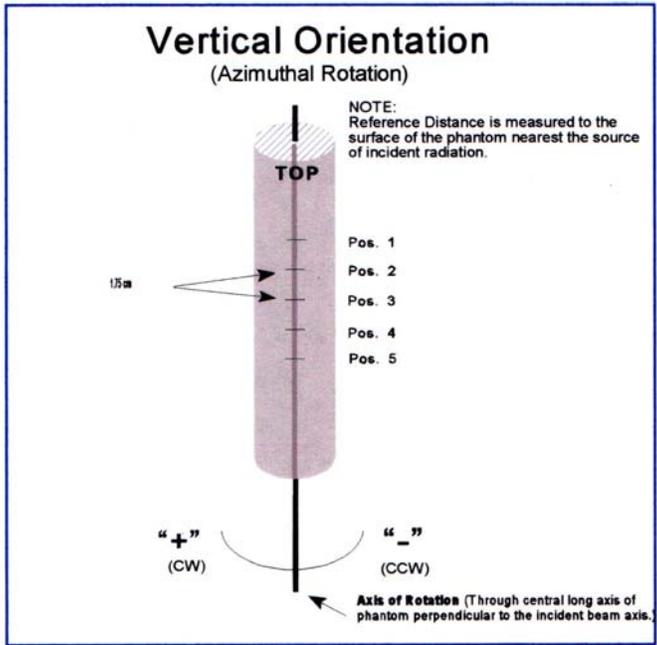
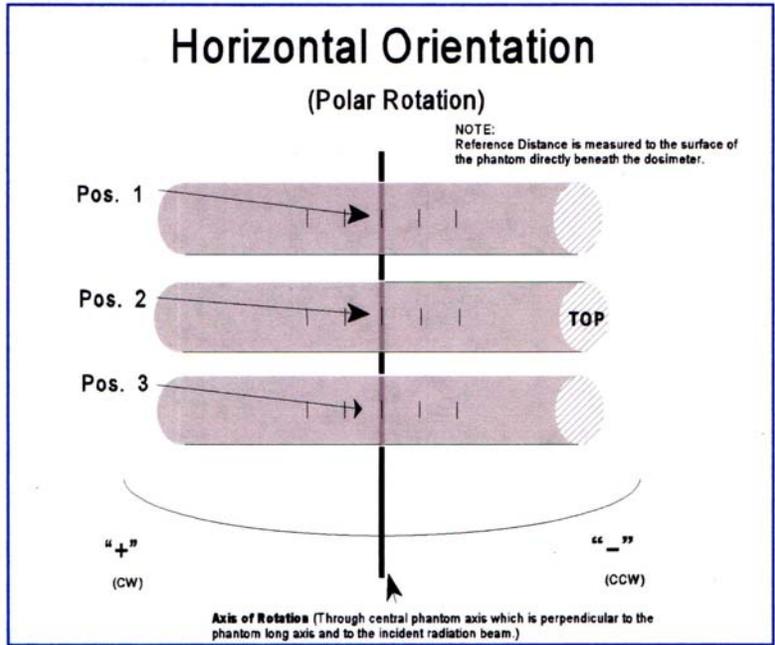


Figure 5.29 Ring Orientation for Angular Dependence Irradiations

5.8.6.5 Photon Energy Dependence

Because there are no energy-flattening filters in the ring and no energy compensation is possible in the algorithm, the photon energy response of the Hanford ring is typical of that for all ^7LiF TL materials and follows closely the theoretical response curve based on the mass energy absorption coefficient for LiF as a function of photon energy. Photon energy response data were developed for the Hanford ring by exposing dosimeters on-phantom to the beam codes and geometries specified in HPS N13.32 (1995). The C_x factors specified in this standard were used to derive the delivered shallow dose equivalent for each beam code. The photon response curve for the Hanford ring dosimeter is shown in Figure 5.30.

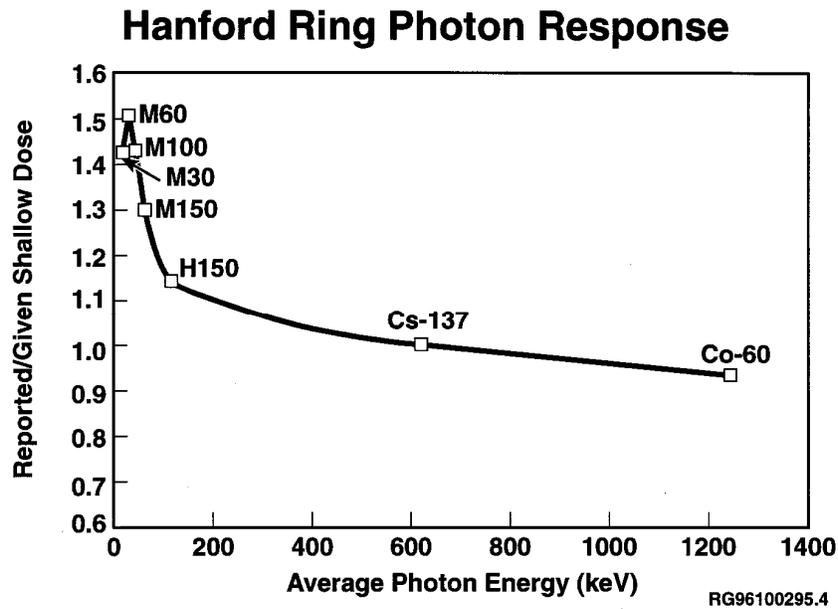


Figure 5.30 HRD Photon Response

5.8.6.6 Beta Energy Dependence

Groups of five ring dosimeters each were exposed to several rad from the following Buchler/PTB beta calibration standard sources: $^{90}\text{Sr}/^{90}\text{Y}$, ^{204}Tl , and ^{147}Pm . The ring response relative to the delivered shallow dose is shown in Table 5.25.

Table 5.25 HRD Beta Response

Source	β_{max} (keV) ^a	β_{avg} (keV) ^a	Reported/Given	BCF
$^{90}\text{Sr}/^{90}\text{Y}$ ^b	2240	931	1.09	0.92
^{204}Tl	765	267	0.23	4.28 ^c
^{147}Pm	225	62	0.00	n/a

- Nominal values. Actual energies are slightly less because of filtration inherent in encapsulation and beam flattener.
- Most of the ^{90}Sr beta particles are removed from the beam by encapsulation and beam flattener.
- This BCF is based on the large ring size. Medium and small parts have slightly thinner windows and a slightly smaller BCF for this source.

5.8.7 Default Correction Factor for Hanford Ring

When the user enters a facility calibration code of 00 for the ring in the REX database, the dose calculation algorithm applies a default correction factor of 2.0 to the uncorrected dose (based on calibration to ^{137}Cs gamma) to obtain the final reported dose. This default correction factor was chosen based on field measurements at Hanford and laboratory measurements that indicate that for ^{90}Y (the primary beta dose contributor at Hanford), the appropriate correction factors for the ring are less than 2.0. For beta-emitters with average energies less than ^{90}Y , larger correction factors may be necessary. It is the responsibility of the user to identify situations where correction factors other than the default are appropriate. The user should therefore characterize work environments and closely monitor work conditions to ensure that large beta/gamma dose ratios do not exist in conjunction with low-energy beta emitters and consult HEDP regarding appropriate correction factors when these conditions do exist.

The primary dose-contributing radionuclides presently encountered in many Hanford work environments are ^{137}Cs and $^{90}\text{Sr}/^{90}\text{Y}$ in secular equilibrium. These nuclides are most often encountered in tank waste characterization work and tank waste remediation work and often in association with large dose rates and dose gradients. Experience has shown large shallow doses to the extremity are most often associated with the handling of tank waste with large Sr/Cs ratios in small containers. Typical containers are centrifuge cones and vials with wall thicknesses of approximately 100 mg/cm², and 125-ml glass sample jars with wall thicknesses of approximately 680 mg/cm². Container walls thicker than 100 mg/cm² remove essentially all of the ^{90}Sr beta particles and begin to degrade the ^{90}Y beta spectrum slightly. To determine the HRD response to the degraded ^{90}Y beta spectra that might result from these containers, filtered $^{90}\text{Sr}/^{90}\text{Y}$ sources were constructed and calibrated for shallow dose rate using an NIST-traceable reference class PTW extrapolation chamber. The sources were constructed using Buchler/PTB beta sources without beam-flattening filters, by adding various

amounts of PMMA filtration directly over the source window. The total filtration for each source configuration, including the source encapsulation window were 122 mg/cm², 325 mg/cm², 557 mg/cm², and 727 mg/cm². Rings were exposed on-phantom at the calibration distance of 30 cm. The ring response to these sources as a function of total source filtration is shown in Figure 5.31. The HRD beta correction factors (BCF) appropriate for these sources, and ²⁰⁴Tl (267 keV average), as a function of the estimated average beta energy, are shown in Figure 5.32. These data are based on the response of small and medium ring sizes. The large ring size has a slightly thicker wall thickness and a larger BCF for ²⁰⁴Tl as shown in Table 5.25, which is based on the large ring part.

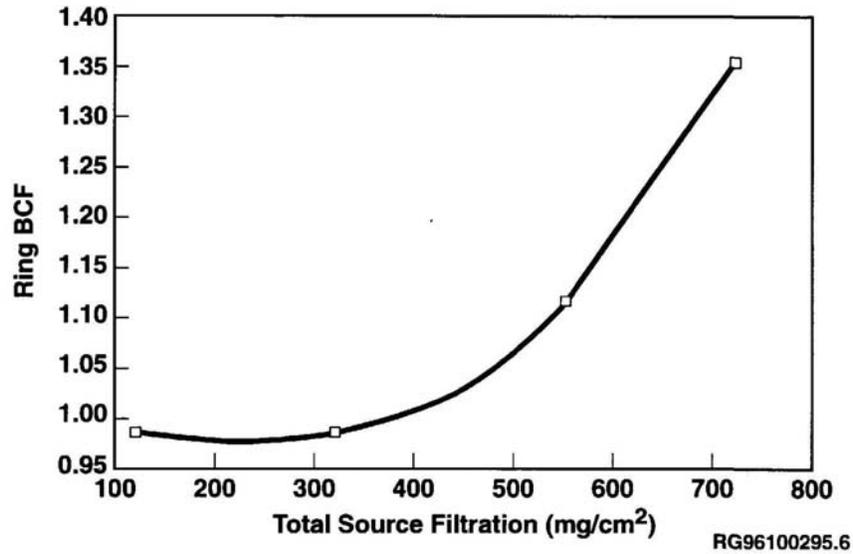


Figure 5.31 Ring BCF vs. ⁹⁰Sr/⁹⁰Y Source Filtration

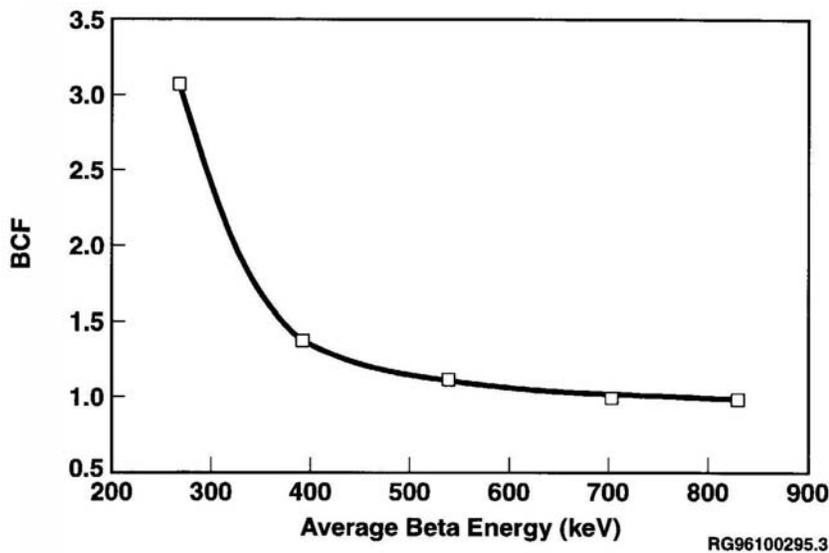


Figure 5.32 Ring BCF vs. Average Beta Energy

Based on the above data, the default ring correction factor of 2.0 should be conservative for most work environments involving tank waste. The exception is the situation where extremity dose is due to beta radiation originating from a thin, unshielded layer of mostly ^{137}Cs contamination. The average beta energy for ^{137}Cs is 187 keV and for ^{204}Tl is 237 keV (Durham 2006). Assuming that the beta correction factors for ^{137}Cs and ^{204}Tl are similar, a correction factor of about 4 would be needed for a thin layer small area source of pure ^{137}Cs contamination at a distance of 30 cm.

In general, beta radiation from surfaces contaminated with $^{90}\text{Sr}/^{90}\text{Y}$ and ^{137}Cs in which the $^{90}\text{Sr}/^{137}\text{Cs}$ activity ratio is less than 1.0 may require a correction factor larger than the default of 2.0. The correction factor depends on the thickness of glove material covering the ring as well as the $^{90}\text{Sr}/^{137}\text{Cs}$ activity ratio. Figures 5.33 and 5.34 show the effect of $^{90}\text{Sr}/^{137}\text{Cs}$ activity ratio and glove thickness on ring correction factor. These figures are based on MCNP modeling of skin dose rates and ring response for large area thin layer sources in contact with the hand (Rathbone et. al. 2002).

Source terms that are primarily ^{137}Cs may also produce significant extremity dose rates when the activity is accumulated in 3D geometries such as pipes, valves, and sample containers (rather than a 2D surface geometry). These geometries tend to selectively shield low-energy beta radiation but not gamma radiation. In this situation, because the predominant contributor to dose is photon radiation, the ring response and the default ring correction factor of 2.0 is generally adequate.

The pattern in Figures 5.33 and 5.34 may be explained as follows: When all beta particles originate from a single layer of activity and traverse through essentially the same thickness of intervening material to reach the skin, it is possible to have a particular thickness such that the chip in the ring lies beyond the range of most of the beta particles (because of the added path through 53 mg/cm² label+ ring casing) while the sensitive layer of skin does not. In this case the ring will under respond.^(a) This situation exists when heavy gloves (i.e. > 100 mg/cm²) are used. One method of shielding/dose reduction that has the added benefit of eliminating the need for ring beta correction factors is to place approximately 50 mg/cm² of material between the skin and the ring. This can be accomplished by wearing the ring on the outside of one cotton liner plus two surgical gloves (approx. 50 mg/cm²). In this case however, an additional outer glove to cover the ring is advised as a contamination barrier and additional shielding. The placement of the material between the ring and the skin effectively places the chip at the same depth as the skin. Laboratory measurements at the 318 Building have shown that the XD740 chipstrate, when placed under the same density thickness material as the point at which dose is to be measured, has better than an 80% response (reported dose/given dose) to ^{204}Tl .

(a) B. A. Rathbone, "Assessment of Ring Correction Factors for Use at Hanford", November 30, 1998, HEDP file.

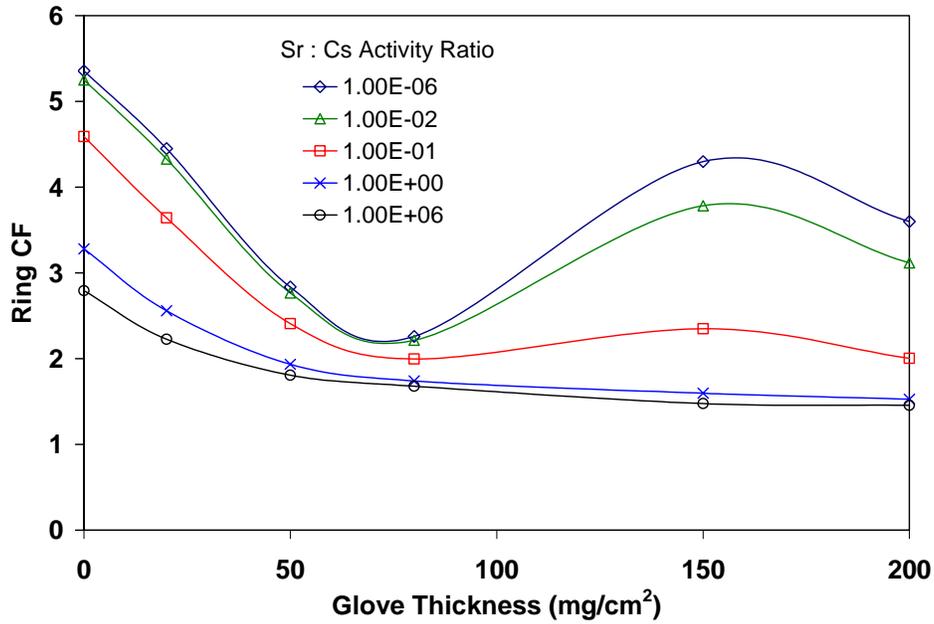


Figure 5.33 Ring Correction Factor as a Function of Glove Thickness for Large Area Source (on contact)

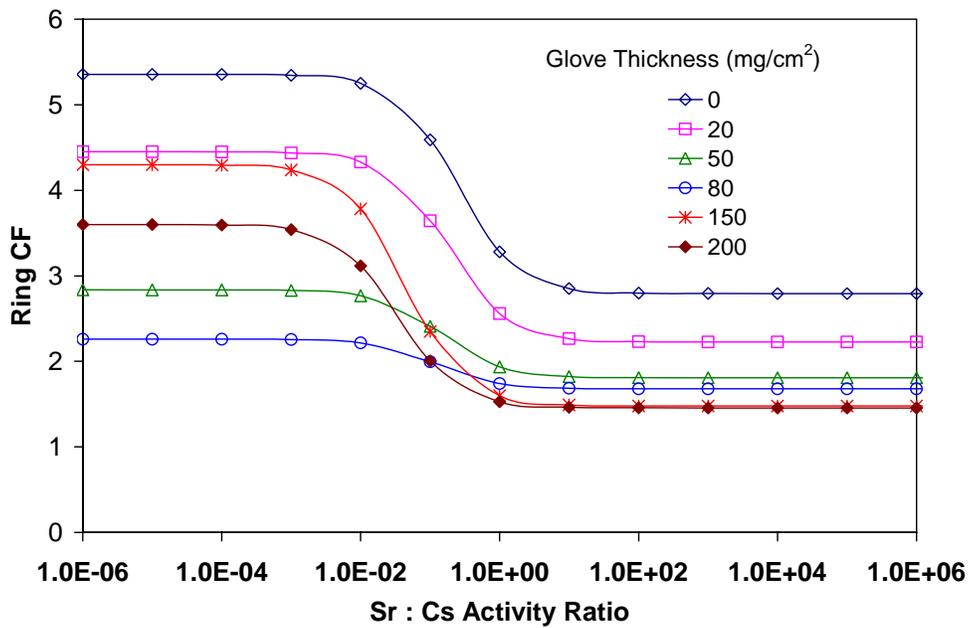


Figure 5.34 Ring Correction Factor as a Function of Sr:Cs Ratio for Large Area Source (on contact)

5.8.8 Ring Correction Factor for the Plutonium Finishing Plant

The Hanford ring dosimeter has essentially no sensitivity to neutrons. Because of the need to account for unmeasured neutron dose to extremities which is incurred during glove box work with plutonium compounds at the Hanford PFP, a ring correction factor of 2.0 has been adopted for use in correcting ring results for PFP workers. The correction factor of 2.0 is based on neutron to gamma dose rate ratios between 1 and 2 assessed at PFP and correction factors used at other DOE sites for similar beta/gamma ring dosimeters used in handling plutonium.^(a)

The factor takes into account the over-response of LiF to low-energy photons, which is about 150% of the true dose for the 60-keV photons from ²⁴¹Am associated with aged plutonium. The factor also takes into account the fact that there is no beta radiation in PFP glove box operations to which the ring might under-respond. More recently, direct measurements inside leaded gloves used in PFP glove boxes produced average neutron to gamma ratios between 0.09 and 0.55 for a variety of plutonium oxide and metal sources in sealed cans (Scherpelz, Fix, and Rathbone 2000). In this study, for the purpose of calculating neutron to gamma ratios, the gamma reading from the TLD 700 ring was used as the gamma dose without correction for over response to low energy photons. Using a nominal neutron *dose* to gamma *reading* ratio of 0.5 obtained from this study, a correction factor of 1.17 on uncorrected ring results would be appropriate to account for neutron dose in the reported extremity dose. However, a variety of factors can have a great influence on the gamma fluence reaching the TLD 700 chip in the ring including; source dimensions (i.e. self shielding in the source), shielding in the cans, lead loading in the gloves used, orientation of the ring on the finger, age of source material, and others (DOE 1998b). For example, in the Scherpelz, Fix and Rathbone (2000) study, ring response was measured with and without gloves to determine the photon attenuation affect of the glove. The glove thickness was shown to be equivalent to almost a half value layer for some of the sources used. A simple addition of one half value layer from additional glove material, or lead shielding in the can, while having a negligible effect on the neutron dose rate would reduce the photon response of the ring by a factor of 2. A ring correction factor of 1.67 would then be necessary to correct for unmeasured neutron dose in the ring result. Given the uncertainties in photon shielding, the currently adopted ring correction factor of 2.0 provides appropriate conservatism.

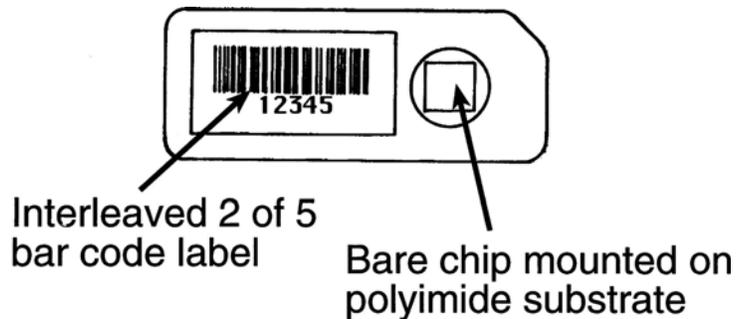
5.9 EXT-RAD Ring Dosimeter

The EXT-RAD Ring dosimeter is the only ring dosimeter that may be used by offsite customers. However, it has been DOELAP accredited and may be used by Hanford as well. For applications involving low energy beta emitters the EXT-RAD is preferred over the Hanford Ring Dosimeter. The beta response of the EXT-RAD is vastly superior to the HRD, with a much smaller risk of under response to low energy particles.

(a) J. J. Fix, "Extremity Dosimetry: Neutron to Photon Ratio," August 4, 1997, letter to HEDP file.

5.9.1 Dosimeter Description

Similar to the Hanford ring dosimeter described earlier, the EXT-RAD ring dosimeter contains a single $^7\text{LiF:Mg,Ti}$ (TLD-700) chip mounted on a thin polyamide (Kapton[®]) substrate with a permanent 5-digit barcode chip ID number. The Kapton[®] and chip assembly is commercially available from Harshaw under the product name Chipstrate[®], and is shown in Figure 5.35. The Harshaw product code for the specific chipstrate used by HEDP is "XD740." The chip consists of an active layer of TLD-700 phosphor in hot-pressed chip form, adhesively bonded to a dosimetrically inert ^7LiF base. The dimensions of the TLD-700 chip are 3.2 mm x 3.2 mm x 0.15 mm and the dimensions of the inert base are approximately the same. The laminated chip is adhesively bonded to the Kapton[®] substrate. The permanent chipstrate ID number allows application of a chip-specific sensitivity factor to the dose result.



G00040106.2

Figure 5.35 Chipstrate

The EXT-RAD extremity dosimeter is prepared with the chipstrate sealed inside a vinyl pouch as shown in Figure 5.36. This pouch has an integral beta window with a density thickness of 7 mg/cm^2 .

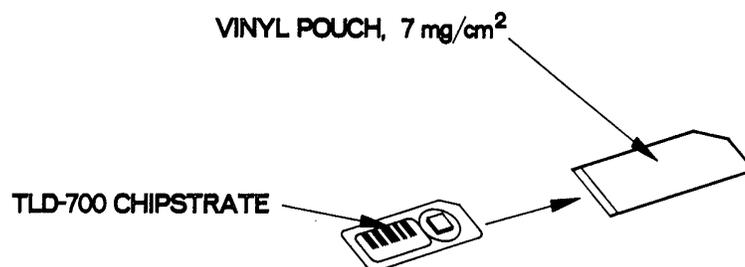


Figure 5.36 Illustration of Chipstrate Sealed in Vinyl Pouch

The vinyl pouch is inserted into a flexible black plastic holder with straps and a buckle that allow adjustment to individual finger size. An illustration of the EXT-RAD dosimeter is shown in Figure 5.37.

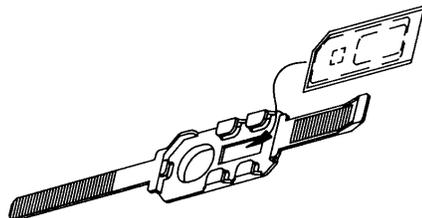


Figure 5.37 EXT-RAD Extremity Dosimeter

5.9.2 Reader Description

The reader system is precisely the same as that described earlier for the Hanford ring dosimeter.

5.9.3 Dosimeter Use Cycle, System Calibration, and Dose Algorithm

The EXT-RAD dosimeter is handled in the same way as the Hanford ring dosimeter throughout the use cycle except that for offsite customers, there are no file transfers to or from REX. In all other ways, the two systems are identical. For offsite customers, the data for the CHANGE, ISSUE, and RETURN files are typically handled through e-mail or by other means. For some customers, the CHANGE or RETURN files are created by HEDP personnel based on instruction from the customer. Results are typically sent directly to the customer via e-mail or other mail service.

The reader calibration, QC and readout procedures for the EXT-RAD dosimeter are identical to that for the Hanford ring dosimeter.

The dose algorithm for the EXT-RAD dosimeter is also identical to that for the Hanford ring dosimeter except for a slightly different ^{137}Cs relative response factor^(a). For offsite customers, the RETURN file (containing the facility calibration factor) is not obtained from REX. Instead, it is generated by the customer or generated by HEDP personnel based on instruction from the customer.

5.9.4 Performance Data

The following sections briefly describe the basic performance characteristics of the EXT-RAD ring dosimeter. The results of formal DOELAP and NVLAP performance testing are available in HEDP files.

(a) S. E. Huneycutt, "Relative Response Factors for Rings," August 30, 2001, letter to HEDP file.

5.9.4.1 Lower Limit of Detection

Initial determination of the LLD for the EXT-RAD ring dosimeter was made using the method described in HPS N13.32 (1996a), *Performance Testing of Extremity Dosimeters*. The calculations were based on dosimeters assembled from the general population of chipstrates used for personnel dosimetry. Five sets of 30 dosimeters were exposed to five sources corresponding to the sources listed in HPS N13.32 (M30, M100, ^{137}Cs , $^{90}\text{Sr}/^{90}\text{Y}$, and ^{204}Tl). A sixth set of 36 dosimeters was left unexposed. Only 30 of the 36 unirradiated dosimeters were used for the LLD calculations in order to match the size of the exposed sets. The dosimeters were processed 85 days after they were annealed as a single group. The results of the LLD calculations for these sources can be seen in Table 5.26. To allow determination of the LLDs for the M60 and M150 beam codes shown in Table 5.26, a second LLD calculation was performed using the alternate method described in HPS N13.32 (1996a). This calculation used the results of all 36 of the unirradiated dosimeters discussed earlier along with the results of the NVLAP performance tests (B and S) from the test session completed in January 2002. The calculated LLDs for all sources are shown in Table 5.26. The raw data and calculations are documented in greater detail in HEDP files^(a).

Possible reasons why the calculated LLDs from this study are lower than the LLDs for the Hanford Ring shown in Table 5.23 include the following: 1) the EXT-RAD ring dosimeters remained at the 318 Radiological Calibration Facility and never went through an exchange cycle to and from the field, 2) the chipstrates used for the study were new and recently calibrated, 3) the time between anneal and readout was shorter.

Table 5.26 LLDs for EXT-RAD Ring Dosimeter

Source	Ring CF	LLD (mrem)
M30	1.43	3.4
M60	1.59	3.0
M100	1.60	3.0
M150	1.45	3.3
^{137}Cs	1.00	4.8
^{90}Y	1.06	4.5
^{204}Tl	0.84	5.5

(a) S. E. Huneycutt, "LLD Calculations for EXTRAD Ring Dosimeter," July 3, 2002, letter to HEDP file.

5.9.4.2 Linearity

Because linearity is a function of the TL phosphor and annealing/readout protocol, it is assumed that this characteristic for the personnel dosimeters and chipstrates will be essentially the same. Based on the response of Teflon[®] encapsulated TLD-700 chips using the same readout and annealing protocols as used for chipstrates, linearity for chipstrates is within $\pm 5\%$ of the given dose from 10 mrad to 100 rad. Above 100 rad, supralinearity corrections are necessary.

5.9.4.3 Angular Response

A study was conducted to measure the angular response of the EXT-RAD ring dosimeter to photons and beta particles of different energies. The study was performed using the sources and protocols described in HPS N13.32-1995 *Performance Testing of Extremity Dosimeters* (1996a). Two sources from category II (M30 and M100), one source from category III (¹³⁷Cs), and two sources from category IV (⁹⁰Sr/⁹⁰Y and ²⁰⁴Tl) were used in this study. The delivered shallow dose for all sources was approximately 5 rem. Exposures were made on phantom at angles of 0°, $\pm 30^\circ$, $\pm 60^\circ$, $\pm 85^\circ$, and 180° vertical orientation and $\pm 30^\circ$, $\pm 60^\circ$, and $\pm 85^\circ$ horizontal orientation. Rotation in the horizontal orientation is illustrated as Polar Rotation while rotation in the vertical orientation is illustrated as Azimuthal Rotation in Figure 5.29. Positive angles are in the clockwise (CW) direction. Negative angles are in the counter-clockwise direction (CCW). Irradiations with photon sources were made at a distance of 100 cm while irradiations with beta sources were made at 35 cm (⁹⁰Sr/⁹⁰Y) and 30 cm (²⁰⁴Tl). The ²⁰⁴Tl exposures were conducted with a flattening filter in place whereas the ⁹⁰Sr/⁹⁰Y irradiations were not. All irradiations were conducted by the Battelle Calibration Research and Accreditation group using the sources, phantoms, geometry, and C_x factors specified in HPS N13.32-1995 (1996a). The results are summarized in Table 5.27 and shown graphically in Figures 5.38 and 5.39. The raw data are included in HEDP files ^(a).

For the photon sources in Table 5.27 the response data for horizontal orientations are based on three rings irradiated on phantom in one exposure and the data for vertical orientations are based on five rings irradiated on phantom in one exposure. For the beta sources, response data for horizontal orientations are based on four rings irradiated on phantom two at a time. The data for vertical orientations are based on three rings irradiated on phantom in one exposure. The angular response for each combination of source, angle and orientation, was calculated as the average reported/given value divided by the average reported/given value at zero degrees for the same source and orientation.

(a) S. E. Huneycutt, "EXTRAD Ring Dosimeter Angular Dependence," July 3, 2002, letter to HEDP file.

Table 5.27 EXT-RAD Ring Angular Shallow Dose Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-30°	0°	30°	60°	85°	180°
M30	20	H	0.44	0.86	0.99	-	0.98	0.89	0.45	-
		V	0.50	0.86	0.97	1.00	0.97	0.87	0.69	0.17
M100	51	H	0.81	0.98	1.01	-	1.03	1.00	0.84	-
		V	0.86	0.96	0.99	1.00	1.00	0.96	0.91	0.60
¹³⁷ Cs	662	H	1.01	1.01	1.00	-	1.00	1.02	1.01	-
		V	0.97	0.99	0.99	1.00	1.00	0.99	0.99	0.91
⁹⁰ Sr/ ⁹⁰ Y	931	H	0.17	0.75	1.03	-	1.07	0.70	0.19	-
		V	0.17	0.72	1.05	1.00	1.03	0.85	0.24	0.004
²⁰⁴ Tl	267	H	0.12	0.42	0.83	-	0.81	0.39	0.12	-
		V	0.13	0.44	0.85	1.00	0.87	0.43	0.17	0.006

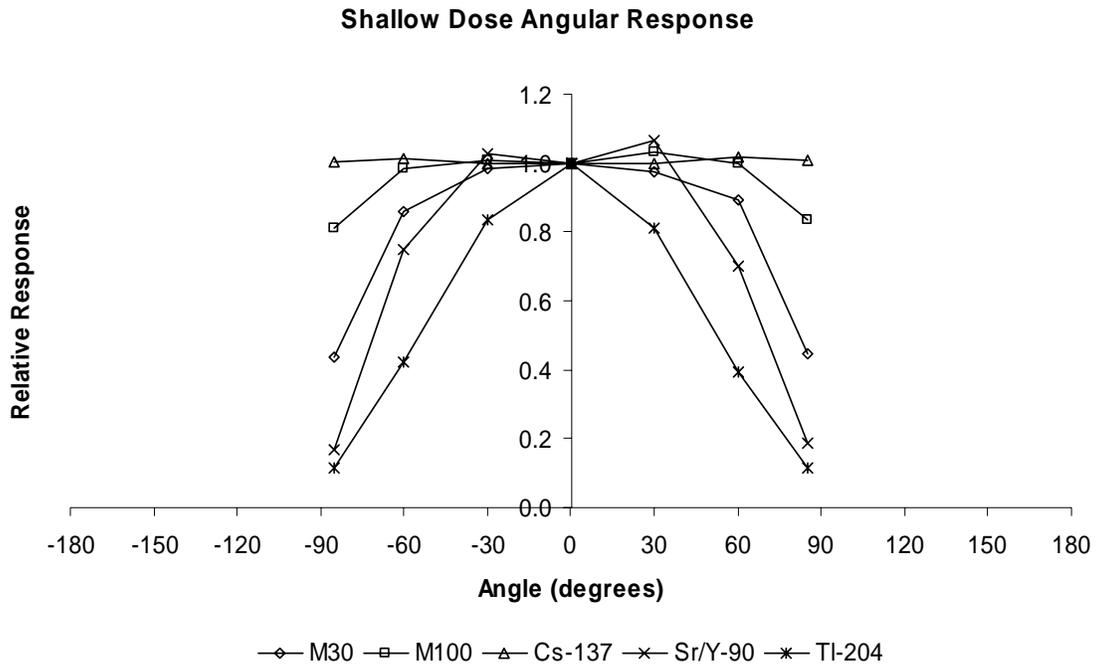


Figure 5.38 EXT-RAD Ring Shallow Dose Angular Response – Horizontal Orientation

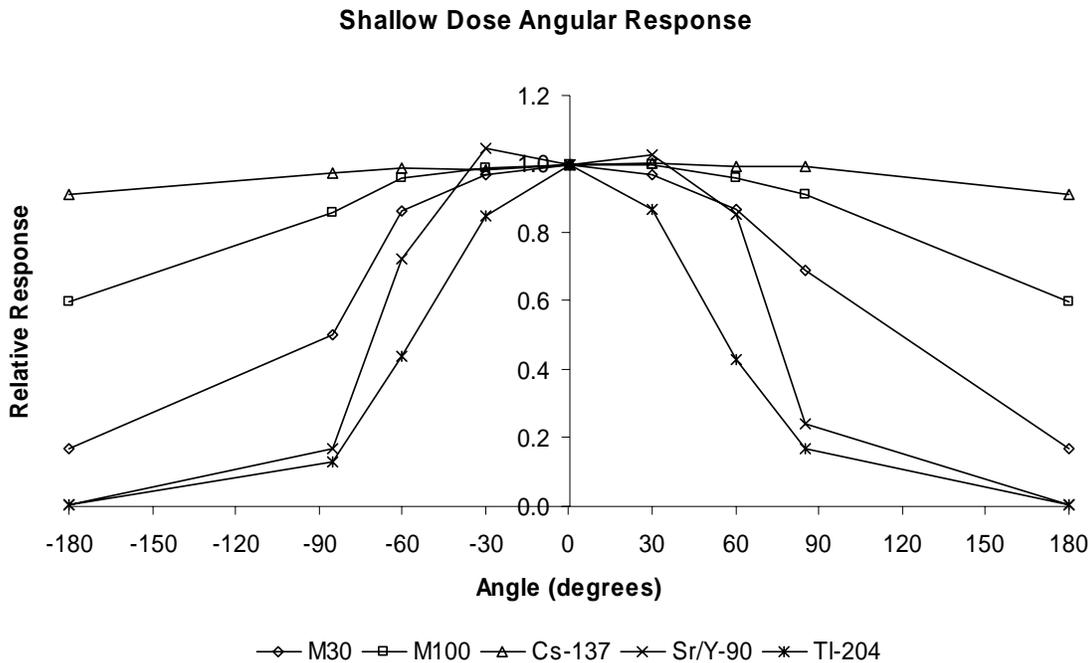


Figure 5.39 EXT-RAD Ring Shallow Dose Angular Response – Vertical Orientation

5.10 Hanford Environmental Dosimeter

The Hanford environmental dosimeter is intended for measurement of ambient radiation levels without phantom. The dosimeter holder is known commercially as a Harshaw 8807 dosimeter. The dosimeter contains 0.89-mm-thick phosphors in all positions: TLD-200 in positions one and two, and TLD-700 in positions three and four. The dosimeter is illustrated in Figure 5.40.

5.10.1 General Features

Tawil et al. (1993) have shown that the 8807 environmental dosimeter meets all applicable requirements of ANSI N545 (ANSI 1975), as modified by the Nuclear Regulatory Commission (NRC's) Regulatory Guide 4.13 (NRC 1977). In particular the following performance was demonstrated:

- Fade: less than 5% per quarter
- Uniformity: less than 3%
- Reproducibility: less than 2.0%
- Light dependence: negligible
- Moisture dependence: negligible
- Self irradiation: negligible
- Energy dependence: $\pm 20\%$ from 20 keV to 1.3 MeV.

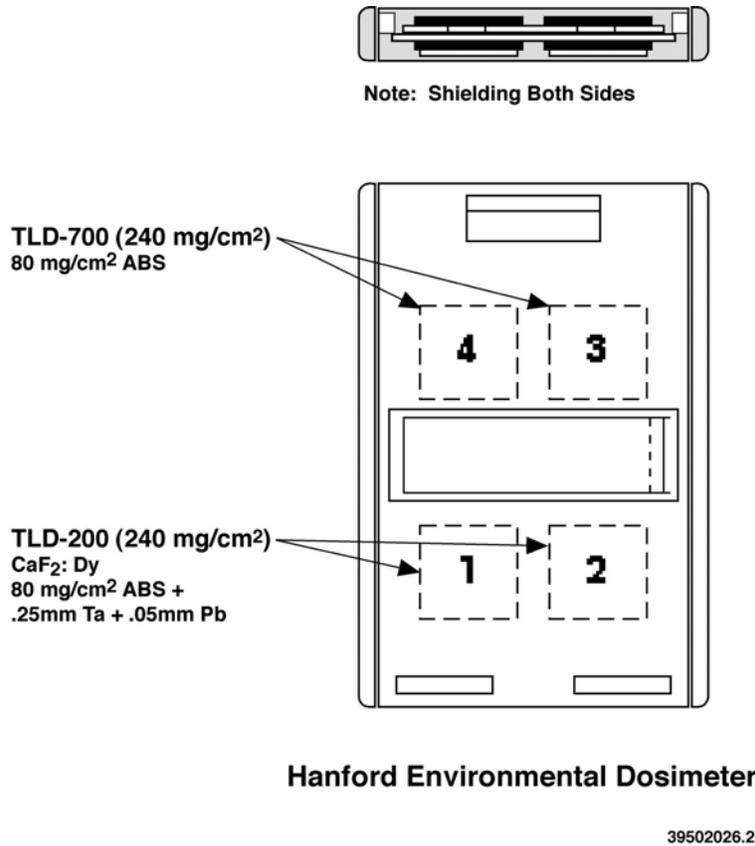


Figure 5.40 Hanford Environmental Dosimeter (Harshaw 8807)

5.10.2 Algorithm

The 8807 algorithm has the following options: 1) use of the two TLD-700 chips for exposure calculation without energy correction, 2) use of the two TLD-700 chips for exposure calculation with energy correction based on the TLD-200/TLD-700 chip ratio, or 3) exposure calculation based on all four chips with energy correction to all four based on the TLD-200/TLD-700 chip ratio. At Hanford, the exposure calculations are currently based on the first option because of the improved reproducibility of results that it offers.

5.10.3 Processing Protocol

The TTPs used for dosimetric readout (TTP 1) and annealing (TTP 2) of the Hanford environmental dosimeter 8807 card type are shown in Table 5.28.

Table 5.28 Hanford Environmental Dosimeter Time-Temperature Profiles

	TTP1(Field Reading)			
Preheat temperature	160	160	50	50°C
Time	25	25	0	0 sec
Temperature rate	20	20	10	10°C/sec
Maximum	300	300	300	300°C
Acquire time	20	20	33	33 sec
Annealing temperature	300	300	300	300°C
Time	0	0	0	0 sec
	TTP2(Annealing)			
Preheat temperature	50	50	50	50°C
Time	0	0	0	0 sec
Temperature rate	20	20	10	10°C/sec
Maximum	300	300	300	300°C
Acquire time	40	40	33	33 sec
Annealing temperature	300	300	300	300°C
Time	0	0	6	6 sec

5.10.4 Energy Response

When run in the mode where energy correction of the TLD-700 readings is not used, the 8807 algorithm can be expected to report results within 30% of the true value. Data on energy response generated at the PNNL 318 Building Calibrations Facility based on the first option are shown in Figure 5.41.

5.10.5 Minimum Measurable Dose

The minimum measurable dose (MMD) of the 8807 dosimeter has been shown to be less than 1 mR for a monthly field cycle (Tawil et al. 1993).

5.10.6 Fading

Fading corrections for the 8807 dosimeter are based on the fade data generated for the TLD-700 phosphors used in HEDP personnel dosimeters. The anneal treatments are identical for TLD 700 phosphors used in personnel and environmental dosimeters. For a quarterly field cycle, the fade correction is about 5%, depending upon the actual number of days between annealing and readout.

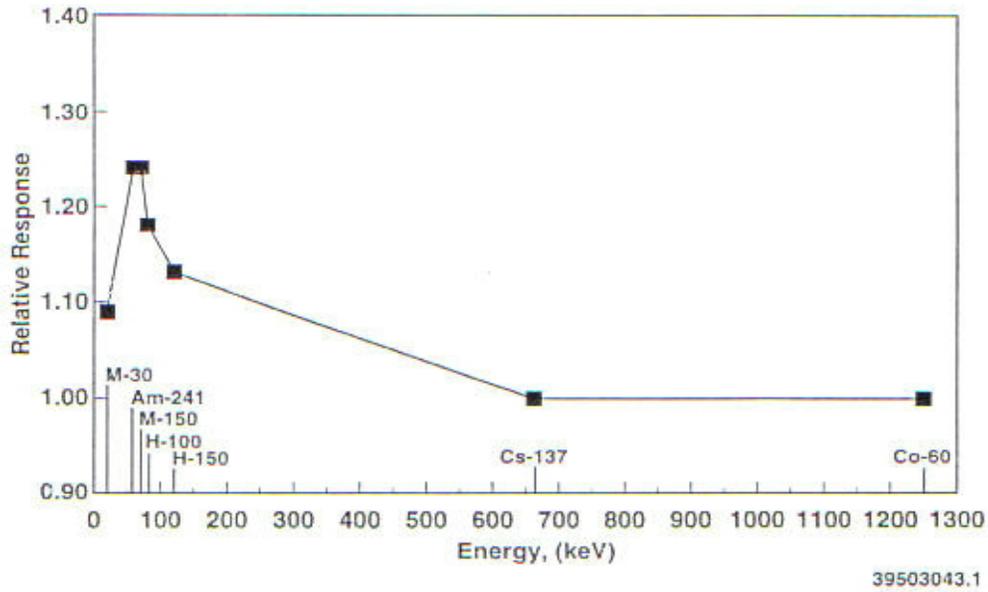


Figure 5.41 Hanford Environmental Dosimeter Energy Response (TLD 700)

5.11 Hanford Nuclear Accident Dosimetry

HEDP provides technical support to Hanford contractors for nuclear accident dosimetry involving four requirements in 10 CFR 835.1304 as follows:

1. a method to conduct initial screening of individuals involved in a nuclear event to determine whether or not significant exposures to radiation occurred
2. methods and equipment for analysis of biological materials
3. a system of fixed nuclear accident dosimeters (FNADs)
4. a system of personal nuclear accident dosimeters (PNADs).

HEDP capabilities to support Hanford contractor compliance in nuclear accident dosimetry are described in this section. Hanford contractors are responsible for assignment of personnel dosimeters and PNADs, analysis of the placement of FNADs, documentation listing the location of each FNAD, and retrieval instructions for each affected facility. FNADs provide supplemental dosimetry information, which can be extrapolated to affected workers, in addition to dosimetry information available from the personnel dosimeter and PNAD assigned to the worker and dosimetry information available from biological samples and/or analyses of personal items (i.e., coins, rings, watches, etc.).

5.11.1 Hanford Nuclear Accident Dosimeters

In order to provide as much dosimetry data as possible in a criticality event, both FNADs and PNADs are used at Hanford. Data from these dosimeters play an essential role in estimating dose in a criticality event.

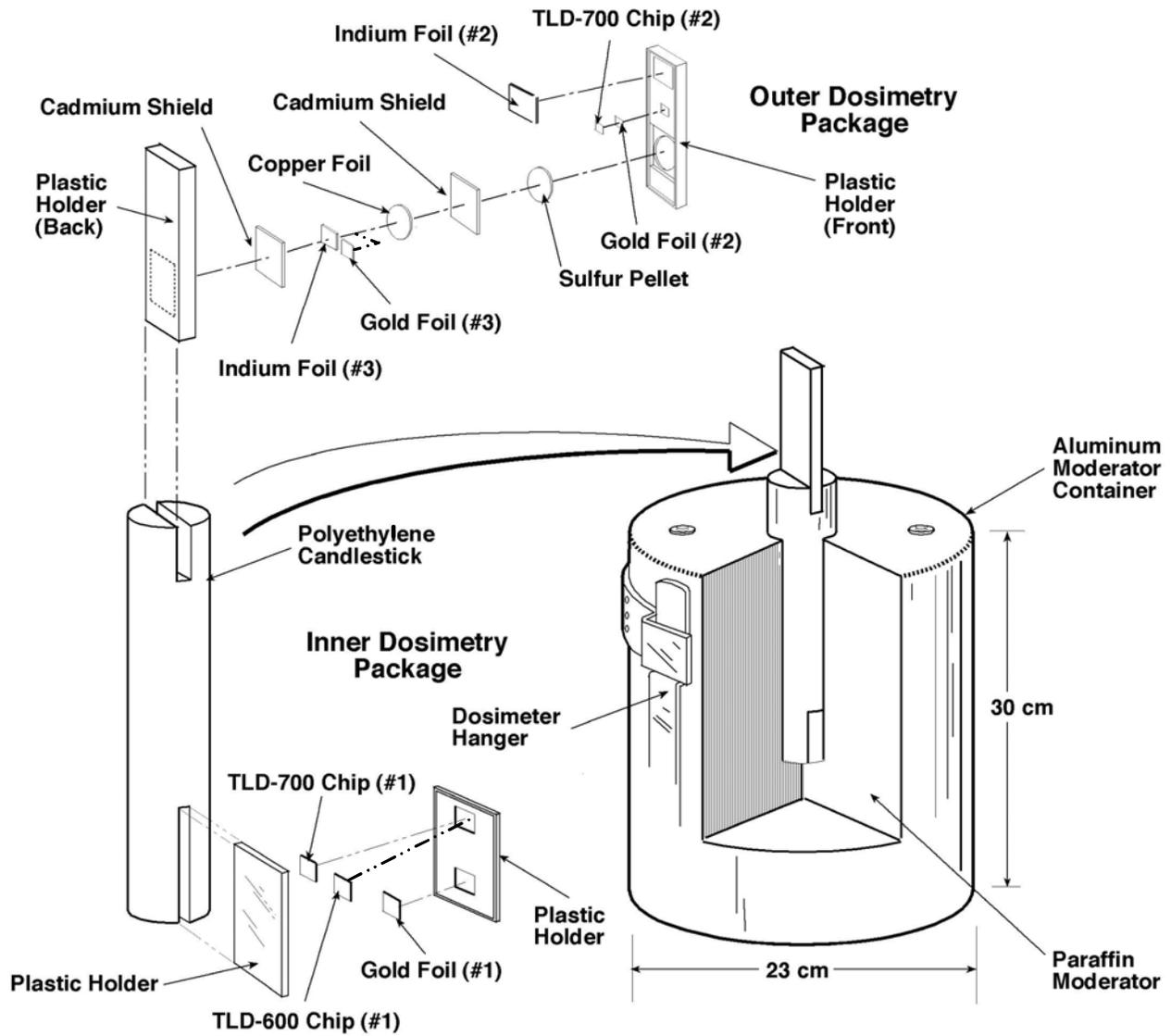
Fixed Nuclear Accident Dosimeter

The Hanford FNAD has an outer and an inner dosimetry package as illustrated in Figure 5.42. The dosimetry materials in the FNAD are summarized in Table 5.29. The inner dosimetry package consists of a gold foil, a TLD 600 chip and a TLD 700 chip. When in place in the FNAD, the gold foil and TLD chips are positioned approximately at the geometrical center of the moderator. The outer dosimetry package consists of several neutron activation foils and a TLD 700 chip. These components are used collectively to provide the best estimate of the neutron and gamma dose resulting from a criticality. The neutron activation foils are used to estimate the neutron fluence in several energy ranges, as follows:

- thermal to 0.4 eV
- 0.4 eV to 2 eV
- 0.4 eV to 10 eV
- 2 eV to 0.5 MeV
- above 1.2 MeV
- above 2.9 MeV.

General features of FNADs are presented in this section. Original design features of the Hanford FNAD are presented in reports by Bramson (1962) and by Glenn and Bramson (1977). The paraffin moderator of the Hanford FNAD is 30 cm high by 23 cm in diameter with 10-cm-thick paraffin walls. The moderator is equipped with a 2.54cm diameter polyethylene “candle” and polypropylene foil holder inserts.

Interpretation of dose is based on the method of calibration for each component, as well as the techniques used in the evaluation. The Hanford FNAD system has been tested several times over the years at the Oak Ridge National Laboratory (ORNL) Health Physics Research Reactor (HPRR) with good performance results. The results of the most recent test (conducted while the HPRR was still operating during August 1985) are maintained in the HEDP files.



39407129.1

Figure 5.42 Hanford Fixed Nuclear Accident Dosimeter

Table 5.29 Materials and Approximate Dimensions of Hanford Fixed Nuclear Accident Dosimeter

Description	Size, cm	Thickness, cm (mil)
<u>Inner Dosimetry Package</u>		
Square gold foil (1) ^(a)	1.0 by 1.0	0.0127 (5)
TLD-700 chip (1)	0.32 by 0.32	0.089 (35)
TLD-600 chip (1)	0.25 by 0.38	0.089 (35)
<u>Outer Dosimetry Package</u>		
Square gold foils (2, 3) ^(a)	1.0 by 1.0	0.0127 (5)
Indium foils (2, 3)	1.3 by 1.6	0.025 (10)
Copper ^(b)	2.2 dia.	0.025 (10)
Sulfur ^(c)	1.27 dia.	0.085 (33)
Cadmium shields	3.2 by 2.2	0.114 (45)
TLD-700 chip (1)	0.32 by 0.32	0.089 (35)

- a. More recent gold foils are 10 mil thick.
- b. More recent copper foils are 5 mil thick.
- c. More recent sulfur pellets are 75 mil thick.

*Personal Nuclear
Accident Dosimeters*

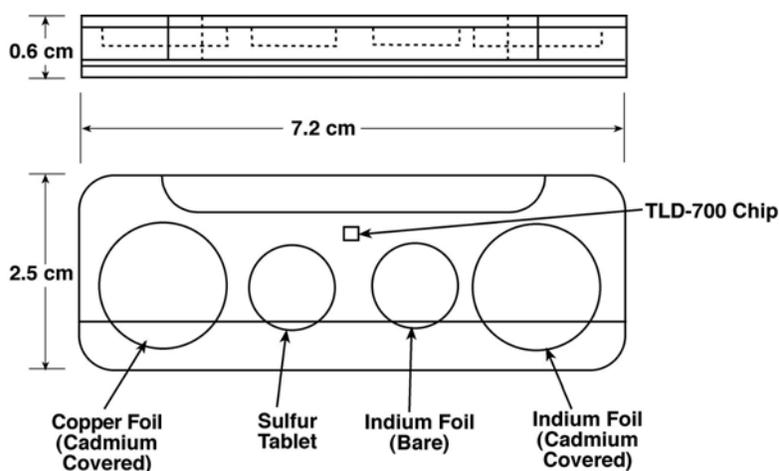
An illustration of the Hanford PNAD is shown in Figure 5.43. Table 5.30 lists the dosimetry components of the PNAD. The design of the Hanford PNAD is based on the outer dosimeter packet of the Hanford FNAD design and the PNAD used at the Los Alamos National Laboratory (LANL) (Vasilik and Martin 1981a). LANL tested their PNAD system at ORNL's HPRR Laboratory and documented these results (Vasilik and Martin 1981b). Performance of the Hanford PNAD is very similar to the performance observed with the outer dosimeter packet of the Hanford FNAD and the LANL documented data for the LANL PNAD. During 1997, a TLD-700 chip was added to the PNAD configuration to provide photon in addition to neutron radiation response characteristics.

The PNAD packets are issued by Hanford contractors to persons working in any area where a nuclear criticality event is possible. Each foil (i.e., including sulfur tablet) contained in the PNAD applies to a certain part of the energy spectrum. The total dose to which the PNAD was exposed is the sum of the individual spectrum-weighted dose components. The dose to the PNAD must be related to the dose to the person wearing the PNAD. The dose to a PNAD facing a criticality event will be different from the dose to a PNAD shielded by the body of the wearer.

Table 5.30 Hanford Personal Nuclear Accident Dosimeter

Position	Description	Diameter, cm	Thickness, cm (mil)
1	Cadmium/indium ^(a)	1.1	0.025 (10)
2	Indium	1.1	0.025 (10)
3	Sulfur	1.2	0.085 (33)
4	Cadmium/copper ^(a)	1.1	0.025 (10)
	TLD-700 chip	0.32 x 0.32 ^(b)	0.089 (35)

- (a) The cadmium enclosure, which contains indium and copper foils, is 0.051 cm (20 mil) thick.
 (b) TLD-700 chip measures 0.32 by 0.32 cm (1/8 by 1/8 inch) square by 0.089 cm (0.035 inch) in thickness.



RG97110128.1

Figure 5.43 Hanford Personal Nuclear Accident Dosimeter

5.11.2 Performance and Placement Criteria

NAD performance criteria are provided in the DOE Radiological Control Standard (DOE 1999c) as follows:

- Be capable of determining neutron dose in rad with an accuracy of $\pm 25\%$ from 10 rads to approximately 10,000 rads.
- Be capable of providing the approximate neutron spectrum for conversion of rad to rem.

- Be capable of measuring fission gamma radiation from 10 rads to approximately 10,000 rads in the presence of neutron radiation with an accuracy of approximately $\pm 25\%$.

PNAD performance criteria are provided in the DOE Radiological Control Standard (DOE 1999c), as follows:

- Be capable of measuring an absorbed dose in or on a phantom from 10 rads to approximately 1,000 rads with an accuracy of $\pm 25\%$.

Criteria for FNAD placement have been adopted through the HPDAC.^(a) Guidance on the placement of FNADs is available in:

- ANSI/ANS 8.3-1986 (ANSI 1986) where the “minimum accident of concern” with nominal shielding is defined to result in a dose of approximately 20 rad in the first minute at a distance of 2 meters.
- ANSI N13.3-1981 (ANSI 1981) provides basic requirements for nuclear criticality dosimetry systems.

Because the potential dose to workers is highly dependent upon circumstances, only general FNAD placement criteria are provided, as follows:

- FNADs should be placed close to the actual work locations with minimal intervening shielding to allow for accurate measurement of dose consistent with DOE nuclear accident dosimetry performance criteria (DOE 1998c).
- Additional FNADs should be placed at greater distances from the radioactive source to allow extrapolation of dose to nearby workers or workers during egress.
- A system of worker-assigned personnel dosimeters and PNADs should be used to permit extrapolation of FNAD data to exposed workers.
- Provision should be available to determine the orientation of exposed workers based on dosimeter and/or biological measurement data.
- The background neutron dose rate at the FNAD location should generally not exceed 20 mrem/h or 175 rem/y. To monitor locations where neutron dose rates exceed 20 mrem/h, the FNADs should be positioned at a distance sufficient to reduce the dose rates to the prescribed dose rate levels or conduct a more frequent candlestick exchange.
- The background gamma radiation exposure rate at the FNAD location should not exceed 3 mR/h or 25 R/y. For areas with a dose rate

(a) D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held December 3, 1997.” Copies of HPDAC minutes are retained in Hanford Radiological Records historical file.

exceeding 3 mR/h, a more frequent candle exchange should be conducted.

- FNADs should be placed where they can be easily retrieved, and where the shielding and obstruction between the dosimeter and the potential radiation source are minimal. For example, FNADs may be placed in a hallway near the room to be monitored if the shielding provided between the hallway and the room is nominal. If this location is not practical, consider placing FNADs near a doorway to facilitate retrieval.
- For large sources (e.g., dimensions >8 m), FNADs should be positioned on approximate 15 m centers, with each FNAD within approximately 2 m of the source material.
- FNADs should be exchanged annually, the dose observed on the TLDs calculated, and the results analyzed to ensure compliance with the foregoing criteria.

5.11.3 Quick-Sort Data Analysis

Quick-sort is a field method for identifying individuals who have received significant neutron dose during a criticality accident. It is based on measurement of ^{24}Na activity in the human body. The activity is produced by activation of naturally occurring ^{23}Na in the body by thermal neutron capture. Although the incident neutrons may be primarily fast in a criticality incident, the moderating effect of the human body is sufficient to produce significant amounts of ^{24}Na . Between 15% and 33% of the incident neutrons are thermalized and captured in the body (Cross and Ing 1985). ^{24}Na decays with a 15 hour half life and emits energetic gamma rays (1.37 MeV and 2.74 MeV with 99% abundance) that are easily detected by most survey instruments.

Measurements can be made by placing a pancake GM probe against the abdomen of the subject who is bent over during the measurement. An alternative approach is to place the GM probe in the armpit and have the individual hold it tightly against his rib cage with his arm. Care should be taken to rule out possible instrument response to contamination by making a measurement with the probe window facing the body and another with the probe facing away from the body and comparing results, or by covering the window of the GM detector with suitable beta shield.

For a pancake GM probe, neutron dose in rad may be estimated as follows:

$$Dose (rad) = 2.2 C/W \quad (5.16)$$

where C is the net count rate in counts per minute decay corrected to the time of the accident, and W is the subject's weight in pounds. Using this formula, a neutron dose of 1 rad would produce a net reading of 91 cpm immediately after exposure on an individual weighing 200 pounds. Since "quick" sort methods are typically applied within a few hours of the accident, decay corrections can be ignored.

This formula is based on experimental measurements made on a saline filled phantom with a hard wall GM instrument after irradiation with 2.1 MeV (avg) neutrons (Wilson, 1962). As shown here, the formula has been adjusted for differences in gamma sensitivity between the hard wall GM probe used in the experiment and the pancake GM probes used at Hanford today. A comparable formula for use with exposure rate instruments can be derived from the information in the Wilson study.

For an exposure rate instrument, absorbed neutron dose in rad may be estimated as follows:

$$Dose (rad) = 8000 R/W \tag{5.17}$$

where R is the measured net exposure rate in mR/h decay corrected to the time of the accident, and W is the subject's weight in pounds. Based on this formula, a neutron dose of 100 rads would produce a net reading of 2.5 mR/h immediately after exposure on an individual weighing 200 pounds. Since "quick" sort methods are typically applied within a few hours of the accident, decay corrections can be ignored.

Table 5.31 Survey Instrument Readings on the Body after an Accident

Weight of Subject (Pounds)	Pancake GM Net Reading (cpm) for a 10 rad Neutron Dose			RO-3 Net Reading (mR/h) for a 100 rad Neutron Dose		
	Immediately After Exposure	4 Hours After Exposure	15 Hours After Exposure	Immediately After Exposure	4 Hours After Exposure	15 Hours After Exposure
125	568	472	284	1.6	1.3	0.8
150	682	567	341	1.9	1.6	0.9
175	795	661	398	2.2	1.8	1.1
200	909	756	455	2.5	2.1	1.2
225	1023	850	511	2.8	2.3	1.4
250	1136	945	568	3.1	2.6	1.6

The data in Table 5.31 are based on equations 5.16 and 5.17. It should be noted that absorbed dose values determined from these formulae represent only the neutron first collision dose. The dose from gamma rays produced by capture reactions within the body is not included. Depending on the incident neutron energy spectrum, capture gammas may contribute as much as 50% of the total absorbed dose attributable to the incident neutrons (Takahashi, Endo and Yamaguchi, 2003). It should also be noted that the above relationships and the data shown in Table 5.31 are based only on ²⁴Na activity in the body and do not account for activated ³⁸Cl present during the first four hours after exposure. Capture of thermal neutrons by ³⁷Cl produces ³⁸Cl which decays with a 37 minute half life, and emits 2.17 MeV gammas (47% abundance) and 1.64 MeV gammas (38% abundance). Immediately following exposure, approximately 50% of the blood activity will be from ³⁸Cl (Hankins 1980b). Because ³⁸Cl activity is not accounted for in the above formulae, the error in dose estimates based on these formulae can be as large as 50% for measurements made immediately after an

accident (Mettler and Voelz, 2001) but becomes insignificant for measurements made two or more hours after exposure.

Large uncertainties are inherent in dose estimates obtained with the formulae above. In addition to the unaccounted for capture gamma dose and interference from ^{38}Cl , uncertainties in the incident neutron energy spectrum can cause errors as large as a factor of 3 (Takahashi, Endo and Yamaguchi, 2003), and uncertainties in orientation of the body within the field can cause errors as large as a factor of 1.8 (Cross, 1981). The formulae above are based on unmoderated neutrons and AP exposure geometry. To the extent that actual exposure conditions involve scattered neutrons (particularly from the floor), the above formulae will tend to overestimate absorbed dose. To the extent that exposure is from the side rather than front of the body, the above formulae will tend to underestimate the absorbed dose. Therefore, these two errors tend to counteract each other. Nevertheless, given all the uncertainties involved at the time of a quick sort, any dose estimate obtained with the above methods should be considered a rough approximation, with potential error as large as a factor of 5.

5.11.4 Analysis of Physical and Biological Samples

Neutron radiation present in any criticality event will activate nearby physical and biological materials, depending on the composition (i.e., atomic elements) of the material. Once activated, these materials are radioactive. Analysis of these radioactive materials provides evidence of the fluence and energy of neutron radiation resulting from the criticality. Knowledge of the neutron fluence and energy spectrum enables the dose to personnel near the criticality event to be estimated.

Analysis of Metallic Samples

Metal objects carried by employees can be good indicators of exposure to neutron radiation due to activation of the metal. If samples of metallic objects carried by the person (coins, buckles, eyeglass frames, etc.) are submitted to HEDP staff, the samples can be counted using gamma spectroscopic capabilities, and an assessment of neutron exposure can be made.

Analysis of Biological Samples

Standard man (70 kg) contains about 100 g of ^{23}Na (ICRP 1974). By neutron activation, the sodium is transformed into radioactive ^{24}Na , which emits an energetic gamma ray that can be easily detected. Depending on the type of technique employed, concentrations as low as $3.9 \times 10^{-5} \mu\text{Ci/ml}$ with a 30-minute counting time or $9.4 \times 10^{-5} \mu\text{Ci/ml}$ with a 10-minute counting time can be measured. Similarly, hair samples can be analyzed for ^{32}P , produced by activation of ^{32}S , to determine an employee's fast neutron exposure (i.e., energy $>2.9 \text{ MeV}$). Hair samples are particularly good to determine orientation of the body during exposure if hair samples can be obtained from different locations. Analysis of blood for chromosome aberration may be a useful technique to assist in the estimation of total dose.

Blood Sodium Dose Conversion Factors

The following neutron dose conversion factors (K) for blood sodium activity were empirically determined during simulated blood sodium experiments at the HPRR at ORNL (doses are given in tissue kerma):

Bare spectrum: $K = 0.168 \pm 0.004 \text{ rad/dpm-mg}$

Steel shield:	$K = 0.145 \pm 0.006$ rad/dpm-mg
Concrete shield:	$K = 0.116 \pm 0.116$ rad/dpm-mg
Lucite™ shield:	$K = 0.088 \pm 0.007$ rad/dpm-mg

5.11.5 Interpretation of Personnel Dosimeter Results After a Criticality Event

Analysis of personnel dosimeters for all employees involved in a criticality will be conducted quickly following any criticality. Typically, normal procedures are used to initially estimate the radiation dose measured by each dosimeter. Additional interpretation is made when dose and spectrum measurements become available from the FNAD nearest to the event location and the PNADs worn by affected staff. When evaluating the HSD or HCND results after a criticality, the dose and spectrum information obtained from the PNADs and FNADs allows corrections to be made to the reported neutron dose and dose equivalent. It is expected that each PNAD and FNAD will provide different information because of the location of the respective FNADs and affected workers' positions and movements during the criticality event. Interpretation of dose for each affected person will be necessary on a case-by-case basis.

Laboratory measurements using progressive levels of moderation in ^{252}Cf and PuF_4 spectra, have shown that the TLD albedo capability in the HCND can estimate dose with reasonable accuracy over a wide range of neutron spectra.

5.11.6 Assessment of Dose After a Criticality Event

Early estimates of the severity of an exposure to prompt radiation emitted by a criticality event are estimated based on results of portable survey measurements, personnel dosimeters, and in vivo bioassay measurements. Parameters and dose conversion factors used to determine the dose from PNADs and FNADs are generally based on prior calibration and/or intercomparison testing of Hanford PNADs, FNADs, or data from NCRP Report No. 57 (1978) and the International Atomic Energy Agency Technical Report No. 211 (IAEA 1982).

Later estimates of dose will be based on many additional measurements to confirm and further quantify the neutron, photon, and total doses received by exposed individuals. Measurements likely to be available include the following:

- additional analysis of personnel dosimeter response characteristics
- analysis of PNADs and FNADs
- additional analysis whole body counts for ^{24}Na activation
- blood sample analysis for ^{24}Na activation
- hair sample analysis for ^{32}P activation
- chromosome aberration analysis.

Analysis of dose based on results from HSDs, HCNDs, and PNADs is the preferred method of determining dose because the dosimeters are worn by the person and dosimeter response data for specific neutron spectra are available. Results from FNADs located nearby may be used to provide estimates of dose in the cases where results of the personnel dosimeters and PNADs are compromised

because of shielding, etc., and cannot be directly used. In vivo and in vitro (blood) measurements of ^{24}Na activation should be performed within 2- to 24 hours of the exposure, whereas the ^{32}P can be counted and analyzed several days after the exposure without compromising detection levels and accuracy. In general, it is important to recognize that there is a trade-off between the promptness by which the laboratory analyses of neutron activation samples can be made and the accuracy of the results. Chromosome aberration analysis should be considered when preliminary dose estimates exceed 10 rad.

Response protocols are expected to vary according to the type of measurement and analysis required and the likely severity of the exposure, as indicated by results from quick-sort surveys, personnel dosimeters, and in vivo counts.

Gamma Ray Dose

The gamma ray dose is determined from the personnel TLD. The TLDs are processed and analyzed in accordance with standard TLD procedures. The gamma ray dose estimated from the personnel dosimeters may need to be corrected for attenuation through the body if the individual was facing away from the source of the exposure. This determination is based upon hair sulfur activation results and interviews with the victims.

Neutron Dose

In the case of nuclear events, acute biological effects are predominant and quality factors are not relevant. Neutron dose should be assessed in rad and should refer to the maximum absorbed dose due to incident neutrons. The quick-sort procedure and the whole body count provide estimates of neutron dose only. Early estimates of the neutron dose may also be obtained by other means, such as results from Hanford standard and/or combination neutron personnel dosimeters, and the PNAD.

Neutron dose assessment procedures for HSDs, HCNDs, PNADs, and FNADs are maintained in PNL-MA-841, *Hanford External Dosimetry Procedures Manual*.

Chromosome Aberration

Chromosome aberration analysis may be a useful technique to assist in the estimation of total dose after a nuclear event. However, the amount of chromosome damage produced in human blood lymphocytes depends on the gamma to neutron dose ratio and the gamma dose rate. Chromosome aberration analysis is recommended if an exposure of >5 rad is indicated by in-vivo analysis, blood, or hair radiochemical analyses. Chromosome aberration analysis should be considered when preliminary dose estimates exceed 10 rad.

5.12 Useful Dose Range for Hanford Dosimeters

The useful dose range is defined as the range of delivered dose for which meaningful dose measurement can be made with a dosimeter that is routinely processed without special procedures. For any given type and energy of radiation, this range may be considered to extend from the lower limit of detection to the dose that produces the maximum possible PMT current without substantial non-linearity (e.g. loss of signal from saturation). [With advanced warning of a large dose being delivered to a dosimeter, special measures such as reduced PMT gain or use of neutral density filters can be implemented to extend the range of dose interpretation by an order of magnitude or more up to a maximum of about 50,000 rads, beyond which, the supralinearity correction function becomes double valued.] The point at which the PMT cannot deliver peak current and loss of signal begins is evidenced by a clipping or flattening of the top of the glow curve. For the standard ½ inch diameter PMT used in Harshaw 6600 and 8800 TLD readers, with high voltage set to achieve a nominal sensitivity of approximately 0.2 nC/mR, the maximum integrated current from a normal shaped glow curve was determined to be approximately 442 µC. The nominal sensitivity is based on readout of oven annealed 100 mg/cm² TLD 700 chips using standard TTP, per standard HEDP reader calibration practice. Using the upper limit of useful PMT response, and the fundamental response characteristics of HEDP dosimeter elements to various types and energies of radiation at normal occupational dose levels, the delivered doses for each type and energy of radiation corresponding to PMT saturation were determined for each dosimeter type. Based on this analysis, a summary of the maximum measurable doses (rounded to the nearest 100 rem) for selected HEDP dosimeters and radiation types is given in Table 5.32. The accuracy that is theoretically obtainable at these dose levels is ± 30% at a one-sigma confidence level. A more complete set of results with details of the measurements and calculations is documented in HEDP files. ^(a)

Table 5.32 Maximum Measurable Dose for Hanford Dosimeters

Radiation			Maximum Dose		
Radiation Type	Source	Average Energy (keV)	HSD Deep rem	HCND Deep rem	Ring Shallow rem
x-ray	NIST M30 Technique	20	500	500	1400
x-ray	NIST M150 Technique	73	1000	1000	1400
x-ray	NIST H150 Technique	118	1100	1100	1600
gamma	¹³⁷ Cs	662	1200	1200	1900
beta	⁹⁰ Y	931	-	-	1800
beta	²⁰⁴ Tl	267	-	-	8300
neutrons	Unmoderated ²⁵² Cf	2100	1600	1600	-
neutrons	D ₂ O Moderated ²⁵² Cf	550	200	200	-

For the HSD, the maximum measurable dose at all depths (shallow, eye and

(a) B. A. Rathbone, "Useful Range of Hanford Dosimeters," September 25, 2002, letter to HEDP file.

deep) are provided in Table 5.33. To determine the maximum measurable shallow, eye or deep dose for a mixture of radiation types where the relative contribution of each type to the total dose is known, equation 5.18 may be used in conjunction with the data in Table 5.33.

$$H_{\max} = \frac{1}{\sum_{i=1}^n \frac{w_i}{L_i}} \quad (\text{eqn. 5.18})$$

Where:

- H_{\max} = maximum measurable dose for the mixture
- w_i = fraction of total dose contributed by pure radiation type i
- L_i = maximum measurable dose (limit) for pure radiation type i
- n = number of radiation types in the mixture

NOTE: For any given mixture, H_{\max} must be calculated independently for shallow dose, eye dose and deep dose.

Table 5.33 Maximum Measurable Dose for HSD at Various Depths.

Radiation			Maximum Measurable Dose (rem)		
Radiation Type	Source	Average Energy (keV)	Shallow	Eye	Deep
photon	M30	20	1151	830	478
photon	M60	34	1008	960	837
photon	S60	38	914	914	866
photon	M100	51	872	885	886
photon	Am-241	59	849	910	915
photon	M150	73	904	939	980
photon	H150	118	1034	1061	1108
photon	Cs-137	662	1178	1179	1178
beta	Y-90	931	1668	741	
beta	Tl-204	267	3036		
neutrons only	Cf-252 U	2100			1641
neutrons only	Cf-252 M	550			191

THIS PAGE INTENTIONALLY LEFT BLANK

6.0 Operational Basis

The operational practices involved in the day-to-day administration of an external dosimetry program that are described in this chapter have been developed for use at Hanford. As such, they have been reviewed and concurred to by Hanford radiological control organizations through the HPDAC (described in Chapter 2). Non-Hanford users can subscribe to the Hanford practices as documented here or document their own practices in a site-specific document. To ensure accurate measurement of dose, the practices described here regarding how the dosimeters should be used, are strongly recommended for non-Hanford users as well. Other practices such as selection of persons to be monitored are documented here to support the RPPs of Hanford contractors. Such practices should be documented by the non-Hanford user to comply with their own regulatory and other requirements.

Hanford contractor radiation protection organizations are responsible for field dosimetry practices, including monitoring of exposure conditions in the work environment, controlling worker dose, and properly using HEDP dosimetry and technical support. Radiation protection organizations select the personnel to be monitored, the type of dosimeter to be used, the exchange frequency, and the facility calibration code to use for processing. They maintain portable instrument survey data of the work environments, and conduct evaluations of any lost or missing dosimeter results for their personnel. They are also responsible for the contractor-specific ALARA programs and Area Monitoring programs. HEDP Dosimetrists work closely with contractor radiation protection organizations regarding several operational aspects of the dosimetry program including technical support for special dosimetry applications, dose investigations and identifying the need for field specific correction factors and/or dose algorithms where necessary. HEDP is responsible for maintaining detailed records of dosimeter processing activities and data, including dosimeter results, dose assessments, QA, QC, training, staff qualifications, equipment maintenance and calibration.

6.1 Occupational Dose

DOE requires the dosimetry program to assess only personnel dose resulting from occupational exposure. Dose from medical procedures or from natural background radiation is not to be included in the recorded dose. To help achieve this objective, Hanford worker training includes the statement that personnel are to contact their respective radiation protection organization representative whenever there is a possibility of dose from non-occupational circumstances, such as medical procedures. In these cases, the radiation protection representative together with the person's supervisor will develop an approach to ensure that non-occupational dose is not recorded.

Similarly, Hanford worker training includes instruction to not wear dosimeters while having medical procedures performed (e.g. x-rays) or to take dosimeters with them while on travel (e.g. in checked baggage or carry-on baggage submitted to x-ray security screening devices). As part of the external dosimetry

dose calculation methodology, Hanford background functions are used to compensate for the dosimeter response from naturally occurring environmental radiation (see Chapter 5). For offsite customers, this includes the use of site specific background functions and the use of transit control dosimeters in dosimeter shipments to measure abnormal transit dose.

6.2 Selection of Individuals to be Monitored

In accordance with 10CFR835.402(a) (DOE 1998c), personnel dosimeters shall as a minimum, be provided to and used by:

(1) Radiological workers who, under typical conditions, are likely to receive an external dose greater than or equal to one or more of the following in a year:

- Whole body 100 mrem (effective dose equivalent)
- Lens of eye 1500 mrem (eye dose equivalent)
- Skin 5000 mrem (shallow dose equivalent)
- Extremities 5000 mrem (shallow dose equivalent)

(2) Declared pregnant workers who are likely to receive from external sources a dose equivalent to the embryo/fetus in excess of 50 mrem.

(3) Occupationally exposed minors likely to receive an external dose greater than or equal to one or more of the following in a year:

- Whole body 50 mrem (effective dose equivalent)
- Lens of eye 750 mrem (eye dose equivalent)
- Skin 2500 mrem (shallow dose equivalent)
- Extremities 2500 mrem (shallow dose equivalent)

(4) Members of the public entering a controlled area likely to receive a dose to the whole body in excess of 50 mrem (effective dose equivalent) in a year from external radiation

(5) Individuals entering a high or very high radiation area

In accordance with the Hanford Radiological Health and Safety Document (DOE 2001), personnel dosimeters shall be provided to and used by:

(1) Non-occupationally exposed minors entering RBAs or RMAs

Additional dosimeters may be issued as contractor radiation protection organizations deem appropriate. Contractor radiation protection organizations are responsible for assigning and exchanging dosimeters and determining the type of dosimeter to be assigned in accordance with the guidance in this manual.

6.3 Selection of Dosimeter Types to Use

Two types of whole body dosimeter (HSD and HCND) are available for issue to individuals at Hanford. The HSD is designed to measure shallow, eye, and deep dose equivalent from mixtures of beta and photon radiation fields. In addition, the dosimeter has a neutron-sensitive TLD-600 phosphor for neutron detection. Although not intended as the primary dosimeter for measuring neutron dose, the HSD has been DOELAP accredited in neutron exposure categories and may be used for limited monitoring of individuals who are *not likely* to receive more than 100 mrem of neutron dose per year. Individuals who are *likely* to receive more than 100 mrem of neutron dose per year should be issued a HCND, which provides a more accurate measurement of neutron dose. In addition, individuals who routinely receive more than 100 mrem neutron dose per year *reported* on an HSD should be issued a HCND. The HSD generally provides a conservative measure of neutron dose. However, for most applications, which typically involve a large component of scattered neutrons, the HSD results tend to be excessively conservative (factor of 4 or more), increasing the potential for exceeding administrative control levels based on reported dose results when significant neutron exposure is involved. The HCND offers improved accuracy for beta-gamma dosimetry in the presence of neutrons as well as improved neutron dosimetry. The capabilities of the HSD and HCND are discussed in Section 5.4 and Section 5.5 respectively.

Three types of extremity dosimeter are DOELAP accredited and available for routine use at Hanford (HRD, EXT-RAD, and HSD Extremity). The design features and response characteristics of these dosimeters are discussed in detail in Chapter 5. The HRD is suitable for typical work at Hanford involving exposure to photon radiation and high energy beta radiation. However, if the exposure involves low energy beta radiation, or a mixture of low energy beta radiation and photon radiation where more than half of the dose is from the low energy beta radiation, the EXT-RAD should be used because of improved sensitivity and less energy dependence for beta radiations. In such a situation, the HRD may be used with a suitable field specific correction factor, but the factor may be quite large, resulting in poor detection thresholds and high variability of results at low doses. One situation where special correction factors may be necessary with the HRD is the monitoring of extremity dose in beta-gamma fields produced by unshielded surface contamination consisting primarily of $^{90}\text{Sr}/^{90}\text{Y}/^{137}\text{Cs}$ activity where the $^{90}\text{Sr}:^{137}\text{Cs}$ activity ratio is less than 1:1 (Rathbone et. al. 2002). For this activity profile, if the ring is worn underneath $> 90 \text{ mg/cm}^2$ of glove material or $< 50 \text{ mg/cm}^2$ of glove material, the ring may under respond. See Section 5.8.7.

The HRD and EXT-RAD are suitable for use in PFP photon-neutron fields when processed with the default calibration code 00 (applies calibration factor = 2.0). For use in other photon-neutron fields, a field specific correction factor will need to be determined to compensate for the undetected neutron dose. The HSD Extremity dosimeter is useful for monitoring forearms and ankles, and for general extremity monitoring when beta and photon energies are largely unknown or rudimentary detection and measurement of neutrons is desired.

Dosimetry for specialized applications is also available upon request. An example is the chipstrate used as a band-aid type dosimeter (i.e. without EXT-

RAD strap) for monitoring body locations that are difficult to attach routine dosimetry to (e.g. soles of feet, tips of fingers, eyes).

6.4 Dosimetry Limitations

HEDP dosimetry processing methods and dose calculation algorithms are based primarily on laboratory measurements with traceable calibration sources as is DOELAP performance testing. However, because of limitations in dosimetry technology, laboratory based algorithms are not capable of providing accurate results for all possible field conditions. Because actual field exposure geometries and energy spectra are sometimes difficult to simulate in the laboratory, workplace measurements are sometimes necessary to establish field specific correction factors and/or dose algorithms. Such correction factors and algorithms have already been established for some Hanford applications. However, all possible dosimetry applications at Hanford that may warrant use of special dose algorithms and/or correction factors have not been identified or addressed in this manual. In addition, because of changes in field practices or workplace conditions, existing field specific correction factors and algorithms need to be re-evaluated from time to time. Therefore, Hanford contractor radiation protection organizations should have a mechanism for identifying workplace conditions and dosimetry applications within their facilities that fall outside the established capability of the Hanford dosimetry system and for identifying changes in practices or workplace conditions that may invalidate field specific correction factors and algorithms currently in use. Information in this manual regarding the response characteristics, capabilities and limitations of the various dosimeter designs has been provided for this purpose. Hanford contractor radiation protection organizations should request technical support from HEDP as necessary to meet this objective. Table 6.1 summarizes the intended applications and limitations for Hanford dosimeters and identifies general types of applications requiring special calibration factors.

6.5 Dose Reporting Threshold

Established dose reporting thresholds are applied by dose reporting software to the calculated dose results that reside in the ED database. (*Calculated* dose results in the ED database may be any real number greater than or equal to zero.) The dosimeter dose reporting thresholds are shown in Table 6.2 below. These levels are less than 1% of the respective DOE dose limits. Doses are reported to the nearest mrem (i.e., 11, 12, 111, 1112, etc.). In the case of the HCND, the shallow, eye, and deep photon dose are reported by the 8825 component and the neutron dose is reported by the 8816 component independently (i.e., a separate record).

It should be noted that the calculated LLDs for a given dosimeter type vary with radiation type, depth of interest, and wear period (see Chapter 5). Typically, radiation types for which the dosimeter is less sensitive, produce larger LLDs. Longer wear periods generally correspond to larger LLDs.

Table 6.1 Summary of Dosimeter Applications and Limitations

Dosimeter Type	Facility Cal Code ^(a)	Radiations Measured	Intended Application	Precautions	Limitations
HSD	00	photons 16 keV - 5 MeV, beta 250 keV – 2.2 MeV, neutrons 0.025 eV - 5 MeV	Routine beta-gamma dosimetry, limited low dose neutron dosimetry.	Dosimeter under-responds to betas with energies < 250 keV. Dosimeter significantly over-responds to moderated neutrons.	Should not be used for neutron monitoring if neutron dose is expected to be greater than 100 mrem/y. Special facility cal code required if beta energy < 250 keV average.
HCND	00	photons 16 keV - 5 MeV, beta 250 keV - 2200 keV, neutrons 0.025 eV - 5 MeV	Routine beta-gamma dosimetry, routine neutron dosimetry at Hanford facilities <i>other than</i> PFP	Dosimeter under-responds to betas with energies < 250 keV	Should not be used for neutron monitoring at PFP. Special facility calibration code required if beta energy < 250 keV average.
HCND	01	photons 16 keV - 5 MeV, beta 250 keV - 2200 keV, neutrons 0.025 eV - 5 MeV	Routine beta-gamma dosimetry, routine neutron dosimetry at PFP.	Dosimeter under-responds to betas with energies < 250 keV. Dosimeter may under-respond for neutrons if used outside PFP	Should not be used for neutron monitoring outside PFP. Special facility cal code required if beta energy < 250 keV average.
HRD	00	photons 16 keV - 5 MeV, beta > 400 keV	Routine beta-gamma dosimetry with energetic beta emitters. Suitable for work with mixed fission product (MFP) waste having Sr:Cs activity ratio > 1:1 Routine gamma-neutron dosimetry for PFP workers.	Dosimeter under-responds to betas with average energies < 400 keV. EXT-RAD is preferred dosimeter for beta < 400 keV avg. Dosimeter does not respond to neutrons. Neutron dose is assigned using assumed neutron/gamma ratio = 2.	Should not be used if beta energy < 400 keV average (unless more than half of the extremity dose will be from photon radiation). Should not be used if Sr:Cs activity ratio < 1:1 When used in neutron fields, lead content of gloves should be less than one half value layer. Otherwise, n/γ ratio inside glove may be > 2 and special field calibrations may be necessary.
EXT-RAD	00	photons 16 keV - 5 MeV, beta > 200 keV	Special beta-gamma dosimetry with low energy beta emitters. Best choice for beta intensive work with unknown beta energies.	Dosimeter under-responds to betas with energies < 200 keV. However, any needed correction factor will be much smaller than for HRD and risk of under estimating dose is much smaller.	Should not be used with beta emitters < 200 keV average (unless more than half of the extremity dose will be from photon radiation. <i>or</i> a special facility cal code is used).
HSD Extremity	00	photons 16 keV - 5 MeV, beta 250 keV - 2200 keV, neutrons 0.025 eV - 5 MeV	Routine beta-gamma dosimetry and limited neutron dosimetry of wrists or ankles.	Dosimeter under-responds to betas with energies < 250 keV. Dosimeter has energy dependent response to neutrons.	Special facility cal code required if beta energy < 250 keV average. Special facility cal code required if used for neutron monitoring.

(a) Facility calibration code: A two digit code entered into REX when the dosimeter is returned for processing. This code tells the external dosimetry dose calculation software which algorithm and/or which correction factor to apply when calculating dose. The Intended Applications, Precautions, and Limitations, apply to the combination of Dosimeter Type and Facility Calibration Code shown in the first two columns. The default code applied by REX is 00. The calibration codes listed have been established to support most routine applications at Hanford. Additional calibration codes can be set up as needed to support special applications involving low energy beta emitters and/or unique neutron monitoring requirements.

The Hanford practice for use of reporting thresholds was discussed extensively by the HPDAC.^(a) The basic issue centered around whether to use multiple reporting thresholds corresponding to detection thresholds, or use a simple threshold corresponding to practice at some other DOE sites and past practice at Hanford, or use no thresholds at all. The question of which statistical concept (L_C , L_D , L_Q , or other) would be appropriate to use for a reporting threshold was considered. This nomenclature was first proposed by Lloyd Currie (Currie 1968) and is still widely used today. Questions of what probability for type I and type II errors would be acceptable were discussed. Questions of “unreported dose” were considered. Potential impacts of changes in threshold on collective dose reported for Hanford contractors were evaluated. A policy decision was made by DOE-RL (Radiological Control Steering Committee) to continue using the simplified scheme of 10 mrem thresholds already in place^(b) with the exception of neutron dose on 8816 TLDs (discussed below). Given the fact that the calculated LLDs are for the most part within 10 mrem of the reporting thresholds, regardless of exchange frequency or radiation type, the added complexity of applying multiple thresholds was not considered necessary. Therefore, in the interest of simplicity and consistency with past Hanford practice, a single reporting threshold has been adopted for each dose quantity and dosimeter type regardless of exchange period.

Because the LLD for neutron TLDs depends greatly upon the neutron energy spectra involved, an a priori *reporting* threshold is not applied to the *calculated dose* result. However, the 8816 algorithm *does* apply a threshold of sorts for *calculation* of dose. A minimum level of net neutron signal (mR equivalent) is necessary on each of the three TLD 600 chips before meaningful element ratio analysis and dose calculation can be performed. If sufficient TL signal is not present, then the algorithm sets the “calculated” dose to zero mrem. Based on neutron energy spectra encountered in Hanford facilities, this calculation threshold equates to reported doses between approximately one and ten mrem. DOE-RL (Radiological Control Steering Committee) reviewed and approved this new approach to reporting thresholds for neutron dose on the HCND in September 1999.^(c) Removal of the a priori reporting threshold that had been applied to calculated neutron dose on HCNDs was implemented October 1, 1999.

-
- (a) D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on February 23, 1999.”
D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on March 23, 1999.”
D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on July 13, 1999.”
D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on August 17, 1999.”
D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on September 21, 1999.”
D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on October 12, 1999.”
- (b) D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on March 23, 1999.”
- (c) D. E. Bihl, “Minutes of the Hanford Personnel Dosimetry Advisory Committee Meeting Held on September 21, 1999.”

Copies of HPDAC minutes are retained in the Hanford Radiation Records Historical File.

Table 6.2. Dose Reporting Thresholds (mrem)

	HSD	8825 HCND	8816 HCND	HRD	EXT- RAD	HSD Extremity
Shallow	10 ^(a)	10 ^(a)	n/a	10	10	10 ^(a)
Eye	10	10	n/a	n/a	n/a	10 ^(c)
Deep Photon	10	10	n/a	n/a	n/a	10 ^(c)
Neutron	20	n/a	1-10 ^(b)	n/a	n/a	20

(a) 50 mrem for pure beta radiation

(b) Minimum reported dose varies with neutron energy and corresponds to a net neutron signal on TLD 600 = 10 mR equivalent.

(c) These results are reported but not used for the extremity dose of record.

6.6 Dosimeter Exchange and Selection of Frequency

There are four categories of dosimeter assignment at Hanford:

- temporary
- monthly
- quarterly
- annually.

Hanford contractor dosimetry organizations are responsible for determining the dosimeter exchange frequency for each assigned dosimeter. The basis for the assignment is primarily the anticipated dose to be received.

When determining a dosimeter exchange frequency, consideration should be given to the potential for unreported dose as a result of the reporting thresholds described above (Table 6.2). For example, assignment of a monthly dosimeter with a 10 mrem reporting threshold to an individual who receives slightly less than 10 mrem each month could (theoretically) result in 0 mrem reported dose for the year when in fact the actual dose was nearly 120 mrem. This individual might be better served by a quarterly or annual dosimeter. However, statistically speaking, in this example the *most probable* reported dose will be 58% of the true dose or about 70 mrem. The probability of the total reported dose being less than 20 mrem (i.e. unreported dose exceeding 100 mrem) for 12 dosimeters that actually received 10 mrem, is less than 0.5%. For a very large number of dosimeters receiving exactly 10 mrem and being processed with a reporting threshold of 10 mrem, the total reported dose will be very close to 58% of the true dose. This analysis is based on an assumed normal distribution of *calculated* dose results with a mean of 10 mrem and a standard deviation of 2 mrem for dosimeters that were exposed to exactly 10 mrem. ^(a) This assumption is a

(a) D. J. Bates, "Description of Methods Used for Reporting Limit Effects", IOM to B. A. Rathbone, June 28, 2004, HEDP file.

conservative approximation for monthly dosimeters processed with the current dosimetry system at Hanford.

When determining a dosimeter exchange frequency, consideration should also be given to minimizing uncertainty in calendar year recorded dose to the extent practicable. For example, the uncertainty in a single 8816 neutron dosimeter result reported for a PFP worker is approximately $\pm 40\%$ and does not vary substantially with dose level as long as the dose is well above background. If this is an annual dosimeter, then the uncertainty in calendar year recorded dose is $\pm 40\%$. However, if the annual dose is divided approximately equally among four quarterly dosimeters, the uncertainty in the recorded calendar year total will be approximately $\pm 20\%$. A person receiving significant neutron dose might be better served with four quarterly dosimeters than a single annual dosimeter.

In addition to the routine exchange, consideration should be given to exchanging dosimeters when any of the following is suspected of having occurred:

- Damaged dosimeter (Mylar window, red tinted bar code window, external case)
- Breach of holder integrity (e.g. card falls out of holder or is removed from holder)
- Contamination of dosimeter (evaluate possible beta reading from contamination on Mylar window and subtract from dose result)
- Exposure of dosimeter to x-rays or dose from medical isotopes.
- Improper orientation of dosimeter during high dose work.
- Loss of control of dosimeter by user (e.g. dosimeter found on ground in parking lot).
- Unplanned use of dosimeter in radiation fields requiring special calibration factors. (e.g. work with pure beta emitters < 250 keV average)
- Exposure of dosimeter to excessive temperatures (e.g. above 50 C)

6.7 Dosimeter Wearing Practices

The HSD and HCND are used to measure the beta-photon components of shallow, eye, and deep dose equivalent, plus neutron dose equivalent. For routine use, (i.e. uniform radiation fields), these dosimeters should be worn on the front of the torso, between the neck and waist. If a work task requires orientation of the individual with their back to the source for a significant amount of exposure, then the dosimeter should be relocated to the back, or two dosimeters (one front and one back) used for these jobs.

For the HCND, Hanford practice is to wear the dosimeter within 1.27 cm (1/2 inch) of the body at all times. Studies using a bare ^{252}Cf neutron source

irradiation have shown a significant decrease in the TLD response of the HCND when the dosimeter is located more than 1.27 cm from the surface of a phantom (see Chapter 5). For lower-energy neutron fields, such as those typical of Hanford's Plutonium Finishing Plant (PFP), an even greater reduction in measured dose would be expected. However, the angular response characteristics described in Chapter 5 may tend to minimize the under-response under these conditions.

It is also important to understand the dependency of the HCND response on the geometry of the backscattering material. The HCND requires a large volume of hydrogenous backscatter medium (e.g. 5 – 10 liters) and the dosimeter must be at least 10 cm from the edge of the medium before the dosimeter response becomes adequate. This is a particular concern if attempts are made to measure the neutron dose by placing the HCND on different parts of the body (i.e., arms, legs, head, etc.). In these situations allowances should be made for the fact that the measured dose will under estimate the true dose.

General guidance on wearing extremity dosimeters includes the requirement for the dosimeter to be worn in a manner to maximize the recorded dose. For example, a ring dosimeter should be worn facing the palm of the hand if vials containing radioactive material are being handled. Because of the wide variety of possible circumstances, facility radiation protection staffs are directly involved in determining how and where to wear the dosimeters.

6.7.1 Dosimeter Use with Protective Clothing

When protective clothing is used, and the radiation field is primarily penetrating radiation, whole body dosimeters may generally be worn under the protective clothing such as on a lanyard or in a pocket. When a substantial non-penetrating component (e.g. beta radiation, or photon radiation < 20 keV average) is likely to be present, and the eyes or substantial areas of skin are unprotected (e.g., the face and neck), then the dosimeter should be placed on the outside of the protective clothing to ensure proper measurement of skin and lens of eye dose. When wearing whole body dosimetry outside protective clothing, it will be necessary to ensure that the dosimeter does not become contaminated while preserving the shallow dose response of the dosimeter (e.g., by using a thin plastic bag). When a single whole body dosimeter must be used in conjunction with a bullet proof protective vest, it should be worn on the outside of the vest. For bullet proof protective vests, an HEDP dosimetrist should be consulted regarding the potential effects of vest composition on dosimeter response.

6.7.2 Dosimeter Use with Lead Aprons or Vests for Work in Uniform External Fields

Lead aprons or vests are potentially useful ALARA tools. In terms of dose reduction to the body, lead aprons have a relatively small shielding effect for neutrons (< 10% reduction) but can be very effective for low energy photons. A lead apron with a rated effective thickness of 0.5 mm of Pb @ 85 kVp results in essentially no reduction in shallow, eye or deep dose for 662 keV photons, but an approximate 10 fold reduction for 59 keV photons, and greater than a 100 fold

reduction for 17 keV photons.^(a) In some Hanford environments, photons < 100 keV have been shown to contribute a large enough fraction of the photon dose to make lead aprons worth consideration. At PFP locations where plutonium is sometimes stored in thin sealed steel cans,, an apparent dose reduction factor between 2.5 and 4.0 has been measured under one 0.5 mm layer of lead apron. The photon response of HSD and HCND under a lead apron is considered to be relatively accurate and representative of the dose received by portions of the body under the apron. However, when worn on top of a lead apron, the photon response of these dosimeters may be affected and their results may need to be corrected (see discussion below). HSD and HCND neutron response is relatively unaffected whether the dosimeters are worn on top of or underneath the lead apron and does not need correction.

Two recommended methods for use of dosimeters with lead aprons are described in the sections below. Both methods apply to situations where the external radiation field is uniform and the only non-uniformity in dose to the body is that created by the presence of the lead apron. Additional dosimeters may be required for non-uniform external fields and each situation should be evaluated on a case by case basis.

6.7.2.1 Use of a Single Dosimeter Outside the Lead Apron

When a lead apron is to be used, but the dose rates are generally low, a single whole body dosimeter should be worn on the outside of the apron between the neck and waist. This method is recommended when low doses are expected, conservatism in the dose of record can be tolerated, and the potential reduction in recorded dose afforded by multipack use with EDE calculation does not outweigh the costs of tracking, exchanging, and processing multipacks. Use of a single chest dosimeter outside the apron is recommended when the photon eye dose to be received while wearing the lead aprons is expected to be less than 11.74 mrem/d x dosimeter wear period (days) or to be less than 200 mrem total. [The expected photon eye dose rate will be roughly equivalent to the closed window CP reading and can be readily determined from survey data.] If the expected photon eye dose exceeds these guidelines then use of a multipack should be considered. These guidelines correspond to the dose levels at which corrections to the photon eye dose reported by the HSD or 8825BP component of the HCND may be necessary due to under-response of the dosimeter to low energy photons when worn on the outside of the lead apron.

When a single HSD or HCND dosimeter is worn on the outside of a lead apron, whole body dose can generally be assigned on the basis of the reported dosimeter results without correction (except as noted below) with the understanding that the reported dose may overestimate the true whole body (EDE) dose depending on the shielding effectiveness of the apron and the number of body compartments shielded by the apron. If the external exposure is significant, the conservatism may be excessive and unacceptable. To reduce the overestimate and take credit for the reduction in dose afforded by the apron, the dose of record could in

(a) B. A. Rathbone, "Recommendations on the Use of HCNDs with Lead Aprons at PFP" September 30, 2003, Letter to R. L. Hill (in HEDP files).

theory, be based on calculated EDE using the compartment weighting factors in Table 6.4. However, the calculation requires knowledge of two things: 1) knowledge of the percent dose reduction afforded by the apron and 2) knowledge of the amount of exposure received while wearing the apron (or the fraction of the dosimeter reading obtained while wearing the apron). In actual practice, it is rare that the second piece of information is known or readily obtainable. This is particularly true when a routine chest dosimeter is only occasionally used with a lead apron. Therefore, when significant exposure is anticipated with lead aprons, dedicated multipacks as described below are a more practical and preferred method of providing an accurate estimate of whole body dose and avoiding excessive conservatism (see Section 6.7.2.2 below). Alternate guidance on calculating EDE when protective lead aprons are used, is given in NCRP Report No 122 (NCRP 1995).

When the HSD or HCND is worn outside the apron, it will provide acceptable neutron dose results for all parts of the body, but it may under estimate (depending on energy) the true shallow, eye, and deep photon dose to *portions of the body not shielded by the apron.*^(a) When worn on top of a lead apron, the HSD and the 8825BP component of the HCND report approximately 90% of the true dose to unshielded body parts for 17 keV photons, 65% of the true dose to unshielded body parts for 59 keV photons, and approximately 100% of the true dose to unshielded body parts for 662 keV photons.

This observed under response might be explained by the selective removal of backscattered photons by the lead apron, preventing them from reaching the dosimeter. For incident photons less than 100 keV, a large part of a dosimeter's response is normally from photons backscattered from the body. Backscattering of photons reduces their energy. Incident photons that are sufficiently energetic to penetrate the lead apron lose energy by one or more Compton scatters in the body, and may be significantly attenuated by the lead upon return to the dosimeter. (Attenuation coefficients for photons in lead increase dramatically with decreasing energy below 60 keV.) The overall effect is a reduction in all four element readings by an equal amount. (There are no metal filters in the backside of the 8825 dosimeter holder.) A secondary effect is a change in the ratios of the element readings. By reduction of the contribution of backscattered photons to the TL signal, the overall signal is more strongly a product of the incident photons which have passed through metal filters in the front side of the dosimeter holder. The element ratios thus become more strongly a function of the incident photon energy. These ratios are used by the algorithm to apply appropriate dose conversion factors to the element readings based on assessed photon energy. The change in element ratios introduces error into the algorithm's dose conversion.

For demonstrating compliance with regulatory dose limits for whole body dose, the effective dose equivalent (EDE) is the quantity of interest. 10 CFR 835.203 allows the use of deep dose equivalent measured at a single location when the body is uniformly irradiated. For routine personnel monitoring at Hanford, the deep photon dose + neutron dose measured with the chest dosimeter are taken to

(a) B. A. Rathbone, "Recommendations on the Use of HCNDs with Lead Aprons at PFP" September 30, 2003, Letter to R. L. Hill (in HEDP files).

be equivalent to the total deep dose and recorded as the whole body dose (EDE) under the assumption that all parts of whole body received equal deep dose. When all parts of the whole body do not receive equal dose, as when lead aprons are worn in low energy photon fields, it is necessary to either calculate EDE using body compartment weighting factors or demonstrate that the deep photon + neutron dose equivalent reported from the chest dosimeter provides a conservative estimate of the actual EDE received by the individual. The fact that the photon deep dose is slightly under estimated for *unshielded* parts of the whole body is not of real concern, since the photon deep dose to *shielded* parts of the body is greatly over estimated. The body “compartments” shielded by the lead apron have most of the weighting in the determination of EDE from external radiation. The total weighting for body compartments not shielded by the lead apron (head, upper right arm, upper left arm, right thigh, left thigh) is 0.12 whereas the total weighting for shielded compartments (thorax and abdomen) is 0.88 (see Table 6.4). A simple calculation of EDE with lead aprons and various photon energies shows that the photon deep dose reported by the HCND when worn on the outside of the apron will always be greater than or equal to the actual photon EDE received, regardless of the photon energy.

However, because a separate regulatory limit of 15 rem/year has been established for the *lens of the eye dose* for which compliance must be demonstrated, the fact that the HCND reported eye dose might underestimate the actual dose received by the unprotected lens of the eye is a potential concern. Similarly, because a separate regulatory limit of 50 rem/year has been established for the skin and extremities, for which compliance must be demonstrated, the fact that the HCND reported shallow dose might underestimate the actual shallow dose received by unshielded surfaces of skin or extremities is of potential concern. For the purpose of determining compliance with these separate limits, it can be readily shown that eye dose is limiting. In other words, if compliance can be shown for the lens of the eye based on the dosimeter’s reported eye dose, compliance can be assumed for skin and extremity dose as well (assuming a uniform external field)..

The following criteria should be used to determine when corrections need to be performed for the HSD or HCND reported shallow and eye dose results.

Corrections to the reported eye dose from the HSD or 8825BP component of the HCND should be performed when:

$$H_e \text{ (mrem) / dosimeter wear period (days) } > 7.61 \text{ mrem/day}$$

Where H_e is the eye dose reported by the HSD or 8825BP dosimeter.

This is equivalent to an eye dose result of 231 mrem on a monthly dosimeter, 694 mrem on a quarterly dosimeter and 2778 mrem on an annual dosimeter. These action levels for making corrections are conservative because they assume that all of the reported photon eye dose was measured while wearing lead aprons and that the photon energies were in the range producing maximum under-response of the dosimeter.

The 7.61 mrem/day criterion is based on the rationale that if the unrecorded eye dose is less than 1500 mrem/year (the threshold for monitoring of eye dose given in 10CFR835.402(a)), then corrections to the reported eye dose are not required since monitoring for that quantity of dose is not required in the first place. In other words, 1500 mrem/year (one tenth of the annual limit) is a defacto minimum dose of concern for the lens of the eye. The rationale also proceeds from the fact that the 10 CFR 835 limit for eye dose is based on prevention of deterministic effects for which there is a dose threshold, rather than limitation of stochastic risk, for which there is not (ICRP 1991, NCRP 1993).

If the above criteria are met, then corrections to the reported eye dose should be performed as follows:

$$H_e' = H_e / (1 - 0.35 * F)$$

where:

$$H_e = \text{HSD or 8825BP reported eye dose}$$

$$H_e' = \text{HSD or 8825BP corrected eye dose}$$

$$F = \text{estimated fraction of total photon eye dose received while wearing lead aprons}$$

For the purpose of estimating the value of F, pencil dosimeter data recorded while wearing the lead aprons are a reasonable approximation. If an estimate of F cannot be made, then it should be assumed that F = 1. For this reason, it is desirable (but not necessary) that pencil data be logged separately against lead apron use. The formula for correcting reported eye dose given above is conservative in that it assumes all of the photons are 59 keV photons.

Whenever corrections are made to the reported eye dose, corrections should also be made to the reported shallow dose as follows:

$$H_s' = H_s / (1 - 0.35 * F)$$

where:

$$H_s = \text{HSD or 8825BP reported shallow dose}$$

$$H_s' = \text{HSD or 8825BP corrected shallow dose}$$

$$F = \text{estimated fraction of true photon shallow dose received while wearing lead aprons}$$

For the purpose of estimating the value of F, pencil dosimeter data recorded while wearing the lead aprons are a reasonable approximation. If an estimate of F cannot be made, then it should be assumed that F = 1. For this reason, it is desirable (but not necessary) that pencil data be logged separately against lead

apron use. The formula for correcting reported shallow dose given above is conservative in that it assumes all of the photons are 59 keV photons.

The formulae above are based on the calculation path of the 8825 algorithm where neutrons are not detected. If neutrons are detected on an HSD that has been processed using the default facility calibration code (00), then the maximum under response to eye photon dose is only 20% rather than 35%, and the above corrections will be slightly conservative. [The 8825BP component of the HCND is insensitive to neutrons and thus should never have neutrons detected in the 8825 algorithm.]

In general, it should be rare that corrections to reported eye dose and shallow dose are needed based on the 7.61 mrem/d criteria. If corrections are needed, then the dose rates are large enough that multiple whole body dosimeters and EDE dose assessment methodology should be used for more accurate assessment of dose. The measurements upon which the above criteria are based are documented in HEDP files.^(a)

6.7.2.2 Use of Multiple Dosimeters with Lead Aprons

This method is recommended where large doses are expected and/or improved accuracy in whole body dose determination is desired. If the photon component of eye dose received while wearing a lead apron has the potential to exceed 200 mrem and to exceed 11.74 mrem/day x dosimeter wear period (days), (e.g. 357 mrem/month, 1071 mrem/quarter, or 4286 mrem/year), then this method should be used. [The expected photon eye dose rate will be roughly equivalent to the closed window CP reading and can be readily determined from survey data.] This method allows the whole body dose of record to reflect the dose reduction achieved by the lead apron via EDE calculation, and thereby avoids excessive conservatism. It also provides a more technically defensible dose result that relies less on assumptions and has lower uncertainty. The criteria above correspond to the dose levels at which corrections (and associated paperwork) would be necessary for the reported photon shallow and eye dose for a single routine chest dosimeter worn outside the apron.

This method requires a multipack dedicated for sole use with lead aprons that consists of an HCND (or HSD) and a separate 8825BP. The HCND (or HSD) should be worn under the lead apron in the chest area, and the 8825BP should be worn outside the apron on the head or the collar of the apron as close to the head and neck as possible. The 8825BP is not an HSD. It is the same as the beta-photon dosimeter used in the HCND package. These wear locations are consistent with recommendations for use of multiple dosimetry with lead aprons contained in NCRP Report No. 122. The multipack should be used only in conjunction with lead aprons. When lead aprons are not being used, the worker would need to wear their routine chest dosimeter (or a different multipack if appropriate).

(a) B. A. Rathbone, "Recommendations on the Use of HCNDs with Lead Aprons at PFP" September 30, 2003, Letter to R. L. Hill (in HEDP files).

[NOTE: *Because low energy photons at Hanford are usually accompanied by significant neutron dose requiring measurement with an HCND, the description of this method is written for use of an HCND under the apron and 8825BP outside the apron. In the event that measurement of neutron dose is not necessary, the same method can be applied for use of an HSD under the apron with an 8825BP outside the apron.*]

The extremity, skin, eye and effective dose equivalent (EDE) from external radiations for the periods during which the multipack is worn will need to be evaluated as follows:

To determine dose equivalent to the skin and to the extremities, the shallow dose result from the 8825BP dosimeter worn on the head or collar should be added to the neutron dose equivalent from the 8816 component of the HCND chest dosimeter.

To determine dose equivalent to the lens of the eyes, the eye dose result from the 8825BP head/collar dosimeter should be added to the neutron dose result from the 8816 chest dosimeter.

To calculate EDE, the calculation methodology and compartment weighting factors described in Section 6.9.3 should be used.

To calculate the EDE from photons, the deep photon result from the 8825BP head/collar dosimeter should be used to represent the arms, legs and head compartments, and the deep photon result from the 8825BP chest dosimeter (in the HCND) should be used to represent the chest and abdomen compartments.

To calculate EDE from neutrons, the neutron result from the 8816 component of the HCND chest dosimeter should be used for all compartments.

Total EDE would then be the summation of EDE from photons and EDE from neutrons.

IF the 8825BP head/collar dosimeter is worn on top of the lead apron at the collar (rather than on the neck or head), it will be necessary to adjust the results for the under-response caused by the lead apron underneath before its results can be used for any of the above extremity, skin, eye or EDE determinations. The adjustments to make are as follows:

DOSE CORRECTIONS FOR 8825BP COLLAR DOSIMETER

$$\begin{aligned} \text{Corrected } H_s &= \text{reported } H_s * 1.54 \\ \text{Corrected } H_e &= \text{reported } H_e * 1.54 \\ \text{Corrected } H_{dp} &= \text{reported } H_{dp} * 1.54 \end{aligned}$$

These corrections are based on the worst case under-response of the collar dosimeter worn outside the apron (i.e. for 59 keV photons). For aprons with only 0.25 mm effective lead thickness, the size of the corrections would be less but are unknown at this point, therefore the corrections above should be used for either thickness.

6.8 Hanford Recorded Dose

Each individual's external dose of record at Hanford is expressed in terms of the protection quantities, e.g. EDE, defined in 10 CFR 835. These quantities are determined from the operational quantities, e.g. deep dose, measured by Hanford dosimeters the results of which are stored in the REX database. The protection quantities are not "stored" but are calculated from the operational quantities recorded for a given time period as necessary. Hanford practice for determining the *external* dose of record from the operational quantities reported by the *current* dosimetry system can be described by the following equations:^(a)

$$\begin{aligned}\text{Whole body dose}^{(b)} &= \beta\text{-}\gamma \text{ deep dose } (H_{dp}) + \text{neutron dose } (H_n) \\ \text{Skin dose}^{(c)} &= \beta\text{-}\gamma \text{ shallow dose } (H_s) + \text{neutron dose } (H_n) \\ \text{Extremity dose}^{(d)} &= \text{Skin dose} + \text{ring dose } (H_r) \\ \text{Lens of Eye dose} &= \beta\text{-}\gamma \text{ eye dose } (H_e) + \text{neutron dose } (H_n)\end{aligned}$$

These equations generally provide conservative results (i.e., doses measured by chest dosimeter and rings are both recorded as extremity dose). Generally, workers do not wear their ring dosimeters every day, and the adopted practice eliminates the tedious paperwork that would be necessary to base extremity dose on the ring result plus only part of the shallow dose result from the chest dosimeter. Also, the adopted practice compensates to some degree for uncertainty in recording of neutron dose received at the extremities. There are no readily available extremity dosimeter designs which accurately measure neutron dose to the extremities. Although Hanford ring dosimeters do not directly detect or measure neutrons, facility calibration codes are used to identify rings used in neutron environments, and apply appropriate ring correction factors based on assessed neutron-gamma ratios.

For multi-packs where the whole body and ring dosimeters were always worn together, the conservatism in recorded extremity dose can be corrected if necessary, by reducing the recorded ring dose by the amount of shallow dose assessed from the whole body dosimeters in the packet. This can be accomplished after the dosimeters have been processed by means of the IODR form. The 300-mg/cm² depth-dose due to beta and/or photon radiation is routinely calculated for the HSD and HCND. This operational quantity is commonly referred to as "eye dose" but is not the same as the protection quantity "lens of eye dose" calculated by REX.

(a) When calculating external dose for time periods that include historical dosimeter designs, the "operational" quantities reported by these dosimeter designs as recorded in REX, must be incorporated. To accomplish this, REX actually uses the following equations based on the respective data fields defined in REX. (See PNL-MA-553 *Hanford Radiation Records Program Manual*). For data from current dosimeter designs, "deep" = H_{dp} and "shallow" = H_s .

$$\begin{aligned}\text{Whole body dose} &= \text{deep} + \text{neutron} + \text{tritium dose} + 35\% \text{ of x-ray} \\ \text{Skin dose} &= \text{shallow} + \text{neutron} + \text{x-ray}\end{aligned}$$

- (b) Total recorded "WB" dose in any calendar year is calculated as TEDE and includes CEDE from occupational intakes.
(c) Recorded dose also includes assessed shallow doses from contaminations > 10 cm² on skin of the whole body.
(d) Recorded dose also includes assessed shallow doses from contaminations > 10 cm² on skin of the whole body and the extremities.

6.9 Multiple Dosimeters for Work in Non-Uniform Fields

The discussion of multiple dosimetry in this section, includes whole body and extremity dosimeters. Multiple dosimeters should be used when a dose to a portion of the whole body or to the extremities may significantly exceed the dose measured with the reference (i.e., chest) dosimeter. In particular, when the anticipated external EDE is significantly greater than the anticipated deep dose equivalent measured by the chest dosimeter, multiple whole body dosimeters should be worn. The need for assignment of multiple dosimeters is determined by the responsible contractor radiation control organization and should be documented in the applicable Radiation Work Permit.

NOTE: 10 CFR 835 and the *External Dosimetry Program Guide* (DOE1999b) define deep dose equivalent to include both photon and neutron dose equivalent, whereas historically the two quantities have been recorded separately at Hanford and other DOE facilities. The REX database field called “deep” stores the deep dose equivalent from photons and the field called “neutron” stores the dose equivalent from neutrons. However, the sum of both is implied by the term “deep dose equivalent” in the guidance documents used as the basis for this section. It should also be noted that, although 10 CFR 835 and the *External Dosimetry Program Guide* define EDE to include radiation from both external and internal sources, only EDE from external sources is implied in this Technical Basis Manual and in HPS N13.41, *Criteria for Performing Multiple Dosimetry*, (HPS 1997).

Extremity dosimetry should be worn for specific jobs in non-uniform fields with large dose gradients in which the extremities may receive a shallow dose more than 10 times greater than the deep photon + neutron dose received by the chest, and the extremities may receive a shallow dose greater than 500 mrem. The rationale for the ratio of 10 is the fact that the 10 CFR 835 limits for extremity dose (shallow dose) and whole body dose (deep photon +neutron) differ by a factor of 10. By ensuring compliance with the whole body limit, compliance with the extremity limit will be ensured by adherence to the above criteria. Extremity dosimetry should also be considered for jobs with large dose gradients and variable exposure geometries resulting in unpredictable dose rates. The above criteria are minimum guidelines. They do not preclude the use of extremity dosimetry under any circumstances where sound health physics judgment would warrant their use.

Eye dosimetry should be worn near the eyes for a specific job when the dose equivalent to the lens of the eye (at a depth of 300 mg/cm²) may exceed the deep photon + neutron dose recorded by the chest dosimeter by 300% and also exceed 100 mrem. This guidance is based on the fact the limit for lens of eye dose equivalent in 10 CFR 835 is a factor of 3 greater than the limit for whole body dose (deep photon + neutron).

Multiple whole body dosimetry should be worn when either of the following two criteria are met.

1. The calculated EDE is expected to exceed the deep photon + neutron dose equivalent measured by the reference dosimeter by more than 30%, and is expected to exceed 100 mrem.

2. The calculated EDE is expected to exceed the deep photon + neutron dose equivalent measured by reference dosimeter by more than 100 mrem.

The above criteria should be considered as an acceptable alternative to the criteria in Article 512.4 of DOE-STD 1098-99 *DOE Standard - Radiological Control* (DOE 1999c). They do not preclude the use of multiple dosimetry if deemed appropriate (e.g., because of uncertainties in worker movement or radiation field strength). The 30% difference criteria was chosen based on the approximate percentages by which an actual EDE could exceed a chest dosimeter result under worst-case conditions, before multi-badging would be required under current guidance in Article 512.4.

Guidance on when to multi-badge is normally applied to a particular job episode, typically lasting not more than one month. For jobs that exceed one month in duration and involve multiple whole body dosimetry, the dosimetry should be processed at the end of each calendar month. For jobs that exceed one month in duration and involve routine chest and extremity dosimetry only (i.e., not a multipack), the dosimetry may be worn until the end of the calendar quarter before processing, if appropriate (i.e., if doses are expected to be low).

6.9.1 Evaluating Dose for Non-Routine Jobs with Multiple Whole Body Dosimeters

Multiple whole body dosimeters should be issued as a packet for each individual. The packet must include a temporary chest dosimeter to replace the routine chest dosimeter as the person's primary (reference) dosimeter. Records must be maintained of the actual placement location for each dosimeter. Codes have been prepared for use by the Hanford dosimetry organizations to identify the location of the respective multiple dosimeters as shown in Table 6.3.

If the individual's routine chest dosimeter is believed to have significant dose (e.g., greater than 100 mrem) or the individual's year-to-date dose is near an administrative control level (ACL), then it should be processed before or in conjunction with the multiple dosimeter packet to establish the individual's current exposure status at the end of the job episode. After completion of the job, a temporary chest dosimeter would then need to be issued to the individual to be used as the primary (reference) dosimeter until the end of the normal dosimeter exchange period. However, if the routine chest dosimeter is known to have low dose, then it may be temporarily stored during multipack use, and worn as the primary (reference) dosimeter at times when the multipack is not being used, (including the remainder of the dosimeter's exchange period after the routine job has ended).

The external dose of record as shown in REX status reports and screens is expressed in terms of protection quantities such as EDE (or whole body dose), skin dose, lens of eye dose, and extremity dose. These protection quantities are calculated from dosimeter results stored in REX using the general relationships shown in Section 6.8 with the following caveat: on REX screens and reports, "whole body dose" refers to TEDE, and includes both the CEDE and external

EDE contributions as well as (when recorded) the historical quantities called “tritium dose” and “35% of x-ray.”^(a)

Table 6.3. Multiple Dosimeter Location Codes

Body Location	Code		Description
Hand	left right	= A, = B	The hand includes the area from below the wrist to the end of the fingers.
Eye	left right	= C, = D	The eye includes only the eye; the rest of the face is included in the head.
Head		= E	The head includes the complete head and the neck, both front and back, except for the eyes.
Abdomen		= F	The abdomen includes the frontal area below the bottom of the rib cage and above the groin.
Wrist	left right	= G, = H	The wrist includes the wrist and lower arm below the elbow.
Thigh	left right	= I, = J	The thigh includes the leg area below the groin and above the knee.
Knee	left right	= K, = L	The knee includes only the knee area.
Lower Leg	left right	= M, = N	The lower leg includes the leg area below the knee and above the ankle.
Foot	left right	= O, = P	The foot includes the ankle and the foot to the end of the toes.
Groin		= Q	The groin is the frontal area of the body at the junction of the thighs and the trunk of the body.
Chest		= R	The chest includes the frontal area below the neck and above the bottom of the rib cage. However, if the primary dosimeter is placed at the belt line or above and below the neck, it will be considered as the chest.
Back		= S	The back includes the area of the back of the body trunk below the neck and above the thighs.
Upper Arms	left right	= T, = U	The upper arm includes the elbow and the arm above the elbow and below the shoulder.

The methodology used to evaluate the dose of record for multiple dosimetry is actually a methodology for determining the amounts of the basic shallow, eye, deep, and neutron operational quantities to be added to (or subtracted from) the individual’s record where appropriate. When a dosimeter is processed as a supplemental dosimeter under REX note code 85 (supplemental dosimeter-normal processing) or 86, (supplemental dosimeter-special processing), its results are not automatically entered into the individual’s record. When a dosimeter is processed under any note codes other than 85 or 86, its results are are automatically entered into the record unless a reject flag has been previously set for the dosimeter in REX. In those cases where REX has automatically entered the

(a) PNL-MA-553 *Hanford Radiation Records Program Manual*

results into the individual's record, an evaluation of any needed changes to the record will require a detailed knowledge of how results were interpreted by REX. For this reason, the recommended method for processing multiple dosimetry is to submit all dosimeters (including chest dosimeter) under note code 85 or 86. For the sake of simplicity, the following discussion assumes that all dosimeters in the multipack were processed under note code 85 or 86 and that results have not been automatically entered into the record by REX.

- **Deep Dose + Neutron Dose.** The deep dose and neutron dose of record are summed by REX together with any internal dose commitment committed effective dose equivalent (CEDE) to obtain "whole body dose" total effective dose equivalent (TEDE) and printed on REX reports or screens. The external EDE for the job needs to be calculated from the multipack dosimeter results using the methods and weighting factors described in Section 6.9.3. Where both photon and neutron radiations were measured, individual deep photon and neutron EDEs need to be calculated. The photon and neutron external EDEs thus calculated need to be documented on a multiple dosimetry evaluation form to be submitted to the HRRP for inclusion in the individual's radiological records. The EDE numbers are entered on the multiple dosimetry evaluation form as the "deep" and "neutron" dose to be added to the individual's record.
- **Shallow Dose.** For compliance purposes, the shallow dose + neutron EDE assessed for the multipack, when added to the individual's record, is used by REX in calculating "skin" dose as needed for reports and screens. (The necessary adjustments to neutron dose in REX based on neutron EDE are addressed in the preceding bulleted text.) However, the shallow dose measured by all dosimeters placed on the "whole body" must be evaluated using non-compartmental (i.e., highest location) methods to determine the amount of shallow dose to add to the REX record. Special consideration should be given to the shielding of skin and/or dosimeter from beta radiation. Normally, the highest shallow dose on a whole body dosimeter would serve as the basis for the shallow dose of record. In some cases, however, this may not be appropriate. For example, the highest shallow dose reported by a dosimeter worn outside protective clothing may not be the best estimate of actual skin dose received if significant beta dose is involved and a lower reading was obtained near the only bare exposed skin. Conversely, the shallow dose reported by a shielded dosimeter at any location would underestimate the true skin dose received if the person had bare, exposed skin nearby. The shallow dose to be added to the REX record will be the assessed shallow dose from the multipack. The shallow dose to be added to the record will need to be documented on a multiple dosimeter evaluation form and submitted to the HRRP.

- **300 mg/cm² Dose (Eye dose).** The 10 CFR 835 protection quantity “lens of the eye dose equivalent” is calculated in REX as the sum of the 300-mg/cm² dose of record (commonly referred to as “eye dose”) and the neutron dose of record. The 300-mg/cm² dose of record is referred to as “eye dose” on IODR and multiple dosimetry forms but does not normally include neutron dose. The 300-mg/cm² dose + neutron dose measured by the dosimeter worn nearest the eyes should be indicated on the multiple dosimetry form as “eye dose” to be added to the individual’s record in REX. Even though a neutron EDE has already been assessed for the multipack, it may be significantly less than the neutron dose measured by a dosimeter worn on or near the head. Therefore, the inclusion of neutron dose (if measured) in the 300-mg/cm² dose adjustment to REX is necessary to ensure that “lens of the eye dose” appearing on REX reports and screens is not under-reported because of an EDE-based neutron dose of record determined as indicated in the first bulleted test.
- **Shallow Dose to the Extremity.** “Extremity” dose is calculated in REX as the sum of shallow dose + neutron dose + ring dose. The highest measured shallow dose + neutron dose result for all dosimeters placed on the extremities needs to be determined. This value should be indicated on the multiple dosimetry evaluation form as the dose to be added to the “extremity” record in REX.

NOTE: On multiple dosimetry forms, any dose assessed as “extremity dose” will be entered into REX as “ring dose”, i.e., shallow dose to the extremities.

A documented evaluation by the respective contractor dosimetry representative is necessary for assignment of dose from a multiple dosimetry packet, even if the dose assigned is zero.

6.9.2 Evaluating Dose for Routine Jobs with Multiple Whole Body Dosimeters

There may be instances of a recurring job where some portion of the whole body (e.g., the elbow) may be exposed to levels higher than measured with the reference dosimeter. In these cases, an evaluation should be performed to see if the criteria for use of multipacks stated at the beginning of Section 6.9 are met for a one-month period. If the criteria are met, then multipacks including multiple whole body dosimetry should be issued for periods up to one month and the results evaluated for each packet as described in Section 6.9.1 above at the end of each month. (Rings may be used in conjunction with a routine chest dosimeter for up to three months). However, multiple dosimetry may be appropriate even when the criteria of Section 6.9.1 are not met. Multipacks may be issued under any circumstances when deemed appropriate by the field health physicist, or specified by the RWP, and certainly should be considered for monthly use on long-term jobs where large dose gradients may exist and/or the dose rates are unstable over time. Otherwise, under stable conditions, consideration should be given to alternatives such as the use of correction factors applied to chest dosimeter results or relocation of the chest dosimeter.

6.9.3 Calculation of EDE

The deep or neutron external effective dose equivalent is calculated based on the product of the dosimeter-measured deep or neutron dose equivalent and a body compartmentalization factor applicable to each of the dosimeter-wearing locations consistent with the recommendations included in the DOE *External Dosimetry Program Guide* (DOE 1999b). Based on information in HPS N13.41 *Criteria for Performing Multiple Dosimetry* (HPS 1997), the whole body compartmentalization factors shown in Table 6.4 should be used. The basis for these factors is presented in Appendix A of HPS N13.41 and describes the derivation of these factors from the 10 CFR 835 tissue-weighting factors.

Table 6.4. Whole Body Compartmentalization Factors

COMPARTMENT	COMPARTMENT FACTOR
Head and Neck	0.10
Thorax, above the diaphragm	0.38
Abdomen, including pelvis	0.50
Upper Right Arm	0.005
Upper Left Arm	0.005
Right Thigh	0.005
Left Thigh	0.005

From Health Physics Society Standards Committee (HPSSC). 1997. "Criteria for Performing Multiple Dosimetry." HPS N13.41. Health Physics Society, McLean Virginia.

The equation used to calculate the deep photon external effective dose equivalent is as follows:

$$EDE_d = \sum (D_c * CF_c) \quad (6.1)$$

where: EDE_d = external effective dose equivalent from photons (mrem)
 D_c = deep photon dose equivalent (mrem) measured for compartment c of the body
 CF_c = compartment factor for compartment c from Table 6.4

The same equation is used to calculate the neutron external effective dose equivalent is as follows:

$$EDE_n = \sum (D_c * CF_c) \quad (6.2)$$

where: EDE_n = external effective dose equivalent from neutrons (mrem)
 D_c = neutron dose equivalent (mrem) measured for compartment c of the body
 CF_c = compartment factor for compartment c from Table 6.4

To determine the dose to a given compartment, the highest dosimeter result for that compartment is used. If the compartment was not monitored, the result for the nearest compartment monitored may be assigned. For the abdomen, the highest dosimeter result for an adjacent compartment may be assigned

6.10 Fetal Dose

Hanford contractor dosimetry organizations are responsible for assigning dosimeters to monitor the embryo/fetus dose from external radiation. General guidelines to provide consistency in recorded embryo/fetal dose among Hanford contractor organizations are as follows:

- The deep + neutron dose as measured with a monthly exchanged personnel dosimeter is to be recorded.
- The deep + neutron dose recorded is that dose which is most representative of the exposure to the embryo/fetus (i.e., in the mother's lower torso region).
- In uniform radiation fields (i.e., no apparent variation within 50% in dose rate over the torso region of the mother's body), the primary dosimeter worn by the mother is representative of the exposure to the embryo/fetus.
- As determined by contractor radiation protection staffs, particularly if there is a potential for receiving a 50-mrem or greater dose per month, supplemental dosimeters may be assigned in addition to the monthly exchanged compliance dosimeter to monitor accumulated exposure at a frequency more rapid (i.e., weekly or biweekly) than the routine monthly dosimeter exchange period. The supplemental dosimeters should be worn along with the compliance dosimeter.
- In non-uniform radiation fields, including when shielding is used specifically to shield the embryo/fetus from exposure, multiple supplemental dosimeters shall be used as described in Section 6.9. Typically, one supplemental dosimeter is worn in the lower torso region of the mother (e.g., fetal/embryo exposure) and another supplemental dosimeter is worn next to the primary (reference) dosimeter (e.g., mother's exposure). The supplemental dosimeters are exchanged at the same time. The dose, obtained from the supplemental dosimeter results, that is most representative of the dose to the embryo/fetus is recorded. The primary (reference) dosimeter is exchanged on the routine monthly or quarterly schedule.

6.11 Operational Quantities and Dose Conversion Factors

Hanford personnel dosimeters are calibrated to measure the operational quantity Personal Dose Equivalent $H_p(d)$ (ICRU 1993; ICRP 1996) at depths $d = 0.07$ mm, 3 mm and 10 mm in soft tissue. These are generally referred to as shallow dose equivalent, eye dose equivalent and deep dose equivalent, and correspond to

density thicknesses of 7 mg/cm², 300 mg/cm² and 1000 mg/cm² in soft tissue (DOE 1999b). For properly used dosimeters, these quantities can be used to demonstrate compliance with applicable protection limits. In particular, deep dose equivalent results from single dosimeters worn on the torso will generally provide a conservative estimate of the protection quantity Effective Dose Equivalent H_E (NCRP 1995). In 10 CFR 835, (DOE 1998c) deep dose equivalent is accepted as a valid estimate for effective dose equivalent for uniform external exposures.

Dose conversion factors are used in the HPS N13.11 (2001) and DOELAP (DOE 1986a) dosimeter performance standards to relate exposure or air kerma from filtered x-ray spectra and monoenergetic radionuclide sources to shallow or deep dose equivalent in phantoms of various compositions and dimensions. Several references provide monoenergetic photon dose conversion factors for tissue depths of 7 and 1000 mg/cm² and a few references for 300 mg/cm². Small differences in the factors are common, based on differences in the radiation beam, exposure geometry, and composition of the phantom. Monoenergetic photon dose conversion factors for shallow, eye, and deep dose, (Grosswendt 1990), are presented in Table 6.5. These factors can be used to estimate the dose at 7, 300, or 1000 mg/cm², based on knowledge of the incident energy and the absorbed dose in air.

Similar factors are presented for beta radiation in Figure 6.1. In this figure, obtained from Cross, Wong, and Freedman (1991), variations with electron energy of the dose equivalent divided by electron fluence ϕ , at 0.07, 3, and 10 mm, in water are presented for irradiations by broad, normally incident beams of monoenergetic electrons (Cross, Wong, and Freedman 1991).

Table 6.5. Photon Dose Conversion Factors (Grosswendt 1990)

Photon Energy(keV)	Air Kerma to Dose Equivalent Conversion Factors (Sv/Gy) ^(a)		
	7 mg/cm ²	300 mg/cm ²	1000 mg/cm ²
15	0.965	0.665	0.274
20	1.034	0.932	0.625
30	1.224	1.204	1.109
40	1.455	1.494	1.471
50	1.629	1.762	1.758
60	1.752	1.848	1.954
70	1.742	1.835	1.931
80	1.767	1.832	1.948
90	1.744	1.858	1.872
100	1.656	1.772	1.800
120	1.609	1.686	1.720
150	1.530	1.548	1.659
662	1.210	1.210	1.210

(a) These factors are for the 30-cm ICRU slab phantom.

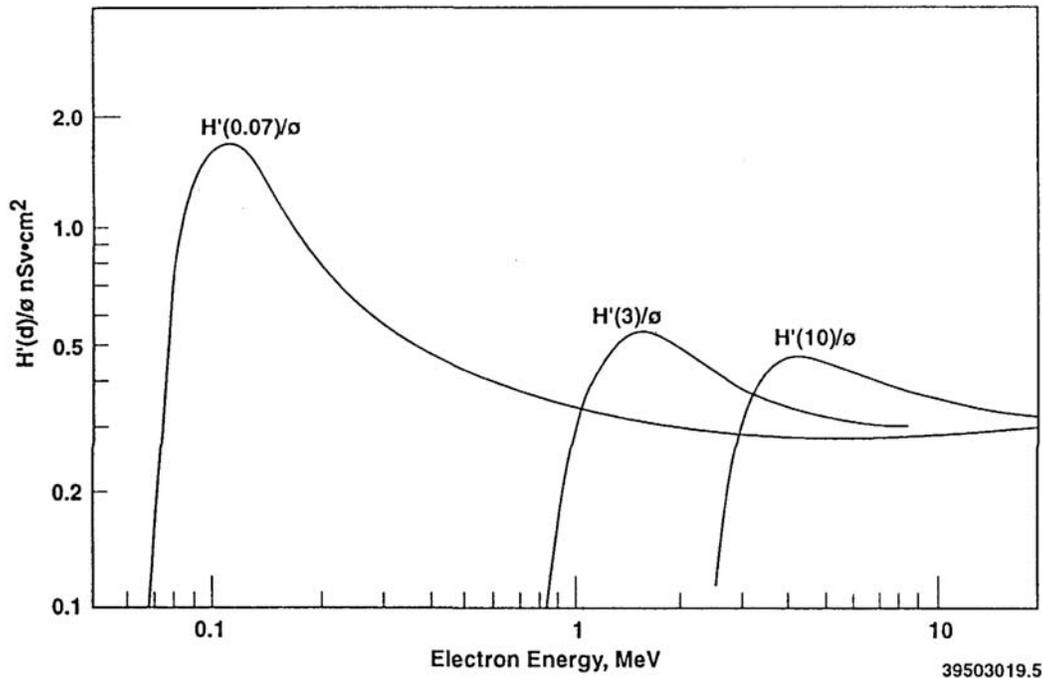


Figure 6.1. Variation in Dose Equivalent for Beta Radiation

From this figure, skin dose per unit fluence varies by about a factor of 3 for different beta energies. If the beta ray fluence rate is measured from a distant source at the surface of the body, the skin dose rate can be estimated within a factor of about 2 (Cross, Wong, and Freedman 1991).

6.12 Personnel Dosimeter Accreditation

During the 1980s, performance testing standards for personnel dosimeters were formally adopted by laboratory accreditation programs administered by the National Institute of Standards and Technology (NVLAP) and the U.S. Department of Energy (DOELAP). The performance tests involved both personnel and accident level doses and several radiation types and mixtures. Accreditation involves a two-step process: the laboratory must first pass a performance test, and then pass a technical program appraisal. Upon successful completion of both steps, the laboratory is accredited. Hanford voluntarily participated in several of these tests during the early 1980s and received DOELAP accreditation for the basic and multipurpose dosimeter designs that were part of the previous Hanford TLD system. The first accreditation was granted, effective January 1, 1990, in all categories requested for testing. This TLD system's performance was successfully retested in 1991, leading to reaccreditation in 1993.

During 1994, 1996, 1998, 2000, 2002 and 2004 DOELAP accreditation was applied for and granted for the HSD, and HCND that are part of the current Harshaw dosimetry system. Beginning in 2002, accreditation for the HCND with CR39 was discontinued. Beginning in 1998, the DOELAP accreditation process

was expanded by DOE to include extremity dosimetry on a voluntary basis. (As of December 2004, DOELAP accreditation in extremity dosimetry is still voluntary). Beginning with the spring 1998 DOELAP test session, Hanford submitted the HRD and HSD Extremity Dosimeter (HSD worn on wrist or ankle) for testing and accreditation. DOELAP granted formal accreditation for these extremity dosimeters in November 1998. They were re-accredited in 2000 and 2002 and 2004. In 2002, and 2004, the EXT-RAD extremity dosimeter was also submitted to DOELAP for performance testing and granted accreditation.

NVLAP accreditation was also obtained in 1997, 2000, and 2002 for the HSD, HCND and EXT-RAD but has since been discontinued. No accreditation programs currently exist for environmental, area, or nuclear accident dosimetry.

6.13 DOELAP Accreditation Categories

The DOELAP categories selected for testing are based on radiation fields expected in Hanford work environments. For the testing performed during 2004 the categories selected for Hanford dosimeters are shown in Tables 6.6 and 6.7.

Hanford Standard Dosimeter (HSD). The DOELAP category IIIB for plutonium work environments was chosen for low-energy photons because of the large inventory of plutonium at Hanford. Category IIIA was chosen because of special radioactive materials and X-ray sources used in PNNL and other labs at Hanford. The general beta radiation category, consisting of ^{90}Sr or ^{204}Tl beta sources, was chosen because of the diversity of potential beta sources at Hanford, including the large quantities of ^{90}Sr material stored at the Hanford Waste Encapsulation Storage Facility and in waste tanks. Waste tank sampling and laboratory analysis activities can involve substantial shallow doses from ^{90}Y beta particles. Category VI (bare and moderated) was chosen for the HSD because it is used on a limited basis as a neutron dosimeter. Workers expected to receive less than 100 mrem/year neutron dose may now be issued an HSD.

Hanford Combination Neutron Dosimeter (HCND). All DOELAP categories requested for accreditation for the HSD were included for the HCND. The moderated ^{252}Cf neutron spectrum was added to the bare ^{252}Cf neutron spectrum in the neutron category because of recent changes in the neutron spectra in Hanford neutron work environments. Specifically, recent changes in the type of work at PFP have resulted in a greater percentage of the neutron exposure occurring in high scatter environments with a softer neutron energy spectrum.

Hanford Ring Dosimeter (HRD), HSD Extremity Dosimeter, and EXT-RAD.

The performance test categories shown in Table 6.7 are adopted from HPS N 13.32 (HPS 1996a) for use by DOELAP. Because the Hanford beta source term includes $^{90}\text{Sr}/^{90}\text{Y}$, and most extremity exposure at Hanford is from point sources, Category IV-C was selected for performance testing for Hanford extremity dosimeters. Slab uranium was not chosen for performance testing because uranium handling activities and slab geometries currently do not represent a significant source of extremity exposure at Hanford.

Table 6.6. Whole Body Dosimeter Test Categories

Test Category	Dosimeter Designations		
	HSD ¹	HCND (w/o CR-39)	HCND (w CR-39)
I. High-Dose^a Low-energy photons only (M150)	X	X	
II. High-Dose^b High-energy photons only (¹³⁷ Cs)	X	X	
III. Low-energy photons (NIST-filtered techniques)			
A. General (M30, S60, M150, H150)	X	X	
B. Plutonium Monoenergetic, 15-20 keV Monoenergetic, 55-65 keV ²⁴¹ Am	X	X	
IV. High-energy photons (¹³⁷ Cs)	X	X	
V. Beta particles			
A. General (Point Geometry) (⁹⁰ Sr/ ⁹⁰ Y, ²⁰⁴ Tl)	X	X	
B. Slab uranium			
C. Special (Point Geometry) ^c (⁹⁰ Sr/ ⁹⁰ Y, ²⁰⁴ Tl)			
VI. Neutron^d			
²⁵² Cf (bare)	X	X	
²⁵² Cf (moderated)	X	X	
VII. Mixtures III & IV III & V IV & V III & VI IV & VI	X	X	
a. Automatically entered into Category IIIA or IIIB b. Automatically entered if entered into Category IV c. Specify which beta source is selected for irradiation. d. Specify which neutron source, or both sources, selected for irradiation.			

Table 6.7 Extremity Dosimeter Test Categories

Test Category	Dosimeter Designations		
	HRD ^b	HSD ^c	EXT-RAD
I. High-Dose A. Low-energy photons only (M150) B. High-energy photons only (¹³⁷ Cs) B. General, low and high energy photons ^a (M150, ¹³⁷ Cs)			
	X	X	X
II. Low-energy photons (NIST-filtered techniques) A. General ^a (M30, M60, M100, M150, H150) B. High-energy ^a (M100, M150, H150)	X	X	X
III. High-energy photons^a (¹³⁷ Cs, ⁶⁰ Co)	X	X	X
IV. Beta particles A. Low-energy only (²⁰⁴ Tl) B. High-energy only (⁹⁰ Sr/ ⁹⁰ Y) C. General ^a (⁹⁰ Sr/ ⁹⁰ Y, ²⁰⁴ Tl) D. Slab uranium			
	X	X	X
a. Each dosimeter will be irradiated with only one of the NIST techniques. b. HRD: Hanford ring dosimeter, Harshaw XD-740 chipstrate in GDS ring casing c. HSD: Hanford standard dosimeter used in wrist/ankle configuration			

6.14 Radiation Types Not Covered by DOELAP Performance Testing

Radiation types and energies not covered in the DOELAP performance testing standard, may require the use of facility specific correction factors and or facility specific algorithms. Examples of this for the HSD and HCND would be neutrons from accelerators or (α ,n) sources, and beta particles from soft beta emitters with average beta energies less than the approximately 250 keV of the softest source used in DOELAP performance testing. Correction factors for special radiation fields may be based on a knowledge of dosimeter response characteristics and a general knowledge of the radiation types and energies involved. However, if significant uncertainty exists, and significant exposure is expected, instrument measurements should be performed to validate the accuracy of the chosen correction factors. For photons, the LiF phosphors in Hanford dosimeters are nearly tissue equivalent. Because of this fact, and the fact that the DOELAP performance test standard is fairly comprehensive in scope for photons, the

likelihood of facility specific corrections and or algorithms being needed for photon fields is relatively small.

Currently, the only Hanford work environments where facility specific calibration factors and/or algorithms are used *on a routine basis* is the PFP where neutron spectra are significantly different from either of the two sources used in the performance test standard. A facility specific neutron dose algorithm was developed for HCNDs used at PFP and a facility specific ring correction factor has been adopted for rings worn at PFP.

6.15 Facility Calibration Codes

Facility calibration codes are necessary to overcome current limitations in dosimeter technology. An awareness of dosimeter limitations and the proper use of facility calibration codes is essential for obtaining accurate dose of record (see Sections 6.3 – 6.7). A two-digit facility calibration code is used to identify facility-specific dose algorithms or facility specific calibration factors to be used by the dose algorithms (see Table 6.1). At present, facility calibration codes are used to identify facility-specific ring correction factors and to identify whether the californium algorithm (cal code 00) or the plutonium algorithm (cal code 01) should be used to calculate dose with the HCND. When a code is not provided by the respective contractor dosimetry organization, the californium algorithm is used as a default, which is expected to calculate the most conservative personnel dose. When a facility calibration code is not provided for rings, the ring algorithm applies a ring correction factor of 2.0 as a default, which is appropriate for most extremity exposure received at Hanford including work at PFP. This factor adequately corrects for under response to beta radiation and, in the case of PFP, the lack of ring response to neutron radiation. Ring correction factors are discussed in greater detail in Chapter 5. The general use of facility calibration codes in dose calculation is discussed in greater detail in Chapter 5.

6.16 Uncertainty in Recorded Dose

Assessment of uncertainty for recorded Hanford dose has been the subject of three PNNL reports (Wilson et al. 1990; Fix, Gilbert, and Baumgartner 1994; Fix, Gilbert, and Baumgartner 1996). These reports conclude that for historical dosimetry systems used until January 1, 1995, when the current state-of-the-art thermoluminescent (TL) dosimetry system was implemented, the dosimetry technology for photon (i.e., x-rays and gamma rays) and high-energy beta radiation was well developed with generally little risk of serious error. However, dosimetry for neutron and lower-energy beta radiation is much more challenging with existing dosimeter technology. For either of these cases, accurate personnel dosimetry is dependent upon associated field instrument measurements and the use of field correction factors where appropriate. Radiation protection personnel need to be aware of the angular and energy dependence characteristics of Hanford dosimeters when assigning dosimeters, particularly with respect to beta and neutron radiation.

For the current dosimetry system good accuracy for personal dose equivalent is expected for any source of photon radiation. For beta-gamma dosimetry the uncertainty in personal dose equivalent is estimated to be about $\pm 30\%$ for shallow dose equivalent, $\pm 15\%$ for deep dose equivalent, and $\pm 15\%$ for shallow dose equivalent to the extremities, when doses are well above natural background levels. ^(a) For neutron dosimetry with the HCND, uncertainty is estimated to be about $\pm 40\%$. ^(b) These are standard (1σ) uncertainties on individual dosimeter results estimated from the results of laboratory and field measurements. The respective uncertainties in the cumulative personal dose equivalent reported over a calendar year or lifetime may be less, depending on the number and magnitude of dosimeter results recorded. Characteristics of the current dosimetry system are described in greater detail in Chapter 5 of this manual.

(a) B. A. Rathbone, "Analysis of Uncertainty in 8825 Dosimeter Results" November 17, 1999, letter to HEDP file.
B. A. Rathbone, "95% Confidence Intervals for 8825 Dosimeter Results" November 22, 1999, letter to HEDP file.
S. E. Huneycutt, "Uncertainty Documentation for the 8816 TLD and CR-39 Track Etch Dosimeters" October 8, 1999, letter to HEDP file.
S. E. Huneycutt, "Re-evaluation of Measurement Uncertainty in XD740 Ring Dosimeter Results" March 30, 2000 letter to HEDP file.

(b) B. A. Rathbone, "Verification of 8816 Performance in PFP Neutron Fields" March 3, 2004, letter to HEDP file.

7.0 Field Measurements, Assessments, and Intercomparison Studies

Knowledge of the spectrum of energies for beta, photon, and neutron radiation in Hanford facility work environments is critically important to the correct interpretation of personnel dose. Technical reports of field measurements (Fix et al. 1981, 1982; Brackenbush et al. 1980, 1991; Endres et al 1996; Scherpelz, Fix, and Rathbone 2000), along with numerous letter reports to HEDP files, have been prepared. Much of this work has been focused on evaluating dosimeter performance in Hanford facility work environments and the overall uncertainty in Hanford recorded dose.

7.1 Methodology

Specialized radiation measurement techniques are used to obtain beta, photon, and neutron energy and dose data in Hanford facilities and environs. Based on this information and the radiation response of Hanford dosimeters as described in Chapter 5, an evaluation of uncertainty in interpreted dose can be estimated. For most types of Hanford radiation conditions, the reported dose based on the dosimeter is considered to be accurate. For other cases such as those involving lower-energy beta radiation, which is important for extremity or skin dose, low-energy photons under some circumstances, and neutron radiation, instrument measurement of the dose is crucial to ensure that the dosimeter-interpreted dose is accurate.

7.2 Measurement Systems

Measurement systems vary depending upon the type and energy of radiation and the dose rate. Hanford contractor organizations routinely assess beta, gamma and neutron dose rates in the work environment using portable survey instruments. These instruments are calibrated for uniform fields and have correction factors that can be applied for non-uniform fields. Dose rate surveys are used in part to determine the type and wear period for dosimeter assignments. For specialized applications, HEDP has capabilities for TEPC dose equivalent measurements and beta, gamma and neutron spectrum measurements to supplement routine survey data.

An important objective in HEDP measurements is a direct assessment of dosimeter performance compared with instrument-measured dose. In these measurements, dosimeters are typically placed on phantoms in the work environment to simulate personnel wearing the dosimeter. Instrument measurements are conducted under the same exposure conditions. A comparison of the dosimeter-interpreted dose to the dose measured with an instrument reveals any problems that may occur in assessing actual personnel dose.

7.2.1 Photon Radiation

Measurement of photon dose is typically conducted using a portable ionization chamber survey instrument and/or the dosimeter. There is a high level of confidence with either technique. For some applications, it is of interest to know the energy spectrum of the photons in the work environment as measured with a gamma spectroscopy system.

Gamma spectroscopy equipment is quite common. HEDP staff have used one or more of these systems to measure dose on several occasions. Techniques for gamma spectroscopy are well defined in the literature (Brackenbush, Baumgartner, and Fix 1991).

7.2.2 Beta Radiation

Accurate measurement of dose from low-energy beta radiation can be very challenging. In general, shielding is used to prevent significant personnel dose because beta radiation can be easily shielded. Thin window ionization chambers, such as used with the Hanford ionization chamber survey instrument, is used to measure the beta dose. This method is quite acceptable if the radiation field is reasonably uniform and without a large angular distribution. For contact measurements of point sources, other methods of dose assessment can be used, consisting of photographic film (i.e., autoradiography), thin thermoluminescent phosphors, etc. In some cases, the beta particle energy spectrum is of interest. This can be measured with a beta spectroscopy system.

7.2.3 Neutron Radiation

Measurements are made with two different types of detectors: multisphere detectors and TEPCs. These devices measure the dose and spectra. These are absolute measurement systems, in the sense that prior knowledge of the neutron energy spectrum is not necessary to accurately measure dose.

Multisphere Spectrometer System

The multisphere spectrometer does not require a calibrated neutron source. The calibration of the multisphere is built into the response function, which is included in the spectrum-unfolding code SPUNIT for the 1.3-cm- (0.5-in.) diameter by 1.3-cm (0.5-in.) ${}^6\text{LiI}(\text{Eu})$ scintillation crystal. Thus, measurements with these detectors exposed to the NIST-calibrated sources are used only to verify the accuracy of the technique and of the computer codes used.

Tissue-Equivalent Proportional Counter

The TEPCs use an internal energy calibration (the proton edge or an internal alpha source). Because the TEPC measures the energy deposited in a known mass of tissue-like material, it directly determines absorbed neutron dose. With appropriate mathematical algorithms, it is also possible to determine quality factor, and hence dose equivalent, directly from first principles.

7.3 Hanford Beta Radiation Measurements

Numerous technical studies and measurements have been conducted of beta radiation in Hanford facilities. Technical reports of primary interest include the following:

- J. J. Fix et al. 1981. *Hanford Personnel Dosimeter Supporting Studies FY-1980*. PNL-3536. Pacific Northwest Laboratory.
- J. J. Fix et al. 1982. *Hanford Personnel Dosimeter Supporting Studies FY-1981*. PNL-3736. Pacific Northwest Laboratory.
- HEDP File: C. D. Hooker et al. *Skin Dose Assessment from Extrapolation Chamber Measurements of Contaminated Clothing*. July 1985.
- HEDP File: L. A. Rathbun, K. L. Swinth, and D. L. Haggard. *Beta Measurements at Hanford*. April 1986.
- HEDP File: L. A. Rathbun. *Beta Measurements at PUREX*. September 16, 1988.
- HEDP File: J. J. Fix, PNL, to D. P Higby, PNL. *Extremity Dose Evaluation of Waste Tank Sample Handling in the 325 Building*. June 28, 1995
- HEDP File: J. J. Fix. *Extremity Dose Evaluation of Yttrium-90 Purification Process in 325 Building*. September 12, 1990.
- HEDP File: B. A. Rathbone, J. J. Fix, A. W. Endres, PNL, and D. S. Cunningham, WHC. *Evaluation of Extremity Dose Associated with Handling Waste Tank Sludge Samples at the Westinghouse Hanford Company 222-S Facility*. January 22, 1996.
- HEDP File: J. J. Fix, PNL, to W. A. Decker, Jr., WHC. *Extremity Dosimeter Facility Calibration Factors*. January 26, 1996.
- HEDP File: B. A. Rathbone, PNL, to L. K. Aldrich, WHC. *Special Evaluation of Ring Results in 241-AZ-101 Thermocouple Incident*. February 26, 1996.
- HEDP File: B. A. Rathbone, PNL, to L. R. McKay, WHC. *Special Evaluation of HSD Results for 241-AZ-101 Thermocouple Incident*. March 4, 1996.
- HEDP File: B. A. Rathbone, PNL, to L. R. McKay, WHC. *Assessment of Ring Correction Factors for 241-AZ-101 Incident*. March 4, 1996.
- HEDP File: B. A. Rathbone, PNL, to J. M. Hammack, Lockheed Martin Hanford Corporation. *Determination of Ring Correction Factors and*

Dose Reduction Factors for Leaded Gloves Used in Grab Sampling Activities at Hanford Tank Farms, July 10, 1997.

- HEDP File: B. A. Rathbone, PNL, to HEDP file, *Assessment of Ring Correction Factors for Use at Hanford*. November 30, 1998. Also published in Proceedings of Bicon/NE TLD Users Symposium, March 1998.
- HEDP File: B. A. Rathbone, PNL, to Nancy Kirner, FDH. *Measurement of Shallow Dose Rate in the Beam of T-Handle Sample Carriers*. March 7, 2000.
- B. A. Rathbone et al. 2002. *Current Challenges in Personnel Dosimetry at the U.S. DOE Hanford Site*. Radiation Protection Dosimetry Vol. 101. Nos. 1-4, pp. 153-166 (2002)

These studies illustrate the strong dependence of personnel dose from beta radiation on energy and the geometry of irradiation. In general, relatively few personnel at Hanford are significantly exposed to beta radiation because it is easy to attenuate the radiation with shielding. Conditions where beta radiation may be a concern generally involve inspection, repair, or maintenance of contaminated equipment. Often in these cases, mixed activation and/or fission products are present, resulting in both beta and photon radiation. Contractor personnel using portable survey instruments can easily identify these locations. Another type of facility where beta radiation can be a concern involves laboratories responsible for sample analysis. Significant extremity doses may occur if samples of pure beta-emitting nuclides are handled. At Hanford, significant quantities of the beta-only-emitting nuclides ^{147}Pm , ^{90}Y , and ^{90}Sr have been handled.

The HSDs and HCNDs have very good dose response characteristics to beta radiation as low as ^{204}Tl , the lowest energy-emitting nuclide included in the DOELAP performance standard. Energy response corrections are necessary for lower-energy beta emitters. The Hanford chipstrate extremity dosimeter requires a field-specific calibration for average beta radiation energies lower than approximately 400 keV.

7.4 Hanford Photon Radiation Measurements

Photon radiation typically is associated with beta and/or neutron radiation in Hanford facilities. The majority of personnel radiation exposure at Hanford is attributable to photon radiation because of its relative abundance and difficulty to shield. Studies of this radiation in Hanford facilities include the following:

- J. J. Fix et al. 1981. *Hanford Personnel Dosimeter Supporting Studies FY-1980*. PNL-3536. Pacific Northwest Laboratory.
- J. J. Fix et al. 1982. *Hanford Personnel Dosimeter Supporting Studies FY-1981*. PNL-3736. Pacific Northwest Laboratory.

- HEDP File: P. L. Roberson and F. M. Cummings. *Gamma Measurements at the 234-5 Facility*. October 1986.
- HEDP File: L. L. Nichols, PNL, to Bill Decker, WHC. *Photon Measurements at PUREX*. August 1, 1988.
- HEDP File: B. A. Rathbone, PNL, to W. A. Decker, Jr. WHC. *Evaluation of 106C Dosimeter Results for Evidence of Low Energy Photon Exposure*. October 6, 1995.
- HEDP File: B. A. Rathbone, PNL, to W. A. Decker, Jr., WHC. *Analysis of 106C Test Dosimeter for Low Energy Photon Exposure*. November 11, 1995.
- HEDP File: B. A. Rathbone, PNL, to HEDP file. *Estimating Average Photon Energy From HSD Element Ratios*, February 4, 1997.

Based on the laboratory information on dosimeter characteristics presented in Chapter 5.0, there is no reason to expect difficulty in measuring personnel dose from this form of radiation. The foregoing studies provide information on the intensity and energy distribution of photons observed in Hanford work environments. The majority of these studies were focused on isolating the dose attributable to beta and/or neutron radiation, where problems in measuring dose may occur, from the dose attributable to photon radiation, which is expected to be relatively free of error. These measurements confirm the substantial confidence in dosimeter results for this form of radiation.

7.5 Hanford Neutron Radiation Measurements

The vast majority of Hanford instrument measurements of dose in the work environment have been conducted for neutron radiation since this is where the greatest technology shortfall exists in personnel dosimetry. Selected studies of neutron dose measurements include the following:

- J. J. Fix et al. 1981. *Hanford Personnel Dosimeter Supporting Studies FY-1980*. PNL-3536. Pacific Northwest Laboratory.
- J. J. Fix et al. 1982. *Hanford Personnel Dosimeter Supporting Studies FY-1981*. PNL-3736. Pacific Northwest Laboratory.
- HEDP File: P. L. Roberson, F. M. Cummings, and J. J. Fix. *Neutron and Gamma Field Measurements at the 234-5 Facility*." September 1985.
- HEDP File: P. L. Roberson, F. N. Eichner, and K. L. Jones. *Evaluation of a Wrist Dosimeter Based on Hankins' Design*. May 1986.
- HEDP File: F. M. Cummings, and L. L. Nichols. *Neutron Field Measurements at the 234-5 Facility*. October 1986.

- HEDP File: L. W. Brackenbush et al. *Neutron Dose and Spectrum Measurements in Westinghouse Hanford Facilities*. September 1987.
- J. J. Fix, W. V. Baumgartner, L. W. Brackenbush, L. L. Nichols, T. J. Paul, and A. W. Endres. 1991. *Hanford Personnel Neutron Dosimetry Problems and Solutions*. CONF-9106235/ PNL-SA-21596, Eleventh DOE Workshop on Personnel Neutron Dosimetry, pp. 33-42, June 3-7, 1991.
- L. W. Brackenbush, W. V. Baumgartner, and J. J. Fix. 1991. *Response of TLD-Albedo and Nuclear Track Dosimeters Exposed to Plutonium Sources*. PNL-7881. Pacific Northwest Laboratory.
- A. W. Endres, L. W. Brackenbush, W. V. Baumgartner, and B. A. Rathbone. 1994. *Site Specific Calibration of the Hanford Personnel Neutron Dosimeter*. ORNL/TM-12817, Proceedings of Fourth Conference on Radiation Protection and Dosimetry, pp. 153-161, October 23-27, 1994, Orlando, Florida.
- A. W. Endres, L. W. Brackenbush, W. V. Baumgartner, J. J. Fix, and B. A. Rathbone. 1996. *Response of the Hanford Combination Neutron Dosimeter in Plutonium Environments*. PNL-10516. Pacific Northwest Laboratory.
- HEDP File: W. A. Baumgartner, PNL, to DS Cunningham, WHC. *A Study of Tank Farm Workers using High Energy Neutron Source*. January 21, 1994.
- HEDP File: W. A. Baumgartner. *Facility Factor for Westinghouse Hanford Company PFP Facility*. January 9, 1995.
- HEDP File: B. A. Rathbone. *Technical Equivalence of TLD and TED in the Hanford Combination Neutron Dosimeter*. February 22, 1995.
- R. I. Scherpelz, J. J. Fix, and B. A. Rathbone. January 31, 2000. *Validation of Hanford Personnel and Extremity Dosimeters in Plutonium Environments*. PNNL-13136 Pacific Northwest National Laboratory.
- HEDP File: B. A. Rathbone. *A New 8816 Algorithm for PFP*. December 18, 2000.
- HEDP File: B. A. Rathbone. *Recommendations on the Use of HCNDs with Lead Aprons at PFP*. September 30, 2003
- HEDP File: R. I. Scherpelz and B. A. Rathbone. *Neutron Measurements at PFP August – September, 2003*. November 14, 2003.
- HEDP File: R. I. Scherpelz. *Neutron Measurements on the ISA Pad*. December 9, 2003

- HEDP File: B. A. Rathbone. *Correction Factors for Area HSD and Area HCND Neutron Dose Results at SNF Facilities*. December 31, 2003.
- HEDP File: R. J. McConn and R. I. Scherpelz. *MCNP Estimate of Dose Rates Surrounding the ISA Pad*. January 23, 2004.
- HEDP File: B. A. Rathbone. *Neutron Correction Factors for HSD Area Dosimeters Located in the Vicinity of the ISA in 200 East Area*. February 12, 2004.
- HEDP File: B. A. Rathbone. *Neutron Response of HSD and HCND Personnel Dosimeters Near Spent Fuel Casks*. February 13, 2004.
- HEDP File: B. A. Rathbone. *Verification of 8816 Performance in PFP Neutron Fields*. March 3, 2004.

Information in the foregoing studies demonstrates the complexity of measuring neutron dose and comparing the instrument-measured dose to the dosimeter-interpreted dose. Throughout the history of the Hanford TLD program, a site-specific calibration has been used because of the significant energy response of TLD albedo dosimeters. Because of the limited capabilities of albedo neutron dosimeters, instrument measurements in the work environment are crucial to ensuring the adequacy of the dosimeter-interpreted neutron dose.

7.6 Hanford Environs Radiation Measurements

Environmental TLDs are routinely used to measure the environmental dose at several selected onsite and offsite locations. Confirmatory measurements of these data are available in the following:

- L. A. Rathbun. 1989. *The Determination of the Penetrating Radiation Dose at Hanford*. PNL-7124. Pacific Northwest Laboratory.
- HEDP File: A. W. Endres. 1994. *Results of the 1991 Environmental Radiation Quality Assurance Task Force of the Pacific Northwest Thermoluminescent Dosimeter Intercomparison*. May 26, 1994.
- B. A. Rathbone, A. W. Endres, and E. J. Antonio. 1994. *Evaluation of New and Conventional Thermoluminescent Phosphors for Use in Routine Environmental Monitoring Programs Using Automated Readers*. ORNL/TM-12817, Proceedings of Fourth Conference on Radiation Protection and Dosimetry, pp. 371-380, October 23-27, 1994, Orlando, Florida.

These reports describe technical challenges in measuring environmental levels of radiation. These data also confirm the adequacy of the Hanford environmental dosimetry system, particularly considering performance in interlaboratory comparison programs as described in Section 7.7.

7.7 Intercomparison Studies

Hanford routinely participates in external dosimeter performance intercomparison studies. These studies are critically important to ensuring the adequate performance of the system. Hanford has participated in the following intercomparison studies in recent years:

- HEDP File: *Summary of PNL's Participation in the DOE Draft Performance Standard for Extremity Dosimeters*. February 20, 1990.
- HEDP File: *Summary of PNL Performance in DOELAP Dosimeter Performance Testing During 1991*. March 24, 1992.
- HEDP File: *Environmental Radiation Quality Assurance Task Force of the Pacific Northwest Thermoluminescent Dosimeter Intercomparison*. September 15, 1992.
- HEDP File: *Summary of PNL's Results from Participation of Hanford in the 18th Personnel Dosimeter Intercomparison Study*. July 1993.
- HEDP File: *Summary of PNL Performance in DOELAP Dosimeter Performance Testing during 1994*. August 15, 1994.
- HEDP File: *PNL's Participation in the Tenth International Intercomparison Project*. August 24, 1994.
- HEDP File: *Summary of PNL Performance in DOELAP Dosimeter Performance Testing during 1996*. June 19, 1996.
- HEDP File: *DOELAP $^{204}\text{Tl}/^{137}\text{Cs}$ Dosimeter Intercomparison – (OARM-RESL-98-234)*.
- HEDP File: *11th International Environmental Dosimetry Intercomparison*.
- HEDP File: *12th International Environmental Dosimetry Intercomparison*.
- HEDP File: *ANSI N13.29 Pilot Test*
- HEDP File: *ANSI N13.11 2001 Pilot Test*.

These intercomparison studies all show acceptable or exemplary performance of Hanford dosimetry systems.

7.8 Uncertainty Analyses

Studies have been performed to estimate the bias and uncertainty in Hanford recorded dose. These evaluations have shown improved performance of Hanford dosimetry systems from the 1940s through the present time. Notable studies include the following:

- J. J. Fix, and E. S. Gilbert. 1991. *Consistency of External Dosimetry in Epidemiologic Studies of Nuclear Workers*. ORNL/TM-11881. Proceedings of the Third Conference on Radiation Protection and Dosimetry. October 1991.
- J. J. Fix, E. S. Gilbert, R. H. Wilson, W. V. Baumgartner, and L. L. Nichols. 1992. *Comments on Evidence of Biased Recording of Radiation Doses of Hanford Workers*. Letter to the Editor, American Journal of Industrial Medicine, volume 22, pp. 281-283.
- J. J. Fix, and E. S. Gilbert. 1992. *Consistency of External Dosimetry in Epidemiologic Studies of Nuclear Workers*. IRPA8, Proceedings of the 8th Meeting of the International Radiation Protection Association, volume 1, pp. 567-570, May 17-22, 1992.
- J. J. Fix, E. S. Gilbert, and W. V. Baumgartner. 1994. *Estimates of Bias and Uncertainty in Recorded Dose*. ORNL/TM-12817, Proceedings of Fourth Conference on Radiation Protection and Dosimetry, pp. 119-125, October 23-27, 1994, Orlando, Florida.
- J. J. Fix, E. S. Gilbert, and W. V. Baumgartner. 1994. *An Assessment of Bias and Uncertainty in Recorded Dose from External Sources of Radiation for Workers at the Hanford Site*. PNL-10066. Pacific Northwest Laboratory.
- E. S. Gilbert and J. J. Fix. 1995. *Accounting for Bias in Dose Estimates in Analyses of Data From Nuclear Worker Mortality Studies*. Health Phys. 68(5):650-660.
- Fix, J. J., R. H. Wilson and W. V. Baumgartner. 1996. *Retrospective Assessment of Personnel Neutron Dosimetry for Workers at the Hanford Site*. PNNL-11196, Pacific Northwest National Laboratory, Richland, WA.
- Gilbert, E. S., and J. J. Fix. 1996. *Laboratory Measurement Error in External Dose Estimates and Its Effects on Dose-Response Analyses of Hanford Worker Mortality Data*. PNNL-11289, Pacific Northwest National Laboratory, Richland, WA.
- HEDP File: B. A. Rathbone *Analysis of Uncertainty in 8825 Dosimeter Results*, November 17, 1999.
- HEDP File: B. A. Rathbone *95% Confidence Intervals for 8825 Dosimeter Results*. November 22, 1999.

- HEDP File: S. E. Huneycutt, *Re-Evaluation of Measurement Uncertainty in the XD-740 Ring Dosimeter Results*, March 30, 2000.
- HEDP File: S. E. Huneycutt, *Uncertainty Documentation for the 8816 TLD and CR-39 Track Etch Dosimeters*, October 8, 1999.

7.9 Summary

Uncertainty in recorded personnel dose is primarily a function of the radiation type, energy, dosimeter design, and irradiation geometry. Extensive efforts have been made at Hanford to document the performance of personnel dosimeters in actual work environments. These assessments have been done to estimate performance of the respective dosimeter systems under actual operational conditions. The following points summarize the current state of dosimetry technology:

- For photon radiation, which contributes the vast majority of personnel dose in Hanford facilities, the dosimeter-interpreted shallow, eye, and deep dose is considered accurate for uniform irradiation exposure geometries.
- For beta radiation greater than about 250 keV (avg.), the dosimeter-interpreted shallow dose is considered accurate for uniform irradiation conditions. For non-uniform irradiation, discussed in Chapter 8.0, or for low-energy beta radiation, confirmatory field instrument measurements are necessary.
- For neutron radiation, the dosimeter-interpreted whole body dose is considered accurate for uniform irradiation conditions where the neutron energy spectra are similar to the calibration spectra. For neutron spectra of either higher or lower energy, compared to the calibration spectra, confirmatory field and/or laboratory measurements are necessary.
- For environmental radiation, the dosimeter-interpreted dose is considered accurate for uniform irradiation conditions, particularly for the higher-energy photon radiation (i.e., >90 keV) typical of the energy spectra for naturally occurring environmental radiation. For beta radiation, special calibration of the dose algorithm and confirmatory field and or laboratory measurements are necessary.

These conclusions are consistent with the Hanford practice of conducting detailed instrument measurements of dosimeter performance in the work environment to document the accuracy of the recorded dose.

8.0 Assessment of Non-uniform Exposure of Skin and Extremities

Non-uniform exposure of skin or extremities may result from discrete radioactive particles or distributed contamination on skin or clothing, point sources within a few inches of the body, or collimated beams of radiation emerging from radiation generating devices, x-ray diffraction units, electron microscopes, or charged particle accelerators. Hanford contractor radiation protection organizations are responsible for identifying cases of non-uniform exposure not adequately monitored by external dosimeters and performing dose assessments in cases where the potential exists for shallow dose to the skin or extremities to exceed 100 mrem. Assessment of dose from non-uniform exposure of the skin and extremities is performed according to the methodology specified in 10 CFR 835.205.

Survey instrument readings from large area, small area and point source contamination residing on the skin that could result in a shallow dose exceeding 100 mrem are provided in Section 8.2. The Hanford adopted 100 mrem screening level for performing formal dose assessments is consistent with guidance in the DOE radiological control standard *DOE-STD-1098-99 Radiological Control* (DOE 1999c) and in *DOE G441.1-4 External Dosimetry Program Guide* (DOE 1999b). Contractor dose assessments are reviewed by an HEDP Dosimetrist and retained by the HRRP in the affected individual's personal exposure history file. When the irradiated area is 10 cm² or greater, the assessed dose to the skin or extremity is entered into the REX database in a manner such that it will be added to the individual's calendar year and lifetime dose totals for skin or extremities in accordance with 10 CFR 835.205(b)(1) and (2). Hanford practices in these areas have been coordinated through and endorsed by the HPDAC^(a).

8.1 Hot Particles

At Hanford, the definition of hot particles includes a minimum activity of 10 μCi , based on the following rationale:

- NCRP Report No. 106, *Limit for Exposure to 'Hot Particles' on the Skin*, contains a recommendation that exposures to hot particles be limited to 75 $\mu\text{Ci-h}$ (NCRP 1989).
- The maximum duration for a normal entry into a surface contamination area is 4 hours.
- A limit of 40 $\mu\text{Ci-h}$ (i.e., 10 μCi x 4 hours) is approximately half of the NCRP recommended limit.

Using the VARSKIN MOD2 code (Durham 1992), the NCRP limit of 75 $\mu\text{Ci-h}$ results in a skin dose of about 300 rad for a nuclide emitting a 1-MeV beta

(a) Fix, J. J. "Minutes of Hanford Personnel Dosimetry Advisory Committee Meeting on December 14, 1994." (A copy is available in the Hanford Radiation Protection Historical Files, Pacific Northwest National Laboratory, Richland, Washington.)

particle for each disintegration. However, for discrete beta-gamma emitting particles on the skin, the “area irradiated” may be considered to be less than 10 cm². When the area irradiated is less than 10 cm², the assessed dose is not added to calendar year totals for the purpose of demonstrating compliance with 10 CFR 835.202(a)(4). Portable survey instrument responses to very small sources of radiation have been measured (described in Section 8.3). The Pancake GM screening level in Table 8.1 for “Contamination Area < Probe Area” is sufficient to identify discrete particles capable of producing a shallow dose of 100 mrem or more after two hours on the skin.

8.2 Contamination Screening Levels

Laboratory measurements were conducted to measure the response of the Eberline Model 260 pancake probe, Model RO-2 ion chamber, and Model RO-3B ion chamber to calibrated 0.2 cm² disk sources and 225 cm² slab sources. These instruments are commonly used at Hanford for radiological surveys. The disk sources were calibration sources routinely used to calibrate Hanford pancake probe instruments. The slab sources were used to simulate instrument response for cases where contamination is more extensive.

Instrument response data for these sources were used to establish the instrument readings corresponding to 100 mrem skin dose for contamination that has been resident on the skin for two hours. In accordance with 10 CFR 835.205(b) methods for dose assessment, doses were calculated to 1 cm² and to 100 cm², depending upon the source size. Conservative screening levels for each instrument corresponding to the DOE recommended screening level of 100 mrem are shown in Table 8.1.

Table 8.1. Portable Survey Instrument Screening Levels for Skin Dose Assessment

Instrument	Readings for Potential Skin Dose > 100 mrem	
	Contamination Area < Probe Area ^a	Contamination Area > Probe Area ^b
Eberline Model 260 Pancake Probe	2,500 cpm	25,000 cpm
Eberline Model RO-2 Ion Chamber (Open Window)	0.2 mrad/h ^c	2 mrad/h
Eberline Model RO-3B Ion Chamber (Open Window)	0.1 mrad/h ^c	1 mrad/h
<p>a. Screening levels for contamination areas smaller than the probe area are based on measurements of dose from 0.2-cm² sources. The table value is the most conservative case for Hanford nuclides, which in all cases was ⁹⁰Sr/⁹⁰Y.</p> <p>b. Screening levels for contamination areas larger than the probe area are determined by multiplying the screening level for small areas by a factor of 10. On the basis of actual measurements with 225-cm² sources, the Pancake Probe, RO-2 and RO-3 showed screening levels of 40,650 cpm, 5.5 mrad/h, and 4.5 mrad/h, respectively, for the most conservative nuclides.</p> <p>c. These values are provided for information only; the pancake probe should be used when such low dose rates are measured with the ionization chamber instruments.</p>		

The following assumptions were used to determine these screening levels:

- Contamination can be represented by one of two geometries:

Contaminated areas smaller than the probe – It is assumed that screening levels based on instrument response to the 0.2-cm² sources will be conservative for contamination areas smaller than the probe, *including point sources* as well as sources only slightly smaller than the probe. This assumption is supported by consideration of the effects of irradiation geometry on instrument response and on the actual shallow dose averaged over 1 cm² of skin.

Contaminated areas larger than the probe - The measured instrument response is from sources (225 cm²) considerably larger than the probe area. For simplicity, the table values for small sources were multiplied by a factor of 10 to establish large area screening levels. It is assumed that this will provide conservative screening levels for all contaminations larger than or equal to the probe area. Actual measurements support this assumption (see Table 8.1 footnote b).

- Contamination is resident for a period of 2 hours.
- The probe survey is done at a distance of 1 cm.

When an instrument measurement exceeds the respective screening level in Table 8.1, a skin dose assessment should be performed to ensure compliance with the requirements in 10 CFR 835.202(a)(4), 835.205(b) and 835.702(b).

Tables 8.2 through 8.8 summarize measurements and VARSKIN MOD2 calculations conducted to support these values.

In addition, ionization chamber measurements of point sources of radiation measuring less than 2 mm² in area were made at several distances.^(a) (see Table 8.9). The results of this study were used to support the screening levels for RO-2 and RO-3B readings established from the response data for 0.2 cm² and 225 cm² sources.

Generally, it is recommended that the data obtained from the pancake GM probe be used to determine the need for formal skin dose assessment. This is the standard instrument used for beta-gamma contamination measurement.

(a) Letter from C. E. Upchurch to J. D. Frey, dated March 23, 1994, "Dose Rate Measurements of Simulated Hot Particles)." Westinghouse Hanford Company.

8.3 Assessment of Dose to Skin or Extremities from Contamination

Hanford Radiation Protection organizations may calculate shallow dose to areas of the skin or extremities using the VARSKIN MOD2 code (Durham 1992) where appropriate. This code considers dose from beta radiation for 2D and 3D area sources, and dose from beta and photon radiation for point sources. The area over which the dose is averaged and the depth at which dose is calculated must be consistent with the requirements given in 10 CFR 835.205. In all cases, the dose must be calculated at a depth of 7 mg/cm². The final assessment of dose and method of recording dose must be consistent with requirements given in 10 CFR 835.205 based on the area irradiated.

8.3.1 Alpha Contamination

If alpha contamination is reported on the skin or clothing, the shallow dose equivalent from alpha radiation may be considered to be negligible (i.e., a 5-MeV alpha particle will penetrate tissue to a depth of approximately 3-4 mg/cm², or less than the 7-mg/cm² depth of regulatory concern).

8.3.2 VARSKIN MOD2

When VARSKIN MOD2 is used to calculate shallow dose, the following methods should be used:

- The total density thickness of all clothing between the layer of contaminated clothing and the individual's skin is considered in the dose calculation. The thickness of the piece of contaminated clothing is not included in this total, unless it can be absolutely shown that the contamination rested on the outside of this piece of clothing. If the survey instrument count rate on the inside of the clothing is provided, this value will be used, which avoids using the thickness of the piece of contaminated clothing.
- If two or more distinct (non-continuous) areas of contamination are present, calculations are performed for each area. Each area is evaluated separately and the highest shallow dose equivalent is the shallow dose equivalent used to assign dose to the skin or extremity for the event being assessed.
- If more than one radionuclide is present, including daughter products, the shallow dose equivalent is calculated for each radionuclide. The total shallow dose equivalent is based on a summation of the dose from all radionuclides.
- If the calculated dose is greater than or equal to 15 rem, a re-evaluation should be conducted to ensure that there is no unrealistic conservatism in the calculated dose. Considerable professional judgment may be necessary, depending upon the particular circumstances of the incident.

- If the calculated dose is greater than or equal to 15 rem and the contaminating material is unknown or in question, the contractor organization should obtain and analyze samples to identify the specific radionuclides involved. If samples are not available, other information may be used to determine the radionuclides such as work history or interviews with workers. If no positive radionuclide identification can be made, the radionuclides and percentages present in the contamination should be conservatively estimated.
- If the calculated dose is greater than or equal to 15 rem, an attempt should be made to obtain and characterize the instrument used for the contamination survey.
- The area over which average dose is calculated and the depth at which dose is calculated must be consistent with the requirements given in 10 CFR 835.205

Table 8.2. Specifications of Sources Used in Instrument Response Measurements and in VARSKIN MOD2 Dose Calculations

Isotope	Source Number	Original Activity (μCi)	Half Life (years)	Original Date	New Date	Decay Time (days)	New Activity (μCi)
Small Source (0.2 cm²)							
¹³⁷ Cs	N-986	0.0136	30	05/01/91	06/14/94	1140	0.0127
³⁶ Cl	1224	0.0190	307,789	09/22/89	05/25/94	1706	0.0190
⁹⁰ Sr/ ⁹⁰ Y	1227	0.0102	28	04/18/90	05/25/94	1498	0.0092
⁹⁰ Sr	1228	0.1020	28	04/18/90	05/25/94	1498	0.0922
⁹⁹ Tc	1223	0.0440	211,855	05/25/89	05/25/94	1826	0.0440
Large Source (225 cm²)							
¹³⁷ Cs	DV 464	0.1076	30	02/23/94	06/14/94	111	0.1068
⁹⁰ Sr/ ⁹⁰ Y	H-674	200.0000	28	06/09/86	06/14/94	2927	164.1073
⁹⁰ Sr/ ⁹⁰ Y	H-670	0.0101	28	05/01/86	06/14/94	2966	0.0083
²⁰⁴ Tl	H-673	500.0000	3.8	06/09/86	06/14/94	2927	116.2556
²⁰⁴ Tl	H-669	0.0102	3.8	05/01/86	06/14/94	2966	0.0023
¹⁰⁶ Ru/Rh	H-675	600.0000	1	06/27/86	06/14/94	2909	2.504

Table 8.3. Measured Eberline Model 260 Pancake GM Probe Response and Calculated Dose for Small (0.2 cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Net Reading (cpm) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate (cpm/[mrad/h])	Dose Rate/ Reading ((mrad/h)/cpm) ^d
³⁶ Cl Source #1224	0.0190	1) 12,148 2) 11,174 3) <u>9,783</u> Avg = 11,035	104	106	9.4 x 10 ⁻³
⁹⁰ Sr/ ⁹⁰ Y Source #1227	0.0092	1) 5,940 2) 5,605 3) <u>4,859</u> Avg = 5,468	109	50.2	2.0 x 10 ⁻²
⁹⁹ Tc Source #1223	0.0440	1) 14,404 2) 12,576 3) <u>11,280</u> Avg = 12,753	143	89.2	1.1 x 10 ⁻²
¹³⁷ Cs Source #N-986	0.0127	1) 4,400 2) 4,560 3) <u>4,650</u> Avg = 4,537	74	61.3	1.6 x 10 ⁻²
<p>a. Activity decay corrected to time of measurement. b. A background rate of 30 cpm was subtracted from the gross measurement. c. VARSKIN MOD2 calculated dose to 1 cm². d. The most conservative case is for ⁹⁰Sr/⁹⁰Y and results in a calculated screening level of 2500 cpm.</p>					

Table 8.4. Measured Eberline Model 260 Pancake GM Probe Response and Calculated Dose for Large (225 cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Net Reading (cpm) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate (cpm/[mrad/h])	Dose Rate/Reading ([mrad/h]/cpm) ^d
⁹⁰ Sr/ ⁹⁰ Y Source #H-670	0.0083	1) 784 2) 765 3) <u>679</u> Avg = 743	0.59	1,259	7.9 x 10 ⁻⁴
¹⁰⁶ Ru/Rh Source #H-675	2.5908	1) 90,365 2) 89,144 3) <u>79,146</u> Avg = 86,218	106	813	1.2 x 10 ⁻³
¹³⁷ Cs Source #DV464	0.1068	1) 8,440 2) 8,430 3) <u>8,375</u> Avg = 8,415	3.8	2,214	4.5 x 10 ⁻⁴
²⁰⁴ Tl Source #H-669	0.0023	1) 84 2) 82 3) <u>70</u> Avg = 79	0.075	1,053	9.5 x 10 ⁻⁴
<p>a. Activity decay corrected to time of measurement. b. A background rate of 109 cpm (measurements in beta room) was subtracted from the gross measurement. The ²⁰⁴Tl data are significantly more uncertain because of the large background count rate. c. VARSKIN MOD2 calculated dose to 100 cm². d. The most conservative case is for ¹⁰⁶Ru/Rh and results in a calculated screening level of 40,650 cpm.</p>					

Table 8.5. Measured Eberline Model RO-2 Ionization Chamber Response and Calculated Dose for Small (0.2 cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Reading (mrad/h) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate ([mrad/h] _{CP} /[mrad/h] _{skin})	Dose Rate/Reading ([mrad/h] _{skin} /[mrad/h] _{CP}) ^d
³⁶ Cl Source #1224	0.0190	0.8	104	7.7 x 10 ⁻³	130
⁹⁰ Sr/ ⁹⁰ Y Source #1228	0.0922	4.1	1,090	3.8 x 10 ⁻³	266
⁹⁹ Tc Source #1233	0.0440	1.5	143	1.0 x 10 ⁻²	95
¹³⁷ Cs Source #N-986	0.0127	0.4	74	5.4 x 10 ⁻³	185
a. Activity decay corrected to time of measurement. b. There was no measurable background dose rate. c. VARSKIN MOD2 calculated dose to 1 cm ² . d. The most conservative case is for ⁹⁰ Sr/ ⁹⁰ Y and results in a calculated screening level of 0.2 mrad/h.					

Table 8.6. Measured Eberline Model RO-2 Ionization Chamber Response and Calculated Dose for Large (225-cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Reading (mrad/h) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate ([mrad/h] _{CP} /[mrad/h] _{skin})	Dose Rate/Reading ([mrad/h] _{skin} /[mrad/h] _{CP}) ^d
⁹⁰ Sr/ ⁹⁰ Y Source #H-674	164.11	1,400	11,700	1.2 x 10 ⁻¹	8.4
¹⁰⁶ Ru/Rh Source #H-675	2.504	14	106	1.3 x 10 ⁻¹	7.6
¹³⁷ Cs Source #DV464	0.1068	1.2	3.8	3.2 x 10 ⁻¹	3.2
²⁰⁴ Tl Source #H-673	116.26	420	3,810	1.1 x 10 ⁻¹	9.1
a. Activity decay corrected to time of measurement. b. There was no measurable background dose rate. c. VARSKIN MOD2 calculated dose to 100 cm ² . d. The most conservative case is for ²⁰⁴ Tl and results in a calculated screening level of 5.5 mrad/h.					

Table 8.7. Measured Eberline Model RO-3B Ionization Chamber Response and Calculated Dose for Small (0.2-cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Reading (mrad/h) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate ([mrad/h] _{CP} /[mrad/h] _{skin})	Dose Rate/Reading ([mrad/h] _{skin} /[mrad/h] _{CP}) ^d
³⁶ Cl Source #1224	0.0190	0.6	104	5.8 x 10 ⁻³	173
⁹⁰ Sr/ ⁹⁰ Y Source #1228	0.0922	2.4	1,090	2.2 x 10 ⁻³	454
⁹⁹ Tc Source #1223	0.0440	0.7	143	4.9 x 10 ⁻³	204
¹³⁷ Cs Source #N-986	0.0127	0.5	74	6.8 x 10 ⁻³	150
a. Activity decay corrected to time of measurement. b. There was no measurable background dose rate. c. VARSKIN MOD2 calculated dose to 1 cm ² . d. The most conservative case is for ⁹⁰ Sr/ ⁹⁰ Y and results in a calculated screening level of 0.1 mrad/h.					

Table 8.8. Measured Eberline Model RO-3B Ionization Chamber Response and Calculated Dose for Large (225-cm²) Radiation Sources

Nuclide	Activity (μCi) ^a	Reading (mrad/h) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate ([mrad/h] _{CP} /[mrad/h] _{skin})	Dose Rate/Reading ([mrad/h] _{skin} /[mrad/h] _{CP}) ^d
⁹⁰ Sr/ ⁹⁰ Y Source #H-674	164.11	1,100	11,700	9.4 x 10 ⁻²	10.6
¹⁰⁶ Ru/Rh Source #H-675	2.504	9.5	106	9.0 x 10 ⁻²	11.2
¹³⁷ Cs Source #DV464	0.1068	1.3	3.8	3.42 x 10 ⁻¹	2.9
²⁰⁴ Tl Source #H-673	116.26	370	3,810	9.7 x 10 ⁻²	10.3
a. Activity decay corrected to time of measurement. b. There was no measurable background dose rate. c. VARSKIN MOD2 calculated dose to 100 cm ² . d. The most conservative case is for ¹⁰⁶ Ru/Rh and results in a calculated screening level of 4.5 mrad/h.					

Table 8.9. Measured Eberline Model RO-2 and RO-3B Ionization Chamber Response and Calculated Dose for Point (<2 mm²) Radiation Sources

Nuclide/ Source Number	Activity (μCi) ^a	Reading (mrad/h) ^b	Dose Rate (mrad/h) ^c	Reading/Dose Rate ([mrad/h] _{CP} / [mrad/h] _{skin})	Dose Rate/Reading ([mrad/h] _{skin} / [mrad/h] _{CP}) ^d
Eberline Model RO-2					
⁹⁰ Sr/ ⁹⁰ Y	7.9	Avg = 198	92,500	2.1 x 10 ⁻³	480
¹³⁷ Cs	7.3	Avg = 192	42,000	4.6 x 10 ⁻³	219
Eberline Model RO-3B					
⁹⁰ Sr/ ⁹⁰ Y	7.9	Avg = 108	92,500	1.2 x 10 ⁻³	860
¹³⁷ Cs	7.3	Avg = 110	42,000	2.6 x 10 ⁻³	380
<p>a. Activity decay corrected to time of measurement.</p> <p>b. Average reading for 5 to 10 measurements. Data for source to instrument window distance of 0.5 in.</p> <p>c. VARSKIN MOD2 calculated dose to 1 cm².</p> <p>d. The most conservative case for the RO-2 and RO-3B is ⁹⁰Sr/⁹⁰Y and results in calculated screening levels 0.1 and 0.06 mrad/h for the RO-2 and RO-3B, respectively.</p>					

THIS PAGE INTENTIONALLY LEFT BLANK

9.0 References

- American National Standards Institute (ANSI). 1975. American National Standard Performance, Testing, and Procedural Specifications for Thermoluminescent Dosimetry (Environmental Applications). ANSI N545, American National Standards Institute, New York.
- American National Standards Institute (ANSI). 1981. Dosimetry for Criticality Accidents. ANSI N13.3, American National Standards Institute, New York.
- American National Standards Institute (ANSI). 1986. Criticality Accident Alarm System. ANSI N8.3, American National Standards Institute, New York.
- American National Standards Institute (ANSI). 1993. Sampling Procedures and Tables for Inspection by Attributes. ANSI/ASQC Z1.4 - 1993, American National Standards Institute, New York.
- Antonio, E. J. 1999. "External Radiation Surveillance" in Hanford Site Environmental Report for Calendar Year 1998. PNNL-12088.
- Antonio, E. J. 2002. "External Radiation Surveillance" in Hanford Site Environmental Report for Calendar Year 2002. PNNL-14295.
- Bartlett, D. T., P. J. Dimbylow, and T. M. Francis, 1990 "Calculated Backscatter from Phantoms for Photon Dosimeter Calibration" Radiation Protection Dosimetry, 32, 123-125: 1990
- Baumgartner, W. V., A. W. Endres, and S. R. Reese. 1992. Quality Control Program for the Hanford External Dosimetry Thermoluminescent Processing System. PNL-8299, Pacific Northwest Laboratory, Richland, Washington.
- Becker, K., J. S. Cheka, and M. Oberhofer. 1970. "Thermally Stimulated Exoelectron Emission, Thermoluminescence and Impurities in LiF and BeO," Health Phys. 18, 1970.
- Bicron ♦NE, 1999. Dose Algorithm: BGN-DOELAP User's Manual, Publication No. ALGM-DN-U-0298-001, Pre-Release Date, March 11, 1999, Chapter 8, pages 14-17.
- Brackenbush, L. W., W. V. Baumgartner, and J. J. Fix. 1991. Response of TLD-Albedo and Nuclear Track Dosimeters Exposed to Plutonium Sources. PNL-7881, Pacific Northwest Laboratory, Richland, Washington.
- Brackenbush, L. W., G. W. R. Endres, J. M. Selby, E. J. Vallario. 1980. Personnel Neutron Dosimetry at Department of Energy Facilities. PNL-3213, Pacific Northwest Laboratory, Richland, Washington.
- Bramson, P. E. 1962. Hanford Criticality Dosimeter. HW-71710, General Electric Company, Richland, Washington.
- Cameron, J. R., N. Suntharalingham and G. N. Kenney. 1968 Thermoluminescent Dosimetry, University of Wisconsin Press
- Cortez, J. R., E. Storm, G. J. Littlejohn. 1977. Photon and Beta Response of a New Thermoluminescent Dosimeter Badge, LA-UR-77-3001, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
- Cross, W. G., 1981. "Neutron Activation of Sodium in Phantoms and the Human Body" Health Physics Vol 41 pp 105 - 121.

Cross, W. G. and H. Ing. 1985. "Sodium Activation in the Human Body." Radiation Protection Dosimetry 10(1-4):265-276.

Cross, W. G., P. Y. Wong, and N. O. Freedman. 1991. "Dose Distributions for Normally Incident Beta Rays." Radiation Protection Dosimetry 35(2):77-91.

Currie, L. A. 1968. "Limits for qualitative detection and quantitative determination" Analytical Chemistry 40: 586-593.

Denham, D. H., R. L. Kathren, J. P. Corley. 1972. A CaF₂:Dy Thermoluminescent Dosimeter for Environmental Monitoring. BNWL-SA-4191. Pacific Northwest Laboratory, Richland, Washington.

Doremus, S. W. and G. A. Higgins, 1994 "Pre-Irradiation Fade and Post-Irradiation Fade for LiF:Mg,Ti, TLD-600 and TLD-700, as a Function of Time" Radiation Protection Dosimetry, Vol 54, No. 2, pp 119-125.

Douglas, J. A. 1981. "Applications of TL Materials in Neutron Dosimetry" in Applied Thermoluminescence Dosimetry, (M. Oberhofer and A. Scharmann, editors) Adam Hilger Ltd. 1981.

Durham, J. S. 1992. VARSKIN MOD2 and SADDE MOD2: Computer Codes for Assessing Skin Dose from Skin Contamination. NUREG/CR-5873, PNL-7913, Pacific Northwest Laboratory, Richland, Washington.

Durham, J. S. 2006. J. S. Durham, VARSKIN 3: A Computer Code for Assessing Skin Dose from Skin Contamination, NUREG/CR-6918 (2006).

Endres, A. W., L. W. Brackenbush, W. V. Baumgartner, J. J. Fix, and B.A. Rathbone. 1996. Response of Hanford Combination Neutron Dosimeter Exposed to Plutonium Sources. PNNL-10516, Pacific Northwest National Laboratory, Richland, Washington.

Fix, J. J., J. M. Hobbs, P. L. Roberson, D. C. Haggard, K. L. Holbrook, M. R. Thorson, F. M. Cummings. 1982. Hanford Personnel Dosimeter Supporting Studies FY-1981. PNL-3736. Pacific Northwest Laboratory, Richland, Washington.

Fix, J. J., W.H. Wilson, and W. V. Baumgartner. 1996. Retrospective Assessment of Personnel Neutron Dosimetry for Workers at the Hanford Site. PNNL-11196, Pacific Northwest National Laboratory, Richland, Washington.

Fix, J. J., E. S. Gilbert, and W. V. Baumgartner. 1994. An Assessment of Bias and Uncertainty in Recorded Dose From External Sources of Radiation For Workers at the Hanford Site. PNL-10066, Pacific Northwest Laboratory, Richland, Washington.

Fix, J. J., G. W. R. Endres, F. M. Cummings, J. M. Aldrich, M. R. Thorson, R. L. Kathren. 1981. Hanford Personnel Dosimeter Supporting Studies FY-1980. PNL-3536, Pacific Northwest Laboratory, Richland, Washington.

Glenn, R. D., and P. E. Bramson. 1977. The Hanford Critical Radiation Dosimeter. PNL-2276, Pacific Northwest Laboratory, Richland, Washington.

Grosswendt. 1990. "Conversion Coefficients for Calibrating Individual Photon Dosimeters in Terms of Dose Equivalents in an ICRU Tissue Cube and PMMA Slabs." Radiation Protection Dosimetry 32(4):215-231.

Hankins, D. E. 1980a. "Dosimetry of Criticality Accidents using Activations of the Blood and Hair" Health Physics Vol 38 pp 529 - 541.

Hankins, D. E. 1981. "Albedo Neutron Dosimeters Used as Area Monitors on Concrete Walls" Health Physics Vol 41 pp 543 - 546.

Harshaw/Filtrol TLD System 8800 Card Reader User's Manual for Use with Radiation Evaluation and Management System (REMS). 1988. Harshaw/Filtrol, Solon, Ohio.

Health Physics Society (HPS). 1993. American National Standard for Dosimetry - Personnel Dosimetry Performance - Criteria for Testing. HPS N13.11, Health Physics Society, McLean, Virginia.

Health Physics Society (HPS). 1996a. American National Standard Performance Testing of Extremity Dosimeters. HPS N13.32, Health Physics Society, McLean, Virginia.

Health Physics Society (HPS). 1996b. American National Standard for Dosimetry , Environmental Dosimetry Performance - Criteria for Testing. HPS N13.29 (Draft), Health Physics Society, McLean, Virginia.

Health Physics Society (HPS). 2001. American National Standard for Dosimetry - Personnel Dosimetry Performance - Criteria for Testing. HPS N13.11, Health Physics Society, McLean, Virginia.

Health Physics Society (HPS). 1997. American National Standard – Criteria for Performing Multiple Dosimetry. HPS N13.41-1997, Health Physics Society, McLean, Virginia

Horowitz, Y. S. 1984. Thermoluminescence and Thermoluminescent Dosimetry. CRC Press, Inc., Boca Raton, Florida

International Atomic Energy Agency (IAEA). 1982. Dosimetry for Criticality Accidents, A Manual. Technical Report Series No. 211, IAEA, Vienna, Austria.

International Commission on Radiation Units and Measurements (ICRU). 1976. Conceptual Basis for the Determination of Dose Equivalent. ICRU Report 25, Bethesda, Maryland.

International Commission on Radiation Units and Measurements (ICRU). 1988. Determination of Dose Equivalents from External Radiation Sources - Part 2. ICRU Report 43, Bethesda, Maryland.

International Commission on Radiation Units and Measurements (ICRU). 1992. Measurement of Dose Equivalents from External Photon and Electron Radiations. ICRU Report 47, Bethesda, Maryland.

International Commission on Radiation Units and Measurements (ICRU). 1993. Quantities and Units in Radiation Protection Dosimetry. ICRU Report 51, Bethesda, Maryland.

International Commission on Radiation Units and Measurements (ICRU). 1998. Conversion Coefficients for use in Radiological Protection Against External Radiation. ICRU Report 57, Bethesda, Maryland.

International Commission on Radiological Protection (ICRP). 1974. Report of the Task Group on Reference Man. ICRP Publication 23. Pergamon Press, New York.

International Commission on Radiological Protection (ICRP). 1977. Recommendations of the ICRP. ICRP Publication 26, New York, New York.

- International Commission on Radiological Protection (ICRP). 1987. Data for Use in Protection Against External Radiation. ICRP Publication 51, New York, New York.
- International Commission on Radiological Protection (ICRP). 1991. Radiation Protection: Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, New York, New York.
- International Commission on Radiological Protection (ICRP). 1996. Conversion Coefficients Use in Radiological Protection Against External Radiation. ICRP Publication 74, New York, New York.
- Johnson, T. L. , and R. B. Luersen. 1980. "Fading of Unannealed LiF (TLD 600) for Thermal Neutrons and Gamma Rays" Health Physics Vol 38 pp 853-856.
- McDonald, J. C., J. E. Tanner, R. D. Stewart, R. Michel, M. K. Murphy and R. J. Traub. 1995. "Effect of Phantom Size and Composition on Neutron Dosimeter Reading," Radiation Protection Dosimetry Vol 59, pp 263-268 (1995)
- McKeever, S. W. S., M. Moscovitch and P. D. Townsend. 1995. Thermoluminescence Dosimetry Materials: Properties and Uses, Nuclear Technology Publishing
- McKinlay, A. F. 1981. Thermoluminescence Dosimetry. Adam Hilger, Ltd., Bristol, England.
- Mettler, F. A. and G. Voelz 2001. "Evaluation of Neutron Exposure" in Medical Management of Radiation Accidents 2nd Edition, (I. Gusev, A. Guskova, and F. Mettler, editors) CRC Press LLC. 2001.
- Moscovitch, M. 1993. "Dose Algorithms for Personal Thermoluminescence Dosimetry" Radiation Protection Dosimetry Vol 47 pp 373-380 (1993)
- Moscovitch, M. and J. E. Rotunda. 1996. Multi-Element Dosimetry System Using Neural Network. U.S. Patent Number 5,572,028, U.S. Patent Office
- Moscovitch, M. 1999. "Personnel Dosimetry Using LiF:Mg,Cu,P", Radiation Protection Dosimetry, Vol. 85, pp. 49-56.
- National Council on Radiation Protection and Measurements (NCRP). 1971. Protection Against Neutron Radiation. NCRP Report No. 38, Bethesda, Maryland.
- National Council on Radiation Protection and Measurements (NCRP). 1978 Instrumentation and Monitoring Methods for Radiation Protection, NCRP Report No. 57, Bethesda, Maryland
- National Council on Radiation Protection and Measurements (NCRP). 1987 Ionizing Radiation Exposure of the Population of the United States, NCRP Report No. 93, Bethesda, Maryland
- National Council on Radiation Protection and Measurements (NCRP). 1989. Limit for Exposure to "Hot Particles" on the Skin. NCRP Report No.106, Bethesda, Maryland.
- National Council on Radiation Protection and Measurements (NCRP). 1992. Maintaining Radiation Protection Records. NCRP Report No. 114, Bethesda, Maryland.
- National Council on Radiation Protection and Measurements (NCRP). 1993. Limitation of Exposure to Ionizing Radiation. NCRP Report No.116, Bethesda, Maryland.

National Council on Radiation Protection and Measurements (NCRP). 1995. Use of Personal Monitors to Estimate Effective Dose Equivalent and Effective Dose To Workers for External Exposure to Low-LET Radiation. NCRP Report No. 122, Bethesda, Maryland.

Oberhofer M. and A. Scharmann (editors). 1979. Applied Thermoluminescent Dosimetry. p 208, Adam Hilger Ltd, Bristol, England.

Plato, P., and Miklos, J., 1985. "Production of Element Correction Factors for Thermoluminescent Dosimeters" Health Physics Vol 49, No. 5 (November), pp 873-881, 1985

Rathbone, B. A., A. W. Endres, E. J. Antonio. 1994. Evaluation of New and Conventional Thermoluminescent Phosphors for Environmental Monitoring Using Automated Thermoluminescent Dosimeter Readers, Proceedings of Fourth Conference on Radiation Protection and Dosimetry, ORNL/TM-12817.

Rathbone, B. A., J. C. McDonald, and R. J. Traub. 2002. "Current Challenges in Personnel Dosimetry at the US DOE Hanford Site" Radiation Protection Dosimetry 101(1-4):153-166. (2002)

Robertson, M.E.A., and W.B. Gilboy. 1971. Studies of the Thermoluminescence of Lithium Fluoride Doped with Various Activators, Proc. Third Int. Conf. Luminescence Dosimetry, Riso-Rep, 249, Vol. 1, Danish AEC, Riso, Roskilde, Denmark.

Scherpelz, R. I., J. J. Fix, and B. A. Rathbone, 2000. Validation of Hanford Personnel and Extremity Dosimeters in Plutonium Environments, PNNL-12136, Pacific Northwest national Laboratory, Richland, Washington

Schwartz, R. B., and C. M. Eisenhauer. 1982. Procedures for Calibrating Neutron Personnel Dosimeters, NBS Special Publication 633, U.S. Department of Commerce/National Bureau of Standards, Washington, DC.

Storm, E., P. L. Buslee, A. W. Blackstock, G. J. Littlejohn, J. R. Cortez, R. V. Fultyn, and J. N. P. Lawrence. 1981. "The Los Alamos Thermoluminescence Dosimeter Badge." Radiation Protection Dosimetry 1 (3): 209-219.

Takahashi, F., A. Endo and Y. Yamaguchi. 2003. "Dose Assessment from Activated Sodium Within a Body in Criticality Accidents." Radiation Protection Dosimetry 106(3):197-206.

Tawil, R.A. 1996. "Thermoluminescent Dosimetry" Applications of New Technology: External Dosimetry, Health Physics Society, 1996

Tawil, R. A., K. J. Velbeck, J. E. Rotunda, C. Flory, and M. Moscovitch. 1993. "A System for Environmental Monitoring." Radiation Protection Dosimetry 47(1/4):317-321.

U.S. Department of Energy (DOE). 1986a. Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems. DOE/EH-0027, Washington D.C.

U.S. Department of Energy (DOE). 1986b. Handbook for the Department of Energy Accreditation Program for Personnel Dosimetry Systems. DOE/EH-0026, Washington D.C.

U.S. Department of Energy (DOE). 1993. Occupational Radiation Protection. Federal Register. Title 10 Part 835. U.S., Code of Federal Regulations, Vol. 58, No. 238, 65458-65512.

U.S. Department of Energy (DOE) 1995. Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems. DOE-STD-1095-95

- U.S. Department of Energy (DOE) 1998a. The Department of Energy Laboratory Accreditation Program Administration. DOE-STD-1111-98
- U.S. Department of Energy (DOE) 1998b. Guide of Good Practices for Occupational Radiological Protection in Plutonium Facilities. DOE-STD-1128-98
- U.S. Department of Energy (DOE). 1998c. Occupational Radiation Protection. Federal Register. Title 10 Part 835. U.S., Code of Federal Regulations, Vol. 63, No. 213, 59662-59689.
- U.S. Department of Energy (DOE). 1999a. Evaluation and Control of Radiation Dose to the Embryo/Fetus Guide. DOE G 441.1-6, Washington, D.C.
- U.S. Department of Energy (DOE). 1999b. External Dosimetry Program Guide. DOE G 441.1-4, Washington, D.C.
- U.S. Department of Energy (DOE). 1999c. DOE Standard - Radiological Control. DOE-STD-1098-99, Washington, D.C.
- U.S. Department of Energy (DOE). 1999d. Quality Assurance. DOE O 414.1A, DOE Orders and Directives
- U.S. Department of Energy (DOE) — Richland Operations Office. 2001 Hanford Radiological Health and Safety Document. DOE/RL-2002-12, Richland, Washington.
- U.S. Department of Energy (DOE). 2003. Quality Assurance Requirements. U.S. Code of Federal Regulations, Title 10 Part 830 - Subpart A, .
- U.S. Nuclear Regulatory Commission (NRC). 1977. Performance, Testing, and Procedural Specifications for Thermoluminescence Dosimetry: Environmental Applications. Regulatory Guide 4.13, Washington, D.C.
- Vasilik, D. G., and R. W. Martin. 1981a. The Los Alamos Personnel and Area Criticality Dosimeter Systems. LA-8848-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
- Vasilik, D. G., and R. W. Martin. 1981b. Nuclear Accident Dosimetry: Los Alamos Measurements at the Seventeenth Nuclear Accident Dosimetry Intercomparison Study at the Oak ridge National Laboratory DOSAR Facility, August 1980. LA-8799-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
- Wilson, R. H., J. J. Fix, W. V. Baumgartner, and L. L. Nichols. 1990. Description and Evaluation of the Hanford Personnel Dosimeter Program From 1944 Through 1989. PNL-7447, Pacific Northwest Laboratory, Richland, Washington.
- Wilson, R. H. 1962. A Method for Immediate Detection of High Level Neutron Exposure by Measurement of Sodium-24 in Humans. HW-73891 Rev. General Electric, Richland, Washington.
- Wilson, R. H. 1987. Historical Review of Personnel Dosimetry Development and its Use in Radiation Protection Programs at Hanford. PNL-6125, Pacific Northwest Laboratory, Richland, Washington.