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 TLD=s 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 track etch dosimetry (TED) used in the HCND, and neutron activation dosimetry used 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 General Characteristics Of TLD Phosphors

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% ^{6}Li and 4.4% ^{7}Li) and TLD-700 (approximately 99.99% ^{7}Li and approximately 0.01% ^{6}Li). The natural isotopic abundance of lithium fluoride is 7.5% ^{6}Li and 92.5% ^{7}Li. 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}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}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}Li. Likewise, it can be made almost insensitive to thermal neutrons by depleting the lithium of ^{6}Li.

When a radiation worker is irradiated with fast neutrons, there is little probability that the ^{6}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}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
- 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, CaF_2: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, 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 high doses. However, after saturation, the LiF 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 (i.e., 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 CaF_2:Dy relative to LiF:Mg,Ti when irradiated with gamma radiation from ^{60}Co, 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 ^{137}Cs. 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)] CaF_2:Dy exhibits a much larger fading rate.

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 CaF_2:Dy. The HEDP uses all of these annealing options to achieve greatly reduced fading rates 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 of 40% relative to ^{137}Cs in the 20- to 70-keV range, which 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 in excess of 100 keV. For CaF_2, 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).

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

5.1.10 Reproducibility

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 reproducibility of 80 TLD elements randomly selected from production inventory and repeatedly exposed to 100 mR from a ^{137}Cs source is better than 1.3% of the mean reading, as determined by vendor testing (Harshaw 1988). 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 exposure to 500 mrad of 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 accurately read and the card processed. The file of processed cards is uploaded to the HEDP VAX 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 contained in a stainless steel-lined sphere (30-cm diameter) containing D_2O. This source provides an abundance of scatter 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, the range of ECCs obtained during card calibration (Section 5.3.2) is evaluated. The combination of these tests ensures that the correct phosphors are contained in the respective HEDP cards and that these phosphors demonstrate acceptable performance.

5.2.4 Light Testing

The TLD phosphors are known to be light-sensitive. However, some phosphors and or Teflon™ enclosures 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 type of dosimeter card 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

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. All dosimeter holders 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 extremity dosimeter is a finger ring. The environmental dosimeter is mounted vertically in air. 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.

Table 5.3. Contents of the HEDP Dosimeters

Dosimeter Type	Card/Holder ID#	Description of Active Elements	Description of Holder[a]
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: 1000 mg/cm^2 Teflon™ABS filtration Back: ABS 173 mg/cm^2 Front: 7.5 mg/cm^2 Mylar™ window 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
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.
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. ABS = acrylonitrile-butadiene-styrene plastic

5.3.1 TLD Reader Calibration

Calibration of each reader system is accomplished by processing a representative sample of previously calibrated reader calibration cards that have been exposed in air without a holder to a known amount of ^{60}Co radiation. The reader calibration cards used for this purpose are exposed to 500 mR and an RCF expressed in units of nC/mR is calculated for each of the four PMT channels according to the following relationships:

$$RCF_i = \frac{\overline{R}_i}{X} \tag{5.1}$$

$$\overline{R}_i = \frac{\sum_{j=1}^{k} R_{ij} * ECC_{ij}}{k} \tag{5.2}$$

where RCF_i = reader calibration factor for i^{th} PMT (nC/mR)
X = exposure value (mR)
R_{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).

5.3.2 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. 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 relationships:

$$ECC_{ij} = \frac{RCF_i}{R_{ij}} X \qquad (5.3)$$

where ECC_{ij} = element correction coefficient for chip i on card j
RCF_i = reader calibration factor for PMT_i (nC/mR)
R_{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 is 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 more than six years old are automatically prevented by the External Dosimetry Data Management System from being issued.

5.3.3 Dosimeter Calibration

HEDP calibrates it's TLD readers with cards exposed in air to ^{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 in air equivalent mR). It is necessary to relate these readings to an on-phantom response to ^{137}Cs as used in the DOELAP standard. Dosimeter calibration consists of determining the relationship between each chip's response to ^{60}Co in air without a holder, and its response to ^{137}Cs when irradiated in a holder and on a phantom. The resulting factor is called the relative response factor (RRF) and is expressed in units of mR/rem for each chip position. The RRF is a function of the two sources used (i.e., in this case there is very little difference between ^{60}Co and ^{37}Cs), the chip thickness, filtration over the chip when in the holder, and the geometry of the two exposures. Therefore, the RRF varies primarily with dosimeter type, chip position, and radiation type. For a given dosimeter type, 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 RRF for that chip position in that dosimeter. 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. For the HEDP dosimetry system, relative response factors 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.[c] RRFs have been determined for each chip position in each of the dosimeter type used at Hanford.

(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.

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

5.3.4 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:

$$X_i = Q_i \times ECC_i/RCF_i \qquad (5.4)$$

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).

5.3.5 Adjusted Element Readings

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

$$Xnet_i = (X_i - E_i) \qquad (5.5)$$

$$D_i = Xnet_i / (RRF_i * F_i * S_i) \qquad (5.6)$$

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 environmental background 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
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.

5.3.5.1 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.

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 1) data and deep dose element (chip 2) data for the HSD are shown in Figures 5.1 and 5.2 respectively. The fact that natural environmental radiation levels at Hanford have varied by less than 10% over a four year period from 1995-1998 (Antonio, 1999) suggests that these 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 for the entire Hanford site indicates that relative to the DOE monitoring threshold of 100 mrem/y, the standard uncertainty of ± 20 mrem/y in recorded dose is acceptable.

(a) B. A. Rathbone, "Re-evaluation of Background Functions for HSD and HCND Dosimeters," October 3, 1999, letter to HEDP file.

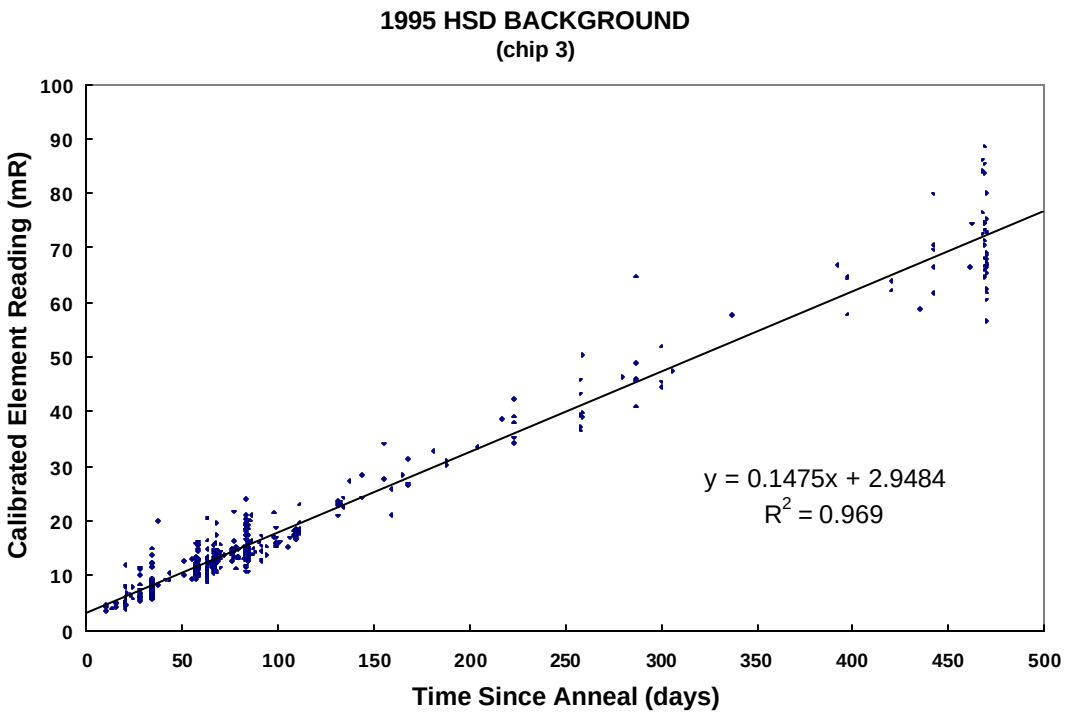


Figure 5.1 Buildup of Environmental Background Signal in HSD Shallow Dose Element

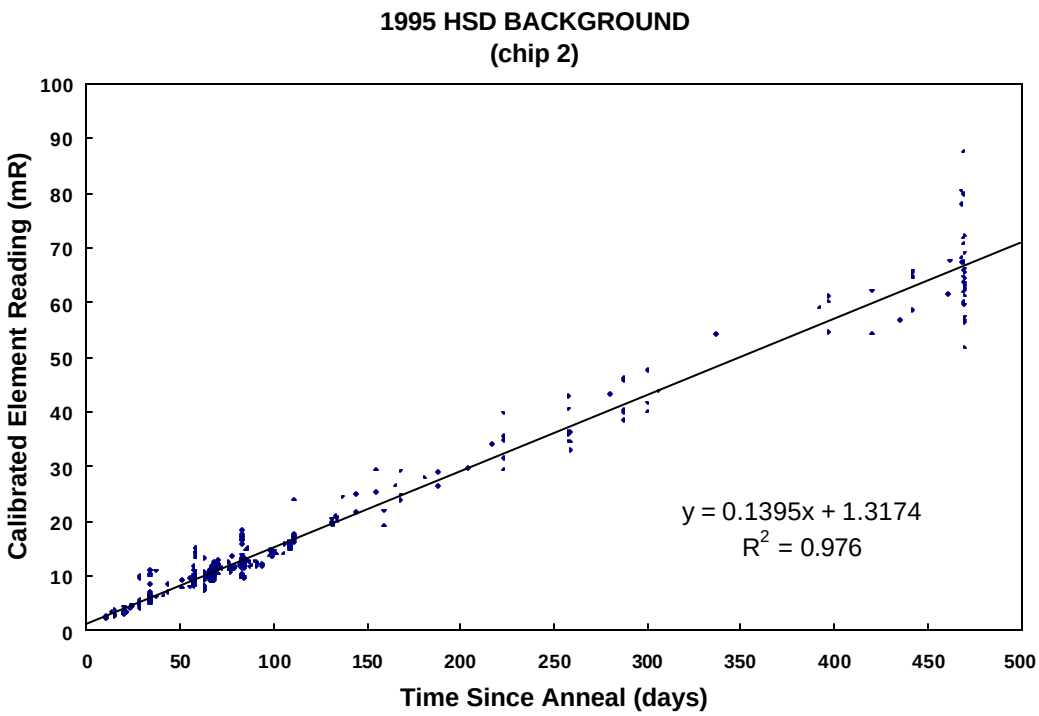


Figure 5.2 Buildup of Environmental Background Signal in HSD Deep Dose Element

5.3.5.2 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 [(a)] 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 same form as follows:

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

where:
- t is the time since irradiation (days)
- R(t) is the net chip response (mR) at time t
- R_0 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 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

(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

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

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 below. This assumes that the two types of fading act independently.

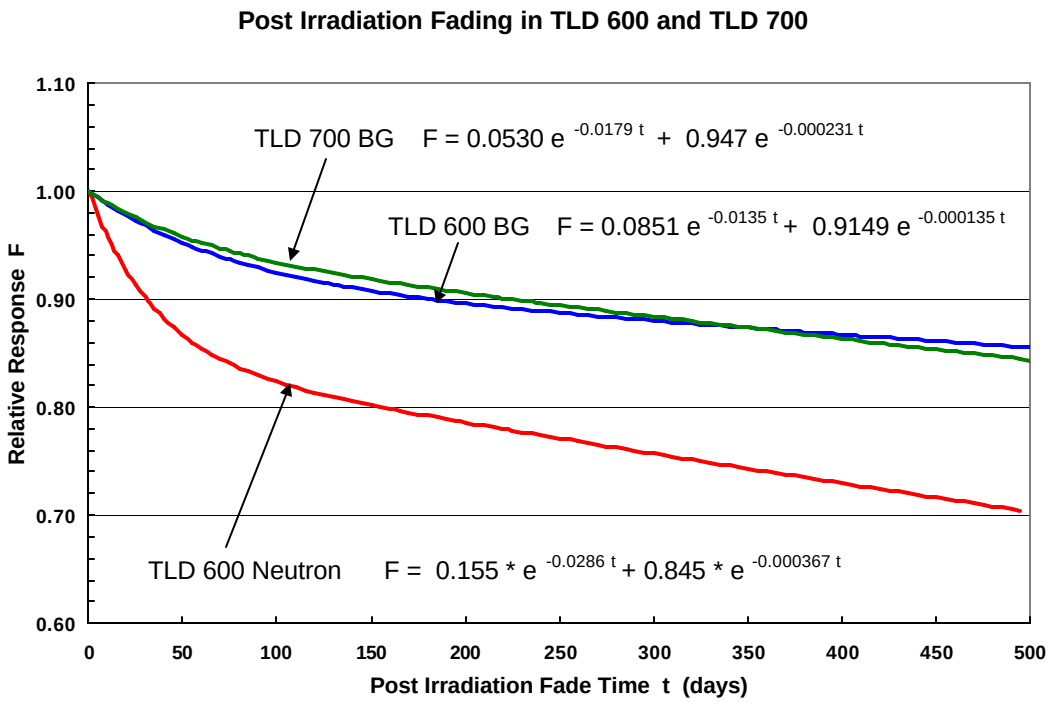


Figure 5.3 Post Irradiation Fade Functions Used for Hanford Dosimetry Materials

(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.

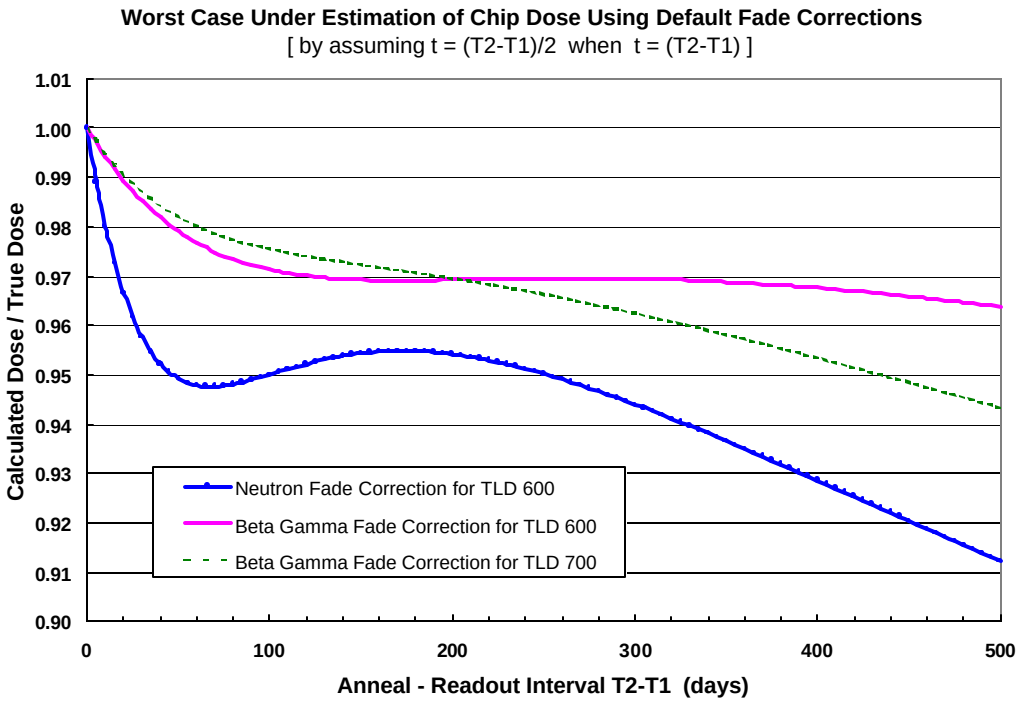


Figure 5.4 Error in default fade correction when entire exposure occurs on first day of use cycle.

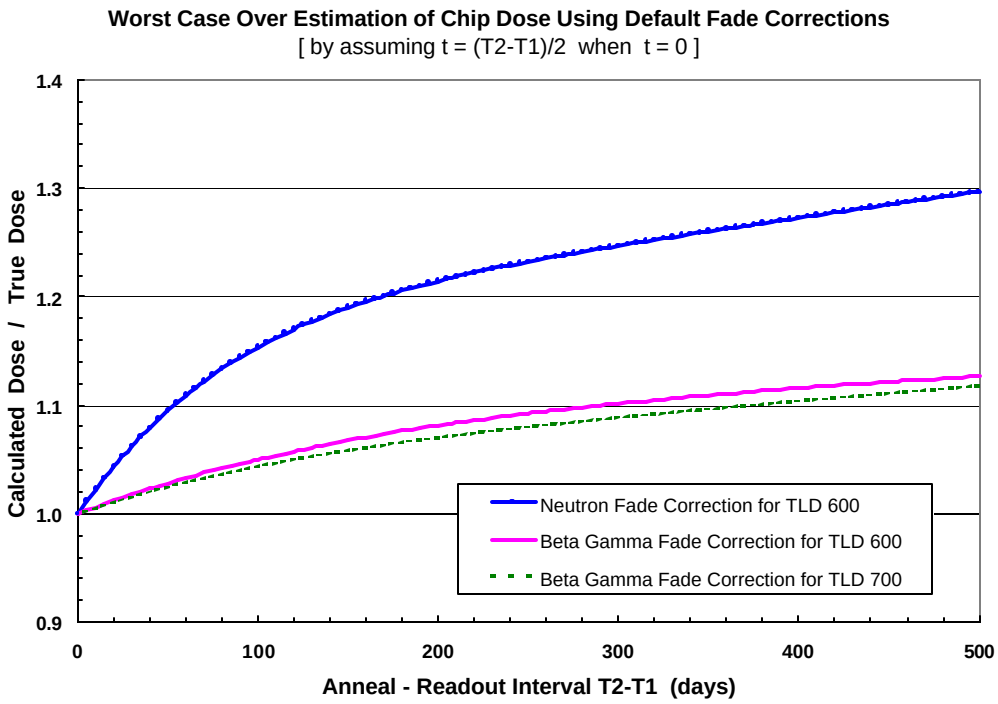


Figure 5.5 Error in default fade correction when entire exposure occurs on last day of use cycle.

5.3.5.3 Models for Supralinearity

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

$$\text{Sgamma} = 1 + 3.411\text{E-}7 * \text{Xnet} \tag{5.9}$$

where:

Sgamma	=	net reading of chip (mR) / given exposure (mR)
Xnet	=	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.

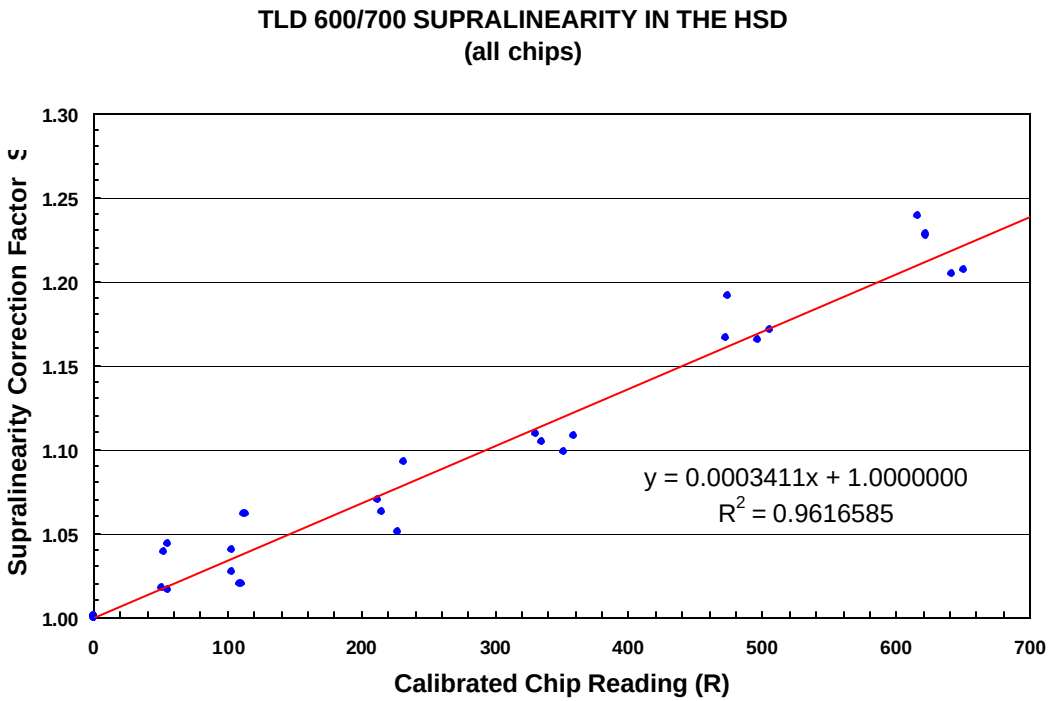


Figure 5.6. Supralinearity Correction for Beta-Gamma Signal in TLD 600 and 700.

This supralinearity model is not appropriate for high LET radiations. In particular, it

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

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 $^{6}Li(n,\alpha)^{3}H$ 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:

$$Sneutron = 1$$

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.

5.3.5.4 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: $i = 1\text{-}4$

If: $Xnet_i > 0$,

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

If: $Xnet_i > Xnet_2$ (neutrons present)

$$Wgamma_i = Xnet_2 / Xnet_i$$
$$Wneutron_i = 1 - Wgamma_i$$
$$Fgamma_i = 0.0851 \exp(-0.0135\, t) + 0.9149 \exp(-0.000135\, t)$$
$$Fneutron_i = 0.1550 \exp(-0.0286\, t) + 0.8450 \exp(-0.000367\, t)$$
$$Sgamma_i = 1 + 3.411E\text{-}7 * Xnet_2$$
$$Sneutron_i = 1$$

$F_i = (Wgamma_i * Fgamma_i) + (Wneutron_i * Fneutron_i)$
$S_i = (Wgamma_i * Sgamma_i) + (Wneutron_i * Sneutron_i)$

Else: (neutrons <u>not</u> present)

$F_i = 0.0851 \exp(-0.0135\, t) + 0.9149 \exp(-0.000135\, t)$
$S_i = 1 + 3.411E\text{-}7 * Xnet_i$

End If

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

If: $Xnet_i > Xnet_1$ (neutrons present)

$Wgamma_i = Xnet_1 / Xnet_i$
$Wneutron_i = 1 - Wgamma_i$
$Fgamma_i = 0.0851 \exp(-0.0135\, t) + 0.9149 \exp(-0.000135\, t)$
$Fneutron_i = 0.1550 \exp(-0.0286\, t) + 0.8450 \exp(-0.000367\, t)$
$Sgamma_i = 1 + 3.411E\text{-}7 * Xnet_1$
$Sneutron_i = 1$
$F_i = (Wgamma_i * Fgamma_i) + (Wneutron_i * Fneutron_i)$
$S_i = (Wgamma_i * Sgamma_i) + (Wneutron_i * Sneutron_i)$

Else: (neutrons <u>not</u> present)

$F_i = 0.0851 \exp(-0.0135\, t) + 0.9149 \exp(-0.000135\, t)$
$S_i = 1 + 3.411E\text{-}7 * Xnet_i$

End If

Else: (TLD 700)

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

End If (card type =)

End If ($Xnet_i > 0$)

End Do (i=1-4)

5.3.6 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 to be calculated for personnel dosimeters are specified in DOE requirements (DOE 1998c). For this reason, HEDP personnel dosimeter algorithms have been developed to calculate personal dose equivalent, in units of mrem, at specific depths in tissue, noted here as H_s, H_e, and H_d:

- H_s = shallow dose, i.e., dose equivalent at 7 mg/cm^2, 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/cm^2, corresponding to the depth of the lens of the eye (0.3 cm)

- H_d = deep dose, i.e., dose equivalent at 1000 mg/cm^2, corresponding to measurement of the whole body dose equivalent at tissue depth of 1 cm.

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/cm^2 in a tissue-equivalent holder could be used to measure the skin, lens of the eye, and whole body 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 ANSI (HPS

(a) B.A. Rathbone, “Update on HEDP Dose Calculation Methodology,”April 8, 2000, letter to HEDP file.

1993) 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, but in the absence of the phantom. For the standard PMMA slab phantom specified in HPS N 13.11, back scatter factors range from 1.10 for 662 keV photons to 1.80 for 50 keV photons (HPS 1993).

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.

5.3.7 Facility Calibration Codes

Contractor radiation dosimetry organizations provide a "facility 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 algorithms for the 8816 neutron dosimeter (^{252}Cf or PuF_4), and to specify correction factors to be applied to the Hanford ring dosimeter.

For Hanford users this two-digit calibration code, commonly referred to as the Afacility 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 used in calculating and reporting personnel dose.

The whole body neutron dose calculated from the 8816 neutron dosimeter is based on contractor input, which identifies the neutron environment as characteristic of either 1) ^{252}Cf sources, or 2) ^{239}Pu sources. The individual algorithms used for each source type are described by Endres et al (1996) and by Scherpelz, Fix, and Rathbone (2000). Both algorithms use element ratios to determine the degree of moderation from an unmoderated spectrum. The default option, in the event that no calibration code is received, is the ^{252}Cf-based formulation. This default will generally result in calculation of the most conservative personnel neutron dose.

The extremity Aring≅ dose is also based on contractor input of a facility calibration code. For rings, the two-digit calibration <u>code</u> provided by the contractor is divided by 10 to obtain the calibration <u>factor</u>. 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 A00" is received, the algorithm interprets this as instruction to apply the default calibration factor of 1.5 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 1.5 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 an unmeasured neutron response, a code of 2.0 is used. [(b)] This practice was recently validated by 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 dosimetry and instrument measurements (see Chapter 7.0) to ensure that the dose of record is not underestimated.

5.4 Hanford Standard Dosimeter

The HSD is issued to all Hanford personnel assigned a dosimeter with the exception of neutron workers. The dosimeter is used to measure the shallow, eye, and deep dose equivalent of record in beta and photon radiation fields. Although not intended for recording dose from neutron radiation, the dosimeter has a neutron-sensitive TLD-600 phosphor for neutron detection
capability. The neutron response is intended to identify personnel who may need to wear the HCND, which has superior neutron dose capabilities. The HCND is discussed in Sections 5.5 and 5.6.

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/cm^2) in positions one, two, and four and 0.15 mm (40 mg/cm^2) in position three. The holder filtration consists of 242-mg/cm^2 ABS plastic plus 91 mg/cm^2 copper over position one, 1000-mg/cm^2 ABS and polyletrafluoroethylene (PTFE) plastic over position two, 8-mg/cm^2 Teflon™ and 9-mg/cm^2 Mylar™ over position three, and 240 mg/cm^2 ABS plastic plus 463-mg/cm^2 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 both the front side (i.e., dosimeter side facing away from the body) and back side (i.e., dosimeter side facing the body). There are no filters on the back side. A rose-colored 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.

(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.

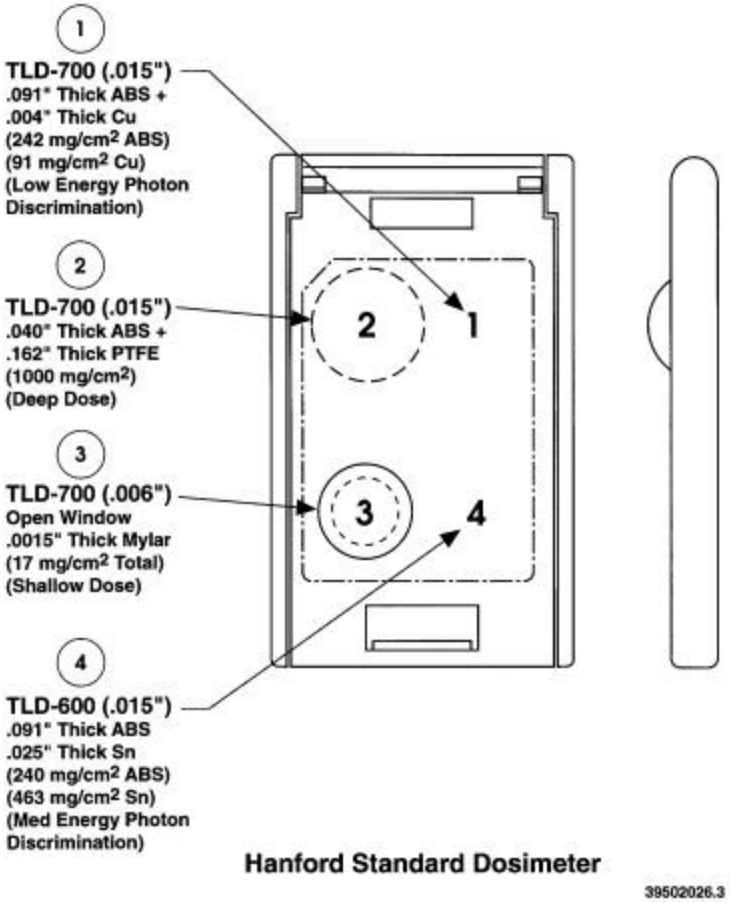


Figure 5.7 Hanford Standard Dosimeter

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 processing. This reader-annealing 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.

- All dosimeter cards are oven-annealed at 80°C for 16 hours before being loaded into a holder. This annealing process reduces the significance of signal fading by eliminating the lower-temperature peaks. 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.

- 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 VAX system to validate the quality of the processing data.

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

5.4.3 Algorithm

The HSD measures the dose equivalent at depths of 7, 300, and 1000 mg/cm^2 from beta and photon radiation. Primary calibration of the HSD algorithm is based on dosimeter response to ^{137}Cs when irradiated on a 30 x 30 x 15 cm^3 polymethylmethacrylate (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 sources specified in DOE/EH-0027 and HPS N 13.11 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/cm^2 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_d). 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/cm^2 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 5.4. 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 ^{137}Cs to obtain the tabled relative values. The relatively good response of the position 3 phosphor to ^{204}Tl 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 4 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 is well documented through formal DOELAP and NVLAP performance testing, as well as in studies documented in HEDP files.[(a)] In preparation for initial DOELAP performance testing, groups of five HSDs each were irradiated to the sources in Table 5.5 according to the specifications contained in the DOELAP standard (DOE 1986a). The mean reported shallow and deep doses calculated by the algorithm were within ±15% of the given dose for all sources shown in Table 5.4. 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 vendor-supplied beta dose algorithm for the HSD. In particular, it was found that 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 50-mCi ^{90}Sr/^{90}Y Buchler beta source with Plexiglass™ 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 a PTW extrapolation chamber. The sources and filtrations are described in greater detail in Section 5.9.7. 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 Apure≅ beta branch of the algorithm was approximately 60% of the delivered eye dose from the unfiltered ^{90}Sr/^{90}Y 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 algorithm. The response of the new algorithm to unfiltered ^{90}Y beta radiation is shown in Table 5.8.

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 was based on C_k factors published by Dr. Chris Soares for various NIST filtered X-ray techniques and for ^{137}Cs. [(b)] The bias in the reported eye dose 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. [(c)]

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

B. A. Rathbone, "HSD Performance Testing Using NVLAP Criteria and C_k", September 30, 1997, letter to HEDP file.

(b) 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.

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

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)] Recently, HPS N13.11 (1993) identified angular response testing at ±40° in addition to the ±30°, ±60°, and ±85° angles identified in the DOELAP standard.

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 K-17, M30, S60, ^{241}Am, and ^{137}Cs sources. Irradiation distances from the source center to the front edge vertical centerline of the phantom were 50 cm for K-17 [(b)] and ^{241}Am irradiations and 100 cm for ^{137}Cs irradiations.

- Beta exposures were made in a similar manner using a 30 x 30 x 5 cm phantom. A ^{90}Sr/^{90}Y source and a ^{204}Tl 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 ^{252}Cf 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.

(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.

(b) Surface of target to surface of phantom.

Table 5.6. Hanford Standard Dosimeter Relative 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}Sr/^{90}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
^{252M}Cf	1.18[c]	1.07[c]	1.16[c]	57.03[c]	0.18[d]	0.16[d]	0.18[d]	8.69[d]
^{252U}Cf	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.

Table 5.7. Hanford Standard Dosimeter Shallow and Deep Dose Algorithm Response

Beam Code	Energy, keV	Shallow Dose Response[a]	Deep Dose Response[a]
K16	16	1.13	0.98
M30	20	1.11	0.85
S60	36	1.22	0.93
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]	2300 (max)	1.04	n/a
^{204}Tl[b]	760 (max)	0.95	n/a

a. Reported/given dose equivalent. Normalized to ^{137}Cs value.
b. Source specifications described in DOELAP standards (DOE 1986a).
n/a = Not applicable.

Table 5.8 Hanford Standard Dosimeter Eye Dose Algorithm Response

Beam Code	**Energy (keV)**	**Reported/Given[a]**
M30	20	1.06
M60	34	1.01
S60	38	1.11
M100	51	1.11
Am-241	59	0.96
M150	70	0.95
H150	117	0.95
Cs-137	662	1.00
Y-90[b]	931	1.02

a Reported values normalized to reported ^{137}Cs value.
b Source specifications described in the DOELAP standard (DOE 1986a)

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 Plexiglass™ 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. For the HCND, only one combination holder was mounted at the center of the phantom surface for each irradiation. For HSD irradiations, two of the three dosimeters 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.

Results

Data collected in the study are summarized 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.

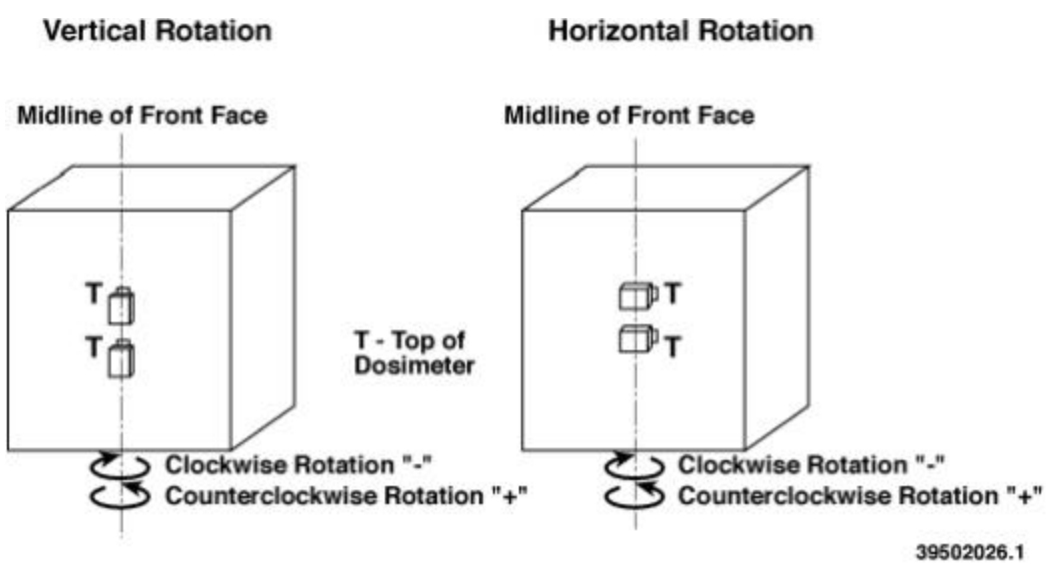


Figure 5.8. Irradiation Setup for Dosimeter Angular Response Evaluation

Table 5.9. Hanford Standard Dosimeter Shallow Dose Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K17	17	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}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 5.10. Hanford Standard Dosimeter Deep Dose [(a)] Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K17	17	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.

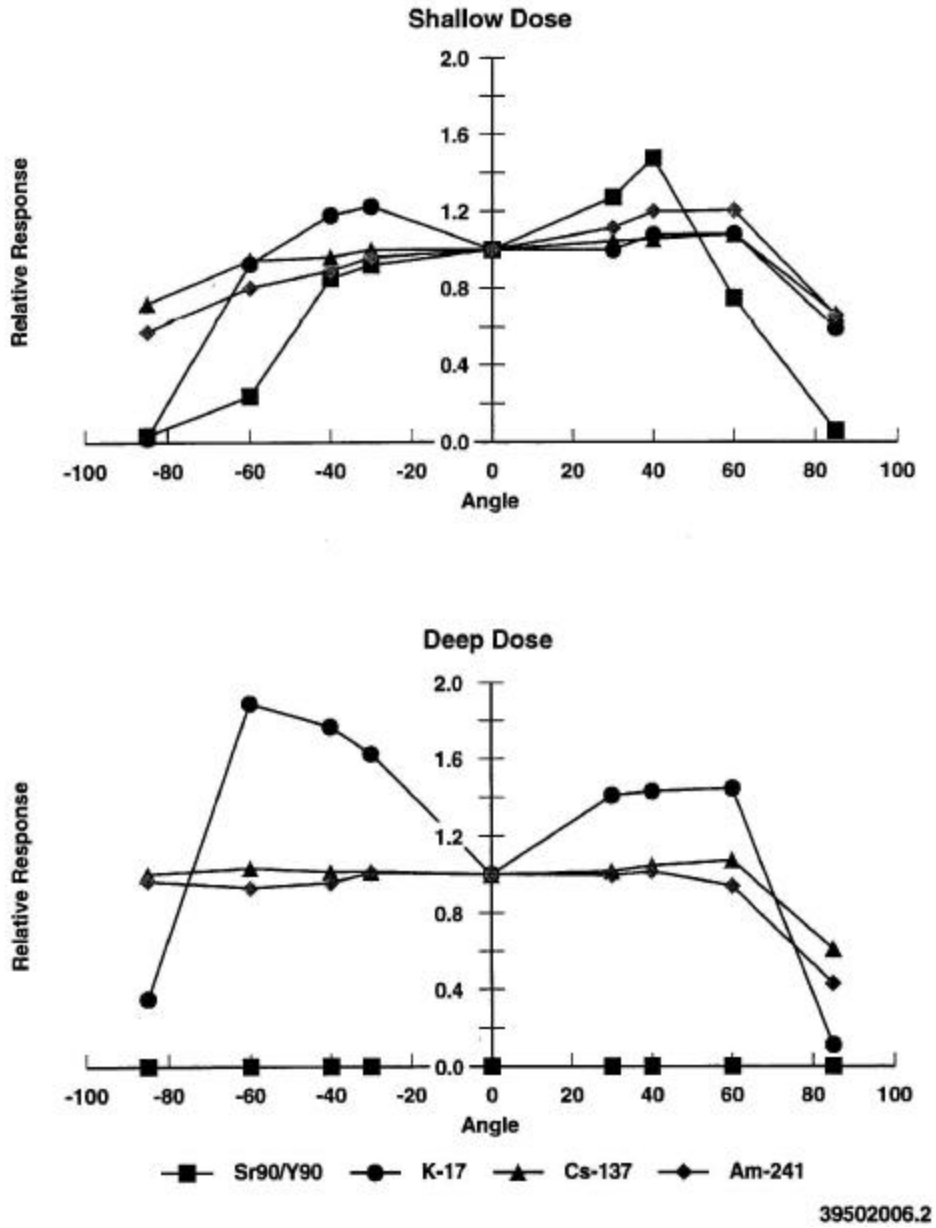


Figure 5.9. Hanford Standard Dosimeter Angular Response – Horizontal Rotation

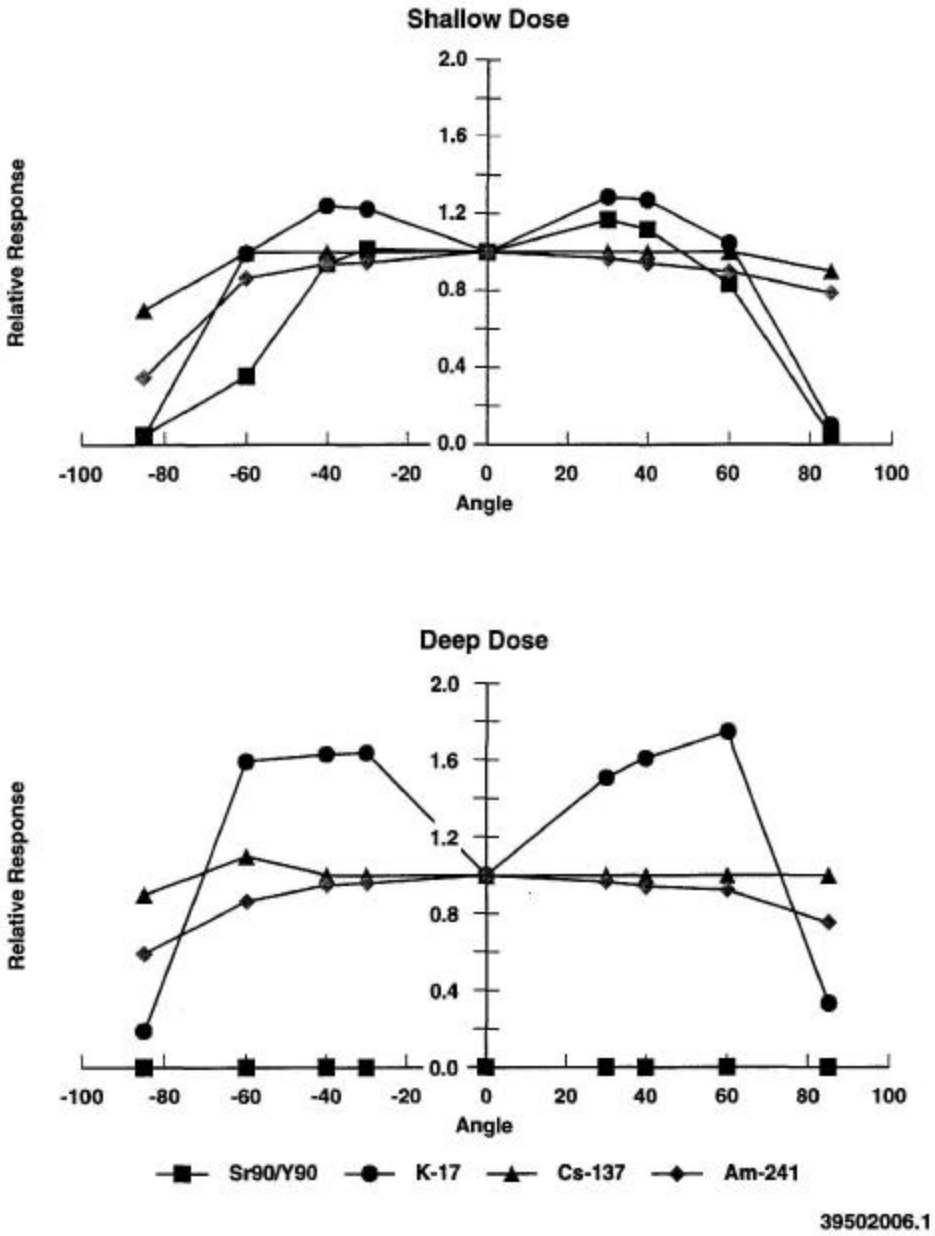
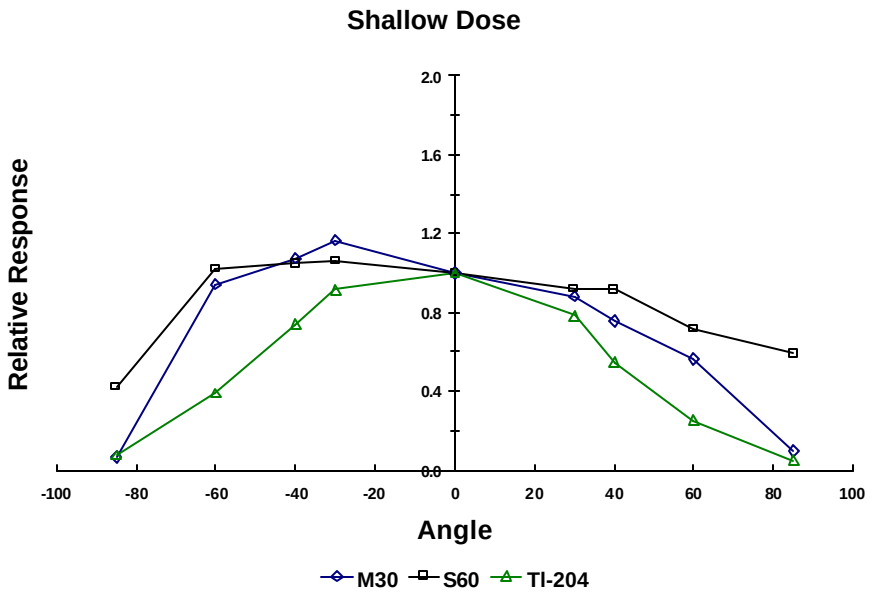


Figure 5.10. Hanford Standard Dosimeter Angular Response – Vertical Rotation



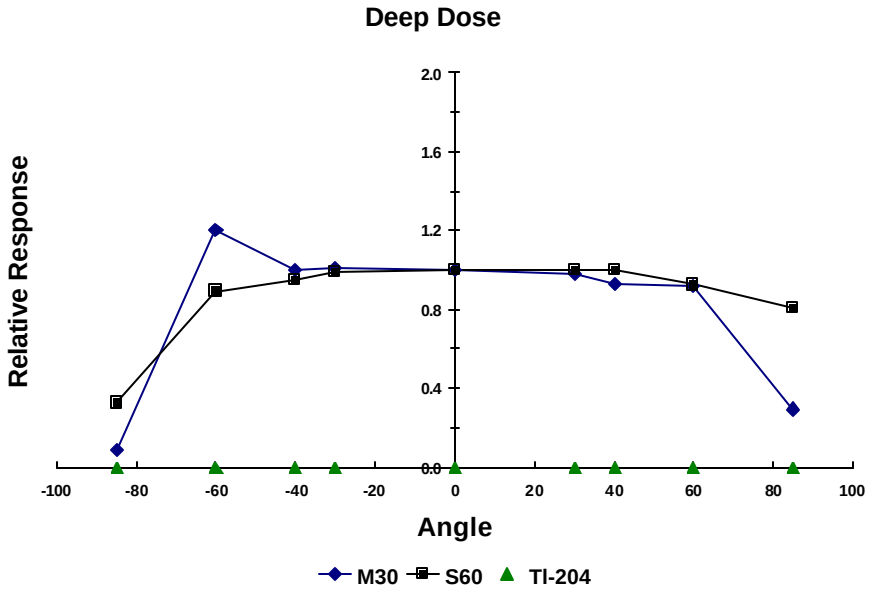
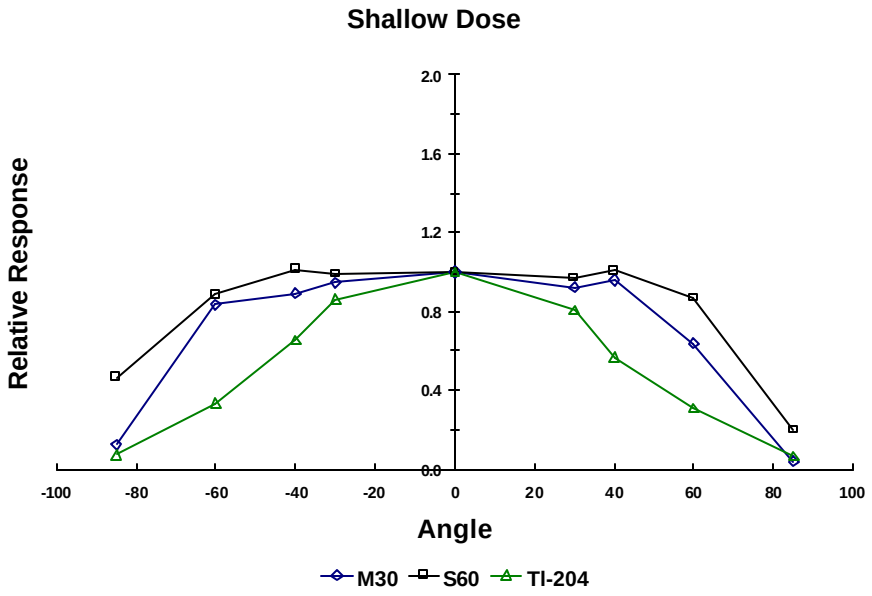


Figure 5.11. Hanford Standard Dosimeter Angular Response – Horizontal Rotation



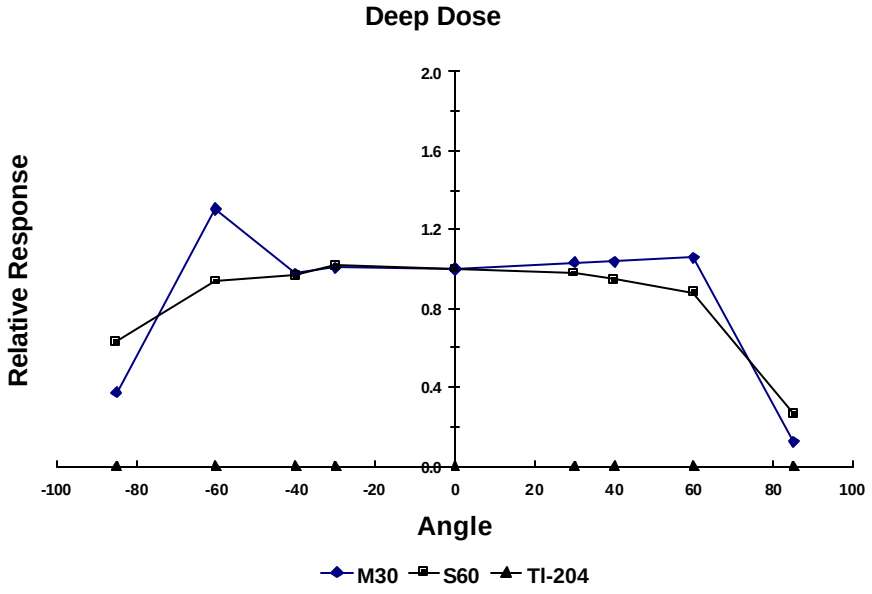


Figure 5.12. Hanford Standard Dosimeter Angular Response – Vertical Rotation

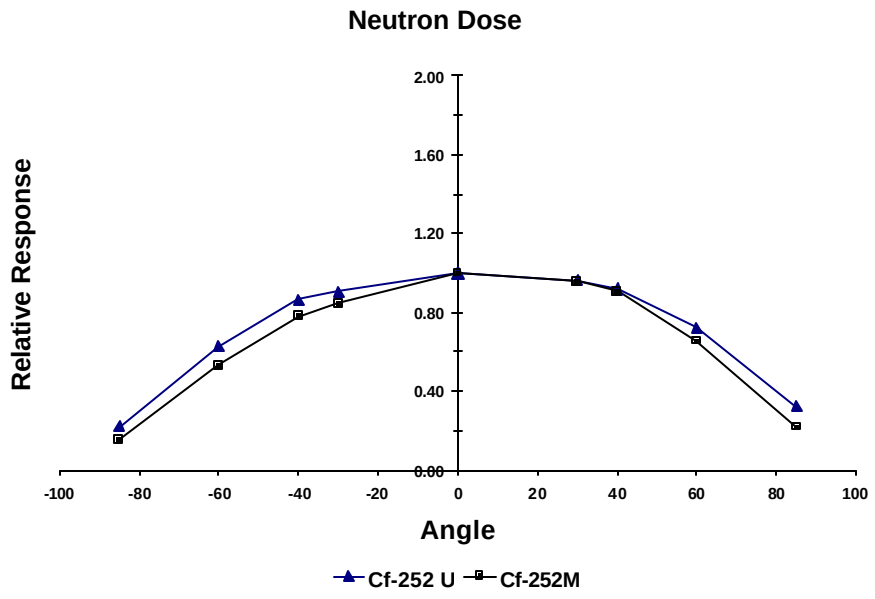


Figure 5.13. Hanford Standard Dosimeter Neutron Angular Response – Horizontal Rotation

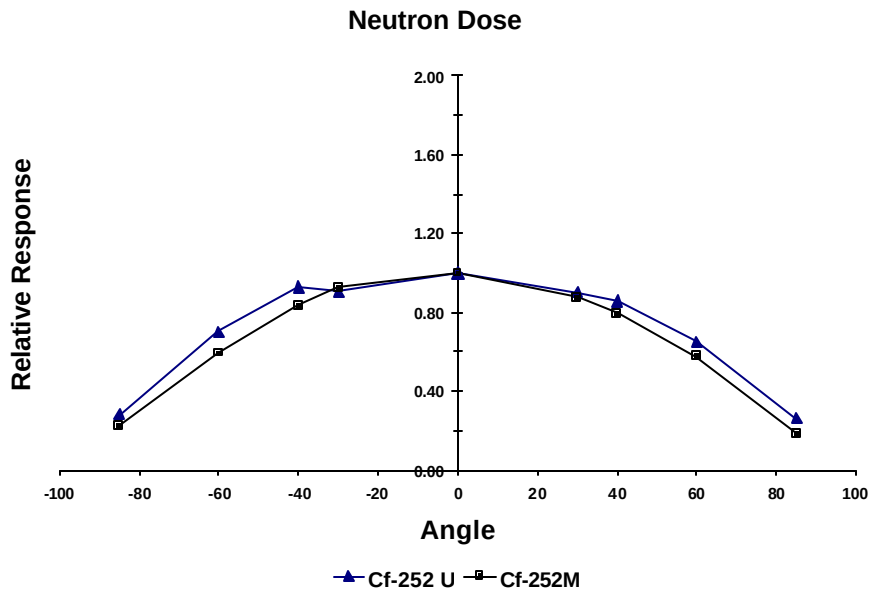


Figure 5.14. Hanford Standard Dosimeter Neutron Angular Response – Vertical Rotation

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 5.11. The symbols Hs, He, Hdp and Hn 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 5.11 Calculated LLDs (in mrem) for the Hanford Standard Dosimeter

Exchange Frequency	DOELAP Category	Parameter	Hs	He	Hdp	Hn (mod)	Hn (bare)
M	Controls	L_C	3.8	3.1	3.1	*	*
	IIIA (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
	IIIA (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
	IIIA (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 ^{60}Co 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 primarily to the sensitivity of the Teflon™ encapsulation to visible and ultraviolet (UV) light. 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 5.3.5.2. In general, fading is less than 15% per year for beta-gamma dose and less than 30% per year for neutron dose.

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

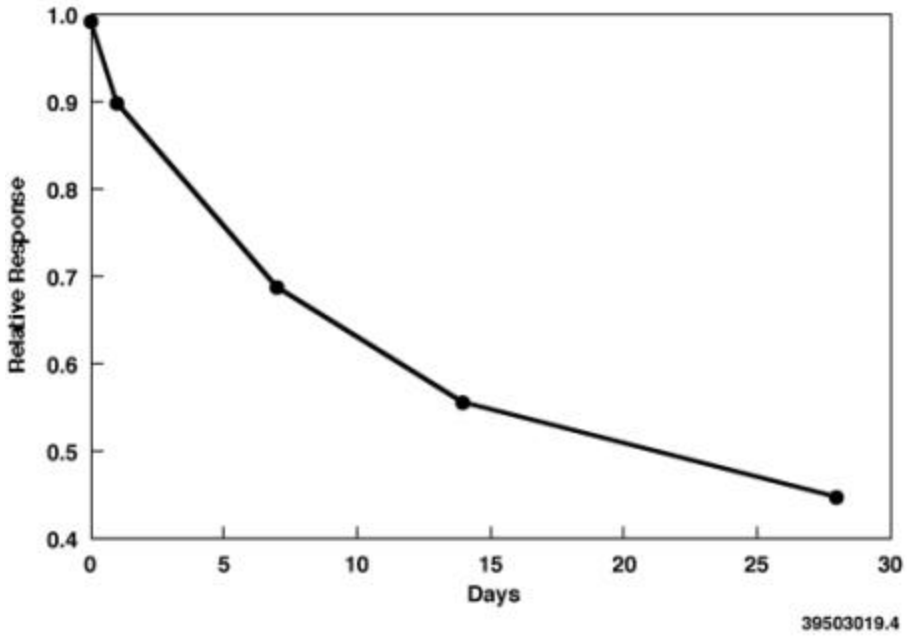


Figure 5.15. Hanford Standard Dosimeter Fading at 80°C

5.5 Hanford Combination Neutron Dosimeter - TLD Component

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 three components:

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

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, two TED foils (CR-39) are housed in the 8816 holder. Detailed design considerations for this dosimeter are provided by Brackenbush, Baumgartner and Fix (1991) and Endres et al (1996). An HCND plastic holder is used to contain all three of these dosimeters, along with the Personnel Nuclear Accident Dosimeter (PNAD), as shown in Figure 5.16. The PNAD is discussed in Section 5.11. The beta-photon 8825 TLD 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.

The TED is described in Section 5.6. Characteristics of the albedo neutron 8816 TLD are described in this section. An illustration of the 8816 albedo neutron dosimeter is shown in Figure 5.17

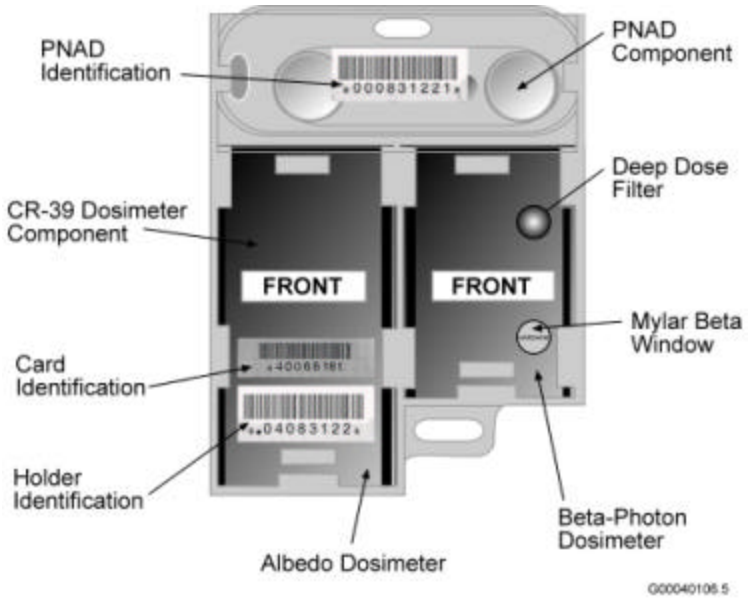


Figure 5.16 Hanford Combination Neutron Dosimeter

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.

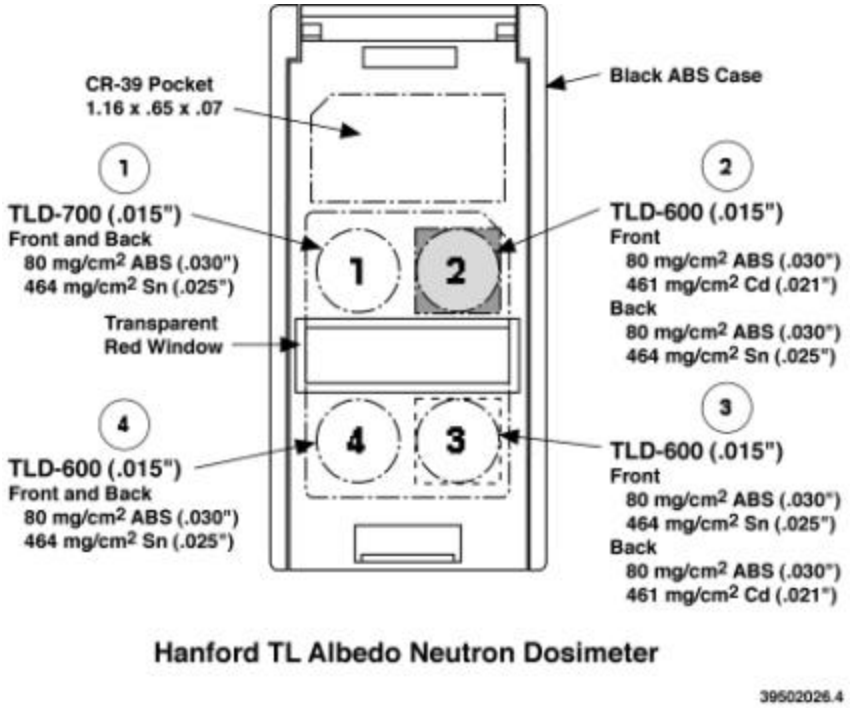


Figure 5.17 8816 Albedo Neutron Dosimeter

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 place the two TED foils when required, into the 8816 holder and load the beta-photon 8825 and neutron albedo 8816 together in a 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. Response functions are used in the algorithm to calculate the neutron dose for one of two neutron sources: ^{252}Cf or PuF_4. Response functions for these two exposure environments were derived from the response of the dosimeter on-phantom to the bare source exposure plus varying thicknesses of Plexiglass™ moderator between the source and dosimeter. The neutron spectra and neutron dose equivalent rates were determined by multisphere and tissue-equivalent proportional counter (TEPC) measurements

of the dose for each exposure geometry (Endres et al 1996).

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 ^{252}Cf 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 ^{252}Cf is 1.05 and 0.16, respectively. For unmoderated ^{252}Cf 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 ^{137}Cs response, is shown in Table 5.12. 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 ^{252}Cf are also shown in Table 5.12.

Table 5.12 8816 Neutron Dosimeter Element Response to DOELAP Sources

	Element Response Per Unit Delivered Dose Equivalent Relative to ^{137}Cs Response							
	Shallow Dose Response[a]				Deep Dose Response[b]			
Beam Code	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
^{0}Sr/^{90}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
^{252M}Cf	1.16[c]	40.46[c]	17.15[c]	44.97[c]	0.18[d]	6.16[d]	2.61[d]	6.85[d]
^{252U}Cf	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 Dose Response

The dose 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 response of the plutonium based TLD algorithm under field conditions is between -20% and +80% of the delivered neutron dose equivalent as determined from TEPC and Bonner sphere measurements (Endres et al 1996).

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 5.8. [(a)] At a distance of 10 cm, the albedo response is approximately 50% of the response measured at 1.27 cm.

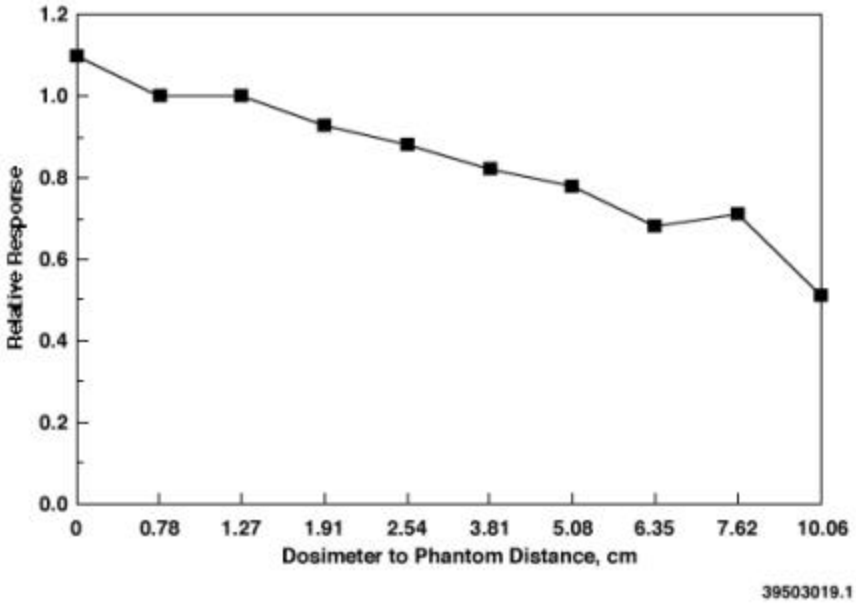


Figure 5.18 Measured Albedo Response of 8816 Neutron Dosimeter

(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. [(a)] The angular response for this dosimeter, as configured for issuance to Hanford contractor organizations, is shown in Figures 5.19 and 5.20.

Table 5.13 Hanford Combination Neutron Dosimeter Shallow Dose Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K17	17	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 5.14 Hanford Combination Neutron Dosimeter Deep Dose [(b)] Angular Response

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
K17	17	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 ^{252}Cf irradiations, neutron component only.

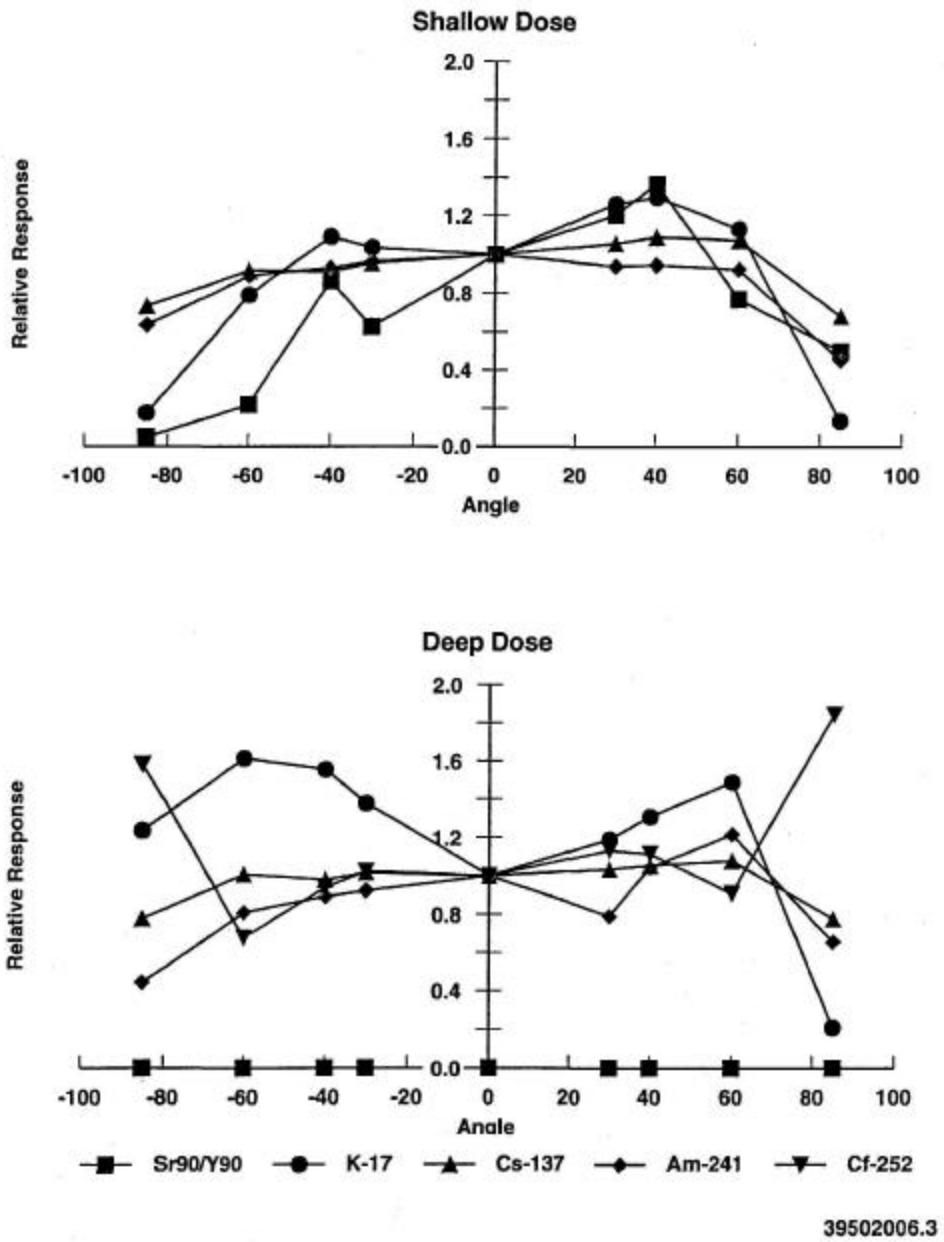


Figure 5.19. Hanford Combination Neutron Dosimeter Angular Response – Horizontal Rotation

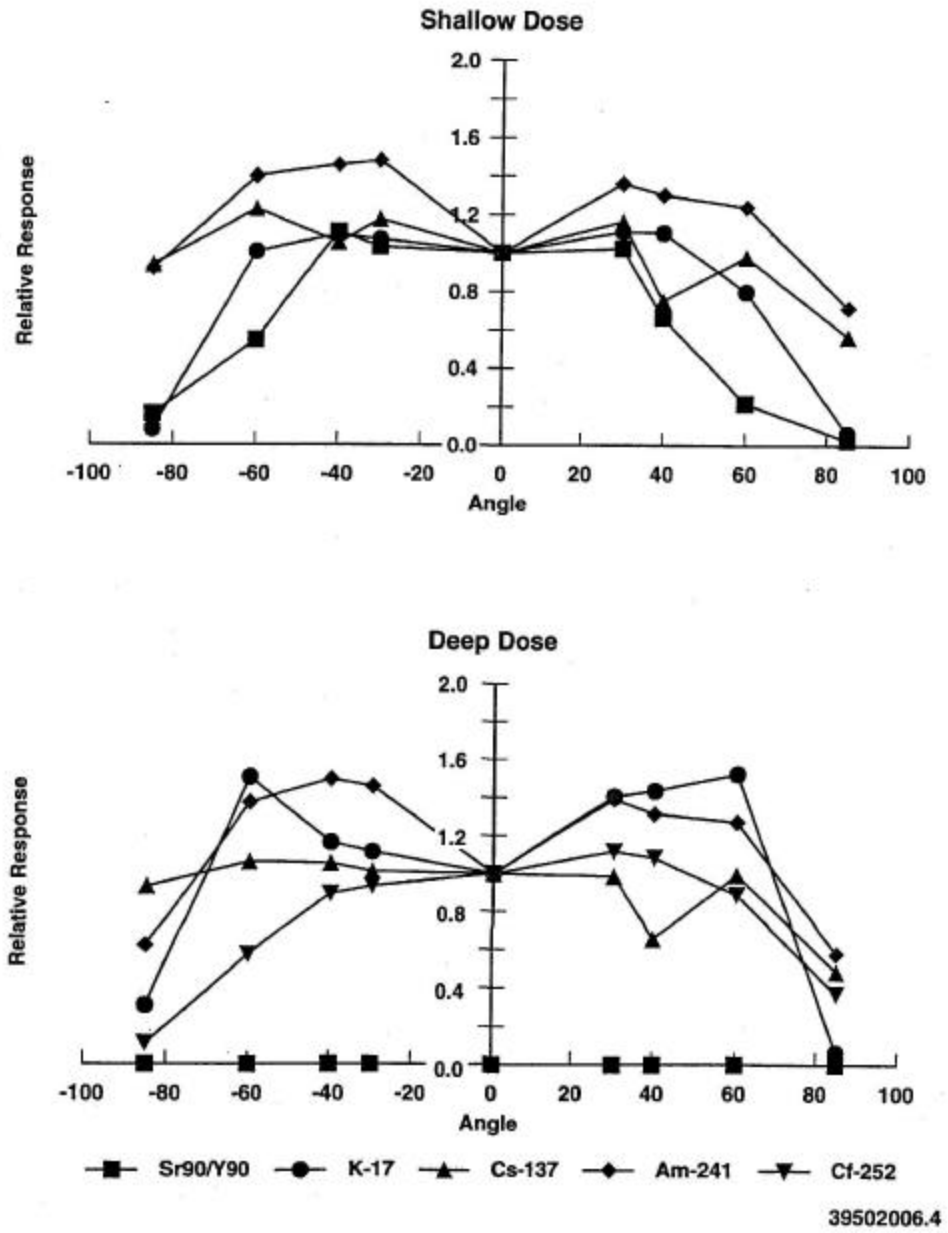


Figure 5.20 Hanford Combination Neutron Dosimeter Angular Response - Vertical Rotation

5.5.8 Lower Level of Detection

The lower level of detection (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 5.15. The symbols Hs, He, Hdp and Hn 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 5.15 Calculated LLDs (in mrem) for the Hanford Combination Neutron Dosimeter

Exchange Frequency	DOELAP Category	Parameter	Hs	He	Hdp	Hn (mod)	Hn (bare)
M	Controls	L_C	3.8	3.1	3.1	0.2	1.2
	IIIA (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
	IIIA (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
	IIIA (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.

5.5.10 Fading

The fade corrections used for TLD 600 and TLD 700 elements in the HSD are described in Section 5.3.5.2. In general, fading is reduced to less than 15% per year for beta-gamma dose and less than 30% per year for neutron dose.

5.6 Hanford Combination Neutron Dosimeter - TED Component

The CR-39 TED component of the HCND provides technique to calculate neutron dose independent from the TLD. CR-39 does not exhibit the severe energy dependence that exists with albedo neutron dosimeters and can provide good results when unknown neutron energy spectra are encountered. The CR-39 plastic, with its dense, uniform molecular structure, is susceptible to radiation damage involving scission of the molecular chains. These 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 from fast neutrons, but can also be caused by alpha particles, protons, and heavy charged particles. Beta and gamma radiations have a low enough linear energy transfer that a track cannot form, thus making CR-39 insensitive to these radiation types. To prevent the alpha interaction, a layer of polyethylene covers both sides.

5.6.1 General Features

There is space in the 8816 TLD albedo neutron dosimeter holder for both the TLD card and two CR-39 foils. The foils are placed, one on top of the other, above the TLD card in the neutron holder with the top side facing towards the front.

Foils are made from clear CR-39 polycarbonate plastic with a thin polyethylene covering. They are approximately 28 mm long, 16 mm wide, and 0.64 mm thick. The polyethylene covering protects the CR-39 from alpha exposure and provide a dense source of hydrogen atoms necessary for proton recoil. Neutrons will produce proton recoil in the polyethylene, which in turn will cause breaks in the polycarbonate. After removal of the covering, an electrochemical process is used to etch the surface of the foil. This results in visible tracks, which can then be counted and used to estimate neutron dose.

Foil Procurement and Labeling

Sheets of CR-39 plastic are procured and laser-cut to specified dimensions. A notch is cut in one corner to distinguish front from back. A unique five-digit number visible to the eye is etched on each foil to serve as identification.

Foil Issue and Receipt

Two CR-39 foils are placed in each neutron dosimeter holder before it is issued. The foils are randomly selected from the available inventory, which has previously

been qualified for use. Upon receipt of the neutron dosimeter from the field for processing, the TLD card is removed and processed. The TED foils remain in the holder until the TLD processing is complete. Based upon the TLD results, foils are selected for processing. Because of the low neutron energies currently encountered in most neutron radiation areas at Hanford, TED foils are currently used only in audit dosimeters, special test dosimeters used for field measurements, and dosimeters of a few selected workers performing special tasks involving higher energy neutrons.

5.6.2 Processing

Processing of the CR-39 TED component is substantially more involved than it is for TLDs. Because of this, the CR-39 foils are processed only when the TLD neutron dose exceeds a threshold level of 200 mrem, and the element ratios of the TLD indicate neutron spectra of predominantly higher (>100 keV) energies. The CR-39 response becomes non-linear at some point beyond 1000 mrem with the routine readout protocol. That is, routine processing uses a lower-power microscope setting to count a relatively large area. For high doses, there is inadequate resolution to distinguish between adjacent tracks and a higher power is necessary for accurate readout. As such, care must be exercised at higher dose levels. If CR-39 is processed, the HEDP dosimetrist must determine which dose (TLD or TED) will be used as the official neutron dose to be reported.

Processing is conducted in a batch of 24 individual foils. A batch contains a maximum of 20 field foils (i.e., 10 HCND dosimeters). Each batch includes two blank foils and two dosed (300-mrem) foils from which batch background and calibration factors are calculated. Once a batch of foils is loaded into the etching chamber, it undergoes an electrochemical etching process to enlarge the size of the tracks. After etching, washing and drying, each foil is read under a microscope to determine track counts (tracks per square centimeter). All foils in a batch are positioned on a tray, which is placed on the microscope's stage. The tray is processed using an automated personal computer (PC) based system. As part of the reading process, the calibration and background factors are calculated.

5.6.3 TED Algorithm

Two foils exposed to bare ^{252}Cf are included in each etching batch to determine a batch calibration factor that relates track count to mrem; the calibration factor has units of mrem/track/cm^2. Two blank foils are also included to determine a batch background factor having units of tracks/cm^2 . Within the exposure range where CR-39 will be processed, the number of track counts is directly proportional to neutron dose received. The neutron dose in mrem is then calculated for each foil by subtracting the chamber background T_B , and multiplying that result by the calibration factor C. That is:

$$T_D = (T_{D1} + T_{D2}) / 2 \quad (5.10)$$

$$T_B = (T_{B1} + T_{B2}) / 2 \quad (5.11)$$

$$C = D_C / (T_D - T_B) \quad (5.12)$$

$$D_F = (T_F - T_B) * C \quad (5.13)$$

Where:

T_{B1}	is the track count in tracks/cm^2 for background foil # 1
T_{B2}	is the track count in tracks/cm^2 for background foil # 2
T_{D1}	is the track count in tracks/cm^2 for calibration foil # 1
T_{D2}	is the track count in tracks/cm^2 for calibration foil # 2
C	is the batch calibration factor in mrem/track/cm^2.
D_F	is the neutron dose on the field foil in mrem

When both TED foils from a given dosimeter have been processed, the average result for the two foils is reported as the dose for the 8816 dosimeter.

5.6.4 Energy Response

The energy threshold of CR-39 is approximately 100 keV. For this reason, care must be exercised when using CR-39 in highly scattered neutron fields where lower-energy neutrons may be a significant component of the personnel dose. PNNL measurements in PFP work environments have shown significant under-response for TEDs in highly thermalized neutron fields (Endres et al 1996; Scherpelz, Fix, and Rathbone 2000).

5.6.5 Dose Response

Variation in dosimeter response as a function of the moderation of ^{252}Cf and PuF_4 sources was measured (Endres et al 1996). Dosimeter and TEPC measurements were taken of the bare source irradiation and with one of several thicknesses of plastic inserted between the source and the dosimeter. These data confirm the excellent energy response characteristics of TEDs. Excellent comparison was observed between the TED and TEPC data. However, once the level of moderation became extreme, such as in the very high-scatter work environments observed at PFP, the TED began to underestimate significantly the TEPC-measured dose.

5.6.6 Angular Response

CR-39 exhibits a significant directional dependence. As the angle of the interactive neutron approaches 90°, the recoil proton enters parallel to the etched surface and does not create a track. The measured angular response of the CR-39 in the HCND enclosure is shown in Figure 5.21.

Table 5.16 CR-39 Angular Response, Horizontal and Vertical Rotation

Source	Average Energy (keV)	Axis of Rotation	-85°	-60°	-40°	-30°	0°	30°	40°	60°	85°
^{252}Cf U	2100	H	0.10	0.31	0.64	0.79	1.00	0.72	0.52	0.28	0.11
		V	0.06	0.27	0.48	0.59	1.00	0.71	0.59	0.47	0.13

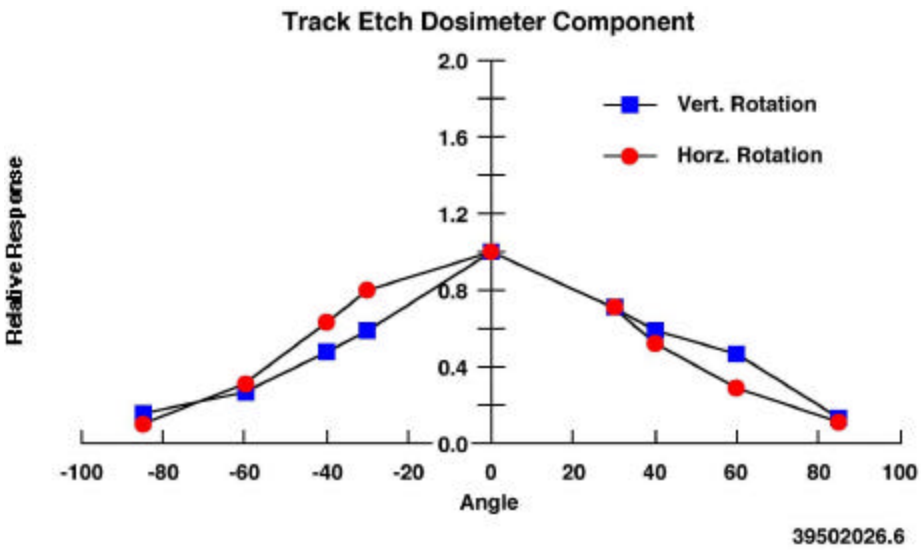


Figure 5.21. CR-39 Angular Response, Horizontal and Vertical Rotation

5.6.7 Lower Level of Detection

There is substantial variability in the low-dosed TEDs. The calculated LLD, based on HPS N13.11 (HPS 1993) formulation, is about 40 mrem. Improved performance in TED data is expected for freshly prepared CR-39 foils with a minimum of background signal.

5.6.8 Sensitivity and Linearity

The sensitivity of the CR-39 plastic is a function of tracks/cm^2-mrem and is calibrated against a known exposure to ^{252}Cf. Determination of sensitivity and linearity is quite complex, being a function of the etching and counting technique. The sensitivity (i.e., different number of tracks/cm^2) can be created by changing either the etching time, temperature, or voltage. Linearity has been demonstrated to about 1000 mrem using magnification of x 4 with the existing HEDP system, at a sensitivity of about 4 tracks/cm^2-mrem.

5.6.9 Fading

It has been shown that if CR-39 is exposed to ambient light and high temperatures (>50°C) for prolonged periods, fading and a decrease in sensitivity results. When the foils are protected from light and excessive heat, little if any fading or change in sensitivity will occur.

5.6.10 Environmental Buildup

CR-39 is relatively unaffected by environmental conditions. However, the background track density on the CR-39 foil will increase with time due to the environmental neutron background and cosmic ray interactions. Background accumulation may be as high as 30 tracks/cm^2/year.

5.7 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).

5.7.1 HSD Area Dosimeter

HSD area dosimeters are identified by an eight digit holder ID beginning with the digits 06. They 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)] Contractor RIDS should treat area dosimetry records in a manner consistent with other workplace surveillance records.

Area dosimeters are physically identical to, have the same response characteristics as, 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.

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 <u>not</u> applied to Area dosimeter results (unlike Personnel dosimeter results). The 8825 algorithm does however apply implicit detection thresholds in it's 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

(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.

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 error in reported results 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.

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 on a wall with the Mylar™ window facing the wall. The dosimeter should always be placed facing the interior of the room being monitored.

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, neutrons can be detected. If neutrons are detected, a neutron dose result will be calculated. The calibration factor used to calculate neutron dose is based on irradiation of the dosimeter on phantom to a bare ^{252}Cf source. If the dosimeter was placed on a phantom, then the reported neutron dose may be conservative by as much as a factor of 8 because most neutrons reaching the dosimeter will likely have been moderated from scatter in hydrogenous shielding and building materials. If this can be shown to be the case, then application of a calibration factor based on moderated ^{252}Cf will be more appropriate. If the dosimeter was not placed on a phantom, and the neutron energy spectrum was unmoderated then the dosimeter may under respond by as much as a factor of 40. [(b)] If the dosimeter was not placed on a phantom, but the neutron energy spectrum was moderated, then the neutron dose calculated using the default calibration factor will (coincidentally) be relatively accurate. If a large thermal component is present, as would be the case under extreme scatter conditions, then an over response by as much as a factor of 2.66 may be seen. Table 5.18 shows the HSD neutron response (reported/given

(a) B. A. Rathbone, "PIC/TLD Response Study," October, 4, 1995, letter to HEDP file.
(b) B. A. Rathbone, "HSD Neutron Response in Air", May 30, 1999, letter to HEDP file.

dose) without phantom when the default calibration factor (bare ^{252}Cf) 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	2100	0.027
^{252}Cf D_2O (w/ Cd)	550	1.072
^{252}Cf D_2O (w/o Cd)	550	2.663

As can be seen from the response of the HSD to the D_2O 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 D_2O moderated ^{252}Cf source without Cd cover (Schwartz and Eisenhaur, 1982). This same fluence produces only 1.5% of the total neutron dose equivalent rate. [(a)] 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.

5.7.2 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 are issued directly to Hanford contractors without tracking through REX and results are reported directly to Hanford contractors without the use of REX. HCND area dosimeter results are not stored in REX. Each contractor is responsible for maintaining records of area dosimeter results for their facilities. [(b)] Contractor RIDS should treat area dosimetry records in a manner consistent with other workplace surveillance records.

(a) 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)

(b) 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.

HCND area dosimeters are physically identical to, 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 detection thresholds in it's 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 accurate dose results, the HCND must be placed on a phantom of adequate size. Acceptable phantoms may be water filled containers or PMMA blocks with minimum dimensions of 30cm x 30cm x 15cm. The typical cubical shaped 5 gallon water containers are an acceptable and readily available phantom. 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. Although current standards in the U.S. specify use of a 40cm x 40cm x 15cm PMMA phantom for calibrations and performance testing, recent investigations have shown minimal differences in albedo dosimeter response for the two phantom sizes (McDonald et. al, 1995).

5.8 HSD Extremity (Wrist/Ankle) Dosimeter

The HSD extremity dosimeter is physically identical to the HSD personnel dosimeter. It's 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.

5.8.1 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.

5.8.2 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.

5.8.3 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 N 13.32 (HPS, 1996a) indicates acceptable performance as a wrist/ankle extremity dosimeter.[(a)] Subsequent DOELAP performance testing has also shown acceptable performance and has lead to DOELAP accreditation of the HSD as an extremity dosimeter.

5.8.4 Algorithm Performance

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

The results of PNNL performance testing of the HSD as an extremity dosimeter are shown in Table 5.19 The results indicate some algorithm bias for M60 and M150 filtered X-ray techniques, but the bias (B) is well within the allowed criteria of B < 0.35.

Table 5.19 HSD Extremity Algorithm Bias

Source	Average Energy (keV)	B	S
M30	20	-0.036	0.012
M60	34	0.193	0.021
M100	51	-0.038	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/Y	931	0.013	0.039

5.8.5 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 (^{137}Cs), and two sources from category IV (^{90}Sr and ^{204}Tl) 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.

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

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/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

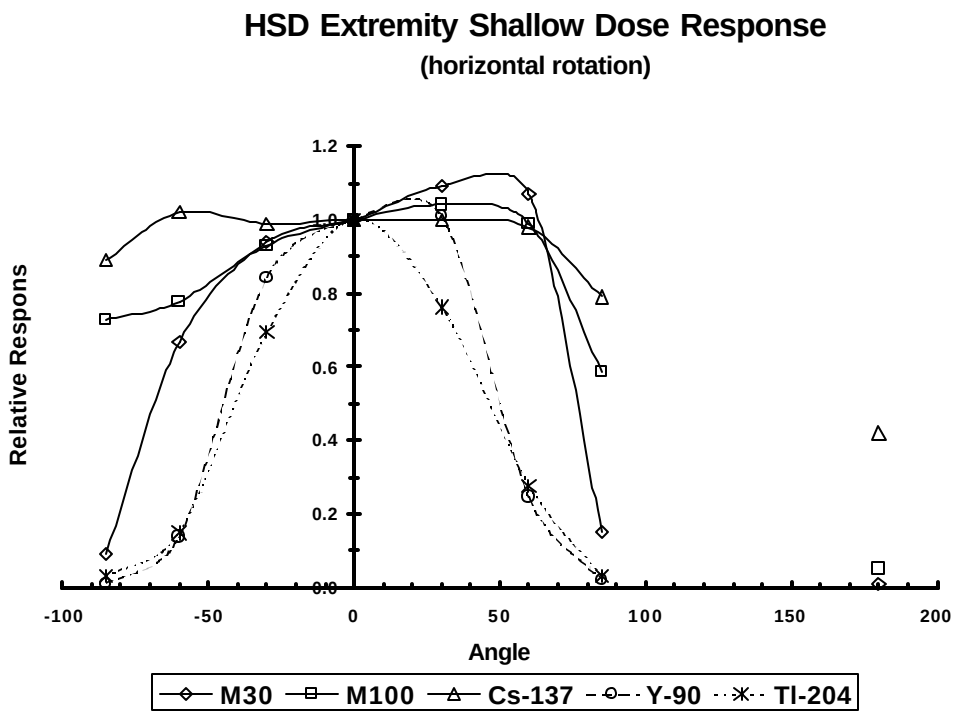


Figure 5.22 HSD Extremity Shallow Dose Angular Response – Horizontal Rotation

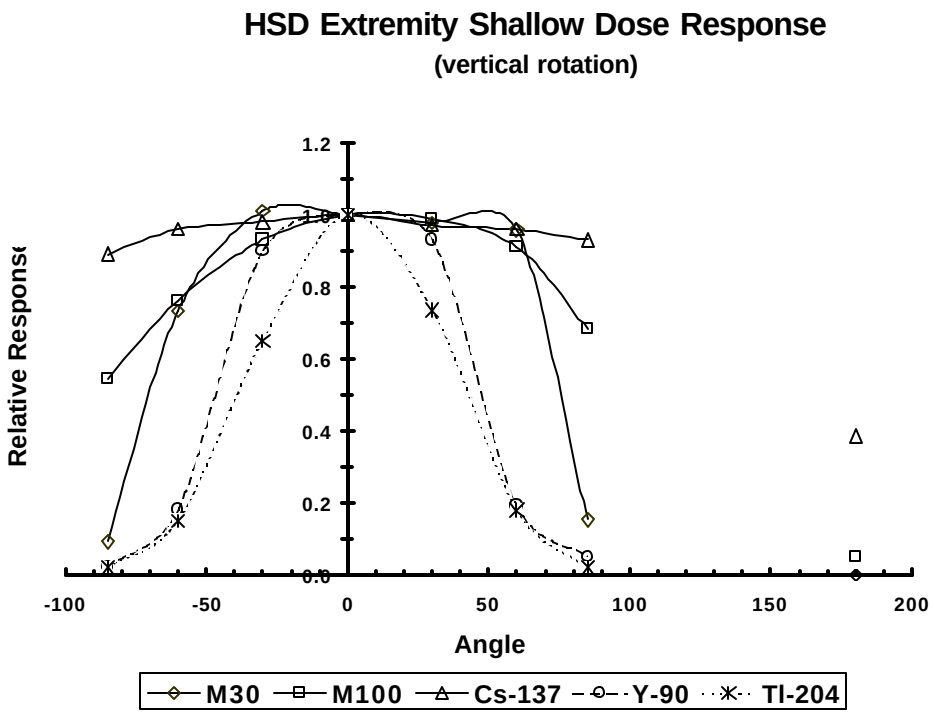


Figure 5.23 HSD Extremity Shallow Dose Angular Response – Vertical Rotation

5.8.6 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, it's 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.

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

Table 5.21 HSD Extremity Shallow Dose LLD

Source	Average Energy (keV)	Shallow Dose LLD (mrem)
^{204}Tl	267	3
^{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

5.8.7 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.

5.8.8 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 contact with sharp objects.

5.9 Hanford Ring Dosimeter

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).

5.9.1 Dosimeter Description

The Hanford ring dosimeter contains a single ^{7}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 ^{7}LiF 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.

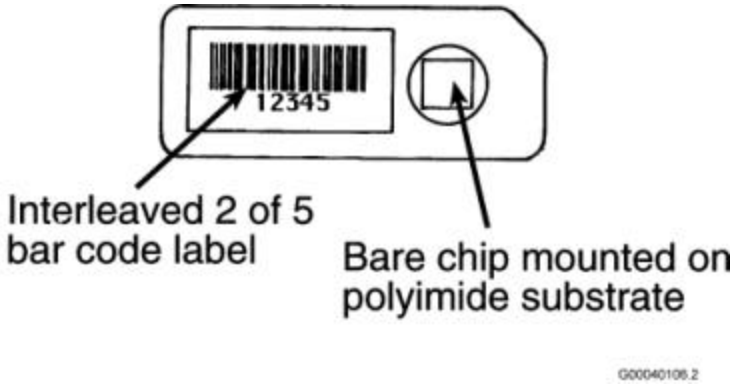


Figure 5.24 Chipstrate

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/cm^2. The density thickness of the label is approximately 16 mg/cm^2. The density thickness of the active layer of the chip is 40 mg/cm^2. The

permanent chipstrate ID number allows application of a chip-specific sensitivity factor to the dose result.

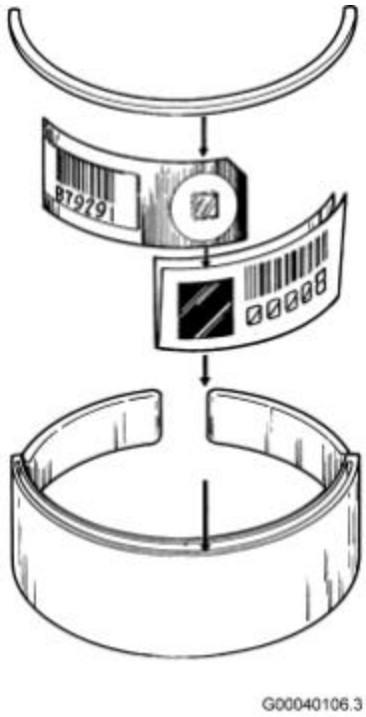


Figure 5.25 Illustration of Hanford Ring Dosimeter

5.9.2 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°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 chemiluminescence 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.

5.9.3 Dosimeter Use Cycle

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

5.9.3.1 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.

5.9.3.2 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.

5.9.3.3 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.

5.9.3.4 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).

5.9.3.5 Dose Calculation

After being processed by the reader, the chipstrate readings are transferred to the VAX 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.

5.9.3.6 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.

5.9.4 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.

5.9.4.1 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 plexiglass™ rack approximately χ-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 an 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 5.3.1. 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).

5.9.4.2 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 5.3.2.

5.9.4.3 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:

$$X = Q \times ECC / RCF \qquad (5.14)$$

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.

5.9.4.4 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 phantom, geometry, and source used as the calibration standard are as specified in HPS N13.32 (HPS 1996a)

5.9.5 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.

5.9.5.1 Shallow Dose Equivalent

$$H_s = D * CF \tag{5.15}$$

where:

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

5.9.5.2 Facility Calibration Factor

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

If facility calibration code = 00
Then CF = 1.5
Else CF = facility calibration code / 10

Where CF = facility specific calibration factor.

5.9.5.3 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:

$$D = (X - E) / (RRF * F * S) \tag{5.16}$$

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.

5.9.5.4 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 5.17. 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.

5.9.5.5 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:

$$E = G * FD + B \quad (5.17)$$

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)

5.9.5.6 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:

$$F(t) = R(t)/R_0 = a\,e^{(-\lambda_1 t)} + (1 - a)\,e^{(-\lambda_2 t)} \quad (5.18)$$

where: t is the time since irradiation (days)
R(t) is the net chip response (mR) at time t
R_0 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 for each phosphor and radiation type are shown in Table 5.22 . The model is shown graphically in Figure 5.26.

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}

(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.

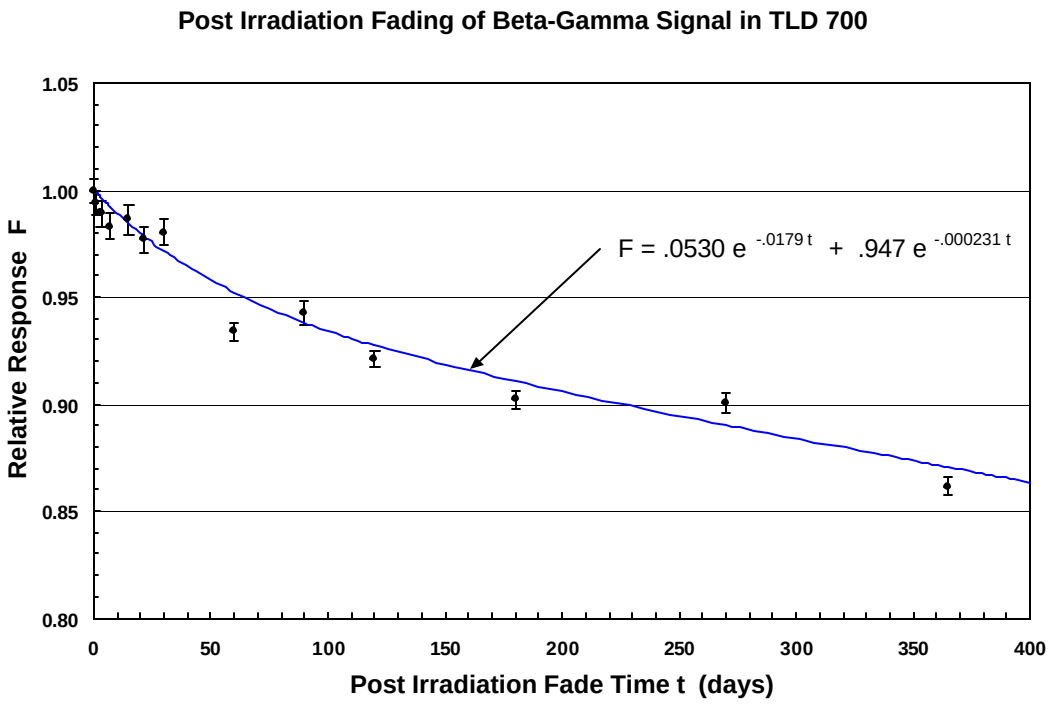


Figure 5.26 Fade Correction for the Hanford Ring

5.9.5.7 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:

$$S = (1.0 + 3.411 \times 10^{-7} * Xnet) \qquad (5.19)$$

where:

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

5.9.6 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.

5.9.6.1 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 plexiglass™ extremity phantom to 1000 mrem of ^{137}Cs 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 ^{60}Co source in air at a distance of 7 meters. The % C.V. of the 20 calibrated readings was 1.5%.

5.9.6.2 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 ^{137}Cs radiation on plexiglass™ 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.

The initial determination of LLD described above was accomplished using new chipstrates which did not leave the TLD lab. A subsequent study was performed using chipstrates from the general pool of chipstrates that had been used for routine dosimetry at Hanford for more than a year.[(a)] This included chipstrates that had been handled and issued many times, and in all likelihood a few that had been contaminated with sweat, talc, and body oils, under field use and subsequently cleaned with methanol. One set of 39 rings was prepared as background controls and spares as part of NVLAP performance testing. A second set of 20 rings was selected from a large group prepared and issued to field dosimetry organizations for general use but subsequently returned for processing unused. This set was not chosen randomly, but rather represented a batch with unusually large and variable readings. Most of the variability was associated with abnormal glow curves, although some may have been due to variability in ambient radiation levels at site storage locations. The set consisted of 20 dosimeters read in succession in the middle of a much larger group undergoing routine processing. LLDs were calculated for both sets using the Aalternate method≅ described in HPS N13.32 (1996a) *Performance Testing of Extremity Dosimeters*. The Aexposed≅ set of dosimeters required for LLD calculation was the set used for actual performance testing as called for in the Aalternate method≅. An LLD value was calculated for each source used in the standard. The results are shown in Table 5.23. As can be seen from the results, those dosimeters physically going through an exchange cycle had LLDs nearly twice those of the Alaboratory≅ set. Both sets had substantially larger LLDs than the unused chipstrates, used for the initial LLD study. Spurious non-radiation-induced glow from triboluminescence, chemiluminescence, and visible and UV light are suspected causes for the larger LLDs seen under field conditions.

(a) B. A. Rathbone, “LLD Calculations for Hanford Ring Dosimeter,” August 18, 1997, letter to HEDP file.

To support issue of the Hanford Ring on a quarterly exchange frequency, a third study was performed according to the alternate method in HSP N 13.32. DOELAP performance test data was used for the exposed dosimeter set and NC70 dosimeter results were used for the unexposed dosimeter set.[(a)] The NC70 data set was chosen such that the time between anneal and readout was about 120 days, typical for a quarterly exchanged dosimeter. Unlike the previous monthly calculation using NC70 data, no special effort was made to select abnormal or highly variable data. The 108 background dosimeters were randomly selected from ring dosimeters returned for processing under note code 70 during the last half of CY98. The results are shown in the last column of Table 5.23. The slightly lower LLD for quarterly rings is believed to be due to adoption of lower lighting levels during loading and unloading of chipstrates, beginning in 1998. The range of calculated LLDs in Table 5.23 demonstrate how easily the results can be influenced by variations in the background data used.

Table 5.23 LLDs for Hanford Ring

Source	Ring CF	Monthly Typical LLD (mrem)	Monthly Worst Case LLD (mrem)	Quarterly Typiccal Field LLD (mrem)
M30	0.710	21	47	13
M60	0.660	20	44	12
M100	0.676	20	45	13
M150	0.742	22	49	14
H150	0.836	25	55	16
^{137}Cs	1.000	29	63	18
^{90}Y	0.916	29	65	19
^{204}Tl	4.281	135	305	91

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

5.9.6.3 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 ±5% of the given dose from 10 mrad to 100 rad. Above 100 rad, supralinearity corrections are necessary.

5.9.6.4 Angular Response

A study was conducted to measure the angular response of the Hanford Ring dosimeter to photons and beta particles of various energies.[(a)] 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 (^{137}Cs), and two sources from category IV (^{90}Sr and ^{204}Tl) were used. The delivered shallow dose for all sources was approximately 5 rem except for the ^{204}Tl source for which the delivered shallow dose was 3600 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°, ±30°, ±60°, ±85°, 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.

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

Table 5.24 Hanford Ring 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
Cs-137	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
Y-90	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
Tl-204	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

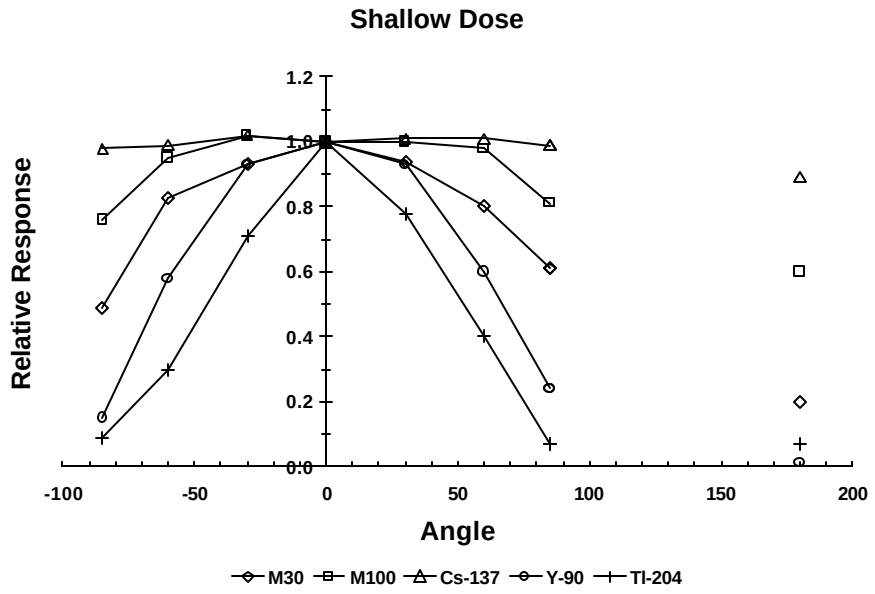


Figure 5.27 Hanford Ring Shallow Dose Angular Response – Horizontal Rotation

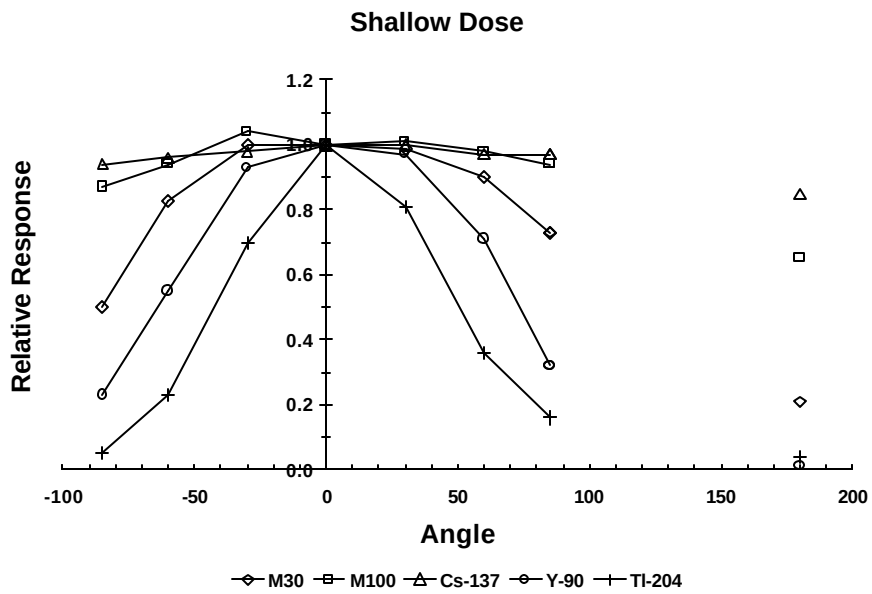
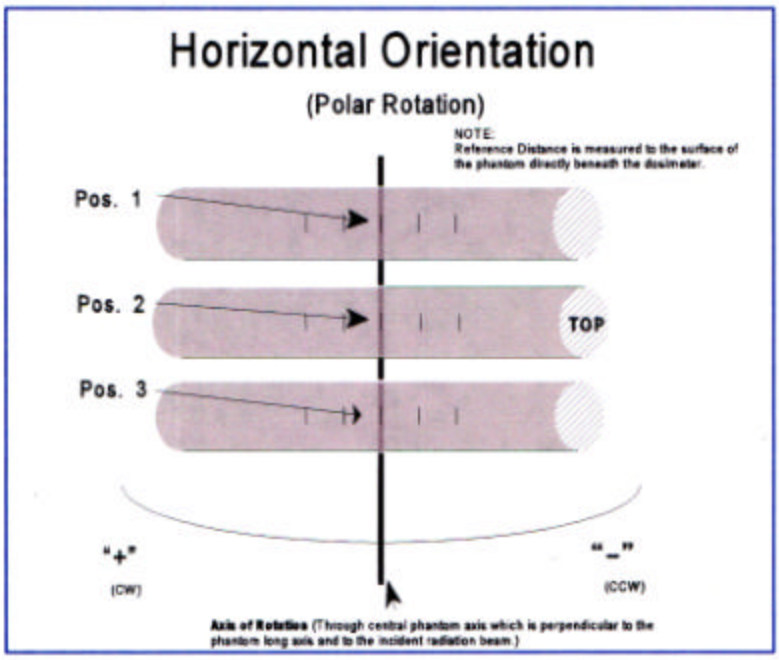


Figure 5.28 Hanford Ring Shallow Dose Angular Response – Vertical Rotation

5.9.6.5 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 ^{7}LiF 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.



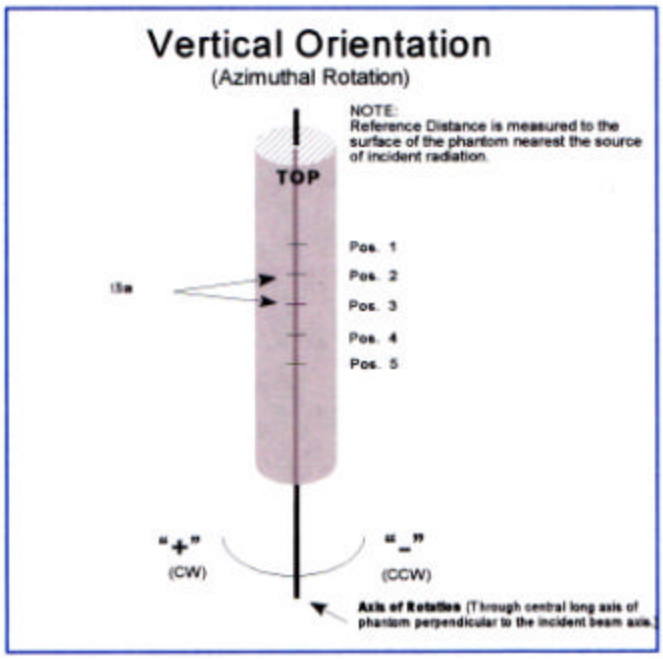


Figure 5.29 Ring Orientation for Angular Dependence Irradiations

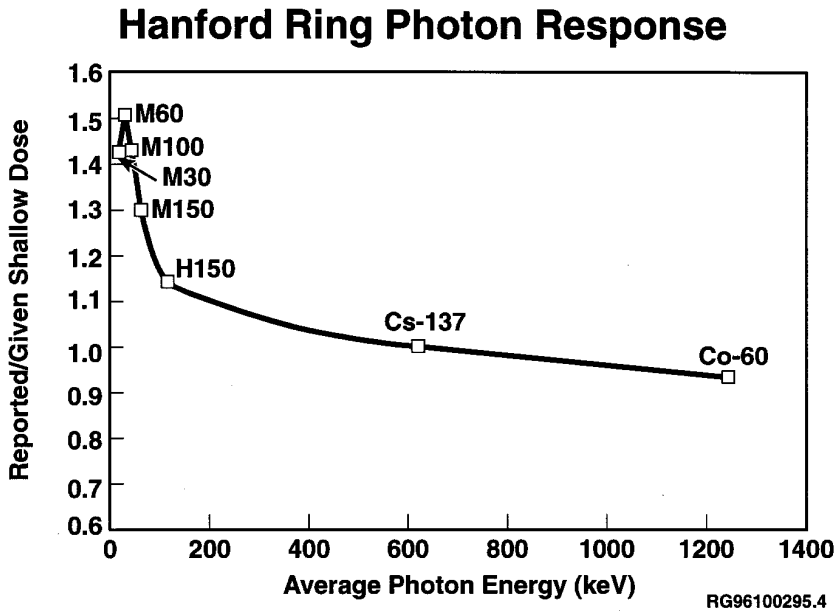


Figure 5.30 Hanford Ring Photon Response

5.9.6.6 Beta Energy Dependence

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

Table 5.25 Hanford Ring Beta Response

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

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

5.9.7 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 1.5 to the uncorrected dose 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 or equal to

1.5. For beta-emitters with average energies less than ^{90}Y, larger correction factors may be necessary. It is the responsibility of the user to provide correction factors other than the default when 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 or else determine the 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}Sr in secular equilibrium with ^{90}Y. 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/cm^2, and 125-ml glass sample jars with wall thicknesses of approximately 680 mg/cm^2. To determine the Hanford ring response to the degraded ^{90}Y beta spectra that might result from these containers, filtered ^{90}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 Buchler 50-mg/cm^2 silver encapsulation window were 122 mg/cm^2, 325 mg/cm^2, 557 mg/cm^2, and 727 mg/cm^2. Hanford 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 ring beta correction factors (BCF) for these sources and ^{204}Tl as a function of their estimated average beta energy are shown in Figure 5.32.

The default ring correction factor of 1.5 will be conservative for most work environments involving tank waste. The exception is the situation where extremity dose is due to a thin layer of nearly pure ^{137}Cs contamination without any attenuation. The average beta energy for ^{137}Cs is 240 keV and for ^{204}Tl is 266 keV (Durham 1992). Assuming that the beta correction factors for ^{137}Cs and ^{204}Tl are similar, a correction factor of about 4 would be needed for thin layers of ^{137}Cs contamination. However, significant extremity dose rates are more likely to be due to significant activity in pipes, valves, and sample containers that selectively shield low-energy beta radiation but not gamma radiation. When all beta particles originate from a single layer of activity and traverse through essentially the same thickness of intervening material, it is possible to have a thickness such that the chip in the ring lies beyond the range of most of the beta particles (because of its added 50 mg/cm^2 window) whereas sensitive layer of skin does not. In this case the ring will under respond.[(a)] 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/cm^2 of material between the skin and the ring. This can be accomplished by wearing the ring on top of cotton liner plus two surgical gloves. In this case however, an additional glove covering the ring are 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

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

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.

5.9.8 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 also 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 ^{241}Am associated with aged plutonium. The factor also takes into account the fact that there is no beta radiation in PFP glovebox 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 response from the TLD 700 ring was used as the gamma dose without correction for over response to low energy photons. Using a nominal gamma *response* to neutron *dose* ratio of 0.5 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.

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

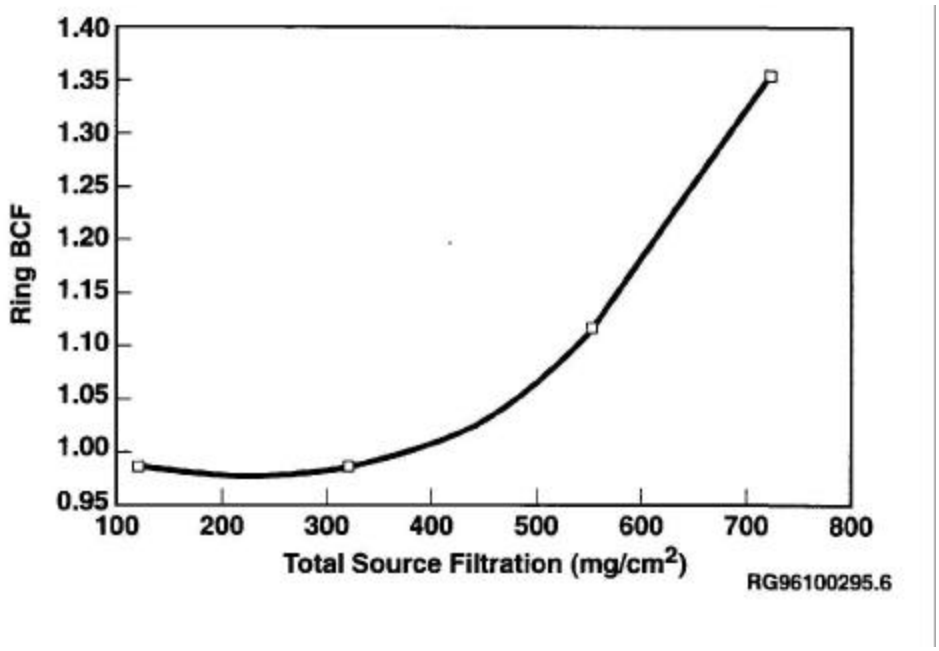


Figure 5.31 Ring Beta Correction Factor (BCF) vs ^{90}Y Source Filtration

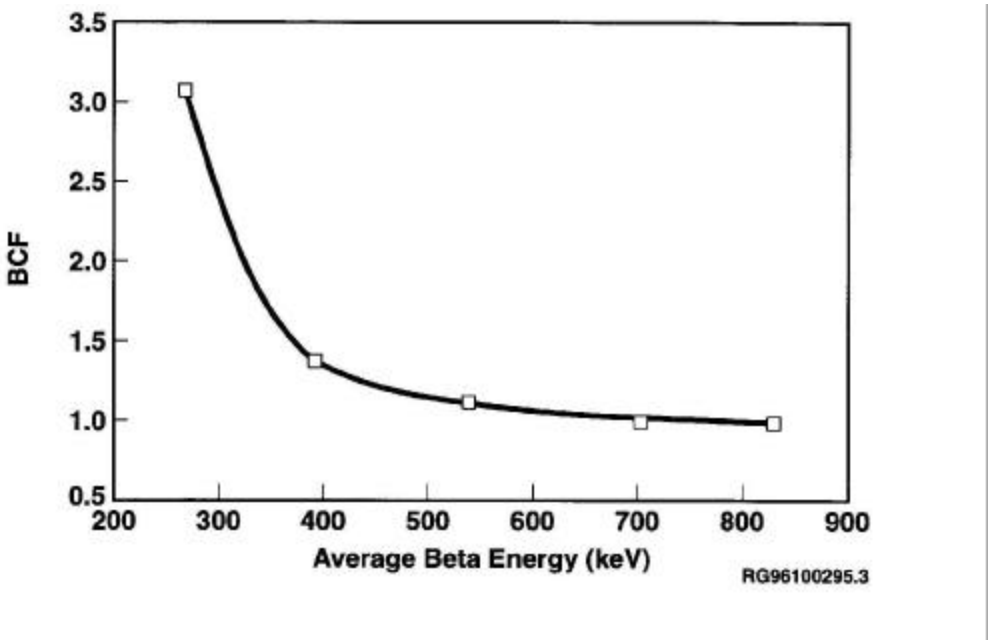


Figure 5.32 Ring BCF vs Average Beta Energy

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 5.33.

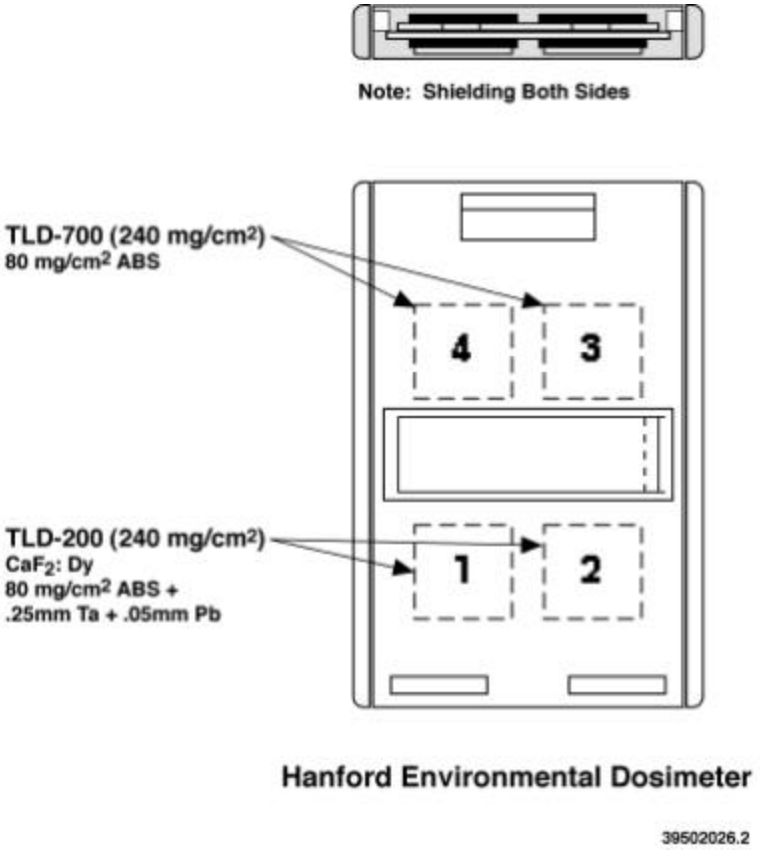


Figure 5.33 Hanford Environmental Dosimeter (Harshaw 8807)

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: ±20% from 20 keV to 1.3 MeV.

5.10.2 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 5.26.

Table 5.26 Hanford Environmental Dosimeter Time-Temperature Profiles

	TTP 1 (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
	TTP 2 (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

5.10.3 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.

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 is shown in Figure 5.34.

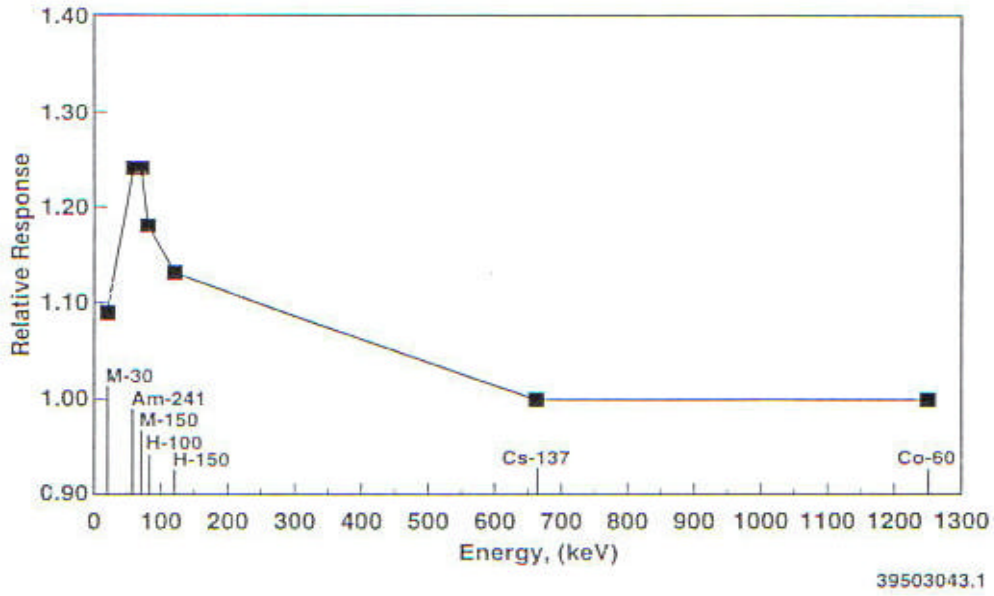


Figure 5.34 Hanford Environmental Dosimeter Energy Response

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.

5.11 Hanford Nuclear Accident Dosimetry

HEPD 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 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 5.35. The dosimetry materials in the FNAD are summarized in Table 5.27. The inner dosimetry package consists of a gold foil and set of ^{6}LiF and ^{7}LiF TLD chips. 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 a several neutron activation foils and TLD-600 and TLD-700 chips. 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.

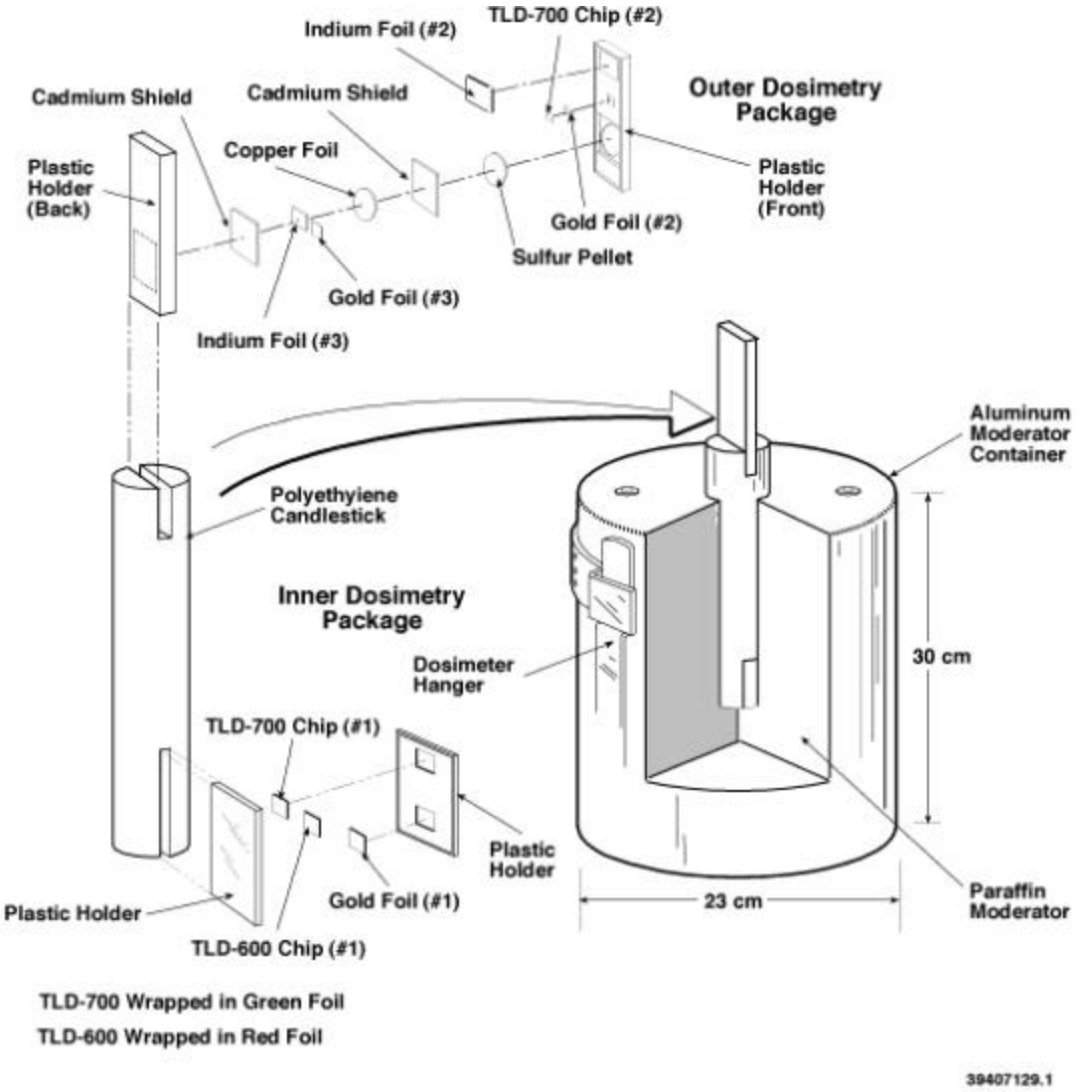


Figure 5.35 Hanford Fixed Nuclear Accident Dosimeter

Table 5.27 Materials and Dimensions of Hanford Fixed Nuclear Accident Dosimeter

Description	Size, cm	Thickness, cm (mil)
Inner Dosimetry Package		
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)	0.32 by 0.32	0.089 (35)
Outer Dosimetry Package		
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)

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.

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 NAD is 30 cm high by 23 cm in diameter with 10-cm-thick paraffin walls. The moderator is equipped with a 2.54-cm-diameter polyethylene "candle" and Lucite™ 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.

Personal Nuclear Accident Dosimeters

An illustration of the Hanford PNAD is shown in Figure 5.36. Table 5.28 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.

Table 5.28 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.

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.

5.11.2 Performance and Placement Criteria

FNAD 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 ± 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 ± 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 ± 25%.

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

a. ANSI/ANS 8.3-1986 (ANSI 1986) where the Aminimum 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.

(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.

b. 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:

a. 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).

b. Additional FNADs should be placed at greater distances from the radioactive source to allow extrapolation of dose to nearby workers or workers during egress.

c. A system of worker-assigned personnel dosimeters and PNADs should be used to permit extrapolation of FNAD data to exposed workers.

d. Provision should be available to determine the orientation of exposed workers based on dosimeter and/or biological measurement data.

e. 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.

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

g. 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.

h. 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.

i. FNADs should be exchanged annually, the dose observed on the TLDs calculated, and the results analyzed to ensure compliance with the foregoing criteria.

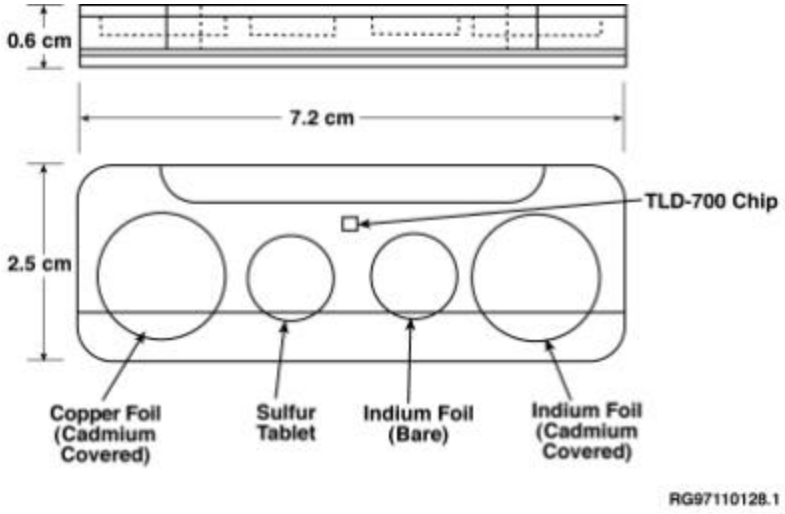


Figure 5.36 Hanford Personal Nuclear Accident Dosimeter

5.11.3 Quick-Sort Data Analysis

The quick-sort is a field measurement of ^{24}Na activity in the human body after a possible exposure to fast neutrons. Measurements are made by placing the probe of a Geiger-Muller (GM) type survey instrument 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. Experimental data indicate an exposure to 4 rad of fast neutrons results in the count rates shown in Table 5.29 from ^{24}Na activation in the body (Wilson 1962).

Neutron dose in rad is calculated as follows:

$$\text{Dose (rad)} = 2.2\ \text{CPM/W} \tag{5.20}$$

where CPM is the initial count rate per minute determined from the GM survey instrument results and W is the subject's weight in pounds.

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.

Table 5.29 Count Rates from ^{24}Na Activation in the Body As a Result of Exposure to 4 Rad of Fast Neutron

Weight of Subject (Pounds)	Count Rate Per Minute Immediately Following Exposure	Count Rate Per Minute 15 Hours After Exposure
125	250	125
150	280	140
175	320	160
200	360	180
225	410	205
250	465	230

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 x 10^{-5} µCi/ml with a 30-minute counting time or 9.4 x 10^{-5} µCi/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 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 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 ± 0.004 rad/dpm-mg

Steel shield: K = 0.145 ± 0.006 rad/dpm-mg

Concrete shield: K = 0.116 ± 0.116 rad/dpm-mg

Lucite™ shield: K = 0.088 ± 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 NADs 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 plus CR-39 foil capabilities in the HCND, can accurately estimate dose over a wide range of neutron spectra. The track-etch CR-39 foil dosimeter component, if present in the Hanford Combination Neutron Dosimeter, will closely estimate the dose to neutrons exceeding an energy threshold of approximately 100 keV.

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 HCND track-etch dosimeter CR-39 foil if used
- 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, HCND with TED CR-39 foils (if available), and PNADs are the preferred method of determining dose because the dosimeters are worn by the person and neutron spectra dosimeter response data 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 valid. Neutron dose should be given in rad and 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, particularly if the track-etch dosimetry CR-39 foil is used, and the PNAD.

Neutron dose assessment procedures for HSDs, HCNDs, TEDs, 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.