Hanford Personnel Dosimeter Supporting Studies FY-1981

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HANFORD PERSONNEL DOSIMETER SUPPORTING
STUDIES FY-1981

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FOREWORD

The Department of Energy-Richland Operations funded eight specific studies during FY-1981 as part of their ongoing program to better characterize the Hanford multipurpose dosimeter to current field conditions and expected future field conditions resulting from probable projects at Hanford (i.e., FMEF, reprocessing, etc.). These studies compliment similar work completed during FY-1980 and documented as PNL-3536, entitled "Hanford Personnel Dosimeter Supporting Studies, FY-1980." Studies included in this report are as follows:

- Study 1 - Dependence of Dose Calculation Algorithm on Reader Characteristics
- Study 2 - Assessment of Existing and Proposed Dosimetry Calibration Techniques
- Study 3 - Hanford Field Measurements
- Study 4 - Dose Calculation Algorithm Upgrade Analysis
- Study 5 - Dosimeter Energy Response Measurements
- Study 6 - Dosimeter Modification and Testing
- Study 7 - Field Response of Hanford Dosimeter
- Study 8 - Dosimeter Annealing.

Studies 3 and 7 were combined into one writeup in this report as Section 4.0. These measurements were coordinated and data interpretation is more informative by presenting all of the data collected for each location together.

SUMMARY

Substantial information is available in this report regarding either possible enhancements of the current Hanford dosimeter system or possibly a redesigned system. It is important to understand the tradeoffs inherent to these systems and the past judgments which have formed the basis of the current system. Information in this report along with information in a previous report documenting FY-1980 studies (PNL-3536) allows the reader an opportunity to better understand the Hanford dosimeter system and its dose response to several radiation fields of interest. It is important to note that a new Hanford automatic reader was being implemented during the latter stages of these studies.

The Hanford dosimeter system determines nonpenetrating, penetrating, fast neutron and slow neutron dose components. Interpretation of these doses requires an understanding of the dosimeter design, readout, dose algorithm and calibration methodology. Studies in this report allow examination of the dosimeter response to selected radiation fields and dependence on specific procedural changes involving calibrations or algorithms. Significant observations have been made by the authors of this report and summarized as follows:

- A blind audit acceptance procedure has been used to determine the validity of processing runs for each dose category (i.e., nonpenetrating, penetrating, fast neutron and slow neutron). This procedure confirms the observed accuracy of the Hanford dosimeter to estimate dose, on the average, received from the laboratory calibration sources used to irradiate the audit dosimeters.
- Based on the measured energy response of the Hanford dosimeter to selected radiation types, energies and doses, the Hanford dosimeter response compared to the actual dose received from typical field exposures can be summarized as follows:
 - The dosimeter overestimates the actual dose at all energies to filtered x-ray techniques using present calibration procedures. Observed bias for deep and shallow doses ranged from 17% to 75% with the maximum response at an effective x-ray energy of 32 keV.

- Dosimeter response to a NBS D₂O moderated Cf-252 source was a factor of 7 higher than the response to the routine calibration exposure.
- The present dosimeter algorithm may calculate significant false-positive fast neutron doses when exposed to thermal neutrons or penetrating photon radiation. Dose equivalents equal to about 30% of the delivered photon dose and as high as a factor of six times the delivered thermal dose equivalent were observed.
- Present dosimeter estimates of tissue dose at 1 cm from very high energy photons (~7 MeV) are about 30-40% low. The shallow dose is overestimated by a factor of two or more. Differences in buildup between the two neutron sensitive chips (3&4) cause the algorithm to calculate false-positive fast neutron doses. Using Chip 5 instead of Chip 2 to calculate the 1 cm depth dose results in good agreement. Dosimeter dose estimates from a N-16 source were in good agreement because of the presence of significant lower energy bremsstrahlung radiation from the accompanying high energy beta decay.
- Field measurements using several techniques, such as a tissue equivalent proportional counter (TEPC), dosimeters, multisphere, Snoopy, etc., at several Hanford locations agreed fairly well. Differences were observed at some locations when the Hanford dosimeter over-responded relative to the results obtained with the tissue equivalent instruments. The Snoopy was observed to also over-respond but at a level less than the Hanford dosimeter.
- For dosimeter exposures to selected laboratory radiation fields used in recent dosimeter intercomparison studies, the Hanford dosimeter using current readout, calibration and algorithm procedures will not assuredly meet the criteria included in the draft standard of the American National Standards Institute, ANSI N13.11 entitled "Criteria for Testing Personnel Dosimetry Performance" for all categories because of several factors as follows:

- Significant differences in calibration sources and energies exist between current Hanford procedures and the ANSI Standard. Adjustment for the dosimeter response to these different sources and/or energies must be employed for a proper comparison. Hanford procedures are based on field measurements and sources available since inception of the TLD/albedo dosimeter in 1971.
- The dosimeter response to a bare Cf-252 source in a low scatter facility (the neutron source originally specified in the criteria) and the dosimeter response to a moderated Cf-252 source (the neutron source specified in recent criteria) is a factor of 2 less and 7 greater, respectively, than the routine Hanford calibration dosimeter response. This results in a significant bias determination.
- The criteria identifies a limit for dosimeter bias and precision. Dosimeter over-response is calculated in the same manner as an under-response. Since the dosimeter over-responds in certain situations, this will either cause or contribute to a possible failure of the category.
- Occasionally, dosimeter results were observed which were significantly in error. This caused a larger value to be calculated for both the bias and the precision and, in some cases, caused failure of certain categories. Generally, a zero dose was reported in these cases.
- Consistent dosimeter readout is critical to the proper functioning of the Hanford dosimeter system. Significant observations include:
 - Control limits established on various reader components and on chip output for control dosimeters processed during the routine runs effectively control the variability in dosimeter results which would otherwise be encountered. Values for these parameters are routinely printed on the reader log along with the results for all dosimeters.

- The current reader temperature ($\sim 300^{\circ}\text{C}$) and readout time (20 seconds) are apparently not sufficient to completely drop the 250°C neutron sensitive trap in TLD-600s and this contributes to apparent differences in sensitivity observed between personnel pool dosimeters, which are seldom exposed to neutrons, and calibration dosimeters, a few of which are routinely exposed to calibration neutron sources. It is expected that through time as more and more of the calibration dosimeters are exposed to neutron radiation, the average sensitivity of the group becomes increasingly different from the personnel pool dosimeters.
- Differences in the frequency of dosimeter readouts, cleaning, etc., and cumulative radiation exposure may contribute to the difference in sensitivity currently observed between personnel pool and calibration dosimeters. At present, the results of the blind audit dosimeters, are used to adjust the response of the calibration dosimeters in an attempt to eliminate this known source of bias.
- During the latter part of these studies a new Hanford reader incorporating several improved features was introduced to the system. Much of the data in this report were obtained using the old reader. Possible effects of differences between the readers were not observed; however, extensive data on the new reader was not available for comparison.
- Dosimeter system modifications were identified which potentially would upgrade the Hanford dosimeter performance. However, these modifications should be carefully examined before implementation to insure that no unforeseen problems occur. Possible modifications include:
 - The existing dose algorithm could be upgraded using the Hanford/Least-Squares Fit algorithm especially including the precalculation criteria presented in Section 5.0, to reduce the problem of calculating false-positive fast neutron doses.

- The existing data obtained from screening of TLD chips in new dosimeter cards for proper placement of TLD-600 and TLD-700 chips as well as physical acceptability of the card could be statistically analyzed as an additional check on the variability of individual chips being introduced into the system. This can be accomplished with very little cost.
- The shallow dose calibration for x-rays could be improved presently, without seriously effecting the Sr-90 or Cs-137 shallow dose response through addition of a second penetrating calibration based on L-K x-rays (see Section 3.0). The observed shallow dose over-response at low energies is reduced considerably.
- A significant enhancement of the Hanford dosimeter system could be achieved if a method was available to routinely account for the variability in sensitivity between TLD chips. Possibly, incorporating a chip sensitivity check in a dosimeter annealing apparatus before removal of the dosimeter identification would solve several problems.
- Dosimeter design modifications in Section 7.0 will increase neutron dose precision while retaining existing beta-gamma capabilities.

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1.0 INTRODUCTION

An automated thermoluminescent dosimeter system was implemented in January 1971 for personnel at Hanford.⁽¹⁾ This system continues to provide the official dose of record for Hanford workers although a few modifications have been made as equipment was replaced. Certainly, the dosimeter volume has greatly increased requiring the routine handling of thousands of dosimeters. During 1980, approximately 60,000 multipurpose dosimeters assigned to personnel were processed along with an additional 28,000 basic dosimeters. In addition, over 5,000 finger rings were processed. Several thousand calibration and control dosimeters are also processed during the year.

A program was initiated during FY-1980 to characterize the performance of the Hanford dosimeter system according to current and possible future field conditions at Hanford. Studies conducted during FY-1980 were documented as PNL-3536⁽²⁾ and this report includes a description of several aspects of the Hanford dosimeter system such as dosimeter design, calibration and dose algorithm. It also includes results of studies of the beta, photon, and neutron response of the Hanford dosimeter. The reader will likely find the information in the present report more understandable if the previous report is reviewed beforehand.

Studies conducted during FY-1981 and contained in this report examined specific functional components of the routine external personnel dosimeter program at Hanford. Components studied included:

- Dosimeter readout (Section 2.0)
- Dosimeter calibration (Section 3.0)
- Dosimeter field response (Section 4.0)
- Dose calibration algorithm (Section 5.0)
- Dosimeter design (Section 7.0)
- TLD chip acceptance procedures (Section 8.0)

Section 6.0 presents additional information regarding the dosimeter response to light- and medium-filtered x-rays, high energy photons and neutrons. This study was conducted to clarify certain data obtained during the FY-1980 studies.

These studies involve all major components of the dosimeter system except for data handling and record keeping practices. Recent changes to the dosimeter holder during FY-1981 are described in Section 7.0 of this report. Chip acceptance procedures for new batches used since the inception of the Hanford TLD/albedo dosimeter system in January, 1971 are described in an appendix to Section 8.0.

During recent years, efforts have been underway to establish dosimeter processor performance standards. Proposed Regulations (46 FR 199689) will require dosimeter processor certification for their licensees by the Nuclear Regulatory Commission contingent upon the processor passing performance criteria on a regular basis.⁽³⁾ Dosimeter intercomparison studies have been conducted by the U.S. Department of Energy^(4,5) and the Nuclear Regulatory Commission using a proposed ANSI Standard.⁽⁶⁾ The proposed criteria specify an acceptable level of dosimeter bias and variance for a specific number of irradiations. Dosimeter designs and/or procedures which result in an over-estimate of the dose received in certain field applications will generally not be acceptable for passing the proposed criteria. This criteria is not consistent with the philosophy involved in the field use of many dosimeter systems. Often, the dosimeter interpretation will result in an over-estimate of the actual dose received.

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2.0 STUDY 1 - DEPENDENCE OF DOSE CALCULATION ALGORITHM ON READER CHARACTERISTICS

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FOREWORD

A study of the dependence of dose calculation algorithms on several reader operating characteristics was conducted. Reader parameters such as variable light pipe efficiencies, reader gain shifts, heater contact, and readout cycle were included in this study. Information from Hanford Reader 2 provided the majority of the data used in the study. A brief discussion of the differences between Hanford Readers 2 and 3 is provided in the text.

SUMMARY

Because of limits placed on various reader components and on expected chip output (control dosimeters), the variability of dose calculation due to reader characteristics is controlled. Significant variability is observed in calibration coefficients from month to month and this reflects variability in reader processing parameters such as heater temperature, cleanliness of heater, photomultiplier tube, and light pipe assembly, as well as reader amplification. Variability between chips contributes also as does any variation received in calibration exposure. However, the current procedure of controlling reader parameters using numerous calibration and control dosimeters is effective.

Light source sensitivity is monitored every 30 minutes and adjusted if it is not within limits. For a typical processing run, Hanford Reader 2 light source readings were controlled to about $\pm 2\%$. Blank and 1T check dosimeters consisting of no exposure and 1 R ^{137}Cs gamma exposure, respectively, are processed every 50 dosimeters. Routine processing is automatically stopped if the reading is not within preset limits. Typically these limits are set at about $\pm 25\%$.

Calibration coefficients are adjusted using blind and/or open audit badges processed throughout a routine run. This adjustment reduces the bias that may

(a) U.S. Testing Company.

have occurred during the run and results in more uniform month-to-month values for the different calibration coefficients.

Reader stability during a long time period was determined from the 1T check dosimeters (1 R ^{137}Cs gamma) by tabulating their averages from run-to-run. Maximum variability of less than 10% is estimated from the data analyzed. Because the individual chip outputs should be nearly equal for 1000 mR photon exposures, reader caused variability such as light pipe efficiencies or reader gain shift can also be estimated from run-to-run.

The chip output for the TLD-600 chips following neutron irradiation was observed to be proportional to the recorded temperature drop of the heater. This is expected to be a source of variability in determining neutron doses. This topic is discussed in more detail in Study 6 of this report. The cycle time is important to both total readout and efficient process time. A 10 second readout time per chip has been determined to be too short to assuredly drop the chip signal. No difference was observed for readout times of 15 and 20 seconds. A larger data set must be analyzed to make a determination. The present readout time is 20 seconds.

INTRODUCTION

During a routine dosimeter processing run, the Hanford readers process several thousand dosimeter cards during a few days. Before each of these scheduled runs, the reader is cleaned and calibrated using a set of dosimeters exposed to known doses. Processing during the run is monitored by the reader microprocessor which solicits critical reader parameters, such as heater temperature or photomultiplier tube voltage, and compares the values obtained to preset limits.⁽¹⁾ In addition, control dosimeters exposed to either no dose (OT blank dosimeters) or 1000 mR of ^{137}Cs gamma radiation (1T check dosimeters) are readout routinely (e.g., every 50th dosimeter at a minimum) during the run. Check dosimeters are uniquely labeled and the chip output must fall within preset limits. If a reading falls outside the present limits, the reader stops, an error message is printed on the reader log and the reader sounds an alarm. Established operating procedures must be followed before continuing routine processing.⁽²⁾

Dose algorithms used to calculate nonpenetrating, penetrating, slow neutron and fast neutron doses are based on the physical characteristics of the dosimeter design and utilize the comparison of chip readings from unknown radiation sources with chip readings from known radiation sources to arrive at dose estimates. Historically, a series of calibration constants (C1 through C7) are determined, as shown in Table 2.1, from the following irradiations:

Nonpenetrating -- Exposure of 10 dosimeters to 4 rads each on the uranium disk sources (equal to 2 rads of ^{90}Sr).⁽³⁾

Penetrating -- Exposure of 10 dosimeters in air to 1R from a ^{137}Cs source.

Slow Neutron -- Exposure of six dosimeters in the graphite moderated sigma pile.

Fast neutron -- Exposure of six dosimeters on a phantom to the PuF_4 source.

These calibration constants are used to interpret the readout of each of the chips in terms of dose (centirad) using the dose algorithms shown in Table 2.2.

It is the purpose of this study to determine the significance of reader operating parameters on the foregoing dose algorithms.

READER VARIABLES

Individual TLD chip data and dose results as well as reader logs from routine dosimeter processing runs were examined to identify the range of values observed for several parameters of interest.

Sensitivity

A relative assessment of the reader sensitivity is available from the reader log where the light source reading is printed every 30 minutes and in terms of dose from the results of the calibration dosimeters. Light source readings recorded on the log during 48 hours of processing for the September 1980 quarterly run on Hanford Reader No. 2 are shown in Figure 2.1. The reader sensitivity is controlled to about $\pm 2\%$ of 325,000 as shown in Figure 2.1. Each

TABLE 2.1. Determination of Calibration Constants^(a)

Nonpenetrating Calibration	Penetrating Calibration	Slow Neutron Calibration	Fast Neutron Calibration
R1 =	R1 =	R2 =	R2 =
R2 =	R2 =	R3 =	R3 =
	R4 =	R4 =	R4 =
$C2 = \frac{2000^{(b)}}{(R1-K2R2)}$	$C1 = \frac{1000^{(b)}}{R2}$	$C4 = \frac{50^{(b)}}{(R3-R4)}$	$K7 = \frac{R4-K6R2-K5 (R3-R4)^{(c)}}{1000^{(b)}}$
C2 =	C1 =	C4 =	K7 =
C3 = C2 x K2	$K2 = \frac{R1}{R2}$	$K5 = \frac{R4-K6R2^{(c)}}{R3-R4}$	$C5 = \frac{1}{K7}$
C3 =	K2 =	K5 =	C5 =
	$K6 = \frac{R4^{(c)}}{R2}$		C6 = K6 x C5
	K6 =		C6 =
			C7 = K5 x C5
			C7 =

(a) Ri where i = 1, 2, 3, 4 or 5 refers to chip position reading minus the respective background count for each position.

(b) Calibration exposures: Nonpenetrating = 2000 mrad (4000 mrad Uranium)
 Penetrating = 1000 mrad
 Slow Neutron = 50 mrem
 Fast Neutron = 1000 mrem.

(c) For 5-chip dosimeters, R5 would be used in place of R2.

TABLE 2.2. Dose Algorithms

Dose	Algorithm ^(a)
Nonpenetrating	$NP = (R1 \cdot C2) - (R2 \cdot C3)$
Penetrating	$P = R2 \cdot C1$
Thermal Neutron	$SN = (R3 - R4) \cdot C4$
Fast Neutron	$FN = (R4 \cdot C5) - (R2 \cdot C6) - ((R3 - R4) \cdot C7)$

(a) Ri, where i = 1, 2, 3, or 4, refers to TLD chip reading in Hanford dosimeter card minus their respective background.

time a value falls outside the acceptable range (shown as X's in Figure 2.1), the reader automatically prints an error message and the reader gain is adjusted to bring subsequent light source readings within the desired range. It is interesting to note that a much larger number of readings which were out-of-limits occurred on the low side. However, the reason for this is not known for certain. One possibility is that the reader may have been adjusted to only slightly above the lower limit.

Calibration Dosimeters and Calibration Coefficients

Results of the calibration dosimeters provide the average chip response per delivered dose for each routine run. Table 2.3 is a summary of results observed for several routine runs. These data are relatively uniform from run to run.

The calibration coefficients defined in Table 2.1 are plotted in Figure 2.2 for each run. This data includes all the calibration sets run during each routine processing run. It is to be expected that the calibration set at the end of a run when the machine is somewhat dirty could vary from a calibration set run on a newly cleaned machine.

A more informative plot is shown in Figure 2.3 of the adjusted calibration constants. Adjustments are made according to the set of blind audit dosimeter results within each process run. The calibration set, usually the initial one, used to calculate doses is adjusted. The adjusted calibration coefficients are seen to be more uniform from month-to-month than the unadjusted calibration coefficients.

Another means of looking at consistency of calibration constants is by examining the ratios of some of the calibration constants shown in Table 2.1. Ratios considered are $C3/C2$, $C6/C5$, and $C7/C5$ because by definition they should be relatively insensitive to several sources of variability. Table 2.4 shows these ratios for the adjusted calibration constants. All of these ratios have coefficients of variability that are less than 10%.

TABLE 2.3. Sensitivity in Terms of Reader Counts per Unit Dose for Calibration Dosimeter Results

Routine Run	Calibration Type ^(b)	Normalized Calibration Dosimeter Results ^(a)			
		Chip 1	Chip 2	Chip 3	Chip 4
October - Set 1	Nonpenetrating	1.37 ± 0.08	0.06 ± 0.01	0.04 ± 0.01	0.05 ± 0.01
	Penetrating	2.09 ± 0.16	2.41 ± 0.20	2.58 ± 0.17	2.11 ± 0.15
	Thermal neutron	0.92 ± 0.22	1.02 ± 0.16	175 ± 7	76 ± 5
	Fast neutron	0.41 ± 0.04	0.49 ± 0.03	3.75 ± 0.36	3.04 ± 0.53
Set 2 ^(c)	Nonpenetrating	1.47 ± 0.15	0.07 ± 0.01	0.03 ± 0.01	0.05 ± 0.01
	Penetrating	2.03 ± 0.10	2.37 ± 0.14	2.52 ± 0.11	2.15 ± 0.14
	Thermal neutron	0.96 ± 0.12	0.92 ± 0.16	169 ± 12	73 ± 7
	Fast neutron	0.42 ± 0.03	0.51 ± 0.02	3.88 ± 0.30	2.88 ± 0.25
Set 3	Nonpenetrating	1.03 ± 0.09	0.03 ± 0.01	0.04 ± 0.01	0.07 ± 0.01
	Penetrating	2.07 ± 0.18	2.56 ± 0.15	2.58 ± 0.13	2.25 ± 0.16
	Thermal neutron	0.94 ± 0.12	1.02 ± 0.20	181 ± 3	82 ± 4
	Fast neutron	0.40 ± 0.04	0.48 ± 0.05	3.63 ± 0.32	2.78 ± 0.22
December - Set 1 ^(c)	Nonpenetrating	1.51 ± 0.10	0.07 ± 0.01	0.04 ± 0.01	0.06 ± 0.01
	Penetrating	2.19 ± 0.14	2.59 ± 0.17	2.66 ± 0.14	2.27 ± 0.12
	Thermal neutron	1.06 ± 0.12	1.22 ± 0.16	174 ± 10	75 ± 5
	Fast neutron	0.42 ± 0.06	0.46 ± 0.04	3.60 ± 0.19	2.79 ± 0.17
Set 2	Nonpenetrating	1.30 ± 0.17	0.06 ± 0.01	0.04 ± 0.01	0.06 ± 0.01
	Penetrating	2.10 ± 0.21	2.50 ± 0.11	2.61 ± 0.15	2.18 ± 0.11
	Thermal neutron	1.06 ± 0.10	1.20 ± 0.20	160 ± 8	70 ± 5
	Fast neutron	0.41 ± 0.03	0.48 ± 0.05	3.32 ± 0.20	2.60 ± 0.22

(a) Average calibration dosimeter results in reader counts divided by calibration dose.

(b) Calibration sources are:

Nonpenetrating - Uranium disk 4,000 mrad assumed equivalent to 2000 mrad of ⁹⁰Sr

Penetrating - ¹³⁷Cs 1000 mR assumed equal to 1000 mrem

Thermal neutron - 50 mrem from sigma pile

Fast neutron - 1000 mrem from PuF₄ source.

(c) Calibration data set used to calculate doses for run.

TABLE 2.3. (contd)

Routine Run	Calibration Type ^(b)	Normalized Calibration Dosimeter Results ^(a)			
		Chip 1	Chip 2	Chip 3	Chip 4
4th Quarter - Set 1 ^(c)	Nonpenetrating	1.25 ± 0.07	0.06 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
	Penetrating	1.92 ± 0.38	2.06 ± 0.18	2.22 ± 0.13	1.91 ± 0.20
	Thermal neutron	0.90 ± 0.18	0.90 ± 0.22	125 ± 14	57 ± 7
	Fast neutron	0.35 ± 0.05	0.37 ± 0.03	2.77 ± 0.33	2.20 ± 0.24
	Set 2				
	Nonpenetrating	1.23 ± 0.14	0.08 ± 0.03	0.04 ± 0.01	0.06 ± 0.01
	Penetrating	1.84 ± 0.10	2.03 ± 0.33	2.02 ± 0.31	2.24 ± 0.16
	Thermal neutron	1.12 ± 0.20	1.26 ± 0.20	95 ± 13	66 ± 6
	Fast neutron	0.40 ± 0.04	0.36 ± 0.08	2.53 ± 0.70	2.63 ± 0.22
January - Set 1 ^(c)	Nonpenetrating	1.45 ± 0.09	0.06 ± 0.01	0.03 ± 0.004	0.0t ± 0.01
	Penetrating	1.99 ± 0.20	2.40 ± 0.20	2.42 ± 0.12	2.16 ± 0.15
	Thermal neutron	1.24 ± 0.16	1.06 ± 0.14	159 ± 5	75 ± 3
	Fast neutron	0.41 ± 0.03	0.46 ± 0.0-1	3.37 ± 0.11	2.68 ± 0.26
	Set 2				
	Nonpenetrating	1.47 ± 0.24	0.06 ± 0.01	0.03 ± 0.01	0.05 ± 0.004
	Penetrating	2.18 ± 0.16	2.60 ± 0.16	2.80 ± 0.19	2.44 ± 0.13
	Thermal neutron	0.80 ± 0.18	0.94 ± 0.18	172 ± 7	79 ± 3
	Fast neutron	0.47 ± 0.04	0.48 ± 0.04	4.02 ± 0.17	3.18 ± 0.16
February - Set 1 ^(c)	Nonpenetrating	1.55 ± 0.12	0.07 ± 0.01	0.04 ± 0.005	0.06 ± 0.01
	Penetrating	2.17 ± 0.19	2.42 ± 0.16	2.65 ± 0.11	2.32 ± 0.14
	Thermal neutron	1.18 ± 0.22	1.32 ± 0.26	163 ± 10	78 ± 6
	Fast neutron	0.44 ± 0.06	0.50 ± 0.05	3.91 ± 0.31	3.15 ± 0.33
	Set 2				
	Nonepenetrating	1.51 ± 0.11	0.07 ± 0.01	0.03 ± 0.004	0.05 ± 0.01
	Penetrating	1.96 ± 0.17	2.23 ± 0.14	2.44 ± 0.13	2.20 ± 0.15
	Thermal neutron	0.98 ± 0.12	0.92 ± 0.12	142 ± 10	69 ± 3
	Fast neutron	0.42 ± 0.05	0.47 ± 0.03	3.29 ± 0.21	2.78 ± 0.12

(a) Average calibration dosimeter results in reader counts divided by calibration dose.

(b) Calibration sources are:

Nonpenetrating - Uranium disk 4,000 mrad assumed equivalent to 2000 mrad of ⁹⁰Sr

Penetrating - ¹³⁷Cs 1000 mR assumed equal to 1000 mrem

Thermal neutron - 50 mrem from sigma pile

Fast neutron - 1000 mrem from PuF₄ source.

(c) Calibration data set used to calculate doses for run.

FIGURE 2.2. All Calibration Coefficient Results Included in Routine Processing Runs

FIGURE 2.3. Adjusted Calibration Coefficient Results Used to Determine Personnel Dose

TABLE 2.4. Selected Ratios of Adjusted Calibration Constants

	<u>C3/C2</u>	<u>C6/C5</u>	<u>C7/C5</u>
	0.893	0.925	0.857
	0.939	0.966	0.839
	0.880	0.912	0.810
	0.853	0.906	0.764
	0.782	0.776	0.712
	0.844	0.873	0.768
	0.889	0.923	0.824
	0.872	0.941	0.914
	0.867	0.938	0.932
	0.828	0.987	0.874
	0.900	0.954	0.894
	0.784	0.877	0.805
	0.835	0.885	0.709
	0.858	0.914	0.865
	0.863	0.969	0.857
	<u>0.798</u>	<u>0.864</u>	<u>0.787</u>
Mean	0.855	0.913	0.826
Standard Deviation	0.043	0.051	0.066
Percent Variability	5%	6%	8%

Stability

An assessment of the stability of the reader during a run is available from the light source readings and the results of the 1T and blank check dosimeters. Results for several runs are shown in Table 2.5.

Light Pipe Efficiency

Differences in efficiency between light pipes over each of the chip positions are expected. The efficiency observed is dependent on the routine cleaning also. Figure 2.4 shows the light pipe assembly illustrating the five individual light pipe fingers, one for each chip position, fading into one central light pipe. The photomultiplier tube is affixed to the central pipe. Table 2.5 summarizes the average chip readings by position observed for several routine processings.

Heater Contact

The thermal contact between the heater and TLD chips is monitored by the maximum temperature drop observed during the readout of each chip. This information for the September quarterly run is shown in Figure 2.5 in which the average chip readings of 1T dosimeters are plotted as a function of the observed temperature drop. All of the data shown is within the statistical range of data observed for 1T dosimeters (Table 2.5). This data apparently indicates that all the chip signal can be readout with even low heater temperature drops for 1T dosimeters (^{137}Cs gamma).

TABLE 2.5. Average Chip Readings for 1T Dosimeters

Run	Reader Number	Chip Position			
		1	2	3	4
October 1980	2	1967	2365	2523	2117
November 1980	2	2156	2686	2671	2193
December 1980	2	2013	2391	2536	2126
4th Quarter 1980	2	1944	2261	2359	2172
January 1981	2	<u>2003</u>	<u>2432</u>	<u>2570</u>	<u>2381</u>
Mean		2016	2427	2532	2198
S.D.		83	158	113	107

FIGURE 2.4. Light Pipe Assembly

FIGURE 2.5. Chip Output as a Function of the Maximum Heater Temperature Drop for 1T Check Dosimeters (^{137}Cs exposure)

Figures 2.6 and 2.7 show the same type of data but for chips 3 and 4 of the September quarterly fast and thermal neutron calibration dosimeters. Both figures show a positive slope for the best fit line. This indicates that the chip reading for positions 3 and 4 of the Hanford dosimeter, for neutron irradiation, is related to the observed temperature drop of the heater. The temperature drop is assumed to reflect the degree of thermal contact between the heater and the chip. It is known that neutrons preferentially populate deeper traps in TLD-600 materials than do photons thereby requiring greater heating to drop the signal. The dependency observed would indicate that this is a source of variability in determining the neutron dose.

Readout Cycle

The readout time of each chip is an important consideration involving not only assuring the complete readout of each chip but the time required to process a run consisting of several thousand dosimeters. For example, a readout time of 20 seconds per chip would take 50 seconds more time per dosimeter than a readout time of 10 seconds for a 5 chip dosimeter. For a run of 5,000 dosimeters, this difference would constitute about 69 hours or nearly 3 days of 24 hour per day processing.

Glow curves for three readout-cycle times, 10, 15, and 20 seconds, are shown in Figures 2.8-2.11. These glow curves show that a 10 second cycle time is too short to readout the chip signal. The rereads, Figure 2.12, for the slow neutron exposures depict this vividly. These dosimeters were readout a second time to see how much signal was left in the chip.

Based on the small data set available, 2 or 3 of each type at each readout cycle time, no preferential statement can be made about the 15 second or 20 second cycle time. From the available glow curves, little difference can be noted. A larger data set needs to be statistically analyzed for variability to determine if, in fact, the readout cycle time could be decreased from the present 20 second cycle time routinely used.

FIGURE 2.6. Chip Output as a Function of Heater Temperature Drop for Fast Neutron Calibration Dosimeters

FIGURE 2.7. Chip Output as a Function of Heater Temperature Drop for Slow Neutron Calibration Dosimeters

FIGURE 2.8. Process Glow Curves (2000 mrad Sr Equivalent)

*THIS VALUE IS UNUSUALLY HIGH. R5 SHOULD BE APPROXIMATELY EQUAL TO R1 THROUGH R4.
THE DOSIMETER SYSTEM IS UNDERGOING A TRANSITION FROM 4 TO 5 CHIP BADGES. THIS CHIP MAY
NOT HAVE BEEN DUMPED ON PREVIOUS READOUT.

FIGURE 2.9. Process Glow Curves (1000 mrem CS-137 Gamma)

(a) THE NORMAL CALIBRATION DOSE IS 1000 mrem OF FAST NEUTRON.

FIGURE 2.10. Process Glow Curves (500 mrem Cf-252 Fast Neutron)

FIGURE 2.11. Process Glow Curves (50 mrem Slow Neutron)

FIGURE 2.12. Rereads of Slow Neutron Calibrations

Table 2.6 shows the chip output and the heater temperature drop for the dosimeters with glow curves.

Reader 3 Versus Reader 2^(a)

Hanford Reader 3 has been added to the dosimeter processing system. This reader is somewhat different than Reader 2. These changes are enumerated in the following paragraphs.

1. The 4 in. long light-pipe assembly as it exists on Reader 2 has been replaced by a 1/4 in. stainless steel cover plate with 3/8 in. diameter holes over each of the 5 TLD chip positions. Since the hole diameter to cover plate thickness ratio is now greater than 1 (as compared to the light-pipe assembly for which it is much less than 1), light transmission through the hole is negligibly affected by the reflectivity (cleanliness) of the hole walls.
2. The photomultiplier tube window and its UV-passing filter cover (transmission above 450 nm) sit approximately 1 in. above Reader 3's cover plate, whereas on Reader 2 they sit about 1 in. above the top of the light-pipe assembly. This puts the PM tube window about 4 in. closer to the TL chips on Reader 3.
3. On Reader 3, the pressurized rubber tube light seal between the cover plate and dosimeter card slide track now overlaps to prevent any light leakage into the reading chamber. In Reader 2, the light seal does not make a full-circle seal due to the brass tee connection it uses and therefore allows for the possibility of a light leak around the tee.
4. On Reader 3, a CO₂ gas flush which flows from above the cover plate and down to and around the dosimeter card is now directed outside the reading chamber through vented slots (by the way of tubes and port-holes) in the dosimeter card slide track. This develops an effective downward flow during dosimeter readout which prevents material sublimated off the dosimeter card from reaching the UV filter over the

(a) Reader 2 is being upgraded using technology incorporated in Reader 3. The renovated Reader 2 will be called Hanford Reader 2a.

TABLE 2.6. Chip Output and Heater Temperature Drop for Glow Curves in Figures 2.8 through 2.11

Dosimeter Number	Delivered Dose/Type	R1	$\Delta H1^{(a)}$	R2	$\Delta H2$	R3	$\Delta H3$	R4	$\Delta H4$	R5 ^(b)	$\Delta H5$
NT046	2000 mrad	683	14	270	7	50	14	39	11	27	3
NT041	Sr-90	1561	18	93	9	70	9	96	6	92	6
NT043	Equivalent	1655	14	99	11	94	11	116	9	107	8
PT109	1000 mrem	411	12	667	6	514	14	361	14	160	11
PT116	Cs-137	1390	14	1337	10	1308	10	1514	8	2674	8
PT114	Gamma	1616	15	1317	11	1356	12	1707	10	3253	9
FT045	500 mrem	43	13	67	8	386	13	217	5	86	5
FT047	Cf-252	93	16	93	10	596	11	476	5	135	8
FT041	(Fast Neutrons)	95	18	88	11	675	11	744	8	121	9
ST011	50 mrem	49	12	57	6	1385	12	632	6	56	11
ST012	Slow	135	14	116	9	3453	8	2072	5	179	7
ST025	Neutron	121	14	125	12	4089	11	2238	7	188	10

(a) ΔH indicates heater temperature drop during readout.

(b) The Hanford Multipurpose dosimeter system is undergoing a transition from 4-chip to 5-chip dosimeters. It appears that some chip 5 data points are too high. The reason for this is expected to be the lack of reading out chip 5 on the previous dosimeter processing. R5 should be approximately equal to R1 thru R4 for 'PT' dosimeters.

PM tube window. In Reader 2, CO₂ gas is flushed into the reading chamber, but once the light seal is made does not flow out because the slots in the dosimeter card slide track are not vented. Therefore a continuous flow does not develop and the light pipes and UV filter are eventually coated with subliming materials after several dosimeter readouts.

5. On Reader 3, the PM tube window crystal is cut such that it contains a square array of four-sided prisms. The angle at which these prisms are cut is the critical angle for transmitting all wavelengths of 450 nm or shorter. All longer wavelengths are reflected back in a direction parallel to their incident rays, similar to the reflectors on a car.
6. Both Reader 2 and 3 have their PM tubes piezoelectrically cooled, however, Reader 3 has a better regulated power supply which holds its PM tube at a constant 5°F. Reader 2's PM tube is not kept quite as cold and is not held at as constant of a temperature.
7. On Reader 3, the resultant heat produced from the cooling of the PM tube is dissipated by about eight horizontal levels of fins which are arranged radially on the PM tube housing. On Reader 2, the cooling fins are parallel plates arranged vertically about the PM tube housing. A fan is used to blow air across the cooling fins on both readers.
8. Reader 3 has a glow worm indicator which displays the current count rate during any chip's readout cycle. The glow worm has a logarithmic indicator scale and gives only the relative count rate so that the reader operator can tell if they are getting a complete chip dump-out. This eliminates the necessity of plotting a glow curve for each chip under question.
9. The slope of the heater probe temperature response line is now set using two definite calibration points: the melting point of tin at 232°C and the equilibrium melting-freezing point of an ice bath at 0°C. Previously, a room temperature reading has been used in place

of the ice temperature. This did not provide the needed accuracy due to the inaccurate measurement of and large fluctuation in the room temperature. A large error could be introduced around 300°C with just a small error at room temperature since the slope of the line is pivoting through the melting point of tin at 232°C. Fortunately, Reader 2's heater probe temperature response line is now calibrated identically to Reader 3's.

10. The bar code label reader on Reader 3 has a more efficient optical detection system incorporating fiber optics.
11. All the electronics, including the PM tube, of Reader 3 are completely RF (radio-frequency) shielded to eliminate all outside noise interference.

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3.0 STUDY 2 - ASSESSMENT OF EXISTING AND PROPOSED DOSIMETER CALIBRATION TECHNIQUES

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FOREWORD

The Hanford dosimeter response to selected beta, photon and neutron irradiations was compared using existing calibration techniques and those utilized in the draft standard for dosimeter performance BSR N13.11. In addition, alternate calibration techniques were developed to improve the shallow dose response of the Hanford dosimeters to xrays.

SUMMARY

As expected, the response of the Hanford dosimeter to sources specified in the draft standard differs significantly from the response to current Hanford calibrations. For unmoderated ^{252}Cf , the dosimeter response is lower than the field calibration for fast neutrons by a factor of two. Due to increased sensitivity at lower neutron energies of the TLD albedo design, the dosimeter response to a moderated ^{252}Cf source exceeds the response to the field calibration by a factor of seven. The difference in response between the uranium beta calibration and an on-phantom ^{90}Sr calibration is approximately 40%. Finally, the change in response when ^{137}Cs calibrations are performed on a phantom is 10%.

Monoenergetic and filtered xray techniques were used to generate penetrating and nonpenetrating calibration constants. The dosimeter response for the xray calibrations was compared to the response for the Cs/Sr calibrations specified in BSR N13.11. Significant improvement in the shallow dose response to xrays was achieved through the use of a separate calibration for the penetrating component of shallow dose. A calibration using Cs for deep dose, Sr-90 for nonpenetrating shallow dose and the filtered technique L-K for penetrating shallow dose provided the best combination. The shallow dose bias to xrays

(a) Pennsylvania Power and Light.

was reduced to less than 20% for most xray techniques without impairing the shallow dose response to Cs-137 or Sr-90.

INTRODUCTION

The calibration procedure for the Hanford personnel dosimetry system specifies the following irradiations for obtaining penetrating, nonpenetrating, thermal neutron and fast neutron calibration:⁽²⁾

Penetrating. Calibration dosimeters are irradiated without a phantom backing at a distance of 50 cm from the ^{137}Cs source. The resulting "free air" dose lacks the backscatter present with a phantom.

Nonpenetrating. A set of natural uranium disc sources is used for the nonpenetrating calibrations. Dosimeters are placed against the surface of the sources, which are covered with approximately 7 mg/cm^2 plastic. The chip 1 position of each dosimeter is centered on a source. Assigned calibration doses from the uranium discs are divided by a factor of 2 to correspond to the dosimeter response to a ^{90}Sr source.

Thermal Neutrons. Dosimeters are irradiated within a sigma pile for the thermal neutron calibration. Badges are aligned perpendicular to the central axes of the pile at 1 m from the PuBe source and are surrounded by graphite.

Fast Neutrons. A PuF_4 source was used for fast-neutron calibrations until recently, when a change to ^{252}Cf was made. Calibration exposure times are adjusted to match the dosimeter response to previous field calibrations.

The draft standard BSR N13.11 prescribes a series of performance tests for dosimetry processors to be performed through a testing laboratory. Performance categories specified by the standard include:

- 1) NBS filtered x-ray techniques LG, LI, LK, MFC, MFG, and MFI,
- 2) ^{137}Cs ,
- 3) aged ^{90}Sr (^{90}Y) filtered by 100 mg/cm^2 of low Z material,

- 4) mixtures of x-rays and ^{137}Cs ,
- 5) mixtures of ^{137}Cs and ^{90}Sr , and
- 6) Mixtures of ^{252}Cf fission neutrons moderated by 15 cm $\text{D}_2\text{O}^{(3)}$ with ^{137}Cs gammas.

A Thermal neutron performance category is not included. All dosimeter irradiations for the tests are performed on a phantom at minimum distances of 35 cm for ^{90}Sr , 50 cm for ^{252}Cf , and 1 m for the photon sources.

The standard does not specify calibration methods. The processor may elect to use the calibrations specified by the testing laboratory or may adjust his calibrations so that the dosimeter response follows the BSR criteria. One of the purposes of this task is to assess what adjustments to the Hanford system may be necessary to meet the performance criteria.

ALTERNATE X-RAY CALIBRATIONS

Dose assignments using the response of the Hanford dosimeter to low-energy photons are particularly dependent upon the calibration technique. Using the current penetrating and nonpenetrating calibration algorithm, the response of the Hanford dosimeter to xrays may differ significantly from the on-phantom doses actually given to the badges (see Table 6.8, page 6.11 for the response of the Hanford dosimeter to filtered xray techniques). A change to the on-phantom ^{137}Cs and ^{90}Sr calibrations described in BSR N13.11 (1981) does not improve the dosimeter performance sufficiently to pass the xray categories in the draft standard. Development of new calibration techniques for xrays is recommended.

Dosimeters were irradiated under controlled conditions to study various calibration techniques. Screened TLD-700s ($\pm 5\%$) were loaded into holders and exposed to various xray energies along with ^{137}Cs and beta calibrations. For the first run, the dosimeters included TLD-600s screened to $\pm 10\%$ in positions 3 and 4.^(a) They were exposed on-phantom to K-fluorescent xray energies of 16.1 keV, 23.7 keV, 34.3 keV, 43 keV, 58 keV, 78 keV, and 100 keV, with eight dosimeters per energy. Groups were also exposed to ^{137}Cs gammas

(a) The Hanford dosimeter design is given by Fix, et al. (1981).

and ^{90}Sr betas. The process was later repeated with groups of six dosimeters using the NBS filtered x-ray techniques, L-I, L-G, L-K, MFC, MFI, MFG, HFI, and MFK, as well as betas from ^{204}Tl and ^{147}Pm . A mixed ^{90}Sr /MFI exposure was included to verify that beta/xray mixtures could be simulated by adding chip responses. The irradiations are summarized in Tables 3.1 through 3.3.

TABLE 3.1. K-Shell X-Ray Calibration Exposures

Assigned Energy keV	First HVL mm Al	Nominal Exposure to badges, mR	Deep Dose ^(a) Conversion Factor, rem/R	Shallow Dose ⁽⁴⁾ Conversion Factor, rem/R
16.1	0.059	500	0.38	1.08
23.7	1.219	500	0.74	1.07
34.3	3.04	500	0.99	1.07
43	5.197	500	1.30	1.28
58	8.672	500	1.54	1.47
78	12.56	500	1.72	1.61
100	14.19	500	1.74	1.59

(a) Previous PNL measurements.

TABLE 3.2. NBS Filtered X-Ray Technique Calibration Exposures

Technique	First HVL ^(a) mm Al	Effective Energy keV	Nominal Exposure mR	Deep Dose ^(a) Conversion Factor, rem/R	Shallow Dose ⁽⁴⁾ Conversion Factor, rem/R
L-G	0.37	15	1500	0.45	1.08
L-I	1.04	21	1500	0.81	1.13
L-K	1.81	26	1500	1.0	1.21
MFC	2.79	32	1000	1.07	1.15
MFG	5.03	42	1000	1.25	1.25
MFI	10.25	64	1000	1.47	1.41
MFK	13.2	84	1000	1.44	1.35
HFI	19.61	167	500	1.31	1.31

(a) Previous PNL measurements.

TABLE 3.3. Cs, Beta, and Mixed Beta/xray Exposures

<u>Source</u>	<u>Energy (MeV)</u>	<u>Shallow Dose to Badge mrad</u>	<u>Nominal Exposure mR (Cs only)</u>	<u>Deep DEI(a) rem/R (Cs only)</u>	<u>Shallow DEI(a) rem/R (Cs only)</u>
<u>Beta and Gamma Exposures</u>					
⁹⁰ Sr	2.28 β ^{-(b)}	500	-	-	-
²⁰⁴ Tl	0.763 β ⁻	500	-	-	-
¹⁴⁷ Pm	0.225 β ⁻	500	-	-	-
¹³⁷ Cs	0.66 γ	545	500	1.09	1.09

Mixed Exposure: 1000 mrad ⁹⁰Sr + 1000 mR MFI filtered technique xrays

(a) Yoder, et al. 1979.

(b) The 2.28 MeV beta is emitted by the ⁹⁰Y daughter. The ⁹⁰Sr beta is absorbed by low-Z filtration.

An algorithm was developed that would 1) screen the data for outlier TLDs, 2) calculate the exposure response, deep-dose response and shallow-dose response by energy and chip position based on averaged chip responses and delivered doses, 3) calculate penetrating and nonpenetrating calibration constants for each penetrating and nonpenetrating calibration energy, and 4) calculate the deep- and shallow-dose response of the badge for each combination of calibration energies. Calculations of penetrating and nonpenetrating calibrations were performed in accordance with presently used algorithms. To summarize, the calibration constants are obtained as follows:

$$C_{1(i)} = \frac{(\text{calibration deep-dose})}{R_{2(i)}}$$

$$K_{2(i)} = \frac{R_{1(i)}}{R_{2(i)}}$$

$$C_{2(i,j)} = \frac{(\text{calibration shallow dose})}{R_1(j) - K_2(i)R_2(j)}$$

$$C_{3(i,j)} = C_{2(i,j)} \cdot K_2(i)$$

where $R_1(i)$ and $R_2(i)$ indicate averaged chip responses for positions 1 and 2 after exposure to penetrating calibration energy i , and the subscript j indicates averaged chip responses for badges exposed to the nonpenetrating calibration energy.

The penetrating, or deep dose is equal to the absorbed dose at a depth of 1 cm in tissue and is calculated as $C_{2(i)}R_2$. The shallow or "skin" dose is the absorbed dose at 0.007 cm in tissue and is the sum of the doses due to penetrating and nonpenetrating components. The nonpenetrating component is calculated as:

$$NP = C_{2(i,j)}R_1 - C_{3(i,j)}R_2$$

and the penetrating component is considered to be equal to the deep dose. Negative values for NP are set to zero. Note that it is not necessary to use the same penetrating calibration energy in the deep and shallow dose determinations. Thus, one calibration energy can be used to calculate C_1 for the deep dose determination, while another may be used to calculate K_2 and C_1 for the penetrating component of the shallow dose.

Calibration deep- and shallow-doses for each energy were obtained using transmission chamber or transfer-standard ionization chamber measurements of exposure multiplied by the appropriate exposure-to-dose conversion factors (Yoder, et al. 1978). Use of the conversion factors given in BSR N13.11 yielded results that were slightly less conservative.

Dosimeter Xray Response Using Draft-Standard ^{137}Cs and ^{90}Sr Calibrations

The response of the dosimeter to low energy K xrays, which are essentially monoenergetic, is depicted in Figure 3.1 for the deep (1.0 cm) dose in

FIGURE 3.1. Deep-Dose Response of the Hanford Dosimeter to K X-rays Using ^{137}Cs and ^{90}Sr Calibrations specified by the draft standard

tissue and in Figure 3.2 for the shallow (0.007 cm) dose. The ratio of the dose calculated from TLD readings to the actual calibration dose is plotted as a function of energy.

For the deep dose, an under-response to energies below 34 keV is seen due to the attenuation of the low energy x-rays by the aluminum filter over position 2. Above 34 keV the LiF response over-compensates for the attenuation of the filter, and the badge over-responds by up to 50%.

The shallow dose response, shown in Figure 3.2, is considerably greater than the deep dose response. Since the penetrating component is included in the calculation of skin dose, the over-response due to depth dose estimation and the over-response of the LiF are additive.

Similar graphs of the deep and shallow dose response for filtered x-ray spectra are shown in Figures 3.3 and 3.4. The over-responses for the spectra are reduced slightly by a "smoothing" effect. The effective energy of the NBS techniques is shown for reference only and should not be considered directly relatable to K-shell x-ray energies when referring to dosimeter response.

Dosimeter Calibrations Using K-Fluorescent and NBS Filtered X-rays

Due to the nature of the algorithm used to calculate the penetrating dose, the badge response for deep dose cannot be improved significantly through changing the calibration. When the calibration energy is varied, the constant C_1 changes, shifting badge responses at all energies by the same factor. The shape of the curve remains constant; therefore, any decrease in dosimeter over-response at intermediate energies is offset by a worsening of dosimeter under-response at low energies. Equally undesirable, the badge response to ^{137}Cs is degraded by the same amount, since cesium is no longer the basis for the calibration. The relative shift in position of the deep dose response curve for selected K x-rays is shown in Figure 3.5 and the effect upon cesium response is summarized in Table 3.4.

The shallow dose response shows greater opportunity for improvement. The objective in calibrating the shallow dose is to lessen the badge overresponse to x-rays without adversely affecting the beta response. One method of achieving this is to retain ^{90}Sr as the nonpenetrating calibration energy while varying the calibration for the penetrating component of shallow dose.

FIGURE 3.2. Shallow-Dose Response of the Hanford Dosimeter to K X-rays Using ^{137}Cs and ^{90}Sr Calibrations specified in the draft standard

FIGURE 3.3. Deep-Dose Response of the Hanford Dosimeter to NBS Technique Filtered X-rays Using ^{137}Cs and ^{90}Sr Calibrations specified in BSR N13.11

FIGURE 3.4. Shallow-Dose Response of the Hanford Dosimeter to NBS Technique Filtered X-rays Using ^{137}Cs and ^{90}Sr Calibrations specified in the draft standard

FIGURE 3.5. Deep-Dose Response Curves for K-Fluorescent X-rays Using Alternate Calibrations

TABLE 3.4. C_1 Values for X-Rays

<u>X-Rays</u>		
<u>Energy keV</u>	$C_1 = \frac{\text{Deep Dose}}{R_2} \text{ (mrem/nC)}$	$C_1(E)/C_1(\text{Cs})$
16.1	4.39	2.27
23.7	1.97	1.02
34.3	1.36	0.70
43	1.26	0.65
58	1.37	0.71
78	1.68	0.87
100	2.01	1.04
(Cs)	(1.93)	(1.00)

NBS Filtered Techniques

<u>Technique</u>	<u>Effective Energy (keV)</u>	$C_1 \frac{\text{(mrem)}}{\text{nC}}$	$C_1(E)/C_1(\text{Cs})$
L-G	15	2.78	1.40
L-I	21	1.97	0.99
L-K	26	1.76	0.88
MFC	32	1.50	0.75
MFG	42	1.46	0.73
MFI	64	1.60	0.80
MFK	84	1.66	0.83
HFI	167	1.85	0.93
(Cs)	(660)	(1.99)	(1.00)

However, there are also several alternate nonpenetrating calibration combinations which are acceptable. Shallow dose response curves for several possible calibration schemes are shown in Figures 3.6 through 3.9.

FIGURE 3.6. Shallow-Dose Response of the Hanford Dosimeter to K X-rays Using Selected K X-ray Calibrations

FIGURE 3.7. Hanford Dosimeter Shallow Dose Response to Filtered X-rays Using L-G as the Nonpenetrating Calibration Technique

FIGURE 3.8. Hanford Dosimeter Shallow Dose Response to Filtered X-rays Using L-I as the Nonpenetrating Calibration Technique

FIGURE 3.9. Shallow Dose Response to Filtered X-rays Using ^{90}Sr as the Nonpenetrating Calibration Technique

The effect of alternate calibrations on the dosimeter response to ^{90}Sr is summarized in Table 3.5. For the calibration using $^{90}\text{Sr}/^{137}\text{Cs}$, the badge over-responds to ^{90}Sr by approximately 10% due to a slight penetrating component detected by the badge. Any alternative calibration yielding a bias of 10% or less for ^{90}Sr in addition to improved xray response is acceptable.

Response to Beta and Xray/Beta Mixtures

In addition to the ^{90}Sr irradiations, dosimeters were irradiated separately with 500 mrad ^{204}Tl and 500 mrad ^{147}Pm . The dosimeter response for the 0.76 MeV (maximum-energy) ^{204}Tl beta was only 18 mrad (3.6% of the actual shallow dose). The 0.2 MeV ^{147}Pm beta, as expected, did not penetrate the security credential.

The dosimeter response to mixtures of Sr-90 and K-fluorescent xrays is shown in Table 3.6. Chip responses were simulated by combining data from separate irradiations. As expected, the shallow dose response of the dosimeter to the xray/ ^{90}Sr mixtures fell between the shallow dose response to ^{90}Sr and the shallow dose response to the given xray energy. The deep-dose over-response to xrays was increased by the penetrating component of ^{90}Sr (^{90}Y). The possibility of using mixtures of 1000 mrad ^{90}Sr and 1000 mR MFI xrays to calibrate the dosimeter was investigated. Use of this mixture as the nonpenetrating calibration resulted in an increased over-response to xrays and a severely-degraded response to betas. Use of the mixture as a penetrating calibration (for shallow dose) in conjunction with a low energy xray non-penetrating calibration provided excellent results for xray shallow dose (Figures 3.7 and 3.8). However, the dosimeter response to ^{90}Sr was degraded.

Recommendations for X-Ray Calibrations

Although no single calibration technique enables the dosimeter to pass all xray performance categories, significant improvement in the xray shallow dose response is possible. Six of the calibration techniques yielded biases of 20% or less for the shallow dose response to filtered xray techniques with effective energies above 40 keV. However, most of those resulted in unacceptable biases for ^{137}Cs and ^{90}Sr . Only the use of ^{90}Sr as the nonpenetrating calibration with LK technique xrays as the shallow-dose penetrating calibration yielded a bias of 15% or less for ^{137}Cs and ^{90}Sr in addition

TABLE 3.5. ^{90}Sr and ^{137}Cs Shallow Dose Response for Selected Filtered X-Ray Calibrations

<u>Nonpenetrating Calibration Energy or Technique</u>	<u>Penetrating Calibration Energy or Technique</u>	<u>^{137}Cs Response ($\frac{\text{Calculated Shallow Dose}}{\text{Actual Shallow Dose}}$)</u>	<u>^{90}Sr Response ($\frac{\text{Calculated Shallow Dose}}{\text{Actual Shallow Dose}}$)</u>
^{90}Sr	^{137}Cs	1.053	1.108
^{90}Sr	L-I	0.990	1.107
^{90}Sr	L-G	1.395	1.150
^{90}Sr	L-K	0.883	1.095
^{90}Sr	MFC	0.752	1.081
^{90}Sr	MFI	0.810	1.087
^{90}Sr	MFG	0.730	1.079
^{90}Sr	HFI	0.983	1.100
^{90}Sr	MFK	0.870	1.090
L-I	^{137}Cs	1.038	0.826
L-I	L-G	3.497	0.150
L-I	L-K	0.883	1.623
L-I	MFC	0.752	1.126
L-I	MFI	0.809	0.856
L-I	MFG	0.730	0.917
L-I	HFI	0.967	0.817
L-I	MFK	0.860	0.816
L-G	^{137}Cs	1.032	0.705
L-G	L-I	0.990	0.827
L-G	L-K	0.883	0.752
L-G	MFC	0.752	0.712
L-G	MFI	0.808	0.691
L-G	MFG	0.730	0.691
L-G	HFI	0.960	0.697
L-G	MFK	0.855	0.688
L-K	^{137}Cs	1.050	1.054
L-K	L-I	3.579	0.107
L-K	L-G	2.733	0.150
L-K	MFC	0.752	2.393
L-K	MFI	0.811	1.169
L-K	MFG	0.730	1.377
L-K	HFI	0.979	1.043
L-K	MFK	0.869	1.057

TABLE 3.6. Badge Response to Selected X Ray/Beta Mixtures
Using ANSI ^{137}Cs - ^{90}Sr Calibrations

Mixture	Beta Dose to Badge (mrad)	X Ray Exposure to Badge (mR)	Deep Dose Response	Shallow Dose Response
$^{90}\text{Sr}/\text{Cs}$	500	500	1.09	1.05
$^{90}\text{Sr}/\text{Cs}$	1000	500	1.18	1.06
$^{90}\text{Sr}/\text{Cs}$	500	1000	1.04	1.03
$^{90}\text{Sr}/16.1 \text{ keV}$	500	500	0.70	1.64
$^{90}\text{Sr}/16.1 \text{ keV}$	1000	500	0.95	1.38
$^{90}\text{Sr}/16.1 \text{ keV}$	500	1000	0.57	1.64
$^{90}\text{Sr}/34 \text{ keV}$	500	500	1.51	1.66
$^{90}\text{Sr}/34 \text{ keV}$	1000	500	1.61	1.47
$^{90}\text{Sr}/34 \text{ keV}$	500	1000	1.46	1.83
$^{90}\text{Sr}/58 \text{ keV}$	500	500	1.47	1.39
$^{90}\text{Sr}/58 \text{ keV}$	1000	500	1.53	1.31
$^{90}\text{Sr}/58 \text{ keV}$	500	1000	1.44	1.46
$^{90}\text{Sr}/100 \text{ keV}$	500	500	1.02	1.16
$^{90}\text{Sr}/100 \text{ keV}$	1000	500	1.07	1.14
$^{90}\text{Sr}/100 \text{ keV}$	500	1000	0.99	1.17

to the low xray bias.. The xray technique with the lowest energy still fails the criteria with a bias of almost 80%, but the improvement is dramatic.

Unfortunately, the deep dose response of the dosimeter does not benefit from alternate calibrations. While a thicker filter would reduce the over-response in the 30-70 keV region, xrays of lower energies would be attenuated further. The only long-term solution appears to be the use of several filter thicknesses in xray dose assignments.

Three photon/beta calibrations may be used in the interim. The deep dose calibration using ^{137}Cs would be retained and strontium would be retained as the nonpenetrating calibration. A second penetrating calibration using the LK filtered xray technique would be added. This would be used to determine the K_2 value for the constants C_2 and C_3 based on the ^{90}Sr nonpenetrating calibration, as well as a " C_1 " value for determining the penetrating component of shallow dose. The LK penetrating calibration would be independent of the ^{137}Cs penetrating deep-dose calibration.

EFFECTS OF CHANGING FROM AN ADJUSTED URANIUM CALIBRATION TO ^{90}Sr

Routine calibrations for the Hanford system utilize a natural uranium slab for determining the constants C_2 and C_3 . The difference in geometry, backscatter, beta energy and photon contribution between the uranium slab and the ^{90}Sr calibration used in the draft standard BSR N13.11 is significant. Although Hanford calibrations are adjusted to closely simulate the Chip 1 response to Sr-90, there are differences in the penetrating components detected by the dosimeter for uranium and ^{90}Sr . These differences must be considered for the Hanford dosimeter to pass the requirements in BSR N13.11 using routine procedures.

Hand-loaded and personnel pool dosimeters were irradiated with a spherical ^{90}Sr source fulfilling the draft-standard specifications for filtration, backscatter from a phantom and geometry. A second set was irradiated, according to routine Hanford calibration procedures, against the surfaces of the uranium slabs. A PNL manual reader was used for the tightly-screened hand-loaded dosimeters, while the Hanford automated system was used for the personnel pool dosimeters. Although the sensitivities of the two systems differ, the ratio of C_2 for uranium to C_2 for strontium should remain constant.

Results are summarized in Table 3.7. Since C_2 is inversely proportional to the dosimeter response, the ratio of C_2 for ^{90}Sr to C_2 for uranium can be interpreted as the increase in nonpenetrating response to uranium relative to a ^{90}Sr calibration. Since the sources differ with regard to the penetrating component measured by the dosimeter, the total shallow dose response is also included in the comparison.

TABLE 3.7. Comparison of Uranium and ^{90}Sr Calibrations

System	$C_2 (^{90}\text{Sr})$	Shallow Dose Response to 1000 mrad Uranium ^(a)
	$C_2 (\text{Uranium})$	Shallow Dose Response to 1000 mrad ^{90}Sr
Hand-Loaded Dosimeters	1.54 ± 0.03	1.39 ± 0.02
Personnel-Pool Dosimeters	1.72 ± 0.07	1.38 ± 0.04

Quoted uncertainties represent the standard deviation of the mean TLD readings.

- (a) The uranium dose has previously been adjusted to normalize the nonpenetrating constants to ^{90}Sr . A quoted dose of 1000 mrad represents an actual uranium dose of 2000 mrad.

The discrepancy between calibration constants for the hand-loaded and automated systems appears to result from differences in chip readings in position 2. The hand-loaded dosimeters contain two chips per filter position. The double-chip configuration "sees" more scatter around the position 2 filter when the dosimeter is placed against the surface of the uranium source. However, the photon subtraction in the shallow dose algorithm compensates for the difference in Chip 2 readings. When the total shallow dose response is calculated, the two systems agree. The factor of two correction to the uranium calibration is apparently insufficient to match the dosimeter response to ^{90}Sr . A 40% difference in calculated doses is observed.

To match the dose responses, values of C_2 (and C_3) obtained for uranium could be increased by 40%. Alternately, the assigned calibration dose for uranium could be reduced. However, it is not desirable to match C_2 values for uranium and ^{90}Sr , since ^{90}Sr has a significant penetrating component factored into the shallow dose.

EFFECT OF ON-PHANTOM CALIBRATIONS FOR PHOTON BEAMS

Dose at the surface of a phantom is enhanced by radiation which has interacted in the phantom and scattered back to the front surface. The increased response of a dosimeter irradiated on a phantom versus in air is

primarily due to this backscattering effect. The magnitude of the back-scattered radiation depends on both the energy of the photon beam and the size of the phantom. The size specified by BSR N13.11 (1981) (30 cm x 30 cm x 15 cm) provides essentially full backscatter for photon energies of ^{137}Cs and below. On-phantom to in-air ratios were measured using the gamma ray from ^{137}Cs and x-rays of average energies of 167 keV and 32 keV.

Dosimeters drawn from the Hanford dosimeter pool were exposed in two groups, one mounted on a phantom and the other suspended in air. The on-phantom exposures were done according to BSR N13.11 (1981) specifications. These dosimeters were mounted on a 30 cm x 30 cm x 15 cm lucite phantom at a distance of 1 meter from the source to the front face of the phantom. Dosimeters were suspended in air at the same locations for the in-air irradiations. Dosimeter calibration data was used to minimize biases in the results. The data analysis procedure is described in Appendix 3.A.

The measured on-phantom to in-air ratios are presented in Table 3.8. The ratios for chips 1 and 2, which have the least amount of filtration, are consistent with published backscatter curves (Johns and Cunningham 1978). The smaller ratios at 167 keV and 661 keV for chips 3 and 4 are probably due to the increased filtration on both front and back. The filters on the back side of the dosimeters partially shield the lower-energy backscatter radiation. The large attenuation of the 32 keV x-ray beam by the filters of chips 3 and 4 resulted in imprecise results.

TABLE 3.8. On-Phantom to In-Air Ratios^(a)

Source	Mean Energy	On-Phantom/In-Air Ratios			
		Chip 1	Chip 2	Chip 3	Chip 4
^{137}Cs	661 keV	1.099 ± 0.023	1.128 ± 0.022	1.077 ± 0.018	1.083 ± 0.023
xray	167 keV	1.284 ± 0.018	1.226 ± 0.022	1.072 ± 0.017	1.064 ± 0.028
xray	32 keV	1.319 ± 0.029	1.347 ± 0.023	1.58 ± 0.09 ^(b)	1.29 ± 0.09 ^(b)

(a) Data taken using calibrated field dosimeters.

(b) These ratios are less precise due to the low penetration of the 32 keV x-rays.

A shift from current calibration techniques to those recommended in BSR N13.11 would change the penetrating calibration constant, C1. Using the recommended conversion factor for ^{137}Cs of 1.03 rem/R, a one rem exposure requires 0.97 R. A three percent lower exposure together with an increase of 13% in the response of chip 2 due to phantom backscatter results in a net 10% decrease in C1.

EFFECTS OF NBS-TRACEABLE ^{252}Cf FAST-NEUTRON CALIBRATIONS

The fast-neutron calibration for the Hanford dosimeter is based on field measurements taken about 1970. Field dose rates were measured at numerous locations throughout the Hanford site using tissue-equivalent proportional counters (TEPC).^(a) The dosimeter response to the field dose rates and to exposures from a PuF_4 source were matched to yield a calibration exposure time. The PuF_4 source was used to calibrate the Hanford dosimeter until mid-1981, when the routine calibrations work was shifted to a ^{252}Cf source in the same exposure room. The dosimeter response to both sources was matched to reproduce the field calibration. The present fast-neutron calibration consists of the exposure of six dosimeters simultaneously at a source to phantom distance of 50 cm.

Before the PuF_4 source was removed from 3745A, its dose rate was compared to that of the ^{252}Cf source in 318 Building using both TEPC's and Hanford dosimeters. The 318 source calibration is traceable to NBS, providing a comparison between the current fast-neutron calibration to traceable calibration rates for unmoderated ^{252}Cf . The current draft of ANSI N13.11 specifies the use of heavy-water moderated ^{252}Cf . To assess the effect of using this type of source, a comparison of moderated and unmoderated ^{252}Cf exposures for the Hanford dosimeter was performed at NBS. This information will provide an estimate of calibration differences between current methods and ANSI-specified calibrations.

(a) Nichols, L. L., private communication.

Methods

Two distinct dosimeter systems were used to compare the PuF_4 source in 3745A Building to the ^{252}Cf source in 318 Building. The first was the tightly-controlled TLD-handling system used exclusively for research projects. The second was the routine dosimeter system used by Hanford contractors.

The hand-loaded system provided precise results with relatively few dosimeters. TLD's tightly-screened for sensitivity were loaded into Hanford dosimeters. The TLD's were read manually and annealed under controlled conditions. The hand-loaded tests provided information on the response of the dosimeter design.

Dosimeters drawn from the routine dosimeter pool were used to help assess the effects of calibration charges on the routine dosimetry system. The dosimeters were read and evaluated by the same methods as routine dosimeters.

The routine fast-neutron calibration source and geometry were used. The source was contained in a can 10 cm in diameter by 12 cm tall. Two opposed phantoms were positioned at 35 cm phantom surface-to-source-center distance in the North-South direction. Three dosimeters were mounted on each 23 cm x 17 cm x 19 cm phantom per irradiation. Both the source and the phantoms were attached to an aluminum jig. The 3745A irradiation facility is relatively small, so that the dosimeter response to neutrons scattered from the concrete floor, walls and ceiling can be significant problems. The closest concrete scattering surfaces were: the floor (1 m from the source) and the South wall (180 cm from the source).

For The ^{252}Cf source located in the 318 Building, the irradiation position is approximately at the center of a 10 m x 16 m x 9 m room. The emission rate has been calibrated by NBS. The conversion factor to dose equivalent is $3.4 \times 10^{-8} \text{ rem-cm}^2$. One phantom was used at a source-to-front-face distance of 50 cm. Up to six dosimeters were mounted on the water-filled lucite box (30 cm x 30 cm x 15 cm) per irradiation. The contribution to the response of the Hanford dosimeter due to scattered neutrons is 6% of the response due to unscattered neutrons at 50 cm.

Tissue-Equivalent Proportional Counter (TEPC) measurements were taken for both the PuF_4 source and the ^{252}Cf source in the 318 Building. The TEPC can directly measure dose to tissue from neutrons. However, because it is insensitive to neutrons of energy below about 20 keV, it is not sensitive to the same spectrum of neutrons as the Hanford dosimeter. The dosimeter is designed to measure the fast neutrons which thermalize in the phantom. It is more sensitive to the lower energy neutrons (cadmium cutoff energy to 20 keV) than to the higher energy neutrons. Thus the TEPCs and the Hanford dosimeter respond differently in an environment with a significant component of lower-energy neutrons.

Analysis

The fast-neutron response function for the Hanford dosimeter is

$$(1) \quad F(\text{source}) = R4 - K6 * R2 - K5 * (R3 - R4)$$

where R2, R3 and R4 are TLD readings and K6 and K5 are constants determined from other calibrations. The fast-neutron dose-equivalent formula is:

$$(2) \quad \text{FN} = C5 * F(\text{source})$$

where

$$(3) \quad C5 = 1000 \text{ mrem}/F(\text{cal})$$

and $F(\text{cal})$ is the response function to a 1000 mrem calibration dose. A change in the calibration conditions will shift $F(\text{cal})$, $C5$ and FN .

The analysis using the hand-loaded dosimeters was straightforward. Unfortunately a complex analysis procedure was required to interpret the data taken using the routine dosimetry system. This procedure is described in Appendix 3.A.

Results

Measurements using the hand-loaded dosimeters are presented in Table 3.9. Both the PuF_4 and ^{252}Cf sources were measured twice with consistent results. The response functions in the last column were calculated using Equation 1,

the TLD readings in columns 4-6 and the K5 and K6 values given at the bottom of the table. The errors were estimated from the fluctuations in the TLD readings.

Table 3.10 contains the measurements using the Hanford pool processed dosimeters. Dosimeters exposed in 318 Building were evaluated in the February monthly run. The PuF_4 response function was calculated from the audit dosimeters processed during that run. The K5 and K6 values used to calculate both response functions are given at the bottom of the table. The error in the PuF_4 response function was estimated from fluctuations in the calibration constants (see Appendix 3.A). The error for the ^{252}Cf source was estimated from the fluctuations in the TLD readings.

The results for the Hanford dosimeter measurements and the TEPC measurements are presented in Table 3.11. The contribution due to scattered neutrons has been removed from the dosimeter response functions. The scattered-neutron contribution to the TEPC results for the ^{252}Cf source is small and has been

TABLE 3.9. Response of Hand-Loaded Dosimeters

Source	Date	Number of Dosimeters	TLD Readings for 1000 mrem Dose ^(a)			Response Function ^(b)
			R2	R3	R4	
PuF_4	12/80	6	86.1	654	586	417 ± 24
		6	86.6	673	581	
		6	86.6	647	577	
	2/81	6	93.9	671	586	405 ± 39
						414 ± 20
			TLD Readings for 1000 mrem Free-Field Dose ^(c)			
^{252}Cf (318 Bldg.)	2/81	10	26.7	321	281	211 ± 6
	3/81	10	25.3	323	281	

(a) Exposure times were based on historical field measurements.

(b) K5 and K6 were calculated using chip 2. K5 = 1.12, K6 = 0.92.

(c) Traceable to NBS.

TABLE 3.10. Response of Hanford Pool Processed Dosimeters

Source	Run	Number of Dosimeters	TLD Readings			Response ^(a) Function
			R2	R3	R4	
PuF ₄	Feb. Monthly	12	(see Appendix 3.A)			1680 ± 80
<u>for 1000 mrem Free-Field Dose^(b)</u>						
²⁵² Cf (318 Bldg.)	Feb. Monthly	10	170	1657	1337	890 ± 90

(a) K5 = 0.895, K6 = 0.954.

(b) Traceable to NBS.

neglected. The two dosimeter measurements are in agreement. The dosimeter response to the field calibration is a factor of two higher than the response to the NBS traceable ²⁵²Cf calibration. The ratio is lower for the TEPC. This is attributed to the effects of scattered neutrons. The larger proportion of scattered neutrons in the 3745A irradiation room produce a greater response in the dosimeter than in the TEPC.

The difference between the field-based and NBS-traceable calibrations does not imply that one of them is in error. The dosimeter responds differently to neutron spectra of differing composition. The neutron spectra in a work environment is more likely to contain a significant lower-energy component because of shielding material and confined spaces. A valid procedure to establish traceability for the fast neutron calibration is to relate the current field-measured neutron response function for the dosimeter to the response function for the NBS-traceable techniques.

The current draft of BSR N13.11 specifies the use of a heavy-water moderated ²⁵²Cf source for fast-neutron calibrations. This source has been shown to more closely resemble typical neutron spectra at nuclear power reactors (Schwartz 1980). The shift in the response of the Hanford dosimeter in going from a bare to a moderated ²⁵²Cf source was measured at NBS using hand-loaded dosimeters. In measurements taken at 50 cm, the response function of the

TABLE 3.11. Comparison of the Historical Field Calibration with a Calibration Traceable to NBS

	Response for 1000 mrem		
	TEPC	Hand-Loaded Dosimeter	Routinely Processed Dosimeters
Field Dose PuF ₄	1.28	414 ± 20	1680 ± 80
NBS-Traceable Dose (²⁵² Cf in 318)	0.87	198 ± 6(a)	840 ± 90(a)
Ratio	1.47	2.09 ± 0.12	2.00 ± 0.24

(a) The contribution to dosimeter response due to the neutron scatter has been removed. The scatter factor is 1.065.

dosimeter was higher by a factor of 13.6 for the moderated source. After removing room scatter, the correction was increased to 14.1. Both values have uncertainties of approximately 6%, and are in general agreement with results reported by Schwartz (1980).

CONCLUSIONS

The Hanford dosimeter exhibits the typical strong energy dependence for neutrons observed for all Albedo type dosimeters. The dosimeter response to a moderated ²⁵²Cf spectrum exceeds the response to a bare ²⁵²Cf spectrum by a factor of 14. In view of this large energy dependence, it is important to use a calibration spectra similar to the neutron spectra observed in the field. The dosimeter is presently calibrated to a field derived PuF₄ spectra.

The use of ⁹⁰Sr (on phantom) in place of the adjusted uranium beta calibrations would increase reported skin doses by 40%. Use of a phantom for ¹³⁷Cs irradiations would have a much smaller effect, decreasing reported doses by approximately 10%. The ⁹⁰Sr and ¹³⁷Cs on phantom calibrations are specified in the draft standard BSR N13.11 (1981).

The current calibration techniques and the design for the Hanford dosimeter result in a conservative assessment of deep and shallow dose from xrays (see Section 6.0). When the on-phantom ^{137}Cs and ^{90}Sr calibrations specified in the draft standard for performance testing of personnel dosimetry systems are used, the estimates are slightly less conservative. The large over-response of the dosimeter precludes any possibility of passing the xray performance categories in the standard. An alternate calibration for shallow dose using ^{90}Sr as the nonpenetrating calibration source and the filtered xray technique LK as the penetrating calibration source provides considerable improvement in the shallow-dose response of the dosimeter. All filtered techniques, with the exception of LG, then pass the shallow-dose criteria. Unfortunately, no real improvement in the deep dose response can result from alternate calibration techniques. The dosimeter may pass some of the deep-dose criteria, but cannot pass the entire xray category.

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APPENDIX A

DATA ANALYSIS USING HANFORD POOL PROCESSED DOSIMETERS

APPENDIX A

DATA ANALYSIS USING HANFORD POOL PROCESSED DOSIMETERS

Dosimeters taken from the Hanford personnel dosimeter pool were exposed to known sources and read according to routine procedures. Because these dosimeters were handled similar to routine dosimeters, comparing their responses to current calibration dosimeters is more relevant to the effect of source changes on the Hanford dosimeter system. However, the interpretation of the data is more complex.

Dosimeters are read in fixed batches according to the routine dosimetry schedule. A reading of a batch of dosimeters, which is called a run, can last for several weeks. The runs follow the field dosimeter turnover schedules. There are monthly (M), quarterly (Q), yearly (Y) and clean-up (CU) runs. Research dosimeters are typically read at the end of a run, in a slow period during a run or just after the conclusion of a run. Dosimeters taken from a calibration pool are exposed to the calibration doses and read before and after each run. Blind audit dosimeters are exposed to a range of doses and are read interspersed throughout each run. Each run uses a minimum of two sets of six calibration dosimeters with twelve audit dosimeters per calibration category (nonpenetrating, penetrating, thermal neutron and fast neutron). There have been several TLD readers brought into service and taken out of service. Each reader has unique characteristics which can affect the data.

Variations in TLD signal during readout may be caused by the following conditions: 1) a variable reader efficiency (even during a run); 2) differing efficiencies for each TLD position of the dosimeter due to light pipe configuration within the reader (reader #2); 3) screening of TLDs so that the standard deviation of the batch is 10-15%; and 4) random errors in TLD readouts. The problem of differing efficiencies for each TLD position is small when the photon component is much smaller than the neutron component and the efficiencies do not change between calibration and readout. The fluctuations in TLD readings for consecutively read dosimeters are dominated by the 10-15% screening variations.

The simplest method of source comparison is to expose a random set of personnel pool dosimeters in the test situations to be compared, then have them read in one group. The errors propagating to the final results are due primarily to TLD screening variations and random reader errors. If the TLD signal variations are random, the estimated error will only be a function of the number of dosimeters used. Unfortunately, this is not always the case. Measurements with a batch of 50 pool dosimeters indicated a bias due to batching of the TLDs. Some of the dosimeters had TLDs in all positions that were more sensitive than the mean for the group. Others had TLDs of lower sensitivity in all positions.

To remove these large biases and to reduce the overall uncertainty in the measurements, the dosimeters were calibrated individually for relative efficiency. Dosimeters were uniformly exposed to ^{137}Cs , and the reading of each TLD was normalized to the mean for that particular filter position. During subsequent measurements, the signal for each TLD was divided by the appropriate normalization factor. The net uncertainty was then due only to random errors in the TLD readout process, a contribution of about 4% per TLD.

For several tests, it was desired to compare known exposures to the routine run calibrations. The variable reader efficiency made this difficult. One problem was that the response of the calibration dosimeters was not representative of the pool dosimeters. Current routine procedures adjust the calibration constants to agree with the audit dosimeter results. Test comparisons used the audit dosimeters, which also provided a better estimate of the average reader efficiency because they are read interspersed throughout a run. Table 3.A.1 contains calibration constants derived from audit dosimeters for the penetrating (C1) and the fast neutron (C5) calibrations over a six month period (see Column 2). The standard deviation of fluctuations in C1 is 8%, which is dominated by fluctuations in reader efficiency (see Column 2). The contribution of random TLD screening errors to C1 is 3% for twelve dosimeters. Column 3 lists C5 for the same period. The estimated standard deviation per entry is 14%, showing a large contribution from the random uncertainty estimated at ~10%. The ratio of the average C5 to the average C1

TABLE 3.A.1. Normalized Fast-Neutron Calibration Constants(a)

RUN		Original Values		Normalized
		C1	C5	C5
Oct	M	0.478	0.652	0.632
Nov	M	0.467	0.666	0.618
Dec	M	0.508	0.613	0.672
Dec	Q	0.539	0.829	0.714
Dec	A	0.435	0.613	0.576
Dec	CU	0.458	0.515	0.606
Jan	M	0.491	0.557	0.650
Feb	M	0.451	0.606	0.547
Mar	M	0.546	0.673	0.723
Mar	Q	0.506	0.738	0.670
Average		0.488	0.646	0.646
% SD of Sample		8%	14%	8%

$$\text{Normalized C5} = \overline{\text{C5}} \times (\text{C1}/\overline{\text{C1}})$$

(a) All values obtained from audit dosimeter results

does not depend on reader efficiency and has a relatively small random error. A normalized C5 can be defined as

$$\text{NORM (C5)} = \overline{\text{C5}} \times (\text{C1}/\overline{\text{C1}})$$

where the bar notation indicates an averaged value. Since $\text{C1}/\overline{\text{C1}}$ is the efficiency of an entry relative to the average, the variation in the normalized C5 is dominated by the reader efficiency. The random error on the normalized C5 is estimated at ~5%.

A comparison test of a known source exposure to the routine dosimeter calibrations is limited by the uncertainty of the reader efficiency at the time

the research dosimeters were read. Because of the known relative bias of subsets of the 50 dosimeters, each subset was normalized to the average sensitivity of the full batch. This sensitivity should be more representative of the pool dosimeters.

4.0 STUDY 3 AND STUDY 7 - HANFORD FIELD MEASUREMENT AND FIELD DOSIMETER RESPONSE

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FOREWORD

This study is a continuation of Study 4 performed in FY-1980 which evaluates radiological conditions at Hanford. The study also tries to identify areas in which analysis of dosimeter data from the Hanford Multipurpose Personnel Dosimeter (HMPD) could result in incorrect dose estimates to personnel. The specific factors investigated include field energy spectra and radiation type as well as a comparison of neutron dose estimates between several techniques of measuring neutron dose.

SUMMARY

Types and locations of measurements that were made are listed in Table 4.1. Generally, measurements performed using the TEPC's, the five-element HMPD and SNOOPY agreed fairly well. The exception occurred at FFTF, where there were differences in the measurements ranging over a factor of ten. A technical difference in the HMPD measurements at various sites was the type of phantom used. At the 234-5 Building, a 1.0 liter water bottle was used as a phantom, while at FFTF and the Pu storage vault in 324, a cylindrical lucite phantom was used.

Table 4.2 summarizes the dose equivalent measurements performed in this study. Compared to the TEPC and PTEPC, the dosimeter responded high by an average of 2.8 ± 3.4 and compared to the SNOOPY, an average of 1.1 ± 0.3 (excluding 234-5 duct level). Generally, the dosimeter responses correlate well compared to the neutron personnel rate meter in use.

The agreement between dosimeters at each site was very good. The data reported are average values for each particular location and the standard deviation remained within 25% of the average.

The predominant gamma emitting radionuclides that were encountered were ^{60}Co , ^{137}Cs and ^{208}Tl . The types of neutron spectra encountered were from plutonium compounds or scattered neutrons from the fast flux reactor. Specific

TABLE 4.1. Location Summary

		<u>Measurements</u> ^(a)
324 Building	Pu Storage Vault	M,H,P,T,D
	A-Cell Gallery	G,D
	C-Cell Gallery	G,D
	Truck Lock	G
331 Building	Room 171	G
	Dog Run Change Room	G,D
340 Building	340-A (outside)	G,D
	Control Room	G,D
	Decon Area	G,D
	Operations Office	G,D
3730 Building	Irradiation Room	G,D
	Hallway	G,D
FFTF	Operating Deck	M,H,T,D,S,R
	Head Compartment	H,T
209-E Building	Mix Room	H,P,D,S,C,T
234-5 Building	3rd Floor	
	Maintenance Area	H,P,T,D,S
	Operations Office	P,D,S
	2nd Floor (duct level)	
	Room 264	H,P,D,S
	1st Floor	
	Hood HA-23	H,M,T,P,S,C
	General Hood Area	P,S,C

(a) M = multisphere, H = ³He spectrometer, T = TEPC, P = PTEPC,
D = HMPD, G = GeLi, S = SNOOPY, C = CP, R = RASCAL.

energy and dose data are presented in the appendices. Suffice it to say, that the photon fields encountered in this study were all of sufficient energy that the dosimeter would adequately detect and accurately assess the exposures associated with these particular fields.

INTRODUCTION

With the exception of the RASCAL and the special beta dosimeter employed during the FY-1980 study, all techniques described therein were used in this

TABLE 4.2. Summary of Neutron Measurements

Building	Location	Multisphere	TEPC	PTEPC	He-3	RASCAL	SNOOPY	HMPD
324	Pu Storage Vault	2.8	4.6	5.1	2.1	--	5.0	6.5
FFTF	Location 8	3.8	5.6	--	14.7	13	18	29.1
	Location 10	1.9	1.2	--	4.1	5.3	12	12.3
209-E	Location 13	--	3.1	3.8	--	--	2.0	1.8
	Location 17	--	--	0.6	--	--	0.4	0.5
234-5	Maintenance Office	--	0.4	0.4	--	--	0.5	0.4
	Duct Level, Col. 16	--	--	1.6	--	--	0.8	0.6
	Duct Level, Under S2	--	--	1.7	--	--	<0.1 ^(a)	2.7
	Duct Level, Over HA23	--	--	2.6	--	--	0.1 ^(a)	5.1
	Pu Hood, Top	2.8	14.7	12.3 ^(a)	3.2	--	10.5 ^(b)	--
	Pu Hood, Side	--	--	7.2	--	--	7.0	--
	General Background	--	--	1.2	--	--	1.5	--

(a) These SNOOPY readings are suspect due to geometry differences.

(b) Average of four readings.

study. Additionally, a new technique using a portable TEPC was employed for measuring neutron dose equivalent rates.

Areas to be investigated were identified by Hanford contractor personnel involved in operational health physics and personnel dosimetry and summarized in Table 4.1. Criteria for choosing locations were based on: 1) whether the dosimeter in various field situations would accurately represent personnel dose and 2) general interest of the health physics personnel. A concerted effort was made to avoid areas of infrequent occupation, areas with smearable or airborne radioactive contamination and areas which were inaccessible to the semiportable instrumentation.

Personnel dosimeters were placed at representative locations and measurements were made with electronic instruments 1) to characterize the energy spectra of the source radiations and 2) to attempt to verify the dose estimates using dosimeter data from the HMPD.

MATERIAL AND METHODS

Measurement systems employed during this study were selected to characterize the energy spectrum of the predominate radiation type(s) at each location. Complementary neutron instrumentation was used to characterize the neutron radiation at several locations. Four neutron energy spectra and dose measurement methods were used:

1. multisphere spectrometer system
2. tissue equivalent proportional counter (TEPC)
3. portable tissue equivalent proportional counter (PTEPC)^(a)
4. helium-3 neutron spectrometer.

Gamma spectroscopy was done using germanium-lithium drifted detectors. Gamma fields were characterized according to predominant radionuclides and relative activity.

(a) Portable Tissue Equivalent Proportional Counter manufactured by EG&G, Inc., Goleta, California.

Except for the portable tissue equivalent proportional counter (described below), the design and use of each of these instruments is described in Section 6 of PNL-3536. Data collected and analyzed for each of the Hanford locations are included in appendices for each location and summarized in Table 4.2.

Portable Tissue Equivalent Proportional Counter (PTEPC)

A portable tissue equivalent proportional counter (PTEPC) was used to determine the neutron dose equivalent rates at the sites containing measurable neutron fields. The PTEPC uses an LET counter as the detector, with a preamp and H.V. supply incorporated in the rear of the LET counter housing. A linear amplifier is used for signal conditioning resulting in a series of unipolar pulses whose height represents energy deposition in tissue. Four current digitizers are used to digitize the linear amplifier output into four pulse height (LET) bins. Within each bin each pulse is converted into a series of counts whose number is proportional to the area of each pulse. These counts are next multiplied by a quality factor appropriate for the pulse height or LET range of each bin. All four outputs are then summed and displayed on a scaler. This display is proportional to neutron dose equivalent in REM. A schematic showing the components of the counter is shown in Figure 4.1.

System calibration involves setting the gain of the linear portion (H.V. and amplifier gain) and then determining a calibration factor, from ^{252}Cf irradiation, relating the scaler counts to REM. A series of calibration measurements were conducted in 318 Building using a ^{252}Cf source. A counter sensitivity was determined for neutron dose equivalent rates ranging from 1 to 50 mrem/hr. A built-in alpha source allows system gain to be easily maintained. The alpha source (^{244}Cm) appears in the uppermost channel and has a stable counting rate. Adjustments in amplifier gain can be used to return the system to a known count rate, such as the one used during the calibration procedure.

Due to the portability and relative high sensitivity (~7 cts/sec/mrem/hr) of the PTEPC, we were able to take several measurements at each location quickly and easily. These measurements were used to map out the neutron field (using dose equivalent rate) so that we could determine the best location for further measurements using the other neutron detectors and dosimeters. Also,

FIGURE 4.1. Portable Tissue Equivalent Proportional Counter

a regular or nonportable tissue equivalent proportional counter (TEPC) was used some of the time to verify the (PTEPC) measurements. Both counters yielded the same results (within 5%) when used at the same locations throughout the field measurements.

APPENDIX A

300 AREA

APPENDIX A

300 AREA

BUILDING 324

Neutron Measurements

Neutron dose rate and spectrum measurements were made in the plutonium storage vault and other locations in the 324 Building. As shown in Figure 4.A.1., dose rates and neutron spectra were measured in the center of the vault utilizing the multisphere technique, the portable TEPC, the standard

FIGURE 4.A.1. Locations of Neutron Dose Rate and Spectral Measurements

TEPC, Hanford multipurpose dosimeters and a ^3He spectrometer. The agreement between measurements was very good and ranged from 2.1 mrem/hr using a combination of ^3He spectral data and multisphere data to 6.5 mrem/hr using the HMPD's. The average neutron energy was calculated from multisphere data and found to be 0.44 MeV.

Table 4.A.1 summarizes dose equivalent rates and neutron spectrum data. Table 4.A.2 summarizes flux and energy data from the multisphere measurements, while Figure 4.A.2 is a graphical representation of the neutron flux distribution.

TABLE 4.A.1. Comparison of Neutron Dose Equivalent Rates and Spectral Measurements at 324 Bldg. Pu Storage Vault

<u>Multisphere</u> <u>(mrem/hr)</u>	<u>TEPC</u> <u>(mrem/hr)</u>	<u>PTEPC</u> <u>(mrem/hr)</u>	<u>HMPD</u> <u>(mrem/hr)</u>	<u>^3He(a)</u> <u>(mrem/hr)</u>	<u>SNOOPY</u> <u>(mrem/hr)</u>
2.8	4.6	5.1	6.5	2.1	5.0
$\phi^{(b)}$ <u>(N/cm²-sec)</u>	<u>Dose Equivalent^(c)</u> <u>Factor</u> <u>(mrem/hr/n/cm²-sec)</u>		<u>$\overline{QF}^{(b)}$</u> <u>(rem/rad)</u>	<u>$\overline{QF}^{(c)}$</u> <u>(rem/rad)</u>	<u>$\overline{QF}^{(d)}$</u> <u>(rem/rad)</u>
52.9	0.0402		9.0	8.3	11.0

(a) Dose equivalent rate = product of ^3He dose equivalent factor and multisphere flux (ϕ) measured with multispheres.

(b) From multisphere data.

(c) From ^3He data.

(d) From TEPC data.

TABLE 4.A.2. Multisphere Data - 324 Bldg, Pu Vault

Location	E(I) (MeV)	Differential Flux (n/cm ² -MeV-sec)	Energy Band (MeV)	Group ₂ Flux (n/cm ² -sec)
1	2.07E-07	2.32E+07	3.89E-07	9.01E+00
2	5.32E-07	5.07E+06	2.69E-07	1.36E+00
3	9.93E-07	1.15E+06	7.63E-07	8.73E-01
4	2.10E-06	2.74E+05	1.61E-06	4.42E-01
5	4.45E-06	7.12E+04	3.42E-06	2.44E-01
6	9.42E-06	2.03E+04	7.22E-06	1.47E-01
7	2.00E-04	6.47E+03	1.53E-05	9.92E-02
8	4.22E-05	2.31E+03	3.23E-05	7.45E-02
9	8.94E-05	9.27E+02	6.89E-05	6.39E-02
10	1.89E-04	4.23E+02	1.45E-04	6.13E-02
11	4.04E-04	2.19E+02	3.18E-04	6.96E-02
12	8.55E-04	1.29E+02	6.40E-04	8.23E-02
13	1.80E-03	8.59E+01	1.38E-03	1.19E-01
14	3.80E-03	6.49E+01	2.91E-03	1.89E-01
15	8.05E-03	5.49E+01	6.20E-03	3.40E-01
16	1.70E-02	5.15E+01	1.30E-02	6.72E-01
17	3.61E-02	5.23E+01	2.77E-02	1.45E+00
18	7.63E-02	5.51E+01	5.86E-02	3.22E+00
19	1.58E-01	5.54E+01	1.13E-01	6.24E+00
20	3.18E-01	4.55E+01	2.27E-01	1.03E+01
21	6.39E-01	2.35E+01	4.56E-01	1.07E+01
22	1.29E+00	5.94E+00	9.20E-01	5.46E+00
23	2.59E+00	7.28E-01	1.85E+00	1.35E+00
24	5.22E+00	5.18E-02	3.73E+00	1.93E-01
25	1.05E+01	2.57E-03	7.50E+00	1.93E-02
26	1.96E+01	1.07E-04	1.09E+01	1.16E-03

FIGURE 4.A.2. Flux Distribution as a Function of Neutron Energy, 324 Building--Pu Storage Vault

Gamma Measurements

The areas of interest identified by the radiation monitoring group included the A and C cell operations galleries and the truck lock area. Dosimeters were placed in galleries to determine the exposure rates and spectral measurements were performed using a Ge-Li diode to assure that the photons were mainly in the energy range of flat response by the HMPD. The data are summarized in Table 4.A.3.

TABLE 4.A.3. Gamma Exposure and Spectral Measurements
in the 324 Hot Cell Operations Galleries

<u>Location</u>	<u>Multipurpose Dosimeter (mR/hr)</u>
A Cell Gallery	0.3
C Cell Gallery	0.0

NOTE: Multipurpose dosimeter placement varied from GeLi diode location and geometry. Therefore the two measurements should not be compared quantitatively.

Plots of gamma spectra measurements taken at various locations are listed below with each location heading, isotope identification and a corresponding column titled γ/s (gammas/second). The gammas/second column is merely an indicator as to the relative amount of each identified radionuclide.

<u>Location</u>	<u>Plot Figure No.</u>	<u>GeLi Diode</u>	
		<u>Prominent Nuclide</u>	<u>Relative Activity (γ/sec)</u>
A Cell Gallery	4.A.3	^{137}Cs	6.7
C Cell Gallery	4.A.4	^{137}Cs	2.3
Truck Lock	4.A.5	^{137}Cs	26.7

4.A.6

FIGURE 4.A.3. Operator Station - A Cell - 324 Building

4.A.7

FIGURE 4.A.4. Operator Station - C Cell - 324 Building

4.A.8

FIGURE 4.A.5. Truck Lock Area - 324 Building

FACILITY 340

Gamma Measurements

The major area of concern at this waste transfer facility is exposure from fission product materials, namely ^{60}Co and ^{137}Cs . Data presented reflect static working conditions, but exposures will increase when the fully loaded waste transfer rail cars are present at the facility. Data are summarized in Table 4.A.4.

TABLE 4.A.4. Gamma Exposure and Spectral Measurements
at 340 Waste Transfer Facility

<u>Location</u>	<u>Multipurpose Dosimeter (mR/hr)</u>
Facing 340-A on outside storage vault	0.6
Control Room	0.1
Sample Prep Hood, Decon Room	0.4
Decon Area Sump	0.0
Operations Office	0.0

NOTE: Multipurpose dosimeter placement varied from GeLi diode location and geometry. Therefore the two measurements should not be compared quantitatively.

Plots of gamma spectra measurements taken at various locations are listed below. Figure 4.A.6 details the counting locations in the 340 area.

<u>Location</u>	<u>Plot Figure No.</u>	<u>GeLi Diode</u>	
		<u>Prominent Nuclide</u>	<u>Relative Activity (γ/sec)</u>
Facing 340-A on out- side storage vault	4.A.7	^{137}Cs	326.2
Control Room	4.A.8	^{137}Cs	10.1
Decon Sump	4.A.9	^{137}Cs	49.1
Operations Office	4.A.10	^{137}Cs	0.1

FIGURE 4.A.6. Counting Locations in 340 Area. Locations are denoted by an "X".

FIGURE 4.A.7. Outside Near 340A Storage Vault

FIGURE 4.A.8. Control Room - S.E. Corner 340 Building

4.A.13

FIGURE 4.A.9. Decontamination Room 340 Area

FIGURE 4.A.10. Office - 340 Area

FACILITY 3730

Gamma Measurements

The operator's desk is in the irradiation room of this facility. The high level cobalt, cesium and californium sources are stored in a 30 foot deep water tank placed in the southwest corner of the room. Neutron dose rates were not detectable under storage conditions, so the predominant nuclides were the gamma emitting ^{137}Cs and ^{60}Co . An interesting point is that the exposure rate at the viewing window in the hall was an order of magnitude higher than general room levels. The dosimeters at the window location had a clearer and closer view of the sources themselves. Data are presented in Table 4.A.5.

TABLE 4.A.5. Gamma Exposure and Spectral Measurements at 3730-Cobalt Irradiation Facility

<u>Location</u>	<u>Multipurpose Dosimeter (mR/hr)</u>
Operator Desk	0.1
South Wall	0.2
Viewing Window	2.6

NOTE: Multipurpose dosimeter placement varied from GeLi diode location and geometry. Therefore the two measurements should not be compared quantitatively.

Plots of gamma spectra measurements taken at various locations are listed below. Figure 4.A.11 shows the spectral measurement locations in 3770.

<u>Location</u>	<u>Plot Figure No.</u>	<u>GeLi Diode</u>	
		<u>Prominent Nuclide</u>	<u>Relative Activity (γ/sec)</u>
Operator Desk	4.A.12	^{60}Co	1.4
Viewing Window	4.A.13	^{60}Co	2.4

3730 BUILDING

FIGURE 4.A.11. Viewing Window. Spectral measurement locations are denoted by an "X".

FIGURE 4.A.12. Operators Desk - 3730 Building

4.A.18

FIGURE 4.A.13. Hallway at Viewing Window Adjacent to Irradiation Tank - 3730 Building

BUILDING 331

Gamma Measurements

The 331 Building presents a unique problem of a change room being adjacent to a radioisotope sample preparation hood. Therefore, a gamma field exists in the change room at levels significantly above background. The major contributor to exposure in the change room is Thallium-208. Exposure rates and relative activities are given in Table 4.A.6.

TABLE 4.A.6. Gamma Exposure and Spectral Measurements
in the 331-Dog Facility

<u>Location</u>	<u>Multipurpose Dosimeter (mR/hr)</u>
E Wall of Change Room	0.1
S Wall of Change Room	0.1
S Wall of Toilet	0.5
Janitor's Closet in Dog Run	0.7

NOTE: Multipurpose dosimeter placement varied from GeLi diode location and geometry. Therefore the two measurements should not be compared quantitatively.

Plots of gamma spectra measurements taken at various locations are listed below.

<u>Location</u>	<u>Plot Figure No.</u>	<u>GeLi Diode</u>	
		<u>Prominent Nuclide</u>	<u>Relative Activity (γ/sec)</u>
Office	4.A.15	^{208}Tl	1.99
		^{137}Cs	0.22
Change Room (SE)	4.A.16	^{208}Tl	0.38
		^{137}Cs	4.60
Change Room (Toilet)	4.A.17	^{208}Tl	11.84
		^{137}Cs	6.70
Janitor's Closet Dog Run	4.A.18	^{208}Tl	6.03
		^{137}Cs	7.03

Figure 4.A.14 shows the locations of the gamma spectral measurements.

FIGURE 4.A.14. Spectra Locations in 331 Building

Anomalies in the peak shapes of this data was caused by a faulty capacitor in the signal shaping circuit. The peak areas are broadened but representative of the relative amounts of each radionuclide present.

4.A.21

FIGURE 4.A.15. General Room Spectrum, Room 117

4.A.22

FIGURE 4.A.16. South Wall in Change Room

FIGURE 4.A.17. Southwest Corner in Change Room

4.A.24

FIGURE 4.A.18. Janitor Closet Near Dog Run Entrance

APPENDIX B

400 AREA

APPENDIX B

400 AREA

FAST FLUX TEST FACILITY

Neutron Measurements

Dose equivalent rate and spectral measurements were made on the operating deck of FFTF directly above the head compartment. At that time, a stainless steel research thimble was in one of the bundle tubes and allowed neutrons to stream from the core to the head compartment. Iron has a neutron resonance at 26 keV, so it was expected that the average energy of neutrons which were detected would be somewhat less. The multisphere data indicated that the average energy was between 15 and 50 keV. The disagreement of that data and the average energy determined using the ^3He system (as seen in the difference of quality factors) lies in the fact that the width of the thermal peak in the ^3He overshadows everything up to about 30 keV.

Dose equivalent rates ranged from 4 mrem/hr using multisphere to 30 mrem/hr using the HMPD at location 8. At location 10, the dose equivalent rates ranged from 1 mrem/hr using the TEPC to 12 mrem/hr using the HMPD and SNOOPY. Multisphere data appear in Table 4.B.2 and 4.B.3 for locations 8 and 10 respectively, with flux data being illustrated in Figures 4.B.1 and 4.B.2, respectively.

TABLE 4.B.1. Comparison of Neutron Dose Equivalent Rates and Spectral Measurements at FFTF

<u>Location</u>	<u>Multisphere (mrem/hr)</u>	<u>TEPC (mrem/hr)</u>	<u>HMPD (mrem/hr)</u>	<u>He^{3(a)} (mrem/hr)</u>	<u>RASCAL (mrem/hr)</u>	<u>SNOOPY (mrem/hr)</u>
8	3.8	5.6	29.1	14.7	13	18
10	1.9	1.2	12.3	4.1	5.3	12
Head Com- partment	---	45.0	---	---	---	---

<u>Location</u>	<u>ϕ (n/cm²-sec)</u>	<u>Dose Equivalent Factor^(c) (mrem/hr/n/cm²-sec)</u>	<u>$\overline{QF}$^(b) (rem/rad)</u>	<u>$\overline{QF}$^(c) (rem/rad)</u>	<u>$\overline{QF}$^(d) (rem/rad)</u>
8	648	0.0227	3.3	6.9	9.2
10	172	0.0237	5.0	7.2	9.1
Head Com- partment	---	0.0480	---	6.4	9.0

(a) Dose equivalent rate = product of ³He dose equivalent factor and neutron flux (ϕ) measured with multispheres.

(b) From multisphere data.

(c) From ³He data.

(d) From TEPC data.

TABLE 4.B.2. FFTF - Operating Deck, Location 8 - 12/22/80

Location	E(I) (MeV)	Differential Flux (n/cm ² -MeV-sec)	Energy Band (MeV)	Neutron Flux (n/cm ² -sec)
1	2.07E-07	2.29E+07	2.89E-07	1.28E+01
2	5.32E-07	2.12E+07	2.69E-07	5.70E+00
3	9.93E-07	1.29E+07	7.63E-07	3.84E+00
4	2.10E-06	7.28E+06	1.61E-06	1.17E+01
5	4.45E-06	3.77E+06	3.42E-06	1.23E+01
6	9.42E-06	1.85E+06	7.22E-06	1.34E+01
7	2.00E-05	8.95E+05	1.53E-05	1.37E+01
8	4.22E-05	4.47E+05	3.23E-05	1.44E+01
9	8.94E-05	2.39E+05	6.89E-05	1.65E+01
10	1.89E-04	1.40E+05	1.45E-04	2.03E+01
11	4.04E-04	9.02E+04	3.18E-04	2.87E+01
12	8.55E-04	6.26E+04	6.40E-04	4.01E+01
13	1.80E-03	4.45E+04	1.38E-03	5.14E+01
14	3.80E-03	2.99E+04	2.91E-03	8.70E+01
15	8.05E-03	1.70E+04	6.20E-03	1.05E+02
16	1.70E-02	7.33E+03	1.30E-02	9.53E+01
17	3.61E-03	2.21E+03	2.77E-02	6.12E+01
18	7.64E-02	4.65E+02	5.86E-02	2.72E+01
19	1.58E-02	7.25E+01	1.13E-01	8.19E+00
20	3.18E-01	9.17E+00	2.27E-01	2.08E+00
21	6.40E-01	1.02E+00	4.56E-01	4.65E-01
22	1.29E+00	1.06E-01	9.20E-01	9.75E-02
23	2.59E+00	1.05E-02	1.85E+00	1.94E-02
24	5.22E+00	1.02E-03	3.73E+00	3.80E-03
25	1.05E+01	9.78E-05	7.50E+00	7.34E-04
26	1.96E+01	9.28E-06	1.09E+01	1.01E-04

TABLE 4.B.3. FFTF - Operating Deck, Location 10 - 12/22/80

Location	E(I) (MeV)	Differential Flux (n/cm ² -MeV-sec)	Energy Band (MeV)	Neutron Flux (n/cm ² -sec)
1	2.07E-07	7.57E+06	3.89E-07	2.94E+00
2	5.32E-07	5.45E+06	2.69E-07	1.47E+00
3	9.93E-07	3.61E+06	7.63E-07	2.75E+00
4	2.10E-06	2.07E+06	1.61E-06	3.33E+00
5	4.45E-06	1.01E+06	3.42E-06	3.45E+00
6	9.42E-06	4.39E+05	7.22E-06	1.17E+00
7	2.00E-05	1.79E+05	1.53E-05	2.74E+00
8	4.22E-05	7.31E+04	3.23E-05	2.36E+00
9	8.94E-05	3.17E+04	6.89E-05	2.18E+00
10	1.89E-04	1.53E+04	1.45E-04	2.22E+00
11	4.04E-04	8.47E+03	3.18E-04	2.69E+00
12	8.55E-04	5.42E+03	6.40E-04	3.47E+00
13	1.80E-03	3.97E+03	1.38E-03	5.48E+00
14	3.80E-03	3.22E+03	2.91E-03	9.37E+00
15	8.05E-03	2.68E+03	6.20E-03	1.66E+01
16	1.70E-02	2.06E+03	1.30E-02	2.68E+01
17	3.61E-02	1.24E+03	2.77E-02	3.43E+01
18	7.64E-02	4.92E+02	5.86E-02	2.88E+01
19	1.58E-01	1.17E+02	1.13E-01	1.32E+01
20	3.18E-01	1.73E+01	2.27E-01	3.93E+00
21	6.40E-01	1.83E+00	4.56E-01	8.30E-01
22	1.29E+00	1.53E-01	9.20E-01	1.41E-01
23	2.59E+00	1.11E-02	1.85E+00	2.05E-02
24	5.22E+00	7.22E-03	3.73E+00	2.69E-03
25	1.05E+01	4.38E-05	7.50E+00	3.29E-04
26	1.96E+01	2.57E-06	1.09E+01	2.80E-05

4.B.5

FIGURE 4.B.1. FFTF - Operating Deck, Location 8 - 12/22/80

FIGURE 4.B.2. FFTF - Operating Deck, Location 10 - 12/22/80

APPENDIX C

200 EAST AREA

APPENDIX C

200 EAST AREA

209-E CRITICALITY FACILITY

Neutron Measurements

Dose equivalent and spectral measurements were performed in the mix room at the 209-E facility. The radionuclide of concern is plutonium. Two locations were chosen for investigation: 1) the table in the southwest corner of the room, location 17, and 2) at the center glove port on the east side of the glove box, location 13 (Figure 4.C.1). Measurements were in very close agreement as is summarized in Table 4.C.1. Dose equivalent rates clustered at roughly 3 mrem/hr at location 13 and roughly 0.5 mrem/hr at location 17.

FIGURE 4.C.1. Locations (denoted by "X") of Measurements Performed in Mix Room of Critical Mass Laboratory, 209-E Building

TABLE 4.C.1. Comparison of Neutron Dose Equivalent Rates and Spectral Measurements in 209-E Mix Room

<u>Location</u>	<u>PTEPC (mrem/hr)</u>	<u>SNOOPY (mrem/hr)</u>	<u>HMPD (mrem/hr)</u>	<u>TEPC (mrem/hr)</u>
13	3.8	2.0	1.8	3.1
17	0.6	0.4	0.5	-

<u>Location</u>	<u>Dose Equivalent Factor^(a) (mrem/hr/n/cm²-sec)</u>	<u>$\overline{QF}$^(a) (rem/rad)</u>	<u>$\overline{QF}$^(b) (rem/rad)</u>
13	0.0425	8.7	7.8

(a) From ³He spectrometer data.
(b) From TEPC data.

APPENDIX D

200 WEST AREA

APPENDIX D

200 WEST AREA

BUILDING 234-5

Neutron Measurements

It was discovered by the RHO dosimetrist that the maintenance supervisor's office was located 2 floors directly above a plutonium storage hood. In order to determine the dose-equivalent rate at which the supervisor was subjected, extensive measurements were made: (1) at his office, (2) on the duct level, directly over the hood, and 3) on the top of the storage hood itself. Additionally, the dose-equivalent rates of various offices on the third floor were determined because they were located over a staging area used to store and prepare various neutron sources for shipping. Generally, dose-equivalent rates were too small to be detected by the multisphere technique, however, where those measurements were made, the data agreed favorably with other techniques.

The maintenance office exhibited a rate of ~ 0.5 mrem/hr; the other office dose rates were negligible and the dose-equivalent rates over the hood were on the order of 15 mrem/hr. Table 4.D.1 summarizes the dose-equivalent rate data, while Table 4.D.2 summarizes the spectral data. Multisphere flux information is found in Table 4.D.3 with a graphic representation in Figure 4.D.1.

TABLE 4.D.1. Comparison of Neutron Equivalent Rate and Spectral Measurements at 234-5 Building

<u>Location</u>		<u>Multisphere</u> (mrem/hr)	<u>TEPC</u> (mrem/hr)	<u>PTEPC</u> (mrem/hr)	<u>SNOOPY</u> (mrem/hr)	<u>HMPD</u> (mrem/hr)	<u>^3He (a)</u> (mrem/hr)
3rd Floor	Maint. Office	---	0.4	0.4	0.5	0.4	---
	308-1	---	---	<0.1	<0.1	0.1	---
	308-9	---	---	<0.1	<0.1	0.0	---
Duct Level	Column 16	---	---	1.6	0.8	0.6	---
	Under S2	---	---	1.7	<0.1	2.7	---
	Over HA23	---	---	2.6	0.1	5.1	---
Pu Storage Hood HA-23	1	---	---	7.8	7.0	---	---
	2	---	---	12.1	11.0	---	---
	3	---	---	14.4	13.0	---	---
	4	2.8	14.7	14.7	11.0	---	3.2
	Side of Hood	---	---	7.2	7.0	---	---
	Gen. Background	---	---	1.2	1.5	---	---

(a) Dose equivalent Rate = Product of dose equivalent factor and neutron flux (ϕ) measured with multispheres.

TABLE 4.D.2. Comparison of Spectral Measurements at 234-5 Building

<u>Location</u>	ϕ ^(a) <u>(n/cm²-sec)</u>	Dose Equivalent Factor ^(b) <u>(mrem/hr/n/cm²-sec)</u>	$\overline{QF}$ ^(a) <u>(rem/rad)</u>	$\overline{QF}$ ^(b) <u>(rem/rad)</u>	$\overline{QF}$ ^(c) <u>(rem/rad)</u>
Hood HA-23	57.5	0.0561	9.1	9.4	10.8
Duct Level					
Over HA-23	---	0.0313	---	7.7	---
Column 16	---	0.0320	---	7.9	---
Under S2	---	0.0420	---	8.8	---
Maint. Office	---	0.0673	---	6.5	14.4 ^(d)

(a) From multisphere data.

(b) From ³He spectrometer data.

(c) From TEPC data.

(d) This QF is too high. Data available were insufficient to calculate a more realistic value.

TABLE 4.D.3. Multisphere Data - 234-5 Pu Storage Hood

<u>Location</u>	<u>E(I) (MeV)</u>	<u>Differential Flux (n/cm²-MeV-sec)</u>	<u>Energy Band (MeV)</u>	<u>Neutron Flux (n/cm²-sec)</u>
1	2.07E-07	3.75E+06	3.89E-07	1.46E+00
2	5.32E-07	4.84E+06	2.69E-07	1.30E+01
3	9.93E-07	7.21E+04	7.63E-07	5.49E+02
4	2.10E-06	1.31E+04	1.61E-06	2.12E+02
5	4.45E-06	2.99E+03	3.42E-06	1.02E+02
6	9.42E-06	8.49E+02	7.22E-06	6.13E+03
7	2.00E-05	3.00E+02	1.53E-05	4.60E+03
8	4.22E-05	1.30E+02	3.23E-05	4.21E+03
9	8.94E-05	6.92E+01	6.89E-05	4.76E+03
10	1.89E-04	4.43E+01	1.45E-04	6.41E+03
11	4.04E-04	3.37E+01	3.18E-04	1.07E+00
12	8.55E-04	3.01E+01	6.40E-04	1.93E+00
13	1.80E-03	3.10E+01	1.38E-03	4.29E+00
14	3.80E-03	3.62E+01	2.91E-03	1.05E+00
15	8.05E-03	4.68E+01	6.20E-03	2.90E+01
16	1.70E-02	6.46E+01	1.30E-02	8.43E+01
17	3.61E-02	9.07E+01	2.77E-02	2.51E+01
18	7.63E-02	1.18E+02	5.86E-02	6.91E+01
19	1.58E-01	1.20E+02	1.13E-01	1.36E+01
20	3.18E-01	7.48E+01	2.27E-01	1.70E+00
21	6.39E-01	2.30E+01	4.56E-01	1.05E-01
22	1.29E+00	3.51E-00	9.20E-01	3.23E-01
23	2.59E+00	3.49E-01	1.85E+00	6.45E-02
24	5.22E+00	2.68E-02	3.73E+00	9.99E-03
25	1.05E+01	1.76E-03	7.50E+00	1.32E-04
26	1.96E+01	1.06E-04	1.09E+01	1.16E-05

4.D.5

FIGURE 4.D.1. Flux Distribution as a Function of Neutron Energy 234-5 Building--Pu Glove Box

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5.0 STUDY 4 – DOSE CALCULATION ALGORITHM UPGRADE ANALYSIS

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FOREWORD

A study of existing dose calculation algorithms and potential methods of upgrading the algorithms was conducted. Information available from routine calibration and check dosimeter results as well as results available from the DOE Technical Guidelines Program and the DOE Personnel Neutron Dosimeter Upgrade Program were included in the study.

SUMMARY

Three alternatives to the present system of Hanford equations were examined. All three alternatives involve a system of simultaneous equations based on the observed response of the dosimeter chips to the different calibration exposures. The alternatives are the Gauss-Seidel Method of solving simultaneous equations, the Least Squares Fit (LSF) Method of solving simultaneous equations, and a hybrid system of the present Hanford equations and the Least Squares Fit Method.

No noticeable improvement is seen for the 4-chip data except that the LSF and hybrid tend to not report "extraneous" doses. For example, both the present Hanford equations and the Gauss-Seidel algorithms calculate large fast neutron doses (e.g., 290 and 279, respectively) for a known 50 mrem slow neutron exposure. The LSF and hybrid system calculated a maximum dose of 21 mrem. The single iteration technique for the LSF and hybrid methods is better than the multiple iteration technique. It reports doses that are closer to the known exposure.

A major finding of this study is the significant variability observed from chip-to-chip and between dosimeters receiving identical exposures. The average dose of several dosimeters generally agrees closely with the given dose. However, the variability is significant. A standard deviation of 30% was observed for dosimeter results for ~300 mrem exposure. This variability precludes refinement of the algorithms to provide excellent precision.

INTRODUCTION

Dose algorithms are developed from the response characteristics of the dosimeter to known radiation fields and doses. The formulation adopted is dependent on the method of data interpretation employed, such as statistical methods of minimizing error between observed and predicted or utilizing most representative chip information based on the dosimeter design. This latter method is the technique adopted in current dose algorithms. Potential algorithms generally involve using more of the TLD chips to calculate the respective nonpenetrating, penetrating and neutron doses as well as providing a statistical basis for calculating these doses. The variation in the response of each chip combined with the similarity of chip response for certain radiations results in uncertainty of dose calculation in certain situations.

Typical chip output per unit dose for different radiation types is shown in Table 5.1. The sensitivity of the Hanford albedo dosimeter to thermal neutrons is apparent (i.e., ~150 reader counts/mrem response for chip 3). These ratios will vary somewhat depending on the sensitivity of the chips, the gain of the reader, and the efficiency of the different light pipes (see Study 1).

TABLE 5.1. Normalized Chip Output per Unit Dose

Calibration Source	Units	Position ^(a)				
		1	2	3	4	5
^{60}Co ^(b)	mrad	1.4	0.07	0.03	0.05	0.05
^{137}Cs	mR	2.0	2.0	2.0	2.0	2.0
Sigma Pile	mrem	1.2	1.2	150.0	70.0	1.0
PuF_4	mrem	0.4	0.4	3.5	2.5	0.4
^{252}Cf	mrem	0.2	0.3	6.3	4.0	0.3

(a) Chip data collected on Hanford Reader 2. Tabled data are in terms of reader counts per mrad, mR, or mrem of radiation delivered.

(b) Using 4000 mrad uranium disk irradiation as equivalent to 2000 mrad of strontium-90. Also, there is a geometry dependence involved in the chip responses in that the uranium disk is centered on the chip 1 position. The disk diameter is about one inch.

The existing dose algorithms use information from certain TLD chips to calculate the type of radiation and dose received by the dosimeter. This is shown as follows:

<u>Dose</u>	<u>Chips Used</u>
Nonpenetrating	1 and 2
Penetrating	2
Thermal Neutron	3 and 4
Fast Neutron	3, 4, and 2(5)

Chip 5 would be used in place of chip 2 in calculating a fast neutron dose for a 5-chip dosimeter. Calculation of the radiation dose is done using the computer code shown in Table 5.2 where C_i ($i = 1, 7$) and R_i ($i = 1, 4$ or 5) refer to the calibration coefficients and chip output, respectively, discussed in Study 1. There are criteria included in the code which must be satisfied before a dose is calculated. All negative doses are zeroed. All calculated doses are added to 5 mrem (0.5 centirem) and any non-integer quantity is truncated.

ALTERNATE ALGORITHMS

The most likely means of improving the existing algorithms is to include a statistical basis for the precalculation criteria, and to utilize the information from all of the chips for each radiation type. Three alternate algorithms were developed. All three alternatives involve solving simultaneous equations which describe the expected response of each chip for the four categories of calibration exposures (^{90}Sr , ^{137}Cs , Sigma Pile, PuF_4). Two alternatives, the Least Squares Fit (LSF) and a hybrid involving the existing Hanford algorithms and the LSF, use similar techniques on the same set of equations. The other alternative is a Gauss-Seidel solution of another system of equations. Computer code listings for each of these alternatives are included in Appendices B through D.

Gauss-Seidel

One methodology of upgrading the dose algorithms is to establish a set of simultaneous equations using the calibration data. This approach is based on the additive property of the thermoluminescent signal from different radiation types and irradiations.

TABLE 5.2. Computer Code Used to Calculate Doses (centirads)

```

900      If R2 < 0, then P = 0; go to 1000
          P = R2*C1
          P = P - (Y1*0.18)
          If P < 0, then P = 0; go to 1000
          P = INT (P + 0.5)

1000     If R1 < 0, then NP = 0; go to 1100
          NP = (R1*C2) - (R2*C3)
          NP = INT (NP + 0.5)
          If NP <= 0, then NP = 0

1100     If R4 < 0, then FN = 0; go to 1200
          If R3 <= 0, then FN = 0; go to 1200
          If (R4 - R2) < 0, then FN = 0; go to 1200
          If (R3 - R4) < 20, then FN = 0; go to 1200
          FN = (R4*C5) - (R2*C6) - ((R3 - R4)*C7)(a)
          FN = INT (FN + 0.5)
          If FN <= 0, then FN = 0

1200     SN = (R3 - R4)*C4
          SN = INT (SN + 0.5)
          If SN <= 0, then SN = 0

```

(a) For a 5-chip dosimeter, R5 would replace R2 in second parenthesis.

For a 4-Chip Dosimeter

A system of four equations is constructed from the results of the calibration irradiations to beta, gamma, slow neutron, and fast neutron sources as follows:

$$\begin{aligned}
 Y(1) &= B(1) \cdot X_1 + G(1) \cdot X_2 + SN(1) \cdot X_3 + FN(1) \cdot X_4 \\
 Y(2) &= B(2) \cdot X_1 + G(2) \cdot X_2 + SN(2) \cdot X_3 + FN(2) \cdot X_4 \\
 Y(3) &= B(3) \cdot X_1 + G(3) \cdot X_2 + SN(3) \cdot X_3 + FN(3) \cdot X_4 \\
 Y(4) &= B(4) \cdot X_1 + G(4) \cdot X_2 + SN(4) \cdot X_3 + FN(4) \cdot X_4
 \end{aligned}$$

where $Y(i)$, $i = 1, 4$ refers to the chip response for chips 1, 2, 3, and 4.

$B(i)$, $i = 1, 4$ refers to the net chip response, i.e., minus respective chip background) in nanocoulombs per millirad from the beta calibration exposure for chips 1, 2, 3, and 4.

$G(i)$, $i = 1, 4$ refers to the net chip response in nanocoulombs per millirem from the gamma calibration exposure for chips 1, 2, 3, and 4.

$SN(i)$, $i = 1, 4$ refers to the net chip response in nanocoulombs per millirem from the thermal neutron calibration exposure for chips 1, 2, 3, and 4.

$FN(i)$, $i = 1, 4$ refers to the net chip response in nanocoulombs per millirem from the fast neutron calibration exposure for chips 1, 2, 3, and 4.

X_1 , Beta dose received in millirad

X_2 , Gamma dose received in millirem

X_3 , Thermal neutron dose received in millirem

X_4 , Fast neutron dose received in millirem.

An example of the application of this method is shown in Appendix A.

Least Squares Fit

The Least Squares Fit (LSF) method determines the most probable value by minimizing the deviation between an expected value and the observed thermoluminescent signal for each chip. The discrepancies between expected values of R_1 through R_4 or R_5 and the actual values are to be minimized. The expected values are a function of the four calculated dose categories.

There are two techniques for handling negative doses. The multiple iteration technique sets the negative doses to zero one at a time, and recalculates the remaining doses until no negative doses are calculated. The single iteration technique sets the negative doses equal to zero but does not recalculate the positive doses.

A detailed discussion of the LSF method is included in Appendix B of Study 6 (Section 7.0).

Hanford/Least Square Fit Hybrid Method

Another methodology for upgrading the current algorithm is the creation of a "hybrid" system. This system uses one technique for calculating non-penetrating and penetrating dose, another technique for neutron dose calculation, and pre-calculation dose type check criteria.

Pre-Calculation Criteria

Often dosimeters are not exposed to neutrons of any kind, making neutron calculations superfluous. A method was derived which could be used to determine if any neutron dose was received. This method compares the expected differences between TLD-600's and TLD-700's due only to gamma and beta radiation with the actual difference observed. If the difference is greater than expected, then neutrons are assumed to be present and a neutron dose is calculated. Otherwise it is assumed that there were no neutrons present.

For the 5-chip dosimeter, the method involves determining a coefficient, G3, which has a numerator that characterizes the amount of neutron response (i.e., G3 is positive if neutrons are present and close to zero if not). The numerator is:

$$0.67*M4*R3 + 0.33*M5*R4 - R5$$

where 0.67, 0.33 = weighted average of chips 3 and 4

M4 = factor to convert the gamma response of R3 to the
gamma response of R5

M5 = factor to convert the gamma response of R4 to the
gamma response of R5

R3 = chip 3 reading

R4 = chip 4 reading

R5 = chip 5 reading.

The weighting factors for R3 and R4 were chosen to be 0.67 and 0.33, respectively, because R3 is a more sensitive indicator of neutron exposure. The denominator for G3 is the expected standard deviation of the numerator due to gamma and beta radiation. It is based on the system variability, the conversion factors listed above, and the weighted averages listed above. The specific information used for the variabilities in the denominator is included in Study 8, Assumption 2 on page 10.31 and Table 10.4, of the Hanford Personnel Dosimeter Supporting Studies FY-1980 (PNL-3536).

The denominator is:

$$\text{SQRT}[(S1 \cdot R5)^2 + (S2 \cdot M4)^2 + (S3 \cdot M5)^2 + S4^2]$$

where S_i , $i = 1, 6$ are factors used to account for system variability (these factors are derived from the coefficients of variability for positional reader counts and control TLD output listed in Table 10.4 of PNL-3536).

The final result for G3 is a neutron index that is directly proportional to the neutron dose received.

$$G3 = \frac{0.67 \cdot M4 \cdot R3 + 0.33 \cdot M5 \cdot R4 - R5}{\text{SQRT}[(S1 \cdot R5)^2 + (S2 \cdot M4)^2 + (S3 \cdot M5)^2 + S4^2]}$$

To calculate neutrons, G3 must be greater than 2.0. This value is chosen so that only 1-in-40 dosimeters exposed to only beta-gamma radiation would have a neutron dose calculated; and also, most, if not all, significant neutron exposures would be calculated.

For the 4-chip dosimeter, the decision to calculate neutrons is complicated by the fact that R2 responds more to beta radiation than do R3 and R4. As a result before a neutron decision can be made, a decision must be made as to whether or not beta radiation is present.

The beta decision was based on a beta index $R1 - M1 \cdot R2$ divided by its standard deviation. This quotient is called "G1" and is:

$$G1 = \frac{R1 - M1 \cdot R2}{\text{SQRT}[(S5 \cdot M1 \cdot R2)^2 + S6^2 + (S4 \cdot M1)^2]}$$

where $M1$ = the factor used to convert the gamma response of R2 to the gamma response of R1.

G1 must be greater than 1.65 for a positive beta radiation. If G1 is less than 1.65, the neutron test is done; otherwise all radiation types are calculated. Regardless of G1's value, non-penetrating dose is always calculated.

The neutron test for the 4-chip dosimeter without significant beta radiation is identical to the 5 chip check, except R2 is substituted for R5 and there are corresponding conversion factors, as follows:

$$G3 = \frac{0.67*M2*R3 + 0.33*M3*R4 - R2}{\text{SQRT}[(S1*R2)^2 + (S2*M2)^2 + (S3*M3)^2 + S4^2]}$$

where M2 = the factor used to convert the gamma response of R3
to the gamma response of R2
 M3 = the factor used to convert the gamma response of R4
to the gamma response of R2.

Dose Calculation

The calculation decisions are shown graphically in Figure 5.1 for a 5-chip dosimeter and in Figure 5.2 for a 4-chip dosimeter.

- Five-Chip Dosimeter

If G3 is less than 2.0, non-penetrating and penetrating doses are calculated by the current Hanford equations and the neutron doses equal zero. If G3 is greater than 2.0, non-penetrating and penetrating are still calculated by the current Hanford equations and the neutron doses are calculated by the Least Squares Fit technique (see Thorson, Study 6).

- Four-Chip Dosimeter

Beta radiation is checked for first. If G1 is less than 1.65, the dosimeter has not seen substantial beta radiation and goes on to check for neutrons. If G1 is greater than 1.65, non-penetrating and penetrating doses are calculated by the current Hanford equations and the neutrons doses by LSF.

G3 is calculated if no beta is present. If G3 is less than 2.0, then no neutrons are present (FAST=0, SLOW=0) and non-penetrating and penetrating doses are calculated by the current Hanford equations. If G3 is greater than 2.0, neutron dose is calculated by LSF and the current Hanford equations are used to determine penetrating and non-penetrating dose.

FIGURE 5.1. Decision Flow Diagram for 5-Chip Dosimeter Dose Calculation

FIGURE 5.2. Decision Flow Diagram for 4-Chip Dosimeter Dose Calculation

COMPARISON OF METHODS

A comparison of the four methods of dose calculation for the mean dose calculated and the standard deviation of the mean is presented in Table 5.3. Using percent standard deviation, improvement can be seen in the fast neutron calculation with the LSF and hybrid. This is the only place where decreased variability can be seen. The data in Table 5.3 are summarized in Tables 5.4 through 5.7. From these tables, another important feature of the LSF and hybrid methods becomes apparent. The false calculation of fast neutron doses is greatly decreased. For example, the current Hanford method and the Gauss-Seidel Method calculated a maximum false fast neutron dose of 290 mrem and 279 mrem, respectively. Whereas, the LSF and hybrid methods had maximum false fast neutron doses of 21 mrem.

The present Hanford algorithm rounds to the nearest 10 mrem. This is noticeable on the 50 mrem slow neutron exposure. Without this "rounding" process there might be some variability.

Note, too, that all of these calculations use 4-chips worth of data and not 5. It is felt that the LSF would provide a greater improvement for the 5-chip dosimeter (see Thorson, Study 6). No 5 chip data is used in this task because most of the data used was actual Hanford routine data. Minimal fifth chip data from routine processing was available at the time of this study.

Proper Calibration

An attempt was made to "prove" the superiority of the hybrid system over the present Hanford equations. The hybrid system should calculate neutron doses better. A small set of ^{252}Cf exposures, 300 and 800 mrem, was used in the dose calculation comparison. Both single and multiple iteration results were included for the hybrid results. Recall that the first iteration is the most probable solution but that negative doses are zeroed and the other doses are not recalculated.

TABLE 5.3. Calibration Dose Calculation Comparison

Dose/Type	Hanford Equation		Gauss-Seidel		LSF		Hybrid	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1000 mrem PuF ₄ (fast neutron)	998	140 (14%)	1001	138 (14%)	926	85 (9%)	926	85 (9%)
2000 mrad Sr equivalent	1903	97 (5%)	1877	97 (5%)	1835	152 (8%)	1897	98 (5%)
1000 mrem ¹³⁷ Cf gamma	972	43 (4%)	968	56 (6%)	958	39 (4%)	950	43 (5%)
50 mrem slow neutron (graphite moder- ated sigma pile)	50	0(a) (0%)	50	4 (8%)	48	4 (8%)	48	4 (8%)

(a) The Hanford equation values are rounded to the nearest 10th. For the data analyzed, all the values are the same. Therefore, there is no variance.

Table 5.8 shows the results. Using the same 5-chip calibration data for each system, they perform approximately the same. The mean difference between doses calculated for 300 and 800 mrem exposures is less than 1% and approximately 8%, respectively.

This comparison is made to show that if carefully calibrated the present Hanford equations will give results as good as the hybrid system alternative. This is not to say that the calculation by either system is exceptionally accurate. The average dose calculation for 300 mrem exposures using both systems is approximately 300 mrem but with a standard deviation of 30%. The standard deviation observed at 800 mrem was about 20%.

REFERENCES

1. Carnahan, B., et al. 1969. "Applied Numerical Methods." John Wiley and Sons, New York.

TABLE 5.4. Present Hanford Method

Chip Readings				Calculated Dose ^(a)			
R1	R2	R3	R4	NonPen	Pen	Fast	Slow
413	472	3574	2566	10	200	900	10
407	465	3801	2600	10	190	840	10
392	521	3579	2843	0	220	1170	10
331	414	3357	2543	0	170	1010	10
420	469	3633	2828	20	200	1160	10
421	451	3150	2385	30	190	910	10
2308	118	117	158	1780	40	0	0
2523	113	77	95	1960	40	0	0
2445	128	122	179	1890	50	0	0
2379	119	137	149	1840	40	0	0
2684	161	224	200	2060	60	20	0
2441	171	79	107	1890	40	0	0
2111	2292	2497	2041	160	1000	0	10
1882	2390	2596	2114	0	1040	0	10
1824	2215	2536	1949	0	960	0	10
1927	2234	2418	2133	50	970	0	0
1758	2117	2469	2162	0	920	0	0
1836	2162	2357	1819	20	940	0	0
48	76	7425	3398	0	20	290	50
57	42	6618	2732	10	10	0	50
57	77	7608	3065	0	20	0	50
49	55	7713	3272	0	10	40	50
72	48	7711	3296	20	10	70	50
58	56	7224	2854	0	10	0	50

(a) Doses are reported to the nearest ten.
Units NONPEN [=] mrad
PEN, FAST, SLOW [=] mrem

TABLE 5.5. Gauss-Seidel Method

Chip Readings				Calculated Dose ^(a)			
R1	R2	R3	R4	NonPen	Pen	Fast	Slow
413	472	3574	2566	8	20	908	2
407	465	3801	2600	8	29	848	5
392	521	3579	2843	0	0	1174	0
331	414	3357	2543	0	0	1005	0
420	469	3633	2828	16	0	1158	0
421	451	3150	2385	29	11	912	0
2308	118	117	158	1764	0	37	0
2523	113	77	95	1940	0	0	0
2445	128	122	179	1867	0	51	0
2379	119	137	149	1820	0	18	0
2684	161	224	200	2036	0	443	0
2441	171	79	107	1835	0	363	0
2111	2292	2497	2041	152	990	32	0
1882	2390	2596	2114	0	1051	0	1
1824	2215	2536	1949	0	982	0	3
1927	2234	2418	2133	43	942	167	0
1758	2117	2469	2162	0	882	216	0
1836	2162	2357	1819	19	962	0	2
48	76	7425	3398	0	0	279	45
57	42	6618	2732	12	3	0	46
57	77	7608	3065	0	37	0	55
49	55	7713	3272	0	0	35	52
72	48	7711	3296	19	0	68	51
58	56	7224	2854	3	35	0	53

(a) Doses calculated as negative are reported as zero. Doses are rounded to the nearest whole number.

Units NONPEN [=] mrad

PEN,FAST,SLOW [=] mrem

TABLE 5.6. Least Squares Fit Method

Chip Readings				Calculated Dose ^(a)			
R1	R2	R3	R4	NonPen	Pen	Fast	Slow
413	472	3574	2566	8	20	908	2
407	465	3801	2600	8	28	848	5
392	521	3579	2843	0	0	1046	0
331	414	3357	2543	0	0	849	3
420	469	3633	2828	13	0	1015	1
421	451	3150	2385	29	15	890	0
2308	118	117	158	1788	0	7	0
2523	113	77	95	1604	0	0	0
2445	128	122	179	1929	0	8	0
2379	119	137	149	1824	0	4	0
2684	161	224	200	2058	13	0	1
2441	171	79	107	1807	0	0	0
2111	2292	2497	2041	0	996	154	0
1882	2390	2596	2114	0	1000	28	0
1824	2215	2536	1949	0	953	0	1
1927	2234	2418	2133	42	970	23	0
1758	2117	2469	2162	0	901	88	0
1836	2162	2357	1819	40	927	0	0
48	76	7425	3398	0	0	21	52
57	42	6618	2732	3	0	0	41
57	77	7608	3065	0	6	0	50
49	55	7713	3272	0	0	0	50
72	48	7711	3296	11	0	0	48
58	56	7224	2854	2	0	0	47

(a) Doses calculated as negative are reported as zero. Doses are rounded to the nearest whole number.

Units NONPEN [=] mrad

PEN,FAST,SLOW [=] mrem

TABLE 5.7. Hanford/Least Squares Hybrid Method

Chip Readings				Calculated Dose ^(a)			
R1	R2	R3	R4	NonPen	Pen	Fast	Slow
413	472	3574	2566	10	174	908	2
407	465	3801	2600	10	170	848	5
392	521	3572	2843	0	195	1046	0
331	414	3357	2543	0	148	849	3
420	469	3633	2828	17	172	1015	1
421	451	3150	2385	30	164	890	0
2308	118	117	158	1783	18	7	0
2523	113	77	95	1960	15	0	0
2445	128	122	179	1887	22	8	0
2379	119	137	149	1839	18	4	0
2684	161	224	200	2058	37	0	1
2441	171	79	107	1854	41	0	0
2111	2292	2497	2041	154	975	0	0
1882	2390	2596	2114	0	1018	0	0
1824	2215	2536	1949	0	941	0	0
1927	2234	2418	2133	44	950	0	0
1758	2117	2469	2162	0	898	0	0
1836	2162	2357	1819	19	918	0	0
48	76	7425	3398	0	0	21	52
57	42	6618	2732	12	0	0	41
57	77	7608	3065	0	0	0	50
49	55	7713	3272	0	0	0	50
72	48	7711	3296	20	0	0	48
58	56	7224	2854	4	0	0	47

(a) Doses calculated as negative are reported as zero. Doses are rounded to the nearest whole number.

Units NONPEN [=] mrad

PEN,FAST,SLOW [=] mrem

TABLE 5.8. Neutron Dose Calculation

<u>Delivered Dose (mrem)</u>	<u>Hanford Equation</u>	<u>Hybrid</u>	
		<u>Multiple Iterations</u>	<u>Single Iteration</u>
300	400	286	407
300	267	115	266
300	390	206	400
300	176	182	182
300	178	183	183
300	345	183	325
300	267	155	294
300	266	152	266
300	232	140	218
300	<u>471</u>	<u>305</u>	<u>427</u>
mean	299	191	297
s.d.	99	61	91
800	867	663	892
800	852	677	998
800	797	424	835
800	767	521	804
800	<u>452</u>	<u>512</u>	<u>512</u>
mean	747	559	808
s.d.	170	108	181

APPENDIX A

EXAMPLE OF GAUSS-SEIDEL METHOD

APPENDIX A

EXAMPLE OF GAUSS-SEIDEL METHOD

Background Mean Dosimeter Readings

$$\text{Chip 1} = 19$$

$$\text{Chip 2} = 16$$

$$\text{Chip 3} = 22$$

$$\text{Chip 4} = 19$$

Beta Irradiation Coefficients (2000 mrad)

$$B(1) = (2735 - 19)/2000 = 1.36$$

$$B(2) = (128 - 16)/2000 = 0.056$$

$$B(3) = (76 - 22)/2000 = 0.027$$

$$B(4) = (103 - 19)/2000 = 0.042$$

Gamma Irradiation Coefficients (1000 mrem)

$$G(1) = (1937 - 19)/1000 = 1.918$$

$$G(2) = (2321 - 16)/1000 = 2.305$$

$$G(3) = (2481 - 22)/1000 = 2.459$$

$$G(4) = (2031 - 19)/1000 = 2.012$$

Thermal Neutron Irradiation Coefficients (50 mrem)

$$SN(1) = (46 - 19)/50 = 0.54$$

$$SN(2) = (51 - 16)/50 = 0.7$$

$$SN(3) = (8750 - 22)/50 = 174.56$$

$$SN(4) = (3810 - 19)/50 = 75.82$$

Fast neutron Irradiation Coefficients (1000 mrem)

$$FN(1) = (406 - 19)/1000 = 0.387$$

$$FN(2) = (486 - 16)/1000 = 0.470$$

$$FN(3) = (3752 - 22)/1000 = 3.730$$

$$FN(4) = (3037 - 19)/1000 = 3.018$$

The following simultaneous equations result from the foregoing:

$$Y(1) = 1.36 X_1 + 1.918 X_2 + 0.54 X_3 + 0.387 X_4$$

$$Y(2) = 0.956 X_1 + 2.305 X_2 + 0.7 X_3 + 0.47 X_4$$

$$Y(3) = 0.027 X_1 + 2.459 X_2 + 174.56 X_3 + 3.73 X_4$$

$$Y(4) = 0.042 X_1 + 2.012 X_2 + 75.82 X_3 + 3.019 X_4$$

APPENDIX B

HANFORD/LEAST-SQUARES HYBRID COMPUTER CODE LISTING

```

LNP!
1:      CHARACTER TYPE*6(4)
2:      CHARACTER ETX*1/0003/
3:      DIMENSION X(5,4),E(4,5),S(5),R(5)
4:      DIMENSION GA(5),BKG(5)
5:      DIMENSION CD(4),IK(4)
6:      REAL K2,K5,K6,K7,NONP,M1,M2,M3,M4,M5
7:      DATA TYPE/'GAMMA ','FN      ','BETA ','THN      '/
8:C
9:1      WRITE(6,900)ETX
10:     READ(5,*)ID
11:     IF(ID.EQ.5)GO TO 25
12:     DO 15 I=1,4
13:     WRITE(6,917)TYPE(I)
14:     READ(5,*)X(1,I),X(2,I),X(3,I),X(4,I)
15:     WRITE(6,931)TYPE(I),ETX
16:     READ(5,*)CD(I)
17:15    CONTINUE
18:     GO TO 37
19:25    DO 35 I=1,4
20:     WRITE(6,929)TYPE(I)
21:929    FORMAT(1H0,'ENTER THE AVERAGE R1,R2,R3,R4,R5 FOR ',A6,
22:    + 'CALIBRATION')
23:     READ(5,*)X(1,I),X(2,I),X(3,I),X(4,I),X(5,I)
24:     WRITE(6,931)TYPE(I),ETX
25:931    FORMAT(1H0,'ENTER ',A6,'DELIVERED DOSE IN MREM',A1)
26:     READ(5,*)CD(I)
27:35    CONTINUE
28:37    WRITE(6,906)
29:     READ(5,*)(BKG(I),I=1,ID)
30:     WRITE(6,938)ETX
31:     READ(5,*)Y
32:938    FORMAT(1H0,1X,'INPUT Y, AS IN PEN=R(2)*C1-Y*0.18.',
33:    +/,1X,'USE 75 FOR MONTHLY AND 135 FOR QUARTERLY.',A1)
34:     WRITE(6,939)
35:939    FORMAT(1H0,1X,'INPUT CALIBRATION ADJUSTMENT FACTORS. ',
36:    + 'IF NONE ARE USED ENTER SEVEN 1.0')
37:     READ(5,*)AC1,AC2,AC3,AC4,AC5,AC6,AC7
38:     WRITE(6,39)

```

```

39:39      FORMAT(1H0,1X,'THE CALIBRATION SET IS:')
40:      DO 40 I=1,4
41:      WRITE(6,41)(X(I,J),J=1,4)
42:41      FORMAT(1H0,1X,4F7.0)
43:40      CONTINUE
44:C
45:C      .....SUBTRACT BACKGROUND.....
46:      DO 46 J=1,ID
47:      DO 45 K=1,4
48:      X(J,K)=X(J,K)-BKG(J)
49:45      CONTINUE
50:46      CONTINUE
51:      WRITE(6,909)
52:909      FORMAT(1H0,1X,'THE CALIBRATION SET MINUS BACKGROUND'
53:      + ' IS:')
54:      DO 48 I=1,4
55:      WRITE(6,41)(X(I,J),J=1,4)
56:48      CONTINUE
57:C
58:C      .....FAST NEUTRON CALIBRATION REDUCTION OPTION.....
59:      WRITE(6,903)ETX
60:      READ(5,*)FNR
61:      IF(FNR.EQ.0)GO TO 200
62:100      RAT1=(X(3,2)+X(4,2))/(503.4+308.6)
63:      DAVE=RAT1*2.63
64:      RAT2=(2.0*DAVE-X(2,2)-X(1,2))/(-1.0*(X(1,1)+X(2,1)))
65:      DO 110 K=1,ID
66:      GA(K)=X(K,1)*RAT2
67:110      CONTINUE
68:      DO 120 J=3,4
69:      X(J,2)=X(J,2)-GA(J)
70:120      CONTINUE
71:      X(1,2)=20.0
72:      X(2,2)=20.0
73:      IF(ID.EQ.5)GO TO 125
74:      WRITE(6,904)(X(J,2),J=1,4)
75:      GO TO 126
76:125      WRITE(6,905)(X(J,2),J=1,5)
77:126      CONTINUE

```



```

78:C
79:C      .....CALCULATE CALIBRATION CONSTANTS.....
80:200    IF(ID.EQ.4)GO TO 210
81:      K6=X(4,1)/X(5,1)
82:      K5=(X(4,4)-K6*X(5,4))/(X(3,4)-X(4,4))
83:      K7=(X(4,2)-K6*X(5,2)-K5*(X(3,2)-X(4,2)))/CD(2)
84:      GO TO 220
85:210    K6=X(4,1)/X(2,1)
86:      K5=(X(4,4)-K6*X(2,4))/(X(3,4)-X(4,4))
87:      K7=(X(4,2)-K6*X(2,2)-K5*(X(3,2)-X(4,2)))/CD(2)
88:220    K2=X(1,1)/X(2,1)
89:      C1=(CD(1)/X(2,1))*AC1
90:      C2=(CD(3)/(X(1,3)-K2*X(2,3)))*AC2
91:      C3=(C2*K2)*AC3
92:      C4=(CD(4)/(X(3,4)-X(4,4)))*AC4
93:      C5=(1.0/K7)*AC5
94:      C6=(K6*C5)*AC6
95:      C7=(K5*C5)*AC7
96:      M1=K2
97:      M2=X(2,1)/X(3,1)
98:      M3=X(2,1)/X(4,1)
99:      M4=X(5,1)/X(3,1)
100:     M5=X(5,1)/X(4,1)
101:     WRITE(6,945)C1,C2,C3,C4,C5,C6,C7
102:C
103:C      .....READ CHIP DATA.....
104:300    WRITE(6,901)ETX
105:     READ(5,*)(R(J),J=1,ID)
106:     DO 310 J=1,ID
107:     R(J)=R(J)-BKG(J)
108:310    CONTINUE
109:     G1=0.0
110:     G3=0.0
111:C
112:C      .....DETERMINATION OF 4 OR 5 CHIP DOSIMETER.....
113:     IF(ID.EQ.5)GO TO 500
114:C
115:C      .....BETA CRITERION FOR 4 CHIP.....
116:400    G1=(R(1)-M1*R(2))/SQRT((0.1005*M1*R(2))**2.+9.44**2.+4.85

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117:      +**2.)
118:      IF(G1,GE.1.645)GO TO 600
119:C
120:C      .....NEUTRON CRITERION FOR 4 CHIP (NO BETA).....
121:      G3=((2.*M2*R(3)+M3*R(4))/3.-R(2))/
122:      +SQRT((0.1136*R(2))**2.+(4.367*M2)**2.+(2.027*M3)
123:      +**2.+4.85**2.)
124:      IF(G3,GE.2.0)GO TO 600
125:      GO TO 700
126:C
127:C      .....NEUTRON CRITERION FOR 5 CHIP.....
128:500      G3=((2.0*M4*R(3)+M5*R(4))/3.-R(5))/
129:      +SQRT((0.1136*R(5))**2.+(4.367*M4)**2.+(2.027*M5)
130:      +**2.+4.85**2.)
131:      IF(G3,GE.2.0)GO TO 600
132:      GO TO 700
133:C
134:C      .....HANFORD-LEAST SQUARES HYBRID.....
135:600      PEN=R(2)*C1-Y*0.18
136:      NONP=(R(1)*C2)-(R(2)*C3)
137:C
138:C      STANDARD DEVIATIONS
139:C
140:      JKL=0
141:      S(1)=SQRT((.0716*R(1))**2.+9.44**2.)
142:      S(2)=SQRT((.0794*R(2))**2.+4.85**2.)
143:      S(5)=SQRT((.0845*R(5))**2.+4.85**2.)
144:      S(3)=SQRT((.1084*R(3))**2.+6.55**2.)
145:      S(4)=SQRT((.1084*R(4))**2.+6.08**2.)
146:C
147:C      MATRIX SOLVING
148:C
149:610      DO 630 I=1,4
150:      E(I,5)=0.
151:      DO 620 K=1,4
152:      E(I,K)=0.
153:      DO 615 J=1,ID
154:      E(I,K)=E(I,K)+X(J,K)*X(J,I)/S(J)**2.
155:615      CONTINUE

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```
156:620      CONTINUE
157:         DO 625 J=1,ID
158:         E(I,5)=E(I,5)+R(J)*X(J,I)/S(J)**2.
159:625      CONTINUE
160:630      CONTINUE
161:         IF(JKL.EQ.0)GO TO 631
162:         GO TO 634
163:631      DO 633 I=1,4
164:         WRITE(6,632)(E(I,J),J=1,5)
165:632      FORMAT(1H0,1X,5F14.5)
166:633      CONTINUE
167:C
168:634      IF(JKL.EQ.0)GO TO 645
169:C
170:         DO 640 J=1,JKL
171:         IJ=IK(J)
172:         DO 635 I=1,4
173:         E(I,IJ)=0.
174:         E(IJ,I)=0.
175:635      CONTINUE
176:         E(IJ,5)=0.
177:         E(IJ,IJ)=1.
178:640      CONTINUE
179:C
180:645      DO 665 N=1,4
181:         A=E(N,N)
182:         DO 650 M=1,5
183:         E(N,M)=E(N,M)/A
184:650      CONTINUE
185:C
186:         DO 660 L=1,4
187:         IF(L.EQ.N) GO TO 660
188:         C=E(L,N)
189:         DO 655 K=1,5
190:         E(L,K)=E(L,K)-C*E(N,K)
191:655      CONTINUE
192:660      CONTINUE
193:665      CONTINUE
194:C
```

```

195:      DO 675 I=1,4
196:      WRITE (6,670) (E(I,J),J=1,5)
197:670    FORMAT(1H0,1X,5F10.5)
198:675    CONTINUE
199:C
200:      IF(AMIN1(E(1,5),E(2,5),E(3,5),E(4,5))
201:      +.GT. -.0001) GO TO 682
202:      JKL=JKL+1
203:      IJ=1
204:C
205:      DO 680 I=2,4
206:      IF(E(I,5)*CD(I).LT.E(IJ,5)*CD(IJ)) IJ=I
207:680    CONTINUE
208:      IK(JKL)=IJ
209:      GO TO 610
210:C
211:682    FAST=E(2,5)*CD(2)
212:      SLOW=E(4,5)*CD(4)
213:      WRITE(6,915)(R(I),I=1,ID)
214:      IF(G1.NE.0.0.AND.G3.NE.0.0)GO TO 685
215:      IF(ID.EQ.5)GO TO 690
216:      WRITE(6,924)G1
217:      GO TO 695
218:685    WRITE(6,921)G1,G3.
219:      GO TO 695
220:690    WRITE(6,916)G3
221:695    WRITE(6,922)NONF,PEN,FAST,SLOW
222:      GO TO 800
223:C
224:C      .....NO NEUTRON CALCULATION.....
225:700    PEN=R(2)*C1-Y*0.18
226:      NONF=(R(1)*C2)-(R(2)*C3)
227:      FAST=0.0
228:      SLOW=0.0
229:      IF(ID.EQ.4)GO TO 725
230:      WRITE(6,915)(R(I),I=1,ID)
231:      WRITE(6,916)G3
232:      WRITE(6,922)NONF,PEN,FAST,SLOW
233:      GO TO 800

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234:725      WRITE(6,920)(R(I),I=1,10)
235:          WRITE(6,921)G1,G3
236:          WRITE(6,922)NONP,PEN,FAST,SLOW
237:          CONTINUE
238:C
239:C          .....REQUESTING ANOTHER DATA SET.....
240:800      WRITE(6,930)ETX
241:          READ(5,*)A
242:          IF(A.EQ.0)GO TO 950
243:          WRITE(6,935)ETX
244:          READ(5,*)ANS
245:          IF(ANS.EQ.1)GO TO 300
246:          GO TO 1
247:C
248:C          .....FORMAT STATEMENTS.....
249:900      FORMAT(1H0,1X,'IS THE DOSIMETER 4 OR 5 CHIP?',A1)
250:901      FORMAT(1H0,1X,'ENTER CHIP READINGS.',A1)
251:903      FORMAT(1H0,1X,'DO YOU WANT THE FAST NEUTRON CALIBRATION
252:          +,' GAMMA REDUCED? 1=Y,0=N',A1)
253:904      FORMAT(1H0,1X,'THIS IS THE GAMMA REDUCED FAST NEUTRON ',
254:          +,'CALIBRATION',/,4F8.1)
255:905      FORMAT(1H0,1X,'THIS IS THE GAMMA REDUCED FAST NEUTRON ',
256:          +,'CALIBRATION',/,5F8.1)
257:906      FORMAT(1H0,1X,'INPUT THE AVERAGE FOR THE BACKGROUND ',
258:          +,'DOSIMETERS. ')
259:915      FORMAT(1H0,1X,'THE VALUES FOR THE CHIP READINGS MINUS ',
260:          +,' THE BACKGROUND ARE:',/3X,5F7.0)
261:916      FORMAT(1H0,1X,'THE NEUTRON CHECK CRITERION, G3, EQUALS ',
262:          +F6.2)
263:917      FORMAT(1H0,1X,'ENTER THE AVERAGE R1,R2,R3,R4 FOR ',
264:          +A6, 'CALIBRATION')
265:920      FORMAT(1H0,1X,'THE VALUES FOR THE CHIP READINGS MINUS ',/
266:          +,' THE BACKGROUND ARE:',/3X,4F7.0)
267:921      FORMAT(1H0,1X,'THE BETA CHECK CRITERION, G1, EQUALS ',
268:          +F6.2/1H,1X,'THE NEUTRON CHECK CRITERION, G3, EQUALS ',
269:          +F6.2)
270:922      FORMAT(1H0,1X,'THE CALCULATED DOSES ARE AS FOLLOWS:',/
271:          +1X,'NON PENETRATING = ',F7.1,/,1X,'PENETRATING = ',
272:          +F7.1,/,1X,'FAST NEUTRON = ',F7.1,/,1X,'SLOW NEUTRON = ',

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273:      +F7.1)
274:924      FORMAT(1H0,1X,'THE BETA CHECK CRITERION FOR A 4 ',
275:      + 'CHIP DOSIMETER, G1, EQUALS',F6.2)
276:930      FORMAT(1H0,1X,'DO YOU WANT TO CALCULATE THE DOSES RECEIVED ',
277:      + 'FOR ANOTHER DOSIMETER? 1=Y,0=N',A1)
278:935      FORMAT(1H0,1X,'DO YOU WANT THE SAME CALIBRATION SET? 1=Y',
279:      + '0=N',A1)
280:945      FORMAT(1H0,1X,'THE CALIBRATION CONSTANTS, '
281:      +,'C1 THRU C7, ARE',/,7F8.5)
282:950      CONTINUE
283:      STOP
284:      END

```

APPENDIX C

GAUSS-SEIDEL COMPUTER CODE LISTING

@ED,R READER.G-S
 READ-ONLY MODE
 CASE UPPER ASSUMED
 ED 16R1-MON-09/21/81-14:55:39-(27,)
 EDIT
 0:>LNP!

```

1:      DIMENSION A(20,20),X(20),B(20),C(20,20)
2:      INTEGER FLAG,AN,ANS
3:      CHARACTER ETX*1/0003/
4:      CHARACTER CH*3(7)
5:      DATA CH/'1ST','2ND','3RD','4TH','5TH','6TH','7TH'/
6:      DATA ANS/0/
7:C      THIS PROGRAM USES THE GAUSS-SEIDEL METHOD OF
8:C      SOLVING N SIMULTANEOUS EQUATIONS TO DETERMINE
9:C      DOSE RECEIVED BY HANFORD PERSONNEL.
10:C
11:C      THE ARRAY A CONTAINS THE N BY (N+1) AUGMENTED
12:C      COEFFICIENT MATRIX.  THE VECTOR X CONTAINS THE
13:C      LATEST APPROXIMATION TO THE SOLUTION.  THE
14:C      COEFFICIENT MATRIX SHOULD BE  DIAGONALLY DOMINANT
15:C      AND PREFERABLY POSITIVE DEFINITE.  ITMAX IS THE
16:C      MAXIMUM NUMBER OF ITERATIONS ALLOWED.  EPS IS USED
17:C      IN CONVERGENCE TESTING.  IN TERMINATING THE ITERATIONS,
18:C      NO ELEMENT OF X MAY UNDERGO A MAGNITUDE CHANGE
19:C      GREATER THAN EPS FROM ONE ITERATION TO THE NEXT.
20:C
21:C      .....READ INPUT PARAMETERS,COEFFICIENT MATRIX,
22:C      AND STARTING VECTOR - THEN WRITE THEM OUT.....
23:1      WRITE(6,100)ETX
24:      READ(5,*)N,ITMAX,EPS
25:C
26:      NP1=N+1
27:      IF(ANS.EQ.1) GO TO 12
28:C
29:      DO 10 K=1,N
30:      WRITE(6,110)CH(K)
31:      READ (5,*)(A(K,J),J=1,NP1)
32:10     CONTINUE
33:      DO 11 L=1,N
34:      DO 11 M=1,N
  
```



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35:      C(L,M)=A(L,M)
36:11      CONTINUE
37:C
38:      GO TO 15
39:12      WRITE(6,160)
40:      READ(5,*)(B(I),I=1,N)
41:      DO 13 K=1,N
42:      A(K,NP1)=B(K)
43:13      CONTINUE
44:      DO 16 L=1,N
45:      DO 16 M=1,N
46:      A(L,M)=C(L,M)
47:16      CONTINUE
48:C
49:15      WRITE(6,120)
50:      READ(5,*)(X(I),I=1,N)
51:C
52:      WRITE(6,200)N,ITMAX,EPS
53:      DO 2 I =1,N
54:2      WRITE(6,201)(A(I,J),J=1,NP1)
55:      WRITE(6,202)(X(I),I=1,N)
56:C
57:C      .....NORMALIZE DIAGONAL ELEMENTS IN EACH ROW.....
58:      DO 3 I=1,N
59:      ASTAR=A(I,I)
60:      DO 3 J=1,NP1
61:3      A(I,J)=A(I,J)/ASTAR
62:C
63:C      .....BEGIN GAUSS-SEIDEL ITERATIONS.....
64:      DO 9 ITER=1,ITMAX
65:      FLAG=1
66:      DO 7 I=1,N
67:      XSTAR=X(I)
68:      X(I)=A(I,NP1)
69:C
70:C      .....FIND NEW SOLUTION VALUE, X(I).....
71:      DO 5 J=1,N
72:      IF(I.EQ.J)GO TO 5
73:      X(I)=X(I)-A(I,J)*X(J)

```

```

74:5      CONTINUE
75:C
76:C      .....TEST X(I) FOR CONVERGENCE.....
77:      IF (ABS(XSTAR-X(I)).LE.EPS)GO TO 7
78:      FLAG=0
79:7      CONTINUE
80:      IF(FLAG.NE.1)GO TO 9
81:      WRITE(6,203)ITER,(X(I),I=1,N)
82:      WRITE(6,130)ETX
83:      READ(5,*)AN
84:      IF(AN.EQ.0)GO TO 20
85:      WRITE(6,140)ETX
86:      READ(5,*)ANS
87:      GO TO 1
88:9      CONTINUE
89:C
90:C      .....REMARK IF METHOD DID NOT CONVERGE.....
91:      WRITE(6,204)ITER,(X(I),I=1,N)
92:      WRITE(6,130)ETX
93:      READ(5,*)AN
94:      IF(AN.EQ.0)GO TO 20
95:      WRITE(6,140)ETX
96:      READ(5,*)ANS
97:      GO TO 1
98:C
99:C      .....FORMATS FOR INPUT AND OUTPUT STATEMENTS.....
100:100    FORMAT(1H0,1X,'INPUT NUMBER OF EQUATIONS, MAXIMUM NUMBER ',
101:    + 'OF ITERATIONS'/1H,1X,'AND TOLERANCE FOR CONVERGENCE ',
102:    + 'TESTING.',A1)
103:110    FORMAT(1H0,1X,'INPUT ',A3,' LINE OF COEFFICIENT MATRIX')
104:120    FORMAT(1H0,1X,'INPUT THE APPROXIMATION TO THE ',
105:    + 'SOLUTION VECTOR')
106:130    FORMAT(1H0,1X,'READ ANOTHER SET OF DATA? Y=1,N=0',A1)
107:140    FORMAT(1H0,1X,'DO YOU WANT THE SAME MATRIX A(1,1)',
108:    + '...A(N,N)? 1=Y,0=N',A1)
109:160    FORMAT(1H0,1X,'INPUT A(I,N+1),I=1,N')
110:200    FORMAT(1H0,1X,'SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS',
111:    + ' BY GAUSS-SEIDEL METHOD, WITH'/1H0,5X,'N      =',I4/1H,
112:    +5X,'ITMAX  =',I4/1H,5X,'EPS    =',F10.5/1H0,1X,'THE',

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113:      +' COEFFICIENT MATRIX A(1,1)...A(N+1,N+1) IS')
114:201      FORMAT(1H0,7F12,4)
115:202      FORMAT(1H0,1X,'THE STARTING VECTOR X(1),...X(N) IS'/1H0,
116:      +7F12,4)
117:203      FORMAT(1H0,1X,'THE PROCEDURE CONVERGED WITH ITER = ',I4/1H0,
118:      +1X,'THE SOLUTION VECTOR X(1)...X(N) IS '/1H0,7F12,4)
119:204      FORMAT(1H0,1X,'NO CONVERGENCEAT ITER = ',I4/1H0,1X,'THE ',
120:      +'CURRENT VECTOR X(1)...X(N) IS'/1H0,7F12,4)
121:C
122:20      CONTINUE
123:      STOP
124:      END

```

APPENDIX D

LEAST SQUARES FIT COMPUTER CODE LISTING

```

1:      CHARACTER TYPE*6(4)
2:      CHARACTER ETX*1/0003/
3:      DIMENSION X(5,4),E(4,6),S(5),R(5),SE2(4),SE(4),XB(4),SD(4)
4:      DIMENSION SE26(4),SE6(4),XB6(4),SD6(4),CD(4),IK(4)
5:      REAL K2,K5,K6,K7
6:      DATA TYPE/'GAMMA ','FN ','BETA ','THN '/
7:C
8:      DO 350 I=1,4
9:      WRITE(6,300)TYPE(I)
10:300  FORMAT(1H0,'ENTER THE AVERAGE R1,R2,R3,R4,R5 FOR ',A6,
11:      + 'CALIBRATION')
12:      READ(5,*)X(1,I),X(2,I),X(3,I),X(4,I),X(5,I)
13:      WRITE(6,310)TYPE(I),ETX
14:310  FORMAT(1H0,'ENTER ',A6,'DELIVERED DOSE IN MREM',A1)
15:      READ(5,*)CD(I)
16:350  CONTINUE
17:      NN=0
18:C
19:      DO 5 I=1,4
20:      SE2(I)=0.
21:      SE26(I)=0.
22:      SE(I)=0.
23:      SE6(I)=0.
24:5    CONTINUE
25:C
26:      K2=X(1,1)/X(2,1)
27:      K6=X(4,1)/X(5,1)
28:      C1=1./X(2,1)
29:      C2=1./(X(1,3)-K2*X(2,3))
30:      C3=C2*K2
31:      C4=1./(X(3,4)-X(4,4))
32:      K5=(X(4,4)-K6*X(5,4))/(X(3,4)-X(4,4))
33:      K7=(X(4,2)-K6*X(5,2)-K5*(X(3,2)-X(4,2)))
34:      C5=1./K7

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35:          C6=K6*C5
36:          C7=K5*C5
37:1        WRITE(6,2)ETX
38:2        FORMAT(1H0,'ENTER R1,R2,R3,R4,R5',A1)
39:          READ(5,*)R(1),R(2),R(3),R(4),R(5)
40:C
41:C        STANDARD DEVIATIONS
42:C
43:          JKL=0
44:          S(1)=SQRT((.0716*R(1))**2.+9.44**2.)
45:          S(2)=SQRT((.0794*R(2))**2.+4.85**2.)
46:          S(5)=SQRT((.0845*R(5))**2.+4.85**2.)
47:          S(3)=SQRT((.1084*R(3))**2.+6.55**2.)
48:          S(4)=SQRT((.1084*R(4))**2.+6.08**2.)
49:C
50:C        MATRIX SOLVING
51:C
52:4        DO 40 I=1,4
53:          E(I,5)=0.
54:          DO 20 K=1,4
55:            E(I,K)=0.
56:            DO 10 J=1,5
57:              E(I,K)=E(I,K)+X(J,K)*X(J,I)/S(J)**2.
58:10        CONTINUE
59:20        CONTINUE
60:          DO 30 J=1,5
61:            E(I,5)=E(I,5)+R(J)*X(J,I)/S(J)**2.
62:30        CONTINUE
63:40        CONTINUE
64:C
65:          IF(JKL.EQ.0)GO TO 49
66:C
67:          DO 45 J=1,JKL
68:            IJ=IK(J)
69:            DO 44 I=1,4
70:              E(I,IJ)=0.
71:              E(IJ,I)=0.
72:44        CONTINUE
73:          E(IJ,5)=0.

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74:      E(IJ,IJ)=1.
75:45    CONTINUE
76:C
77:49    DO 100 N=1,4
78:      A=E(N,N)
79:      DO 50 M=1,5
80:        E(N,M)=E(N,M)/A
81:50    CONTINUE
82:C
83:      DO 70 L=1,4
84:        IF(L.EQ.N) GO TO 70
85:        C=E(L,N)
86:        DO 60 K=1,5
87:          E(L,K)=E(L,K)-C*E(N,K)
88:60    CONTINUE
89:70    CONTINUE
90:100   CONTINUE
91:C
92:      DO 120 I=1,4
93:        WRITE (6,110) (E(I,J),J=1,5)
94:110    FORMAT(1H0,1X,5F10.5)
95:120   CONTINUE
96:C
97:      IF(AMIN1(E(1,5)*CD(1),E(2,5)*CD(2),E(3,5)*CD(3),E(4,5)*CD(4))
98:      +.GT. -.0001) GO TO 127
99:      JKL=JKL+1
100:     IJ=1
101:C
102:     DO 42 I=2,4
103:       IF(E(1,5)*CD(I).LT.E(IJ,5)*CD(IJ)) IJ=I
104:42    CONTINUE
105:     IK(JKL)=IJ
106:     GO TO 4
107:127   E(3,6)=C2*R(1)-C3*R(2)
108:     E(1,6)=C1*R(2)
109:     E(4,6)=C4*(R(3)-R(4))
110:     E(2,6)=C5*R(4)-C6*R(5)-C7*(R(3)-R(4))
111:C
112:     WRITE(6,121) (R(I),I=1,5)

```

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113:121      FORMAT(1H0,5F8.0)
114:         WRITE(6,123)C5,C6,C7
115:123      FORMAT(1H0,1X,' C5=',F9.6,' C6=',F9.6,' C7=',F9.6)
116:128      WRITE(6,122) (E(I,6),I=1,4)
117:122      FORMAT(1H ,1X,'E(I,6),I=1,4=',4F10.5)
118:         IF(AMIN1(E(1,6),E(2,6),E(3,6),E(4,6)).GT. -.0001) GO TO 124
119:         DO 126 I=1,4
120:         IF(E(I,6).LT. -.0001) E(I,6)=0.
121:126      CONTINUE
122:C
123:         GO TO 128
124:124      NN=NN+1
125:C
126:         DO 125 I=1,4
127:         SE2(I)=SE2(I)+E(I,5)**2.
128:         SE26(I)=SE26(I)+E(I,6)**2.
129:         SE(I)=SE(I)+E(I,5)
130:         SE6(I)=SE6(I)+E(I,6)
131:125      CONTINUE
132:C
133:         WRITE(6,130)ETX
134:130      FORMAT(1H0,'READ ANY MORE DATA? 1=Y,0=N',A1)
135:         READ(5,*)Q
136:         IF (Q.EQ.1) GO TO 1
137:C
138:         WRITE(6,135)
139:135      FORMAT(1H0,2X,'I',4X,'XB(I)',5X,'SD(I)')
140:         DO 150 I=1,4
141:         XB(I)=SE(I)*CD(I)/NN
142:         XB6(I)=SE6(I)*CD(I)/NN
143:         SD(I)=SQRT((SE2(I)-SE(I)**2./NN)/(NN-1))*CD(I)
144:         SD6(I)=SQRT((SE26(I)-SE6(I)**2./NN)/(NN-1))*CD(I)
145:         WRITE(6,140) I,XB(I),SD(I)
146:140      FORMAT (1H0,1X,I2,1X,2F10.5)
147:150      CONTINUE
148:C
149:         DO 160 I=1,4
150:C

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```
151:      WRITE (6,140) I,XB6(I),SD6(I)
152:140   CONTINUE
153:      STOP
154:      END
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6.0 STUDY 5 - ENERGY RESPONSE MEASUREMENTS

K. L. Holbrook, R. C. Yoder,^(a)
J. P. Holland^(b) and C. D. Hooker

FOREWORD

The response of the Hanford dosimeter to high energy capture gamma and nitrogen-16 beams was investigated along with the effect of high energy photon fields on the beta response. The penetrating and nonpenetrating dose response of the dosimeter to light- and medium-filtration x-ray techniques was compared to the delivered deep and shallow dose. Room return in the PNL neutron irradiation facilities was measured and correction factors for scatter were obtained.

SUMMARY

The shallow dose at 7 mg/cm^2 in tissue from high energy photons is overestimated by a factor of two or more using the current Hanford dosimeter and calibration procedures. Differences in buildup between the two neutron positions cause the algorithm to report false positive fast neutron doses. Estimates of the 1 cm depth dose in tissue from capture gammas were 30-40% low when chip 2 (356 mg/cm^2) was used. The use of chip 5 (901 mg/cm^2) provided an extremely good assessment of the maximum depth dose in tissue for capture gammas. Nonpenetrating components tended to be masked by buildup in chip 2, resulting in a large degree of uncertainty in the shallow dose for high energy photon-beta mixtures.

The dosimeter response to a filtered N-16 field was in good agreement with measured 1 cm depth doses. This apparent inconsistency with capture gamma results is attributed to the presence of low energy secondaries from interaction of the beam with the filter. The dosimeter over-responded at all energies to filtered x-ray techniques. Biases for deep and shallow doses ranged from 17% to 75% with the maximum response at an effective x-ray energy of 32 keV.

Neutron room return measurements in the 318 and 3745A buildings using Hanford dosimeters yielded scatter factors of $10\%/m^2$ and $19\%/m^2$, respectively.

(a) Pennsylvania Power and Light.
(b) Texas A&M University.

The response of a tissue equivalent proportional counter to scatter was slightly lower. Dosimeters respond to low energy scattered neutrons more readily than to unscattered fast neutrons. Scatter factors represent the response of the dosimeter to scatter, rather than the actual contribution of scatter to dose equivalent.

INTRODUCTION

High energy photons may be present in nuclear plant containments due to production of nitrogen-16 and accumulation of certain activation products in piping. Photons with energies above 1 MeV may also be present at breeder facilities from sodium-24. It is necessary to measure the energy response of the Hanford dosimeter at high energies to determine the suitability of the dosimeter and current calibration in these areas. Impairment of the dosimeter response to high energy betas in the presence of high energy photons is another area of concern.

Measurements of the response of the Hanford system to filtered x-ray techniques are useful for predicting the dosimeter performance to the criteria specified in BSR N13.11. Alternate calibration techniques were investigated in Section 3.0 for monoenergetic and filtered techniques. Comparison of the dosimeter interpreted nonpenetrating and penetrating doses with delivered shallow and deep dose was done.

The response of the dosimeter to scattered ^{252}Cf neutrons reflected from irradiation facility walls can affect fast neutron calibrations. Correction factors were obtained for the contribution of scattered neutrons as a function of source-to-phantom distance in the PNL irradiation facilities. Without correction factors for room return, calibrations performed at different source-to-phantom distances cannot be related because of the sensitivity of the dosimeter to scattered neutrons.

HIGH ENERGY CAPTURE GAMMAS

Hand-loaded dosimeters mounted on a phantom were irradiated with high energy photon beams generated at the Texas A&M University TRIGA reactor. Neutrons from the core scattered and thermalized in a graphite reflector and were

absorbed in target material. Targets, placed between the reflector and a beam port, were composed of iron, silicon, sulfur, or calcium. In the absence of target material, water in the target area absorbed thermal neutrons to generate hydrogen capture gammas. The beam port, which was not directly in line with the core, was filled with borated paraffin; thus, the capture gamma beam was highly collimated and free from measurable thermal neutron contamination.

Measurements with a tissue equivalent extrapolation chamber provided a profile of absorbed dose as a function of tissue depth for each beam. Absorbed dose in tissue increases with depth until secondary electron equilibrium is approached; as attenuation begins to dominate, absorbed dose slowly decreases. Tissue equivalent material of varying thicknesses was added to the front face of the extrapolation chamber to produce buildup. The resulting curves for absorbed dose versus tissue depth are included in Appendix A.

Gamma spectra for each beam were examined with a GeLi detector. High energy peaks were distinct; however, low energy gammas were not distinguishable from Compton interactions and pair production within the detector. The depth dose curves measured with the extrapolation chamber provide a better assessment of beam quality. The depth of maximum dose in tissue increases with photon energy, and the relative contribution of low energy photons and betas can be inferred from the shape of the curves at shallow depths. A list of tabulated photon energies for capture gamma interactions is included in Table 6.1, along with maximum dose depths measured at Texas A&M with the extrapolation chamber.

Aluminum encapsulation of the target materials and graphite reflector led to significant aluminum capture-gamma contamination in most of the beams. In the iron beam, the target cross section for thermal neutrons is large enough to overshadow the aluminum contribution. However, this is not the case for the hydrogen, sulfur, calcium and silicon targets (Bartholomew 1967). As a result, the maximum depth doses and dosimeter responses are similar for these beams. Data obtained for the beams is useful; however, only limited conclusions concerning energy dependence of the dosimeter can be drawn.

TABLE 6.1. Capture Gamma Irradiations

<u>Target</u>	<u>Principal Photon Energies, ^(a) MeV</u>	<u>Approximate Photon Abundances ^(a) (%)</u>	<u>Measured Depth of Maximum Dose in Tissue (cm) ^(b)</u>
H	2.22	≥97	2.65
Ca	6.41	22	2.85
	4.42	12	
	2.00	13	
	1.94	39	
Fe	7.63	34	3.81
	1.73	11	
	1.61	10	
Si	7.20	10	2.65
	6.38	14	
	4.93	61	
	3.54	64	
	2.09	20	
	1.27	20	
S	5.42	60	2.65
	4.87	11	
	3.22	20	
	2.93	15	
	2.38	34	
	0.84	60	
Al ^(c)	7.72	17	
	1.78	88	

(a) Photon energies and abundances are taken from Bartholomew, et al. 1967.

(b) Measured maximum dose depths were obtained at Texas A M using a tissue equivalent extrapolation chamber.

(c) Aluminum data is included for reference.

Dosimeters were read manually on the PNL special studies reader and chip responses were averaged by position for each energy. Reported photon doses were based on calibrations for ¹³⁷Cs in air, and ⁹⁰Sr in air. The use of on-phantom calibrations would shift the results by approximately 10% (refer to Section 3.0 for the effects of backscatter from a phantom). Dosimeter results were correlated to extrapolation chamber measurements at 0.007 cm (skin depth), 0.94 cm (1 cm deep dose) and the maximum depth dose. When linear

interpolation was used to estimate the assigned depth dose at 1 cm, values differed by less than 2% from the 0.94 cm measurements. Although reactor power was maintained at 1 MW for all runs, the position of the core was not always reproducible. While the photon spectra were not affected, dose rates varied considerably. Ionization chamber readings were used to normalize dose rates for badge irradiations and depth dose measurements.

Dosimeter results for capture gamma irradiations are shown in Table 6.2 and 6.3. Since the nonpenetrating algorithm is based on the difference in response between chips 1 and 2, buildup in the position 2 filter results in negative values for nonpenetrating dose. These are set to zero, and the algorithm estimates the shallow dose based on the penetrating component (chip 2). (Refer to Tables 2.1 and 2.2, Section 2.0, for a complete description of the Hanford algorithms.)

Secondary electron buildup in the position 2 filter is not sufficient to measure the 1 cm depth dose from high-energy photons. The 0.94 cm depth dose from capture gammas, which is essentially equal to the 1 cm depth dose, was underestimated by approximately 30-40%. The maximum depth dose was more seriously underestimated by position 2. Since the tissue dose at 0.007 cm is considerably smaller than the dose at 1 cm, use of position 2 to estimate the penetrating component led to overestimation of shallow dose by a factor of 2-4.

The use of chip 5 to estimate shallow dose further worsened the shallow dose response and caused the dosimeter to overestimate the 1 cm dose by more than 50%. The maximum depth dose was overestimated by 20 to 45%. The over-response was most severe for the iron target, since the highest energy photons produce the greatest degree of secondary electron buildup in the position 5 filter.

False fast neutron readings presented an unexpected difficulty. A difference in buildup between chip positions 3 and 4 resulted in slightly higher readings in chip 4. The algorithm assumes that chip 3 will always respond higher than chip 4, a reasonable assumption when high energy photons are not present. Subtraction of the chip 5 gamma component was not sufficient to overcome the subtraction of the negative thermal neutron component (R3-R4) in

TABLE 6.2. High Energy Capture Gamma Results

Target	Reported Dose Based on Chip 2	Reported Dose Based on Chip 5	Assigned Shallow Dose	Assigned 0.94 cm Depth Dose	Assigned Maximum Depth Dose
H	564 ± 8	1008 ± 24	226	843	1000
Fe	425 ± 4	1006 ± 28	160	694	1009
Si	505 ± 10	1001 ± 16	207	797	1014
S	480 ± 8	1000 ± 16	197	819	1000
Ca	337 ± 10	653 ± 16	115	477	602

(For capture gammas, reported shallow and deep doses were equal).
Assigned doses were determined from extrapolation chamber measurements.
Quoted uncertainties represent the standard deviation of the mean based on chip variability.

TABLE 6.3. Dosimeter Response to Capture Gammas

Target	Shallow Dose Response	0.94 cm Depth Dose Response	Maximum Depth Dose Response
<u>Using Reported Doses Based on the Standard Algorithm (Chip 2)</u>			
H	2.50	0.67	0.56
Fe	2.66	0.61	0.42
Si	2.44	0.63	0.50
S	2.44	0.59	0.48
Ca	2.93	0.71	0.56
<u>Using Reported Doses Based on Chip 5 Results</u>			
H	4.46	1.20	1.01
Fe	6.29	1.45	1.00
Si	4.84	1.26	0.99
S	5.08	1.22	1.00
Ca	5.68	1.37	1.08

$$(a) \text{ Dose Response} = \frac{\text{Reported Dose}}{\text{Assigned Dose}}$$

the fast neutron algorithm. As a result, fast neutron doses as high as 305 mrem were reported, with large sample variances. Reported neutron doses are included in Table 6.4. This problem could be avoided through a simple change in the algorithm if subtraction of the negative number is disallowed.

HIGH ENERGY PHOTONS WITH HIGH ENERGY BETAS

The current algorithm for calculating the nonpenetrating component of shallow dose involves a factor that relates penetrating radiation energy deposition in the open window position (chip 1) and the filtered position

TABLE 6.4. False Fast Neutron Doses Reported for High Energy Photon Irradiations

<u>Target</u>	<u>Reported Fast Neutron Doses (mrem)</u>	<u>Mean Reported Neutron Dose (mrem)</u>
H	24 7 213 124 -142	45
Fe	110 -27 121 274 -10	94
Si	205 305 219 58 103	178
S	38 84 111 -77 76	46
Ca	19 -31 6	-2

(Negative fast neutron doses are zeroed by the Hanford algorithm.)

(chip 2). This factor is nearly unity for Cs-137 calibration. In the presence of high energy photons, secondary electrons are generated in the position 2 filter. This causes the response of chip 2 to exceed the response of chip 1. In the subtraction of the penetrating component the nonpenetrating response is biased and the dosimeter cannot properly measure betas or low energy photons. The overall dosimeter dose response to high energy beta and photon fields using current procedures is a combination of a too high penetrating dose assessment and a too low nonpenetrating dose assessment. Currently, both the nonpenetrating and penetrating dose components are added to determine skin dose while the penetrating component alone provides the whole body dose estimate.

To assess the magnitude of the problem, hand-loaded dosimeters were irradiated with filtered N-16 beams from the Texas A&M reactor, along with capture gamma beams. The dosimeters were then given a 500 mrad ^{90}Sr exposure at PNL, and read on the PNL manual system. After background subtraction, the ^{90}Sr component was estimated and subtracted from chips 1 and 2 to yield information on the response of the dosimeter with and without the added beta component. Nitrogen-16 beams have an inherent contribution from the 10 MeV decay beta, which is attenuated by the 2 1/4-inch polyethylene filtration.

The N-16 generator consisted of a network of aluminum piping which drew water from the top of the reactor pool, and transported it: 1) to a chamber along one face of the core, 2) through a penetration in the shield wall, 3) into a second chamber at the irradiation area, and 4) back into the pool. Estimated residence times in both chambers are 1 minute for the reactor core and 30 seconds for the irradiation area. Flow rates in the system were sufficiently large for water to reach the irradiation area before the nitrogen decayed. Dose rates of approximately 250 mrem/hr were obtained at the location of the phantom, 23 inches from the face of the chamber, with filtration.

Nitrogen-16 is created through the $^{16}_0\text{n,p)}^{16}_7\text{N}$ reaction, decaying with a 7 second half-life. Photons of 6.13 MeV (69%) and 7.11 MeV (5%) are emitted, along with betas with maximum energies of 10.4 MeV (26%) (Lederer 1967). The beta and bremsstrahlung components resulted in a high shallow dose component relative to other depths. Extrapolation chamber measurements indicated maxi-

mum dose depths of 0.16 cm for the unfiltered beam and 1.16 cm for the filtered beam. Spectra taken with the GeLi detector, which is relatively insensitive to betas, failed to distinguish between filtered and unfiltered beams.

Dosimeter results for the photon/beta mixtures are included in Tables 6.5 through 6.7. The excellent shallow dose response of the dosimeter to the mixtures was a result of the combined over-response to photons and under-response to betas. When the response to ^{90}Sr is determined from the reported non-penetrating components, the reported dose is less than 20-60% of the actual ^{90}Sr dose. The ^{90}Sr irradiation added 54 mrad to the reported penetrating doses based on chip 2.

FILTERED X-RAY RESPONSE

Hanford dosimeters were irradiated on-phantom with NBS filtered x-ray techniques L-G, L-I, MFG, MFC, MFI and HFI and read on the automated system to determine the response of the Hanford system to low energy photons. The group of 50 dosimeters from the personnel pool received a previous screening to ^{137}Cs . Chip results were corrected for TLD variability as described in Appendix 3.A. Corrected chip responses were averaged after background subtraction, and doses were calculated using the monthly Hanford calibrations (refer to Section 3.0 for a description of calibration methods). Assigned doses were based on exposure measured by a beam monitor using conversion factors given in BSR N13.11 (1981).

Results are shown in Table 6.8. The dosimeter over-responded at all energies for both shallow and deep dose. The deep dose response using the Hanford calibrations (^{137}Cs in air) was slightly higher than the response for the ^{137}Cs on-phantom calibrations given in Section 3.0. Shallow dose responses for the natural U slab calibration were approximately 40% lower than the responses given in Section 3.0 for a ^{90}Sr on-phantom calibration.

TABLE 6.5. Mixed Capture Photon/Beta Irradiation
Shallow Dose Results

Target	Reported Nonpenetrating Component (mrem)	Reported Penetrating Component (mrem)	Reported Shallow Dose (mrem)	Assigned Shal- low Dose, Pho- ton Component (mrem)	Total Assigned Shallow Dose (Photon + ⁹⁰ Sr) (mrem)
H	100 ± 16	486 ± 8	586 ± 18	170	670
Fe	234 ± 38	311 ± 16	545 ± 41	102	602
Si	203 ± 41	352 ± 16	555 ± 44	121	621
S	202 ± 35	366 ± 18	586 ± 40	123	623
Ca	190 ± 21	390 ± 8	580 ± 22	115	615
Filtered N-16	299 ± 17	436 ± 4	735 ± 17	336	836

Reported doses were calculated using averaged chip responses and the standard algorithm (chips 1 and 2). Quoted uncertainties represent the standard deviation of the mean. Assigned photon components were based on extrapolation chamber measurements.

TABLE 6.6. Mixed Photon/Beta Irradiations Reported and
Assigned Deep Doses

Target	Reported Dose Based on Chip 2	Reported Dose Based on Chip 5	Assigned 0.94 cm Depth Dose (TEEC)	Assigned Maximum Depth Dose (TEEC)
H	486 ± 8	754 ± 20	634	752
Fe	311 ± 16	644 ± 44	439	641
Si	352 ± 16	606 ± 44	466	593
S	366 ± 18	646 ± 34	503	644
Ca	390 ± 8	692 ± 16	477	602
Filtered N-16	436 ± 4	543 ± 6	400	431

Assigned doses are based on tissue equivalent extrapolation chamber measurements. Uncertainties quoted for dosimeter results represent the standard deviation of the mean based on chip variability.

TABLE 6.7. Shallow and Deep Dose Responses to High Energy Photon/Beta Mixtures

<u>Target</u>	<u>Shallow Dose Response, Photons + ⁹⁰Sr</u>	<u>Shallow Dose Response, ⁹⁰Sr Only*</u>	<u>0.94 cm Depth Dose Response</u>	<u>Maximum Depth Dose Response</u>
<u>With Penetrating Response Based on the Standard Algorithm (Chip 2)</u>				
H	0.87	0.20	0.77	0.65
Fe	0.91	0.47	0.71	0.49
Si	0.89	0.41	0.76	0.59
S	0.94	0.40	0.73	0.57
Ca	0.94	0.38	0.82	0.65
Filtered N-16	0.91	0.60	1.09	1.01
<u>With Deep Dose Response Based on Chip 5</u>				
H			1.19	1.00
Fe			1.47	1.00
Si			1.30	1.02
S			1.28	1.00
Ca			1.45	1.15
Filtered N-16			1.36	1.26

Dose Response = Reported Dose/Assigned Dose.

* ⁹⁰Sr Response = Nonpenetrating Reported Dose/⁹⁰Sr Dose (500 mrad).

TABLE 6.8. Hanford Dosimeter Response to Filtered X-rays

Technique	Effective Energy, ^(a) (keV)	Deep Dose ^(b) Response	Shallow Dose ^(c) Response
L-G	15	1.17	1.48
L-I	21	1.42	1.71
MFC	32	1.73	1.75
MFG	42	1.61	1.57
MHI	64	1.35	1.36
HFI	167	1.17	1.17

(a) Effective energies are based on half-value layers (Yoder et al. 1979).

(b) Deep Dose Response = $\frac{\text{Reported Penetrating Dose}}{\text{Assigned dose or 1 cm in tissue}}$

(c) Shallow Dose Response = $\frac{\text{Reported skin dose (penetrating + nonpenetrating)}}{\text{Assigned dose at 0.007 cm in tissue}}$

DOSIMETER RESPONSE TO SCATTERED NEUTRONS

The presence of room-scattered neutrons can significantly affect the Hanford dosimeter response to fast neutrons. As the neutron energy decreases, the dosimeter response per unit fluence increases; for 1 MeV and 1 eV neutrons the effect is a factor of four (Section 7.0, Figure 7.5). While the dosimeter response per unit fluence increases at lower energies, the actual dose equivalent per unit fluence decreases. The result is a significant over-response to low energy scattered neutrons relative to an unmoderated ²⁵²Cf calibration.

Eisenhauer and Schwartz have described a straightforward method of measuring room return (Eisenhauer 1981). A uniform field of scattered neutrons in the room is assumed. The fluence or "free field" dose from unscattered neutrons decreases with the square of the distance from the source, while the contribution due to room return remains constant. The equation for the total dose becomes

$$D(r)' = D(r) \cdot (1 + Sr)^2$$

where $D(r)'$ is the dose rate due to incident and scattered neutrons at distance r from the source, $D(r)$ is the dose rate due to incident neutrons and S is the

room return. Since S is a measure of deviation from inverse r^2 , the units are percent per square unit distance ($\%/m^2$). If $D(r) \cdot r^2$, the product of the measured dose rate and the square of the distance from the source, is plotted against r^2 , a line can be fit to the data. The room return measured by the detector is equal to the ratio of the slope to the intercept.

Measurements of room return in a high scatter environment (3745A building) and low scatter environment (318 building) were conducted using a tissue-equivalent proportional counter and Hanford dosimeters from the personnel pool. The response of the tissue equivalent proportional counter is partially corrected for linear energy transfer and is therefore a closer approximation of the actual scatter contribution to dose equivalent. Dosimeter results can be used to correct for dosimeter response as a function of calibration distance. The linear fit of the data is shown in Figures 6.1 through 6.3. For the 318 building the dosimeter response to room scatter was $10\%/m^2$ with an uncertainty of $2\%/m^2$. The TEPC response was $6\%/m^2$ with an uncertainty of $1\%/m^2$.

Measurements in the 3745A facility were initially averaged over all directions, at three distances from the source. These measurements revealed a "general" room scatter of $19\%/m^2$ as determined from the dosimeter. A similar treatment of TEPC results yielded a room return of $18\%/m^2$. Both quantities have an uncertainty of $2\%/m^2$. Dosimeter measurements were corrected for a $3.7\%/m^2$ air scatter contribution derived from air scatter calculations.

The measurements were repeated with Hanford dosimeters placed along a single axis in a westerly direction from the source. The linear regression for the seven distances showed a much higher scatter, $47\%/m^2$. It appears from this data that scatter in the 3745A facility is highly anisotropic.

CONCLUSIONS

Dosimeter response can be corrected for the room-scatter component using the results summarized in the previous section. The corrected response is

FIGURE 6.1. Hanford Dosimeter Room-Scatter Measurements in 318

FIGURE 6.2. TEPC Room-Scatter Measurements in 318

FIGURE 6.3. Hanford Dosimeter and TEPC Room-Scatter Measurements in 3745A Averaged Over All Directions

equal to the measured response divided by $(1 + S r^2)$. For the Hanford dosimeter, S is approximately 0.10 (10%/m²) in the 318 building and 0.47 (47%/m²) in the 3745A facility. Additional information concerning the two facilities is given in Study 2.

The dosimeter under-responded by 30-40% to the dose at 1 cm for high energy photons when the chip 2 position was used to calculate penetrating components. When chip 5 was used to calculate the deep dose, the dosimeter over-responded to the 1 cm dose. Chip 5 provided an excellent estimate of the maximum depth dose for capture gammas (within a 15 percent), although there was a 26% over-response to the ¹⁶N beam. Analysis of the data indicates that the 1 cm depth dose would be better estimated by a filter slightly thicker than 356 mg/cm² (chip 2).

The shallow dose algorithm and fast neutron algorithms are not valid in the presence of high energy photons. Buildup in the position 2 filter masks the nonpenetrating component of chip 1 and causes the penetrating component of shallow dose to be severely overestimated. While the shallow dose may be correctly estimated in some cases, the uncertainty due to the algorithm is large. False Neutron doses appeared in some instances due to the difference in buildup in chip positions 3 and 4. In short, the algorithms based on attenuation in dosimeter filters become invalid when significant buildup is present.

For low energy x-ray mixtures (NBS filtered techniques) the Hanford dosimeter over-responds to deep and shallow doses when the Hanford standard calibrations are used. There was a slight difference in response between the hand-loaded dosimeters (Study 2) and the Hanford personnel dosimeters at low energies. Although use of the hand-loaded system to predict the response of the Hanford personnel dosimetry system appears to be valid, caution should be exercised in drawing conclusions for low energy photons.

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APPENDIX A

TEEC DEPTH-DOSE MEASUREMENTS

FIGURE 6.A.1. Relative Dose Versus Tissue Depth - N-16,1" Filter

FIGURE 6.A.2. Relative Dose Versus Tissue Depth - Hydrogen

FIGURE 6.A.3. Relative Dose Versus Tissue Depth - Silicon

FIGURE 6.A.4. Relative Dose Versus Tissue Depth - N-16, Unfiltered

FIGURE 6.A.5. Relative Dose Versus Tissue Depth - Iron

FIGURE 6.A.6. Relative Dose Versus Tissue Depth - Sulfur

FIGURE 6.A.7. Relative Dose Versus Tissue Depth - Calcium

7.0 STUDY 6-DOSIMETER MODIFICATION AND TESTING

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FOREWORD

Modifications to the design and readout of the Hanford multipurpose dosimeter to allow improved dose assessment were recommended in the Hanford Personnel Dosimeter Supporting Studies FY-1980 document (Fix et al. 1981). This study documents the effects of several modifications. Primary emphasis was on neutron dosimetry improvements which could be realized without losing the beta-gamma capabilities of the Hanford multipurpose dosimeter.

SUMMARY

Typical of an albedo dosimeter, the Hanford dosimeter has considerable energy dependence and statistical variability in its determined neutron dose. The energy dependence results from its albedo design and necessitates field calibration. The statistical variability is a function of numerous parameters including component variability, dosimeter design, readout procedure, and raw data interpretation. This study examined these last three: dosimeter design, readout procedure, and raw data interpretation. Particularly it evaluated changes which could be made to decrease the statistical variability.

Design changes which were tested included:

- rearranging the filters and TLDs
- placing a plastic disc between the dosimeter and phantom
- replacing the cadmium-tin filters with a solid cadmium filter
- replacing the current teflon film enclosure with a new teflon or teflon-polyimide enclosure
- converting the opaque dosimeter holder to a clear dosimeter holder.

Annealing TLD-600s prior to dosimeter readout was also tested along with a most probable dose interpretation method, called least squares.

Results from these tests indicated that dosimeter precision in neutron fields could be improved by almost a factor of five by incorporating certain changes in the dosimeter design and data processing. This could be accomplished using existing readout and data processing hardware. Apart from any design changes, the precision of the historical 5-chip Hanford dosimeter could be improved roughly by a factor of 1.7 by using the least squares method of dose interpretation.

Other conclusions drawn from this study are:

- Conversion to a clear holder requires an opaque filter behind chip 1 to prevent sunlight induced fading of TLD signal.
- A polyimide-Teflon TLD enclosure would give greater heat stability for TLD readout.
- Replacing the cadmium-tin filter with a solid cadmium filter would slightly improve neutron dosimetry.

CONCLUSIONS

The albedo design is an excellent personnel dosimeter design for neutron energies up to 10 keV. Beyond 10 keV, it is functional when coupled with field spectral measurements. A hybrid albedo dosimeter with a separate capability of distinguishing neutron fluence above 10 keV would be ideal.

The Hanford multipurpose albedo dosimeter could be improved significantly in precision by incorporating the following changes:

- rearrange the filters and TLDs as shown in Figure 7.1
- apply a least squares method of dose interpretation
- attach a plastic disc to the back of the dosimeter as shown in Figure 7.1
- replace the cadmium/tin filter with a solid cadmium filter.

The least squares method could be applied to the current dosimeter once all 5 chips are read out. By itself this would improve precision by about a factor of 1.7. Adoption of all recommended design changes would improve precision by up to a factor of 5, depending upon the type of exposure.

FIGURE 7.1. Modified Multipurpose Dosimeter Design

Conversion to a polyimide-teflon TLD enclosure would increase readout precision and increase chip enclosure durability. Testing of this enclosure and possibly others for a higher anneal temperature may be desirable.

INTRODUCTION

Neutron dose precision of the Hanford Multipurpose Dosimeter is directly related to individual TLD chip precision when read on the Hanford Reader. Historically quality assurance programs have attempted to carefully screen TLD chips for uniform signal strength. Reader maintenance and redundant check dosimeters have kept readout quality within fixed limits. Yet the variability of system components (e.g., TLD chips), reader performance, calibrations, etc., cumulatively combine to give a significant variability in determined dose. This limits the low dose capabilities of the dosimeter, where most personnel exposures occur. These limitations, along with neutron energy dependence are documented in Hanford Personnel Dosimeter Supporting Studies FY-1980 (Fix et al. 1981). Out of this study came recommendations for improving the precision of determined neutron dose as well as ones for providing a better low energy beta-gamma dosimeter.

This study focused on improvements which could be made in neutron dosimetry without sacrificing beta-gamma capabilities of the multipurpose dosimeter. Specifically, this study tested dosimeter design changes which would minimize the way variability of system components (TLDs/reader) combine to create dose variability. It also tested a new method of TLD signal interpretation (least squares) to determine the most probable dose. A fairly detailed investigation was made of the thermal stability of the primary and secondary thermoluminescent peaks, and use of this for mixed field dosimetry.

Results from these tests and others led to observations which could be used for a more precise albedo-type multipurpose dosimeter.

CONCEPT OF AN ALBEDO DOSIMETER

An albedo dosimeter such as the ^6Li - ^7Li -Cd dosimeter used at Hanford measures neutron fluence coming from the environment (ambient neutrons) and neutron fluence reflected from the phantom or body (albedo neutrons). Neutrons detected are primarily those which have energies of 10 electron volts or less. The mechanism of neutron capture^(a) causes all detected neutrons to give the same crystal response, preventing any direct determination of neutron energy. Instead a single distinction of neutron energy between thermal and epithermal is made by placing cadmium or a similar neutron shield on either side of the TLD. Epithermal neutrons must be of sufficient energy to penetrate cadmium, be thermalized by the body and be reflected back to the dosimeter. The albedo dosimeter is able to determine the fluence of these neutrons as well as neutrons which can not penetrate the cadmium shield (i.e., thermal neutrons).

Mechanism of Thermal Neutron Measurement

The fluence of neutrons which cannot penetrate cadmium is determined by subtracting the response of a cadmium shielded TLD-600 from an unshielded TLD-600. The filter and TLD arrangement for the Hanford dosimeter is shown in Figure 7.2. Since none of the ambient slow neutrons shown in this picture would be detected by chip 4 but most would be detected by chip 3, the difference between their measurements would be directly proportional to ambient thermal neutron fluence.

The cadmium filter shown in this picture completely absorbs neutrons below about 0.3 eV and allows neutrons above 2 eV to freely penetrate. It covers 42% of chip 4's total field of view and 84% of the ambient field of view. Its effect upon the fraction of neutrons absorbed by TLD-600 is shown in Figure 7.3. This figure compares the percentage of neutrons absorbed within

(a) When a ^6Li nucleus captures a neutron it promptly decays resulting in an alpha particle and tritium nucleus with a combined energy of 4.8 MeV. Some of this energy is stored in the crystal lattice and is given off as luminescent signal when heated. The amount of signal is proportional to the quantity of neutrons absorbed.

FIGURE 7.2 Filter and TLD Arrangement of the Hanford Neutron Dosimeter

FIGURE 7.3 Effect of Cadmium On TLD-600

the TLD-600 chip when the filtering medium is either cadmium or tin and the angle of neutron incidence is 45° . The curves result from solution of the following equation:

$$\text{adsorption by TLD-600} = e^{-\sigma_{a,Cd} \cdot N_{Cd} \cdot d_{Cd}} \cdot \left[1 - e^{-\sigma_{a,600} \cdot N_{600} \cdot d_{600}} \right] \quad (1)$$

The term for tin was neglected because of its low absorption cross section.

For a definition of each term and all others used in this study refer to the glossary at the end of this section.

Mechanism of Fast Neutron Measurement

The fast neutron fluence is measured by determining how much of the albedo neutron fluence is in excess of that expected from the ambient thermal neutron fluence. It involves subtracting a constant times the ambient thermal neutron response (R3-R4) from the albedo thermal neutron response (R4 minus gamma response). The constant converts the ambient response into the expected albedo response. The albedo response to fast neutrons is greater than the ambient response to fast neutrons because fast neutrons (above 1 keV) coming from the environment are essentially "invisible" to TLD-600, but once they have been thermalized in the body and are reflected back to the dosimeter they are "visible."

On the average, one fast neutron (invisible to TLD-600) entering the body produces less than one thermal neutron (visible to TLD-600) leaving the body. As the neutron energy increases, the fraction of thermal neutrons leaving the body decreases from 0.4 at 0.024 eV to 0.07 at 1 MeV (Nagarajan and Krishnan 1969). In addition, the neutron fluence per unit dose equivalent decreases as the neutron energy increases. A curve depicting this is shown in Figure 7.4. The net effect is an energy dependence for fast neutron response, which is shown in Figure 7.5.^(a) As the neutron energy increases, the response per unit dose equivalent decreases. At neutron energies below 0.4 eV, the neutrons are recognized as being thermal neutrons.

(a) Derivation of the curve in Figure 7.5 is explained in Appendix A.

FIGURE 7.4 Dose Equivalent To Flux Conversion (Attix and Roesch 1968)

FIGURE 7.5 Theoretical Energy Dependence

This energy dependence is inherent to all albedo dosimeter designs. It necessitates a field calibration for each unique spectrum of neutron energies. Fortunately field neutron spectrums generally follow a similar shape^(a) with a main peak at the emission energy of the source and a gradual increase in neutron fluence as thermal energies (0.024 eV) are approached. The Hanford dosimeter due to reflected thermal neutrons is quite sensitive to "fast" neutrons above the cadmium cut off of 2 eV and up to 10,000 eV. Most field dosimeter measurements are probably measuring the fast neutron dose equivalent in this energy range. For a fixed neutron spectrum the dose equivalent in this lower energy range is directly proportional to the total dose equivalent. Therefore, the dose equivalent determined by the dosimeter should be a representative value once field spectral measurements are made.

POTENTIAL IMPROVEMENTS IN THE HANFORD DOSIMETER

The energy dependence of the Hanford dosimeter is inherent to its albedo design. An improved dosimeter from the viewpoint of energy dependence would be able to distinguish neutron fluence between 10 keV and 10 MeV from lower energy neutron fluence. It might be a hybrid of an albedo dosimeter (for 1 eV to 10 keV neutrons) and another dosimeter such as film or track etch (for neutrons above 10 keV). Unfortunately no currently accepted practical dosimeter concept has a flat response curve from 10 keV to 10 MeV.^(b)

Since the energy response curve of an albedo dosimeter varies by only a factor of two between 0.4 eV and 10 keV and most field spectrums have a significant portion below 10 keV, the albedo dosimeter design gives the most practical field dosimeter design currently available apart from hybrid systems.

As explained previously the calculation of fast and slow neutron doses using an albedo dosimeter such as Hanford's requires the subtraction of TLD chips from other TLD chips. The resultant values frequently have a large variability due to TLD sensitivity and reader fluctuations. This variability can be minimized by designing the dosimeter so that major subtractions are avoided.

(a) For field spectrums at Hanford see Hanford Personnel Dosimeter Supporting Studies FY-1980, page 6.A.2 and 6.D.8 and Study 3 of this report.

(b) Brachenbush, Endres, Selby and Vallario 1980.

Rearranging Filters and TLD's To Maximize Precision

The historical Hanford 5-chip dosimeter design was shown in Figure 7.2 and is repeated in Figure 7.6 along with the modified filter arrangement tested in this study. The components of each chip's reading are shown in Table 7.1. How each chip reading is combined and subtracted to calculate slow neutron and fast neutron fluence is shown algebraically in the bottom two sections of this table. Note, that both methods attempt to determine the thermal neutron fluence incident upon the front of the body for slow neutrons and the excess reflected (albedo) thermal neutron fluence reflected from the body for fast neutrons. The old dosimeter design picks up an "epicadmium" fraction, which is the small fraction of neutrons above 0.4 eV which are "seen" by both R3 and R4. It also subtracts the cadmium capture gamma-beta response from the front side neutrons, which is not necessary. The new design does not identify either of these components.

The main advantage of the new dosimeter design results from subtracting small numbers from large numbers to determine dose equivalent instead of large numbers from large numbers. For example the fast neutron equation for the old dosimeter is:

$$FN = C_5 \cdot [R_4 - K_6 \cdot R_5 - K_5 \cdot (R_3 - R_4)]$$

This reduces approximately to:

$$FN \propto (1.87 \cdot R_4 - R_5 - 0.87 \cdot R_3) \quad (2)$$

For a typical mixed field exposure (approximately 150 mrem fast neutrons, 20 mrem gamma, and 1 mrem thermal neutrons) these values might be:

$$FN \propto [1.87 \cdot (7 \pm 0.7) - (1. \pm 0.1) - 0.87 \cdot (10 \pm 1)]$$

$$FN \propto 3.39 \pm 1.58$$

$$FN \propto 3.39 \pm 46\%$$

For the new design the equation is:

$$FN = C_A \cdot [R_4 - R_5' - K_A \cdot (R_3' - R_5')]$$

This reduces approximately to:

$$FN \propto R_4 - 0.13 \cdot R_5' - 0.87 \cdot R_3' \quad (3)$$

FIGURE 7.6 Filter and TLD Arrangement of HMPD and Modified Dosimeter (MMPD)

TABLE 7.1 Components of TLD Readings and Combinations^(a,e)

		Front				Edge				Back			
		γ -B	Th-N	Enhanced ^(d) γ -B	Epicadmium Neutrons	γ -B	Th-N	Epicadmium Neutrons		γ -B	Th-N	Enhanced γ -B	Epicadmium Neutrons
Old Design	K6-R5	A _F				A _E				A _B			
	R3	A _F	B _F		D _F	A _E	B _E	D _E		A _B	B _{B_T}		D _B
	R4	A _F		C _F	D _F	A _E	B _E	D _E		A _B	B _{B_T}		D _B
	R3'	A _F	B _F		D _F	A _E	B _E	D _E		A _B		C _B	D _B
	R5'	A _F		1/2 C _F	D _F	A _E	B _E	D _E		A _B		1/2 C _B	D _B
Old Design	R4-K6-R5			C _F	D _F		B _E	D _E			B _{B_T}		D _B
	R3-R4		B _F	-C _F									
	K5 · (R3-R4)			C _F			B _E				B _{B_{THN}}		
	R4-K6 · R5 -K5 · (R3-R4)				D _F			D _E			B _{B_{FN}}		D _B
New Design	R4-R5' (b)										B _{B_T}		
	R3'-R5' (c)		B _F										
	K4(R3'-R5')										B _{B_{THN}}		
	R4-R5' K4(R3'-R5')										B _{B_{FN}}		

(a) To calculate FN the quantity of thermal neutrons resulting from fast neutrons must be determined. As an option, the quantity of epicadmium neutrons may be determined. To calculate SN, the quantity of thermal neutrons coming from the environment must be determined. I.E., $FN \propto B_{B_{FN}} + K \cdot D$, where K may equal zero.
 $SN \propto B_F$

(b) $C_F - 1/2 \cdot C_F - 1/2 \cdot C_B \sim 0$

(c) $C_B - 1/2 \cdot C_F - 1/2 \cdot C_B \sim 0$

(d) Enhanced γ -B is gamma or beta resulting from cadmium capture of neutrons.

(e) Refer to glossary for definition of all terms.

For the same mixed field exposure these values would be:

$$FN \approx 87 \pm 0.7 - 0.13 \cdot (1.5 \pm 0.15) - 0.87 \cdot (4.3 \pm 0.43)$$

$$FN \approx 3.06 \pm 0.79$$

$$FN \approx 3.06 \pm 26\%$$

The new dosimeter design minimizes the magnitude of numbers subtracted and thereby improves statistics. The complete equations for the old and new dosimeter are shown in Table 7.2.

One other advantage of the rearranged filters comes from placing the neutron sensitive TLD-600s closer together and symmetrically arranged. By placing the TLD-600's in the bottom 3 dosimeter positions their separation from each other is no more than 0.6 in. compared to the current TLD-600 separation of 1 in. Minimizing their physical separation is important so each TLD-600 "sees" the same moderator behind it.

Attaching Plastic

The 50% probability path lengths of neutrons between 0.4 eV and 10 keV in tissue ranges from 0.18 in. to 0.21 in. For thermal neutrons at 0.024 eV it is 0.11 in. (Hughes and Schwartz 1958). This causes the moderator in the first 3/8 in. behind the TLD-600 to be very critical to chip response. To standardize this moderator, polyethylene plastic about 1/4 in. thick could be attached to the back of the dosimeters. The net improvement in the moderator-dosimeter arrangement is shown in Figure 7.7.

Substitution of 34 Mil Cd for 20 Mil Cd

The current thermal neutron filter is composed of 0.020 in. Cd and 0.020 in. Sn. In theory, the tin should shield the TLD chip from the capture gamma produced when cadmium absorbs a neutron, thereby further reducing the neutron created signal. In practice, the tin increases the physical gap between the cadmium filter and TLD-600, thereby allowing more neutrons to come through the edges. The net effect of using the current filter instead of a solid cadmium filter is that less neutron signal is intercepted. An improved arrangement would be 34 mils of cadmium and no tin on the cadmium side.

TABLE 7.2. Equations Used to Calculate Dose

Current Dosimeter ^(a)	Modified Dosimeter ^(a)
NONPEN = C2 · (R1-K2 R2)	NONPEN = C2 · (R1-K2 R2)
PEN = C1 · R2	PEN = C1 · R2
SN = C4 · (R3-R4)	SN = C4' · (R3'-R5')
where,	where,
$C4 = \frac{50 \text{ mrem}}{(R3-R4)}$ 50 mrem thermal neutrons	$C4' = \frac{50 \text{ mrem}}{(R3'-R5')}$ 50 mrem thermal neutrons
FN = C5 · [R4-K6 · R5-K5 · (R3-R4)]	FN = C _A [R4-R5'-K _A · (R3-R5')]
where,	where,
$C5 = \frac{1000 \text{ mrem}}{[R4-K6 \cdot R5-K5 \cdot (R3-R4)]}$ 1000 mrem PuF ₄	$C_A = \frac{1000 \text{ mrem}}{[R4-R5'-K_A \cdot (R3'-R5')]} 1000 \text{ mrem PuF}_4$
$K6 = \frac{R4}{R5}$ 1000 mrem ¹³⁷ Cs	$K_A = \left(\frac{R4-R5'}{R3'-R5'} \right)$ 50 mrem thermal neutrons
$K5 = \left(\frac{R4-K6 \cdot R5}{R3-R4} \right)$ 50 mrem thermal neutrons	

(a) See Figure 7.11.

Figure 7.8 shows a 10 fold blow up of two possible TLD and filter arrangements. The field of view from the chip is closely approximated by calculating the field of view from the center of the chip. Note that when solid cadmium is used, the percent of view that the edge comprises is only 8.7% compared to 16.5% with Cd/Sn. Cadmium capture gamma are not completely eliminated by the Sn filter; however the maximum contribution is less than 3% of the total TLD signal; whereas the amount of signal added due to more edge neutrons is 7.8% of the total TLD signal.

FIGURE 7.7. "Neutron View" of HMPD and MMPD

FIGURE 7.8. Possible Filter and TLD Arrangements

Figure 7.9 shows how TLD-600 responses to edge neutrons and neutrons filtered or not filtered by cadmium. It also shows that edge neutrons generate an important component of the total signal.

The thickness of 0.034 in. was chosen so the gamma attenuation of the cadmium filter would be equivalent to that of the tin filter.

Numerical Analysis

The 5-chip Hanford dosimeter uses the information from five TLD chips to determine dose in four categories: penetrating, non-penetrating, fast neutron and slow neutron. The modified dosimeter likewise has 5 chips for four categories. Rather than use the equations in Table 7.2 an improved method of dose determination would use all 5 chips to determine the dose in each category. Since there are five bits of information to be used in determining a dose for only four categories, the method of minimizing the sums of the squares of the discrepancies could be used to determine the most probable dose.

Least Squares

The method of least squares determines the most probable value by minimizing the deviations between expected values and the observed TLD signals. Applied to the Hanford dosimeter it requires that the discrepancies between expected values of R1 through R5 and the actual values be minimized. Expected values are a function of the four calculated dose categories. Mathematically the sum of the squares of the deviations would be:

$$Z = \left(\frac{R1-R1_x}{SR1} \right)^2 + \left(\frac{R2-R2_x}{SR2} \right)^2 + \left(\frac{R3-R3_x}{SR3} \right)^2 + \left(\frac{R4-R4_x}{SR4} \right)^2 + \left(\frac{R5-R5_x}{SR5} \right)^2 \quad (4)$$

where R1 = actual reading of chip 1

R1_x = expected reading of chip 1, which is a function of the four calculated dose categories

SR1 = standard deviation of readings of chip 1.

Minimizing Z simply requires setting the partial derivatives of Z with respect to the four calculated dose categories equal to zero.

FIGURE 7.9. Filtered and Unfiltered TLD-600 Response To Neutrons

Mathematically this is symbolized as:

$$\frac{\partial Z}{\partial Pen} = 0; \frac{\partial Z}{\partial Nonpen} = 0; \frac{\partial Z}{\partial FN} = 0; \frac{\partial Z}{\partial SN} = 0$$

Four equations result with four unknowns which are easily solved to give the four most probable doses.

Some of the calculated doses may be negative. Since a negative dose is impossible, the most negative calculated dose is set equal to zero and the partial derivatives are calculated for the three remaining variables. These three equations are solved for the three remaining dose categories. If any resulting dose is negative, it is "zeroed" and the above steps are repeated.

A more detailed mathematical explanation of the least squares technique is given in Appendix B.

Annealing to Reduce Beta-Gamma Impact

A method to reduce the influence of beta-gamma exposures upon neutron calculations was investigated. It was designed to take advantage of the relative neutron selectivity of the 255°C thermoluminescent peak.

Trap Selectively

TLD-600 and TLD-700 material have several thermoluminescent traps. The largest, at 195°C, is where 98% of the beta-gamma signal and 80% of the neutron signal is stored. The second largest, at 255°C, stores only 2% of beta-gamma signal but 20% of the neutron signal. Reading the second peak would allow neutron measurements with relatively low beta-gamma background. Unfortunately, the second peak can not be separately read by the existing Hanford readers. The alternative, which was tested, is to remove by annealing the first peak before TLD readout.

Prereadout Anneal

To determine the proper annealing procedure, a series of TLDs were held for 1 hour at temperatures ranging from 20°C to 190°C. Then peak heights of

the 195°C and the 255°C peak were measured. The rate equation for signal loss was then calculated for each peak. The rate equation was found to be first order. The rate constant followed Arrhenius' Law (Levenspiel 1972):

$$\frac{dTL}{dt} = -K_0 e^{(-E/RT)} \cdot TL \quad (5)$$

When integrated, this reduces to:

$$\ln\left(\frac{TL_i}{TL_f}\right) = K_0 \cdot e^{(-E/RT)} \cdot t \quad (6)$$

Which can be converted to the linear equation:

$$\ln\left(\frac{\ln\left(\frac{TL_i}{TL_f}\right)}{t}\right) = \ln K_0 - \left(\frac{E}{R}\right) \cdot \frac{1}{T} \quad (7)$$

A graphical representation of Equation 6 for the 195°C peak is shown in Figure 7.10. The line shown is a weighted linear regression which emphasizes the greater confidence in the center points and also includes the value of 5% signal loss per year at room temperature. The slope is $(-E/R)$. The Y-intercept is $(\ln K_0)$. Thus the decay of thermoluminescence in the 195° peak is a function of time and temperature. Mathematically the best fit line reduces to:

$$\ln\left(\frac{TL_i}{TL_f}\right) = \frac{3.400 \cdot 10^8}{\text{sec}} \cdot e^{(-11760^\circ\text{K}/T)} \cdot t \quad (7)$$

The activation energy (E) was calculated from the slope of the line to be 23.4 Kcal/gmole or 1.0 eV.^(a)

$$(a) \frac{23.4 \text{ Kcal}}{\text{gmole of traps}} \times \frac{\text{gmole of traps}}{6.023 \times 10^{23} \text{ traps}} \times \frac{2.612 \times 10^{22} \text{ eV}}{\text{Kcal}} = \frac{1.0 \text{ eV}}{\text{trap}}$$

FIGURE 7.10. Decay Rate of 195°C Peak

The conditions chosen for annealing the first peak were 170°C for 70 minutes. This was calculated from Equation 7 to produce a 98.5% anneal. Under these conditions, the second peak was annealed less than 5%.

Reduced Thickness of Filters Over Chip 1

Suggestions for improving the beta-gamma capabilities of the Hanford dosimeter were made in Study 4 of Hanford Personnel Dosimeter Supporting Studies FY-1980. Basically these recommendations required dedicating more TLD-chips and filters to beta-gamma dosimetry and less to neutron dosimetry. We felt this could not be accomplished in a good 5-chip multipurpose dosimeter. Most likely this would require a separate beta-gamma dosimeter.

One change that was tested in the multipurpose dosimeter was to replace the security credential over chip 1 with a 0.002-in. thick mylar film. The mylar protected the TLD from sunlight while providing minimum beta-gamma filtration over chip 1.

TESTING OF CHANGES

Each of the previously discussed potential improvements was tested and compared to dosimeters without these changes. The first experiment simultaneously tested the effects of:

- rearranging the filters and TLDs
- using the least squares method
- preannealing the 195°C peak.

The modified dosimeter tested is shown, along side the HMPD, in Figure 7.11.

First Experiment

Experiments were specifically designed to give nearly identical exposures to groups of 10 or 9 HMPDs simultaneously exposed to one source. For beta, gamma, and fast neutron exposures, 10 or 9 HMPDs were symmetrically attached to the base of a 50 liter tap water filled carboy. The base of the carboy directly faced the radiation source, 70 cm away. The arrangement is pictured in Figure 7.12. Radiation sources used were ^{90}Sr , ^{60}Co , and ^{252}Cf . For each source, 10 or 9 HMPDs with two TLD chips per position were exposed to

FIGURE 7.11. Tested MMPD and HMPD

FIGURE 7.12. Gamma, Beta and Fast Neutron Exposure Geometry

dose equivalents ranging from 88 to 121 mrem. In a similar manner, 10 HMPDs were exposed to thermal neutrons from a PuBe source surrounded by a cylindrical shell of D₂O. These dosimeters were symmetrically attached to the base of a 50 liter, tap water filled carboy. The base of the carboy directly faced the radiation source as shown in Figure 7.13. The thermal neutron dose equivalent was 5.8 mrem.

One out of each of the two TLD chips per position was preannealed for 75 minutes at 170°C, then the remaining TLDs were readout on a Harshaw Model 2000A reader. Those TLDs which were preannealed were then also readout on the Harshaw reader. Integration temperatures were changed according to the peak being read.

The identical procedure used for the HMPD was repeated for the modified dosimeter. All exposures were repeated as nearly identical as possible. The TLDs used came from the same batch as used in the HMPD. They were from the same anneal group and were stored together.

Dose equivalent values were determined from the raw data by two methods. First, the dose equivalent was determined using the standard Hanford equations for the 5-chip dosimeter. Dose equivalent values for the modified dosimeter were determined using modified Hanford equations, which are roughly equivalent to the current Hanford equations when applied to the new modified dosimeter. These two sets of equations are shown in Table 7.2. The second method of determining dose equivalent was to perform a least squares fit of the data as shown in the section "Numerical Analysis." Both methods used the mean response of the 10 or 9 dosimeters as the calibration data set.^(a) Therefore, these dosimeters were self calibrated and should show very little "skewed response."

The mean and standard deviation of each dose equivalent was determined for each category of radiation for the specific dosimeter data set and data analysis used. The root mean square (rms) of the standard deviations was also determined as the best overall index of dosimeter precision. The smaller the rms of the standard deviation, the better the precision.

(a) For ²⁵²Cf and PuBe-D₂O, the gamma component of TLD response was subtracted from the calibration set.

SIDE VIEW OF THERMAL NEUTRON EXPOSURE

FIGURE 7.13. Thermal Neutron Exposure

The calculated means and standard deviations for each exposure and method of data analysis are shown in Table 7.C.1 of Appendix C. Values for the recommended multipurpose dosimeter shown in Figure 7.1 were generated by replacing R2 from the modified dosimeter tested with R2 from the HMPD. They are listed in Table 7.C.1 under the heading "Modified Dosimeter-II."

Impact of Filter Change

Rearranging the filters and TLDs greatly improved the statistics of the calculated doses. The rms value, which is an average of the calculated standard deviations, was reduced by a factor ranging from 3.9 for fast neutrons to 1.02 for gamma radiation. Table 7.3 summarizes the average (rms) values for each type of calibration exposure. The first row of each set of two lists the value for the 5-chip Hanford dosimeter. The second row lists the value for the modified dosimeter. In all but one category the modified dosimeter was more precise than the HMPD. The single exception observed was for the least squares method and a ^{60}Co exposure. The modified dosimeter showed the biggest improvement for neutron exposures, where its standard deviation was only 30% of the HMPDs.

From the viewpoint of precision, the HMPD is weakest in neutron fields. This is where the biggest improvement is realized from the modified dosimeter.

Impact of Least Squares Method

The impact of the least squares method upon dosimeter precision is also shown in Table 7.3. Since each value listed is calculated from only 9 or 10 dosimeters, it's only an initial estimate of true dosimeter standard deviation. Nevertheless, the general trend is obvious: the least squares method gives a more precise estimate of the dose. Seven of the eight categories testing the least squares method show a reduced standard deviation.

For the HMPD, the average standard deviation using least squares method was only 60% of that using the standard equations. For the modified dosimeter, the least squares method gave a standard deviation equal to 83% of that from the standard equations.

TABLE 7.3. Effect of Filter Change and Least Squares Method on Average Standard Deviation

Dose Equivalent and Radiation Source	Dosimetry Type(a)	Average Standard Deviation in mrem	
		Using Standard Equations	Using Least Squares Method
116 mrem ^{60}Co	HMPD	± 7.12	± 2.78
	MMPD	± 6.96	± 4.27
88 mrem ^{90}Sr	HMPD	± 5.25	± 3.10
	MMPD	± 2.34	± 2.31
111 mrem ^{252}Cf	HMPD	± 13.3	± 7.22
	MMPD	± 3.43	± 2.44
5.84 mrem $\text{PuBe-D}_2\text{O}$	HMPD	± 22.9	± 20.3
	MMPD	± 6.45	± 6.53

(a) HMPD = Hanford Multipurpose Dosimeter.
MMPD = Modified Multipurpose Dosimeter.

The least squares method determines the most probable dose given four average calibration dosimeter responses. When penetrating and nonpenetrating doses were calculated, calibration readings for ^{60}Co and ^{90}Sr , respectfully, were used. Technically this means that the penetrating dose calculated was actually gamma dose and the nonpenetrating dose was beta dose.

The combination of the modified dosimeter and the least squares method of dose interpretation was more precise for all four radiation sources tested. The largest improvement occurred for fast neutron exposures where the standard deviation was reduced by a factor of 5.5. The smallest improvement occurred for gamma exposures where the standard deviation was reduced by a factor of 1.7.

The least squares analysis provided a significant improvement using just the HMPD. The improvement ranged from a factor of 2.5 for gamma to 1.1 for thermal neutrons.

The average values of calculated dose equivalent are shown in Table 7.C.1 of Appendix C. These averages were roughly the same as the given dose equivalent. Differences observed were considered insignificant. In theory though, multiple iterations of the least squares method will slightly skew the average calculated dose away from the given dose. This is because no negative calculated dose equivalent values are allowed. Therefore, the distribution is not normal. If the data set were considerably less precise than that used for this experiment, the differences between the average value and the given value would have been noticeable.

If dosimeter bias became a significant problem, the first iteration could be used. It is not as precise as multiple iterations, but it has no bias.

Impact of Annealing the 195°C Peak

Annealing the 195°C peak in TLD-600s before dosimeter readout improved statistics only for a pure gamma exposure with a rigidly controlled anneal procedure. For neutron exposures the statistics were worse by a factor of 2.2. The standard deviations with and without annealing prior to readout are summarized in Table 7.4.

Since this procedure improves statistics only in extremely limited circumstances, it was abandoned as an option for a modified dosimeter.

Second Experiment

The next experiment tested the effect of plastic attached to the back of the dosimeter. This was discussed previously on page 7.15. High density polyethylene plastic discs, 1-3/4 in. in diameter, were attached to the back of the dosimeter, as shown in Figure 7.14. The disc thicknesses tested were 1/8 in., 1/4 in., and 3/8 in. Each disc was positioned so that it was evenly centered between each TLD-600 in the MMPD.

A string of dosimeters each with a plastic disc attached were then positioned on the anterior and posterior thorax region of the Rando phantom. The phantom was exposed to about 107 mrem from a ^{252}Cf source directly in front of the phantom and 1 meter away. The setup is shown in Figures 7.15a and 7.15b.

TABLE 7.4. Effect of Annealing 195°C Peak in TLD-600s Before Readout

Dose Equivalent and Radiation Source	Categories of Calculated D.E. (a)	Standard Deviation Using HMPD				Standard Deviation Using MMPD			
		Hanford Equations		Least Squares Method		Modified Hanford Equations		Least Squares Method	
		No Anneal	Anneal	No Anneal	Anneal	No Anneal	Anneal	No Anneal	Anneal
116 mrem ^{60}Co	Pen or Gamma	5.1	5.1	1.5	2.0	6.3	5.9	3.3	4.6
	Nonpen or Beta	11.1	11.1	3.5	3.5	7.6	7.1	6.9	6.4
	Fast Neutron	7.3	7.0	4.0	1.5	9.8	1.2	3.8	1.3
	Slow Neutron	0.1	0.1	0.0	0.0	0.5	0.1	0.1	0.1
88 mrem ^{90}Sr	Pen or Gamma	2.9	3.0	0.2	0.2	0.2	0.2	0.1	0.2
	Nonpen or Beta	10.0	10.7	6.2	5.1	4.6	4.6	4.6	4.6
	Fast Neutron	1.1	4.6	0.5	0.7	0.9	0.6	0.4	1.1
	Slow Neutron	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
111 mrem ^{252}Cf	Pen or Gamma	0.5	0.5	0.2	0.2	0.5	0.5	0.5	0.5
	Nonpen or Beta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Fast Neutron	26.5	66.7	14.4	37.5	6.9	32.9	4.9	16.7
	Slow Neutron	0.3	1.0	0.3	1.2	0.2	0.3	0.1	0.4
5.8 mrem PuBe-D_{20}	Pen or Gamma	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.1
	Nonpen or Beta	0.4	0.4	0.1	0.1	0.0	0.0	0.0	0.0
	Fast Neutron	45.9	49.0	40.6	13.2	12.9	18.6	13.1	16.7
	Slow Neutron	0.9	0.8	0.9	0.5	0.4	0.8	0.3	0.8

(a) The Hanford and modified Hanford equations calculated penetrating and nonpenetrating dose equivalent. Because the calibration data came from beta and gamma exposures, the least squares method calculated gamma and beta dose equivalent.

FIGURE 7.14. Plastic Disc Attached to MMPD

FIGURE 7.15a. Rando Phantom with Dosimeter Placement Around Thorax

FIGURE 7.15b. Rando Phantom with Dosimeter Placement Around Thorax

This experiment was repeated five times. The first used the HMPD and no plastic. The second used the MMPD without plastic. The next three used the MMPD with increasing thickness of attached plastic.

Dose equivalent values were computed using the standard equations of Table 7.2, the first iteration of the least squares method, and the full least squares method. Each dosimeter was assigned a position in degrees from the anterior center position of the phantom. The front center dosimeter was at 0° , the side-left was at 90° and the back-center was at 180° . The results of calculated dose equivalents for all 5 experiments are shown in Appendix D.

Figures 7.D.1 and 7.D.2 show that the modified dosimeter gave a slightly smoother response as the phantom was traversed. Also the full least squares method tended to smooth the response curve. Figures 7.D.2 through 7.D.5 show very little, if any, improvement in dosimeter response as thicker plastic is attached. This is because the high energy ^{252}Cf neutrons penetrate 1 or 2 inches before their first scatter, causing the 0.6 in. separation between TLD-600s to be too small to "see" tissue variations. (The HMPD has a 1 in. separation causing greater dependence on tissue variations.)

The conclusion from this test was that in a high energy neutron spectrum, such as bare ^{252}Cf , the attached discs are not necessary.

Third Experiment

The next experiment tested the possible advantage of the attached polyethylene discs in reducing the dependence of the multipurpose dosimeter on distance from the phantom. For this test, dosimeters were attached to the base of a 50 liter carboy which directly faced the $\text{PuBe-D}_2\text{O}$ thermal neutron source. The experimental setup is shown in Figure 7.13. Five dosimeters were spaced up to 4 cm from the carboy base, directly facing the $\text{PuBe-D}_2\text{O}$ source. Dosimeter attachment is shown in Appendix E. This was done to measure the effect of spacing between the dosimeter and phantom on the calculated fast neutron dose in a thermal neutron field. Results are shown in Figures 7.16 and 7.17.

When there was no plastic attached to the back of the dosimeter, the fast neutron dose was consistently underestimated as the gap between dosimeter and phantom increased. When a 1/4-in. disc was attached to the back of the dosimeter, the data was too scattered to make a definite judgement. However, the response no longer dropped with increasing distance. This was the expected result since the 0.25-in. plastic was over twice the thickness needed to scatter 50% of the thermal neutrons. A 1/4-in. disc of plastic is a reasonably good phantom in a thermal neutron field.

The majority of personnel neutron exposures at Hanford involve thermal neutrons.^(a) The dosimeter is rarely worn flat against the body, but is usually at least a couple centimeters away, often attached to clothing. It is impractical, therefore, to have a dosimeter which shows major distance dependence in these fields. Attaching a 1/4-in. plastic disc to the back of the dosimeter in theory should greatly reduce this distance dependence. Therefore, the modified design which is recommended in this study has a 1/4-in. thick disc attached behind it.

CONVERSION TO A CLEAR DOSIMETER HOLDER

Conversion of the dosimeter holder from the historically opaque ABS plastic to a clear plastic holder is desirable for cheap and rapid filter inspection. However, a clear holder would expose the TLD-700 in position 1 to ultraviolet, visible and infrared radiation. Initial tests indicated that normal sunlight exposure could significantly fade the TLD signal.

Experiments were performed to test for TLD signal fade and buildup. Sets of opaque and clear dosimeters were loaded with freshly annealed TLD chips. Some dosimeters were exposed to 1R ^{137}Cs . Some were given no exposure. Then these dosimeters were exposed to either a U.V. bacteriocidal lamp or to sunlight. Tables 7.5 and 7.6 briefly describe the exposures given and the results.

(a) Aldrich, Cummings, Endres, Fix, Kathren, Thorson, Hanford Dosimeter Supporting Studies, FY-1980, 1981.

FIGURE 7.16. Distance Dependence of MMPD Without Plastic When Exposed to 11.2 mrem Thermal Neutrons

FIGURE 7.17. Distance Dependence of MMPD with Plastic When Exposed to 11.2 mrem Thermal Neutrons

Both fading and buildup were observed in chip 1. Buildup had an equivalent signal strength of only 0.14 mrad per day sunlight. Fading of signal strength was much more important. It averaged about 4% signal loss per day of sunlight. The other TLD chips which are between opaque filters were not affected by the presence or absence of light. Another test demonstrated that an opaque plastic disc placed behind chip 1 would protect it from fading.

As a result of conclusions from this study, a clear dosimeter holder was implemented in January 1981. The savings in prevented filter inspection costs to be incurred by x-raying the holders was about \$1.50 per dosimeter holder. The overall additional cost avoided in the 1981 dosimeter exchange was \$25,000.

Mathematical Description of Fading and Buildup

Using the data from Tables 7.5 and 7.6 and an assumption on the mathematical relationship between thermoluminescence and sunlight exposure, an equation was derived to extrapolate data from low sunlight exposure to high sunlight exposure. The assumption was:

$$dTL = -K \cdot TL \cdot dt + b \cdot dt + c \cdot dt$$

where: TL = thermoluminescence of LiF TLD material in mrad beta
 K = rate of thermoluminescent fading, day sunlight⁻¹
 t = number of days that TLD chip is exposed to sunlight
 b = rate of thermoluminescent buildup from sunlight, thermoluminescence · day-sunlight⁻¹
 c = rate of thermoluminescent accumulation due to ionizing radiation exposure, thermoluminescence · day-sunlight⁻¹
 (For background radiation a value of 0.25 mR/Day⁻¹ would be typical)

b and K were solved for this equation by least squares fit to the data from Runs 2 and 3 (see Tables 7.5 and 7.6). The final integrated equation was:

$$\frac{c + 0.14 - 0.038 \cdot TL_f}{c + 0.14 - 0.038 \cdot TL_i} = e^{-0.038 \cdot t} \quad (9)$$

TABLE 7.5. UV/Sunlight Fade of TLD Thermoluminescence (1 rad ^{137}Cs Dose Through Front of Dosimeter Followed by UV or Sunlight Through Back of Dosimeter)

<u>Data Label</u>	<u>Description</u>	<u>Approximate quantity of radiation received</u>	<u>Percentage that Chip 1's thermoluminescence in the clear dosimeter was more than (+) or less than (-) that in the opaque dosimeter followed by the 95% confidence interval</u>	<u>Probability of this Happening Randomly</u>
Run 1 - Fade	Two opaque and two clear dosimeters each given 1R ^{137}Cs followed by 17 hours of exposure from a mercury vapor bacteriocidal lamp (~254 nm)	~1 kWh/m ² (~254 nm)	-4.2 ± 8.0%	32.7% (statistically insignificant)
Run 2 - Fade	One opaque and one clear dosimeter each given 1R ^{137}Cs followed by 4.7 days of sunlight (some overcast)	~30 kWh/m ² (sunlight)	-14.9 ± 8.4%	0.3% (statistically significant)
Run 3 - Fade	Four opaque and four clear dosimeters each given 1R ^{137}Cs followed by 3 days of sunlight	~20 kWh/m ²	-11.4 ± 4.0%	0.00005% (statistically significant)

TABLE 7.6. UV/Sunlight Buildup of TLD Thermoluminescence (UV or Sunlight Exposure Through Back of the Dosimeter)

<u>Data Level</u>	<u>Description</u>	<u>Approximate Quantity of Radiation REceived</u>	<u>Amount that Chip 1's thermolumine- scence in the clear dosimeter was more than (+) or less than (-) that in the opaque dosimeter followed by the 95% confidence interval. Units are in nanocoulombs (nc). (1 nc = 2.22 mrad beta)</u>	<u>Probability of this Happening Randomly</u>
Run 1 - Buildup	Two opaque and two clear dosim- eters each given 17 hours exposure from a mercury-vapor, bacteriocidal lamp (~254 nm)	~1 kWh/m ² (~254 nm)	-0.19 ± 0.23 nc	87.9 % (statistically insignificant)
Run 2 - Buildup	One opaque and one clear dosim- eter each given 3 days of sunlight	~20 kWh/m ² (sunlight)	+0.177 ± 0.073 nc	0.0008 % (statistically significant)

where: TL_f = thermoluminescence after sunlight exposure
 TL_i = thermoluminescence before sunlight exposure (Units of thermoluminescence are such that one thermoluminescent unit equals one mrad beta).

This equation provides an initial estimate of thermoluminescence signal of TLD chip 1 as a function of amount of sunlight exposure.

Cause of Fading

Fading of TLD signal could have been due to either photon excitation of the crystal by sunlight or thermal excitation. The rate of expected signal loss due to thermal excitation or annealing was previously described in the section "Pre-readout Anneal." Solving Equation 7, a temperature of 180°F for eight hours of each day would have been necessary to produce the same rate of signal loss. This high of a TLD temperature was felt unreasonable because the air temperature during the tests was less than 70°F. We do not think sunlight on these days could have heated the TLDs a full 110°F above ambient.

We believe the signal loss was due to direct photon excitation of the crystal. This correlates well with the activation energy previously determined in the "Prereadout Anneal" section. The activation energy of the main thermoluminescent peak was calculated to be 23.4 Kcal/gmole. This corresponds to electromagnetic radiation of wavelength 1.2 microns. Seventy-nine percent of solar radiation is of shorter wavelength (Weast 1971). Therefore, most sunlight has sufficient energy to activate luminescence in the TLD crystal. We believe visible light activates the TLD luminescent traps so that the crystal gives off some of its stored luminescence. If the TLD crystal is exposed in the holder to light, its signal can also be faded by intense sunlight.

Elimination of Fading

The signal fading in TLD chip 1 can be completely eliminated by attaching an opaque plastic disc behind the dosimeter holder. The disc must prevent essentially all light from directly shining on the TLD. This was demonstrated by repeating the previous experiment with clear and opaque holders irradiated to 1R ^{137}Cs gamma then exposed to 3 days of sunlight. This time the clear

holders had a black plastic disc in the recess behind Chip 1. The clear holders with the opaque disc gave a signal only 0.7% less than the original opaque holders. This was well within the experimental confidence of $\pm 3.7\%$.

TLD ENCLOSURE

TLD chips in the HMPD are currently enclosed in an envelope of Scotch Brand Teflon. This protects the TLD from dirt and chemicals, It also holds the TLD during automated readout. Manufacture of this teflon was discontinued several years ago and the Hanford supplies are rapidly dwindling. Because of the impending need, we looked for a suitable replacement. We tried to find a film with greater heat stability, lower natural luminescence, and equivalent light transfer properties.

Two satisfactory film enclosures were found. One was a teflon product made by duPont which we recommend for immediate replacement of the old teflon. The other was a combination consisting of polyimide on the hot prod side, polyimide spacer and teflon on the light pipe side. This enclosure gives greater heat stability and less dependence upon the reflectivity of the hot prod.

Performance Testing of New Teflon

To solve the short term problem of our Teflon shortage we would ideally want a replacement film which has the same transparency and heat transfer properties as the old Teflon. To test this, 10 inserts were constructed using the old Teflon and 10 with the new Teflon.^(a) Each was exposed to 10 mrem PuBe-D₂O and 200 mR ¹³⁷Cs. Then each was read on Hanford Reader 2. The readings through the new Teflon were 1% higher than those through the old Teflon. This was well within the 95% range of confidence of the experiment ($\pm 4\%$). Thus the new Teflon performance most likely is within 5% of the old Teflon performance.

The replacement film also needs to be durable enough to withstand 10 years of repetitive readings on the Hanford reader. This means it must withstand

(a) The new Teflon is an extruded, fused plastic marketed by L. A. Sanders Engineering under the code S-24.

about 50 readings without stretching enough to allow tearing during normal use. To test this, one insert of each old and new Teflon was repetitively read on Reader 2. When stretching was serious enough to cause a significant risk of tearing under normal field use, the insert was replaced with a new insert. Serious stretching of the old Teflon started after about 12 readings. It was serious enough to replace after 37 readings. The new Teflon stretched much less. After 65 readings, it was about the same as the old Teflon was after 3 or 4 readings. The new Teflon is much better than the old Teflon from the viewpoint of thermal stability.

The old Teflon has a natural thermoluminescence. It corresponds to about the same thermoluminescence expected from a TLD chip after a 2 mR gamma exposure. The new Teflon has almost twice as much thermoluminescence. However, this should not cause major problems because the time between readouts normally is relatively short so that signal build-up should be relatively small.

Better Long Term Replacement

The new Teflon was selected for immediate replacement because it had the same light transfer properties as the old Teflon; thus, it would not require a separate calibration set. A better film combination was also tested which combined the good light transfer of Teflon with the greater heat stability of polyimide film. The combination had polyimide film on the hot prod side, polyimide spacer and Teflon on the light-pipe side. The polyimide film was a "Kapton," type H, made by duPont. After 65 readings on Hanford Reader 2, it showed almost no film stretch. Its heat stability is significantly better than that of both the old and new Teflon. However, the total light transfer of this combination to the photomultiplier tube is only 78% of that of the Teflon combination. This is because polyimide is yellow and prevents much of the light from reflecting off the hot prod and back to the photomultiplier. This is a desirable property in that it reduces the effect of the dirtiness of the hot prod on reader signal. Unfortunately, a gradual transition between the current inserts and this polyimide Teflon "sandwich" would require a dual set of calibrations.

Conversion to the polyimide Teflon "sandwich" would allow a higher anneal temperature than currently used. How high is unknown, although polyimide is rated to 315°C; whereas Teflon is only rated to 260°C. The current readout appears to anneal the TLD to about 230°C.^(a) Ideally the anneal would bring the TLD well above the second thermoluminescent peak of 255°C. Polyimide might provide the needed heat stability for a 50°C increase in anneal temperature, which should be sufficient. This should be tested and demonstrated before implementation.

Conversion to a polyimide-Teflon enclosure could best be accomplished with a complete dosimeter exchange. This would avoid the problem of dual calibrations due to two types of enclosures.

GLOSSARY

A	Component of TLD response resulting from all gamma or beta radiation except that due to Cd capture of neutrons
B	Component of TLD response resulting from thermal neutron radiation
C	Component of TLD response resulting from gamma or beta radiation emitted by Cd when neutrons are captured
Cd	Cadmium
D	Component of TLD response resulting from epithermal neutrons
d	Distance radiation traverses through material
de	Dose equivalent
E	Activation energy of thermoluminescent peak
FN	Fast neutron dose equivalent
HMPD	Hanford Multipurpose Dosimeter
Ko	Reaction rate constant
Ln	Natural logarithm
MMPD	Modified Multipurpose Dosimeter
N	Number of atoms per unit volume
Nonpen	Nonpenetrating dose equivalent

(a) Further information is found in Study 8.

Pen	Penetrating dose equivalent
$\text{PuBe-D}_2\text{O}$	Source for thermal neutron exposures shown in Figure 7.13.
R	Universal gas constant
R1	Thermoluminescent reading of TLD chip 1
R2	Thermoluminescent reading of TLD chip 2
R3	Thermoluminescent reading of TLD chip 3 (R3' denotes modified dosimeter)
R4	Thermoluminescent reading of TLD chip 4
R5	Thermoluminescent reading of TLD chip 5 (R5' denotes modified dosimeter)
rms	Root mean square
$S_{\text{—}}$	Standard deviation of —
SN	Slow neutron dose equivalent
Sn	Tin
T	Temperature in degrees Kelvin
t	Time in seconds
TL	Thermoluminescence in reader counts
Z	Sum of squares of deviations divided by standard deviation
$\sigma_{a,i}$	Cross section for absorption of material i

Subscripts

B	Component of TLD response due to radiation coming through the rear dosimeter filter
E	Component of TLD response due to radiation passing between the front and back filter
F	Component of TLD response due to radiation coming through the front dosimeter filter
X	Expected TLD reading.
600	TLD-600

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APPENDIX A

DERIVATION OF FAST NEUTRON DEPENDENCE

APPENDIX A

DERIVATION OF FAST NEUTRON ENERGY DEPENDENCE

The fast neutron energy dependence of an albedo dosimeter, such as Hanford's, can be separated into three main components:

- energy dependence due to flux to dose equivalent conversion
- energy dependence due to fraction of incident fast neutrons reflected as thermal neutrons
- energy dependence due to neutron absorption by the neutron filters.

All three components combine to give the total response as a function of energy.

The total fast neutron response due to these three components is represented by the following equation:

$$FN \propto \left(\frac{\text{Flux}}{de} \right) \cdot \left[f - \left(\frac{\% \text{ neutrons captured without Cd filter}}{\% \text{ neutrons captured without Cd filter}} - \frac{\% \text{ neutrons captured with Cd filter}}{\% \text{ neutrons captured with Cd filter}} \right)_{\text{THN}} \cdot f_{\text{THN}} \right]$$

where de = dose equivalent

f = fraction of neutrons incident on the body reflected as thermal neutrons

$_{\text{THN}}$ = value when exposed to only thermal neutrons.

At neutron energies above 10 keV the flux to dose equivalent conversion is the dominant factor. Figure 7.4 of the text shows its dramatic decrease as neutron energies increase beyond 10 keV. Between 10 keV and 1 MeV the flux per unit dose equivalent drops by a factor of 25.

The percent of neutrons captured by cadmium is the dominating factor below 1 eV. Above 2 eV it is relatively insignificant. This can be seen in Figure 7.3 of the text.

The fraction of incident fast neutrons reflected as thermal neutrons has a slight effect over the whole spectrum. It decreases gradually as the neutron energy increases. At 1 MeV it is one sixth of that at thermal energies (Nagarajan and Krishnan 1969).

The final solution to the above equation is shown graphically in Figure 7.5.

APPENDIX B

LEAST SQUARES METHOD

APPENDIX B

LEAST SQUARES METHOD

The least squares method minimizes the amount of discrepancy between the data and assigned dose equivalent. Mathematically the minimized sum of squares (Z) is:

$$Z = \left(\frac{R1 - R1_x}{SR1} \right)^2 + \left(\frac{R2 - R2_x}{SR2} \right)^2 + \left(\frac{R3 - R3_x}{SR3} \right)^2 + \left(\frac{R4 - R4_x}{SR4} \right)^2 + \left(\frac{R5 - R5_x}{SR5} \right)^2$$

(The definition of each term is in the Glossary.)

Each expected value of R1 through R5 is a function of the amount of the four radiation types determined. The expected values are shown mathematically below:

$$\begin{aligned} R1_x &= X(1,1) \cdot \text{PEN} + X(1,2) \cdot \text{NONPEN} + X(1,3) \cdot \text{FN} + X(1,4) \cdot \text{SN} \\ R2_x &= X(2,1) \cdot \text{PEN} + X(2,2) \cdot \text{NONPEN} + X(2,3) \cdot \text{FN} + X(2,4) \cdot \text{SN} \\ R3_x &= X(3,1) \cdot \text{PEN} + X(3,2) \cdot \text{NONPEN} + X(3,3) \cdot \text{FN} + X(3,4) \cdot \text{SN} \\ R4_x &= X(4,1) \cdot \text{PEN} + X(4,2) \cdot \text{NONPEN} + X(4,3) \cdot \text{FN} + X(4,4) \cdot \text{SN} \\ R5_x &= X(5,1) \cdot \text{PEN} + X(5,2) \cdot \text{NONPEN} + X(5,3) \cdot \text{FN} + X(5,4) \cdot \text{SN} \end{aligned}$$

The definitions of PEN, NONPEN, FN, and SN are in the Glossary. X(1,1) through X(5,1) correspond to the expected TLD response of chip 1 through 5 to a penetrating exposure of 1 mrem. Similarly X(1,2) through X(5,2) correspond to the expected TLD response of chip 1 through 5 to a nonpenetrating exposure of 1 mrem. X(1,3) through X(5,3) are expected fast neutron responses, and X(1,4) through X(5,4) are expected slow neutron responses of chips 1 through 5.

To minimize Z, the four possible partial derivatives are all set equal to zero:

$$\frac{\partial Z}{\partial \text{PEN}} = 0; \quad \frac{\partial Z}{\partial \text{NONPEN}} = 0; \quad \frac{\partial Z}{\partial \text{FN}} = 0; \quad \frac{\partial Z}{\partial \text{SN}} = 0$$

These yield four equations with four unknowns. The first equation is solved as an example below:

$$\begin{aligned}
0 = \frac{\partial Z}{\partial \text{PEN}} = & 2 \cdot \left(\frac{R1 - X(1,1) \cdot \text{PEN} + X(1,2) \cdot \text{NONPEN} + X(1,3) \cdot \text{FN} + X(1,4) \cdot \text{SN}}{\text{SR1}} \right) \cdot \frac{-X(1,1)}{\text{SR1}} \\
& + 2 \cdot \left(\frac{R2 - X(2,1) \cdot \text{PEN} + X(2,2) \cdot \text{NONPEN} + X(2,3) \cdot \text{FN} + X(2,4) \cdot \text{SN}}{\text{SR2}} \right) \cdot \frac{-X(2,1)}{\text{SR2}} \\
& + 2 \cdot \left(\frac{R3 - X(3,1) \cdot \text{PEN} + X(3,2) \cdot \text{NONPEN} + X(3,3) \cdot \text{FN} + X(3,4) \cdot \text{SN}}{\text{SR3}} \right) \cdot \frac{-X(3,1)}{\text{SR3}} \\
& + 2 \cdot \left(\frac{R4 - X(4,1) \cdot \text{PEN} + X(4,2) \cdot \text{NONPEN} + X(4,3) \cdot \text{FN} + X(4,4) \cdot \text{SN}}{\text{SR4}} \right) \cdot \frac{-X(4,1)}{\text{SR4}} \\
& + 2 \cdot \left(\frac{R5 - X(5,1) \cdot \text{PEN} + X(5,2) \cdot \text{NONPEN} + X(5,3) \cdot \text{FN} + X(5,4) \cdot \text{SN}}{\text{SR5}} \right) \cdot \frac{-X(5,1)}{\text{SR5}}
\end{aligned}$$

The terms of this equation are collected as shown below after dividing through by the factor of 2:

$$\begin{aligned}
& \text{PEN} \cdot \left[\frac{X(1,1) \cdot X(1,1)}{\text{SR1}^2} + \frac{X(2,1) \cdot X(2,1)}{\text{SR2}^2} + \frac{X(3,1) \cdot X(3,1)}{\text{SR3}^2} + \frac{X(4,1) \cdot X(4,1)}{\text{SR4}^2} + \frac{X(5,1) \cdot X(5,1)}{\text{SR5}^2} \right] \\
& + \text{NONPEN} \cdot \left[\frac{X(1,2) \cdot X(1,1)}{\text{SR1}^2} + \frac{X(2,2) \cdot X(2,1)}{\text{SR2}^2} + \frac{X(3,2) \cdot X(3,1)}{\text{SR3}^2} + \frac{X(4,2) \cdot X(4,1)}{\text{SR4}^2} + \frac{X(5,2) \cdot X(5,1)}{\text{SR5}^2} \right] \\
& + \text{FN} \cdot \left[\frac{X(1,3) \cdot X(1,1)}{\text{SR1}^2} + \frac{X(2,3) \cdot X(2,1)}{\text{SR2}^2} + \frac{X(3,3) \cdot X(3,1)}{\text{SR3}^2} + \frac{X(4,3) \cdot X(4,1)}{\text{SR4}^2} + \frac{X(5,3) \cdot X(5,1)}{\text{SR5}^2} \right] \\
& + \text{SN} \cdot \left[\frac{X(1,4) \cdot X(1,1)}{\text{SR1}^2} + \frac{X(2,4) \cdot X(2,1)}{\text{SR2}^2} + \frac{X(3,4) \cdot X(3,1)}{\text{SR3}^2} + \frac{X(4,4) \cdot X(4,1)}{\text{SR4}^2} + \frac{X(5,4) \cdot X(5,1)}{\text{SR5}^2} \right] \\
& = \left[\frac{R1 \cdot X(1,1)}{\text{SR1}^2} + \frac{R2 \cdot X(2,1)}{\text{SR2}^2} + \frac{R3 \cdot X(3,1)}{\text{SR3}^2} + \frac{R4 \cdot X(4,1)}{\text{SR4}^2} + \frac{R5 \cdot X(5,1)}{\text{SR5}^2} \right]
\end{aligned}$$

This process is repeated for the other three partial derivatives. The solution to these four equations with four unknowns is symbolized in matrix form below:

The original four equations with four unknowns is:

$$\begin{array}{cccc|c} \text{PEN} & \text{NONPEN} & \text{FN} & \text{SN} & \\ \left[\begin{array}{c} \\ \\ \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ \\ \end{array} \right] \end{array} \quad \text{Matrix \#1}$$

This reduces to:

$$\begin{array}{cccc|c} 1 & 0 & 0 & 0 & \text{PEN} \\ 0 & 1 & 0 & 0 & \text{NONPEN} \\ 0 & 0 & 1 & 0 & \text{FN} \\ 0 & 0 & 0 & 1 & \text{SN} \end{array}$$

If any dose equivalent value is negative that value is set equal to zero. For example, if the fast neutron dose is calculated as negative, the original matrix would be repeated with fast neutron dose equal to zero, then the matrix would be solved:

$$\begin{array}{cccc|c} \text{PEN} & \text{NONPEN} & \text{FN} & \text{SN} & \\ \left[\begin{array}{c} \\ \\ 0 \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ 0 \\ \end{array} \right] & \begin{array}{c} 0 \\ 0 \\ 1 \\ 0 \end{array} & \left[\begin{array}{c} \\ \\ 0 \\ \end{array} \right] & \left[\begin{array}{c} \\ \\ 0 \\ \end{array} \right] \end{array} \quad \text{Matrix \#2}$$

This reduces to:

$$\begin{array}{cccc|c} 1 & 0 & 0 & 0 & \text{PEN} \\ 0 & 1 & 0 & 0 & \text{NONPEN} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & \text{SN} \end{array}$$

If any dose equivalent values are calculated as negative values, the most negative (largest in absolute terms) value is set equal to zero and another matrix is produced such as the one below:

$$\left| \begin{array}{cc} [&] & [&] & 0 & 0 \\ [&] & [&] & 0 & 0 \\ & 0 & & 0 & 1 & 0 \\ & 0 & & 0 & 0 & 1 \end{array} \right| \left| \begin{array}{c} [&] \\ [&] \\ 0 \\ 0 \end{array} \right|$$

This matrix is solved and the final answer is the most probable dose equivalent.

APPENDIX C

COMPARISON OF MODIFIED DOSIMETER WITH HMPD

TABLE 7.C.1. Calculated Mean $\pm$ Standard Deviation in mrem116 mrem ^{60}Co

Anneal Before Readout 170°C, 75 min	D.E. (a) Category	5 Chip HMPD		Modified MPD		Modified Dosimeter-II	
		Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method
No	Pen/Gamma	117.9 $\pm$ 5.1	116.1 $\pm$ 1.5	118.5 $\pm$ 6.3	115.0 $\pm$ 3.3	117.9 $\pm$ 5.1	113.5 $\pm$ 4.0
Anneal	Nonpen/Beta	8.5 $\pm$ 11.1	4.6 $\pm$ 3.5	4.5 $\pm$ 7.6	4.7 $\pm$ 6.9	4.2 $\pm$ 5.0	5.8 $\pm$ 6.2
Before	Fast Neutron	2.4 $\pm$ 7.3	2.0 $\pm$ 4.0	6.5 $\pm$ 9.8	2.6 $\pm$ 3.8	5.8 $\pm$ 9.5	1.9 $\pm$ 3.7
Readout	Slow Neutron	0.2 $\pm$ 0.1	0.0 $\pm$ 0.0	0.3 $\pm$ 0.5	0.1 $\pm$ 0.1	0.3 $\pm$ 0.5	0.2 $\pm$ 0.3
	rms(s)	7.1	2.8	7.0	4.3	5.9	4.2
Anneal	Pen/Gamma	117.9 $\pm$ 5.1	117.1 $\pm$ 2.0	118.5 $\pm$ 5.9	118.0 $\pm$ 4.6		
Only	Nonpen/Beta	8.5 $\pm$ 11.1	3.1 $\pm$ 3.5	4.4 $\pm$ 7.1	3.7 $\pm$ 6.4		
TLD-600s	Fast Neutron	9.6 $\pm$ 7.0	4.1 $\pm$ 1.5	1.8 $\pm$ 1.2	2.3 $\pm$ 1.3		
	Slow Neutron	0.1 $\pm$ 0.1	0.0 $\pm$ 0.0	0.0 $\pm$ 0.1	0.2 $\pm$ 0.1		
	rms(s)	7.1	2.2	4.7	4.0		
Anneal	Pen/Gamma			142.9 $\pm$ 6.1	139.8 $\pm$ 5.0		
All	Nonpen/Beta			2.4 $\pm$ 3.8	2.1 $\pm$ 3.4		
TLDs	Fast Neutron			1.8 $\pm$ 1.2	1.1 $\pm$ 0.9		
	Slow Neutron			0.0 $\pm$ 0.1	0.1 $\pm$ 0.0		
	rms(s)			3.6	3.0		

(a) The Hanford and modified Hanford equations calculated penetrating and nonpenetrating dose equivalent. Because the calibration data came from beta and gamma exposures, the least squares method calculated gamma and beta dose equivalent.

TABLE 7.C.1. (contd)

88 mrem ^{90}Sr

Anneal Before Readout 170°C, 75 min	D.E. (a) Category	5 Chip HMPD		Modified MPD		Modified Dosimeter-II	
		Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method
No Anneal Before Readout	Pen/Gamma	22.0 ± 2.9	2.0 ± 0.2	2.8 ± 0.2	2.3 ± 0.1	22.0 ± 2.9	1.9 ± 0.3
	Nonpen/Beta	87.7 ± 10.0	85.6 ± 6.2	87.1 ± 4.6	87.3 ± 4.6	88.3 ± 4.7	87.0 ± 6.1
	Fast Neutron	0.6 ± 1.1	0.4 ± 0.5	0.6 ± 0.9	0.2 ± 0.4	0.6 ± 0.9	0.6 ± 0.9
	Slow Neutron	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	rms(s)	5.3	3.1	2.3	2.3	2.8	3.1
Anneal Only TLD-600s	Pen/Gamma	22.2 ± 3.1	2.0 ± 0.2	2.8 ± 0.2	2.4 ± 0.2		
	Nonpen/Beta	87.9 ± 10.7	86.5 ± 5.1	87.1 ± 4.6	87.1 ± 4.6		
	Fast Neutron	17.3 ± 4.6	7.6 ± 0.7	0.5 ± 0.6	3.2 ± 1.1		
	Slow Neutron	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.0		
	rms(s)	6.0	2.6	2.3	2.4		
Anneal All TLDs	Pen/Gamma			35.2 ± 2.6	36.3 ± 2.6		
	Nonpen/Beta			82.6 ± 5.4	80.7 ± 5.4		
	Fast Neutron			0.5 ± 0.6	1.1 ± 0.9		
	Slow Neutron			0.0 ± 0.0	0.1 ± 0.0		
	rms(s)			3.0	3.0		

(a) The Hanford and modified Hanford equations calculated penetrating and nonpenetrating dose equivalent. Because the calibration data came from beta and gamma exposures, the least squares method calculated gamma and beta dose equivalent.

TABLE 7.C.1. (contd)

110.8 mrem ^{252}Cf

Anneal Before Readout 170°C, 75 min	D.E. (a) Category	5 Chip HMPD		Modified MPD		Modified Dosimeter-II	
		Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method
No	Pen/Gamma	7.6 ± 0.5	7.0 ± 0.2	8.9 ± 0.5	7.2 ± 0.5	7.7 ± 0.5	6.6 ± 0.4
Anneal	Nonpen/Beta	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.3	0.1 ± 0.3
Before	Fast Neutron	116.0 ± 26.5	103.5 ± 14.4	108.5 ± 6.8	110.0 ± 4.9	110.8 ± 9.8	112.4 ± 5.5
Readout	Slow Neutron	0.2 ± 0.3	0.2 ± 0.3	0.6 ± 0.2	0.1 ± 0.1	0.6 ± 0.2	0.1 ± 0.1
	rms(s)	13.3	7.2	3.4	2.4	4.9	2.8
Anneal	Pen/Gamma	7.6 ± 0.5	7.0 ± 0.2	8.8 ± 0.5	7.3 ± 0.5		
Only	Nonpen/Beta	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0		
TLD-600s	Fast Neutron	134.1 ± 66.7	91.2 ± 37.5	110.9 ± 32.9	117.8 ± 16.7		
	Slow Neutron	1.9 ± 1.0	0.7 ± 1.2	0.7 ± 0.3	0.3 ± 0.4		
	rms(s)	33.3	18.8	16.5	8.4		
Anneal	Pen/Gamma			36.4 ± 2.7	29.7 ± 2.5		
All	Nonpen/Beta			0.6 ± 2.0	0.7 ± 2.4		
TLDs	Fast Neutron			115.1 ± 31.0	113.3 ± 14.6		
	Slow Neutron			0.7 ± 0.3	0.2 ± 0.3		
	rms(s)			15.6	7.5		

(a) The Hanford and modified Hanford equations calculated penetrating and nonpenetrating dose equivalent. Because the calibration data came from beta and gamma exposures, the least squares method calculated gamma and beta dose equivalent.

TABLE 7.C.1. (contd)

5.8 mrem PuBe-D₂O

Anneal Before Readout 170°C, 75 min	D.E. (a) Category	5 Chip HMPD		Modified MPD		Modified Dosimeter-II	
		Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method	Modified Hanford Equations	Least Squares Method
No Anneal Before Readout	Pen/Gamma	7.2 ± 0.3	6.0 ± 0.2	8.5 ± 0.3	5.6 ± 0.3	7.2 ± 0.3	5.2 ± 0.2
	Non/Beta	0.1 ± 0.4	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Fast Neutron	25.8 ± 45.9	20.2 ± 40.6	7.4 ± 12.9	8.2 ± 13.0	7.4 ± 12.9	9.5 ± 13.8
	Slow Neutron rms(s)	5.8 ± 0.9 22.9	5.4 ± 0.9 20.3	5.8 ± 0.4 6.5	5.7 ± 0.3 6.5	5.8 ± 0.4 6.5	5.7 ± 0.3 6.9
Anneal Only TLD-600s	Pen/Gamma	7.2 ± 0.3	5.9 ± 0.2	8.5 ± 0.3	5.7 ± 0.1		
	Nonpen/Beta	0.1 ± 0.4	0.0 ± 0.1	0.9 ± 0.9	0.0 ± 0.0		
	Fast Neutron	40.3 ± 49.0	5.2 ± 13.2	15.9 ± 18.6	19.8 ± 16.7		
	Slow Neutron rms(s)	5.9 ± 0.8 24.5	6.0 ± 0.5 6.6	5.7 ± 0.8 9.3	5.7 ± 0.8 8.4		
Anneal All TLDs	Pen/Gamma			40.3 ± 2.2	33.7 ± 2.2		
	Nonpen/Beta			0.3 ± 0.9	0.4 ± 1.2		
	Fast Neutron			11.2 ± 16.7	15.1 ± 15.3		
	Slow Neutron rms(s)			5.8 ± 0.9 8.5	5.7 ± 0.6 7.8		

(a) The Hanford and modified Hanford equations calculated penetrating and nonpenetrating dose equivalent. Because the calibration data came from beta and gamma exposures, the least squares method calculated gamma and beta dose equivalent.

APPENDIX D

EFFECT OF ATTACHED POLYETHYLENE DISCS

FIGURE 7.D.1. Current Hanford Dosimeter on Rando Phantom, 104.4 mrem ^{252}Cf

7.D.2

FIGURE 7.D.2. Modified Dosimeter With No Plastic on Rando Phantom, 110.6 mrem ^{252}Cf

FIGURE 7.D.3. Modified Dosimeter With 1/8 Inch Plastic on Rando Phantom, 105.0 mrem ^{252}Cf

7.D.4

FIGURE 7.D.4. Modified Dosimeter With 1/4 Inch Plastic on Rando Phantom, 106.5 mrem ^{252}Cf

FIGURE 7.D.5. Modified Dosimeter With 3/8 Inch Plastic on Rando Phantom, 107.9 mrem ^{252}Cf

APPENDIX E

DOSIMETER ATTACHMENT TESTING DISTANCE DEPENDENCE

FIGURE 7.E.1. Spacing of MMPD Without Plastic From Water Jug

FIGURE 7.E.2. Spacing of MMPD With Plastic From Water Jug

8.0 STUDY 8 - DOSIMETER ANNEALING, SENSITIZATION AND SCREENING

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FOREWORD

The reader annealing process was examined along with other factors affecting dosimeter sensitivity. Buildup in unannealed traps was found to be a major contributor to sensitivity differences among Hanford calibration and personnel pool dosimeters. A correction factor was developed to account for increased sensitivity when dosimeters are read soon after irradiation; however, a similar investigation failed to reveal an effect for short anneal-to-irradiation times. Screening procedures for TLDs entering the Hanford system, which provide a baseline for dosimeter sensitivity, are discussed in Appendix 8.A.

SUMMARY

Analysis of glow curves from Hanford calibration and background dosimeters indicated that the reader anneal time and temperature are insufficient to anneal traps with activation temperatures above 240°C. Incomplete reader annealing of the 250°C neutron-sensitive trap in TLD-600s was observed in new dosimeters after thermal neutron doses as small as 10 mrem. The resulting trap buildup in both TLD-600s and TLD-700s contributes to apparent sensitivity differences among calibration and personnel pool dosimeters. These differences, however, are difficult to quantify without the use of large sample sizes.

The decline in chip response as a function of the time between irradiation and readout was gradual over the three day period studied. Averaged chip responses for the two and four hour decay times were roughly 7% higher than chip responses three days after irradiation. No significant increase in sensitivity was observed when dosimeters were irradiated as soon as two hours after annealing.

(a) U.S. Testing Company.

INTRODUCTION

The annealing process is one of several potential sources of bias and uncertainty in the personnel dosimetry system. Inadequate heating of TLDs results in a gradual buildup in unannealed and partially annealed traps in the phosphor, some of which appears as a false dose during readout. Acceptance and screening procedures for new and recycled phosphor will determine the minimum amount of variance present in the dosimeter population. Tight control over both the annealing and screening procedures is therefore necessary for a good quality assurance program. Other factors influencing dosimeter performance include the readout process, dosimeter handling procedure, the length of time between exposure and readout, and the time between anneal and exposure.

All Hanford multipurpose and "basic" dosimeters are annealed through the Hanford readout cycle. A heater probe, initially at 298–312°C, contacts one side of the teflon surrounding the TLDs. After a drop of approximately 15°C, the probe temperature returns to near 300°C. Dosimeter positions are read successively with some variance in the initial and final probe temperatures. Each chip is heated for 20 seconds. Actual chip temperatures are somewhat lower than the heater temperature, since the dosimeter insert acts as a heat sink. Consequently, several reader anneals are often required to reduce chip readings to "background" levels.

Due to the gradual buildup in trap populations when the reader anneal is used, dosimeters receiving frequent or large exposures appear to be more sensitive than dosimeters with lower cumulative exposures. This increase in response is actually a larger chip "background" component. Apparent sensitivity differences among groups of dosimeters in the Hanford system have been observed for several years. The most serious difference is the higher response of calibration dosimeters when compared to personnel pool dosimeters. Audit dosimeters are used to correct the bias; however, a modification of the annealing process to eliminate the problem would be preferable.

Sensitivity changes are also caused by varying the waiting period between exposure and readout. Low energy traps in the phosphor are annealed at room temperature. As a result, chips read immediately after irradiation yield

higher doses than chips read several days after irradiation. The severity of the effect is a function of the reader heating cycle. In accident situations, dosimeters must sometimes be read within hours. Therefore, it is necessary to determine the increase in response when dosimeters are read immediately.

The same low energy traps may be sensitized by the annealing process. Laboratory TLDs irradiated soon after a 400°C anneal have been observed to exhibit larger responses than TLDs stored for several days before exposure. Since this varies with the annealing and readout processes, it is necessary to determine whether the effect is significant for Hanford personnel dosimeters.

METHODS AND RESULTS

Trap Buildup in Calibration and Background Dosimeters

Investigations of the role of the reader anneal in biasing Hanford calibrations utilized both the Hanford automated system (reader 2) and the PNL manual readers. Chips for several reader-annealed calibration dosimeters were read on the laboratory planchet reader after receiving mixed thermal neutron-gamma irradiations. Chips from unirradiated background dosimeters were also included. The first readout to 280°C measured the signal from dosimetry peaks while the second readout to 400°C represented buildup in higher energy traps. A third readout to 400°C measured the infrared background from the heated TLD and planchet. TLD chips were then laboratory annealed at 400° for one hour and subsequently at 100°C for two hours and the steps were repeated.

Glow curves from the TLDs showed differences in higher temperature trap populations, particularly before and after the laboratory anneal. These are represented in Figures 8.1 through 8.3. Differences in chip response for the calibration dosimeter chips are shown in Table 8.1 with the uncertainties for the last digit shown in parenthesis.

TLD 600 FROM A BACKGROUND
BADGE WITH ABNORMALLY
HIGH READINGS. NOTE THE
SHARP RISE IN LIGHT OUTPUT
AFTER 240-250°C, INDICATING
RESIDUAL TRAP POPULATION

TLD 600 FROM A "NORMAL"
BACKGROUND BADGE FOR
COMPARISON

FIGURE 8.1. Glow Curves - TLDs from Background Dosimeters
(Relative Output, Log Scale, Versus Readout
Temperature)

TLD 600 FROM A READER ANNEALED
CALIBRATION BADGE, GIVEN A
MIXED n - γ EXPOSURE, READ
TWICE TO 280°C THEN 400°C

TLD 600 GIVEN THE SAME
EXPOSURE AFTER A LABORATORY
400°C ANNEAL, READ TO 280°C
TWICE THEN 400°C

FIGURE 8.2. Glow Curves - TLD-600s from Calibration Dosimeters,
After Reader Annealing and Laboratory Annealing
(Relative Output, Log Scale, Versus Reader Temperature)

FIGURE 8.3. Glow Curves - TLD-700s from Calibration Dosimeters, After Reader Annealing and Laboratory Annealing (Relative Output, Log Scale, Versus Reader Temperature)

TABLE 8.1. Reader Annealing Versus Laboratory Annealing –
Trap Buildup in Hanford Calibration Dosimeters

Ratio of chip responses between reader annealed and laboratory
annealed chips(a,b).

	<u>First Readout, 280°C</u>	<u>Second Readout, 400°C</u>
TLD 700s	1.31 ± 0.02	1.68 ± 0.21
TLD 600s	1.37 ± 0.04	1.34 ± 0.09

(a) Chips exposed to 250 mR gamma and 10 mrem thermal
neutrons.

(b) Quoted uncertainties reflect the standard error of the
mean TLD reading.

Chip response ratios for the 0–280°C readout also reflect the buildup in the 250°C peak. This difference of ~30% is consistent with previous observations. Buildup in the 400°C readout is largely due to the presence of a broad peak at 310–360°C. The impact of this peak upon the Hanford readout is uncertain.

Residual Trap Population After One Reader Anneal

New dosimeters which had been previously exposed only during screening were used to measure residual trap populations in reader annealed dosimeter. Dosimeters were reader annealed twice and irradiated with 250 mR gamma and 10 mrem thermal neutrons. All dosimeters were read three days after irradiation with half reread the same day and half reread 24 hours later; any effects due to reader sensitization of the TLDs could be corrected by comparing results for the second readings. Unirradiated new dosimeters were used for TLD and reader background subtraction on all readings.

Results are shown in Table 8.2. Readings were corrected for background. Gamma components were estimated and subtracted from chips 3 and 4 to obtain the neutron components. Little or no residual appeared in the second readouts of TLD–700s; however, the second readings for TLD–600s were significantly above background. Approximately 1–2% of the original neutron signal in chips 3 and 4 appeared in the second readout. No effect was observed from waiting 24 hours to reread the dosimeters, so all second readouts were pooled.

TABLE 8.2. Residual Signal After One Reader Anneal

	<u>Chip 1</u>	<u>Chip 2</u>	<u>Chip 3</u>	<u>Chip 4</u>	<u>Chip 5</u>
First Readings, Neutron + Gamma ($\pm\sigma_u$)	2187 ± 21	2688 ± 28	5295 ± 101	3732 ± 72	2321 ± 36
First Readings, Estimated Neutron Component	-	-	~2474	~1221	-
Second Readings (with reader background)	23.3 ± 1.8	25.9 ± 1.5	49.8 ± 3.2	48.6 ± 2.7	26.3 ± 4.6
Second Readings (reader background subtracted)	-	-	24.5 ± 3.4	20.9 ± 3.4	-

Although this buildup appears to be small, it must be remembered that this is the "best case." Chip responses of this magnitude are disregarded by the Hanford reader algorithm. However, the effect will be much worse for higher neutron doses and older dosimeters. Although the customary multiple reader anneals are beneficial, they are time consuming and will not completely prevent the problem.

Sensitivity Differences Among Hanford Dosimeters

Hanford calibration dosimeters were compared to personnel pool dosimeters in service for over a year (grey inserts) and personnel pool dosimeters in service for less than a year (black inserts). Ten of each type were exposed to 1000 mR Cs-137 gamma with another ten given 10 mrem thermal neutrons. Sample sizes were small due to limitations on reader time and shortages of personnel pool dosimeters.

Comparisons of chip responses after background subtraction are shown in Table 8.3. Differences were smaller than expected and largely masked by chip variance.

TABLE 8.3. Comparison of Calibration and Personnel Pool Dosimeter Sensitivities

Chip Response Ratios for Gamma Exposures(a)

	<u>Chip 1</u>	<u>Chip 2</u>	<u>Chip 3</u>	<u>Chip 4</u>
Ratio of calibration dosimeter response to "new" dosimeter response	0.997(b) ±0.030	1.087 ±0.032	1.063 ±0.027	1.034(b) ±0.048
Ratio of calibration dosimeter response to "old" dosimeter response	0.985(b) ±0.032	1.037 ±0.027	1.034 ±0.042	0.992(b) ±0.056

Chip Response Ratios for Neutron Irradiations(c)

	<u>Chip 3</u>	<u>Chip 4</u>
Ratio of calibration dosimeter response to "new" dosimeter response	1.062(b) ±0.052	1.035(b) ±0.058
Ratio of calibration dosimeter response to "old" dosimeter response	1.066 ±0.044	1.119 ±0.043

-
- (a) Quoted uncertainties represent the estimated standard error of each ratio.
 (b) Based on the results of a rank-sum test, these sensitivities cannot be said to differ significantly.
 (c) Quoted uncertainties represent the estimated standard deviation of each ratio based on σ_{μ} .

Although lower, the chip response ratios do not differ significantly from the audit corrections. Audit corrections to date for 1981 are included in Appendix B for comparison. Large fluctuations in the corrections are understandable, since chip error is propagated in the dose algorithms and only 12 audit dosimeters are used.

Effects of Low Energy Trap Decay After Irradiation

Hanford dosimeters exposed simultaneously to 1500 mR gamma from Cs-137 were read in groups of ten after delays of 2 hours, 4 hours, 8 hours, 24 hours and 3 days along with background dosimeters. Response changes relative to the 3 day waiting period were averaged for all chip positions to obtain an overall dosimeter response change. Results are shown in Figure 8.4.

FIGURE 8.4. Sensitivity Increases for Short Irradiation Readout Times

Much of the low energy trap population decays within 8 hours after irradiation. Little effect is seen after 24 hours. If it is necessary to read dosimeters within 4 hours after irradiation, doses could be corrected downward by 7% to allow for the sensitivity increase; however, this correction may be less than the uncertainty in the measurement.

Dosimeter Sensitization by the Reader Anneal

Increases in sensitivity for short anneal-irradiation times were similarly measured. New dosimeters were annealed twice and groups of ten were irradiated after delays of 2-1/2 hours, 24 hours, 2 days, 4 days, and 6 days. Dosimeters

were read 24 hours after irradiation and background was subtracted. Differences in sensitivity, summarized in Table 8.4, were not statistically significant.

TABLE 8.4. Relative Dosimeter Sensitivity as a Function of Anneal-Exposure Time

<u>Anneal to Exposure Time</u>	<u>Percent Increase in Sensitivity Relative to a 6 Day Delay (Averaged for All Badge Positions)</u>	<u>Percent Absolute Uncertainty (1 Standard Error)</u>
2.5 hours	1.9	2.3
1 day	1.5	1.9
2 days	1.3	0.7
3 days	-2.0	3.2

DISCUSSION

Low energy traps apparently contribute minimally to dose when the U.S. Testing reader is used. Although annealing sensitization has been observed using the laboratory 400°C anneal and PNL manual readers, it is not an important effect for the Hanford system. Dosimeters experienced no change in sensitivity when irradiated as soon as two hours after annealing. Nor is there any reason to believe that repeated reader annealings cause long term increases in dosimeter sensitivity. Chip populations tracked on a laboratory hot gas reader as part of a follow-up study experienced no changes in sensitivity through nine cycles of laboratory reader annealing and irradiation, other than an initial departure in sensitivity after the 400°C laboratory anneal.

Correction factors for short irradiation-readout times are relatively small. Apparently, the short readout does not emphasize traps with low activation energies. A general low energy trap correction of 7% was obtained for gamma exposures read within 4 hours of irradiation and 4% for dosimeters read within 8 hours. These are applicable for short irradiations, but should not be used when doses are delivered over periods of 4 hours or more.

Sensitivity differences among personnel pool dosimeters and calibration dosimeters were difficult to interpret. Although differences in trap buildup undoubtedly exist, they may be of the same order as chip variances. Alternatively, the sample sizes used in this study (limited by demands on reader time) may be too small to reflect actual differences in dosimeter populations.

The overall variability in the chip results was not large for the dosimeters studied. Coefficients of variation for all dosimeter samples were $\leq 5\%$ for TLD-700s and $\leq 10\%$ for TLD-600s, indicating that the screening process is performing as designed. Error propagation in the algorithm, however, can result in much larger errors in the reported doses. No outliers greater than three standard deviations from the mean were observed. Large fluctuations in audit corrections experienced in the past may have been caused by heater temperature variability. When the heater temperature is higher, more of the high energy traps are read out and a large effect is seen. Conversely, cascading from high energy traps is minimized when heater temperatures are lower than previous readouts.

CONCLUSIONS

Buildup in the higher temperature traps for TLDs used in Hanford dosimeters could be reduced substantially by raising chip temperatures and heating times during annealing. Although this is not practical with the reader anneal, it could be implemented by adopting a separate annealing process. Under this system, dosimeters could be read once and transferred to an annealing device. All chip positions could be annealed simultaneously from both sides using opposing sets of heaters. Teflon stretching problems caused by the one-sided reader anneal would be reduced and the need for multiple reader anneals would be eliminated.

A separate anneal will only be effective if the heating period is sufficiently long to anneal traps with activation energies between 240 and 300°C. It is highly unlikely that a heating time of a few seconds will accomplish this. A better method would be to heat chips for at least 60 seconds at 300°C. Since the 100 second readout limits the dosimeter processing rate, no additional processing time would be required for a separate anneal.

The annealing time and temperature must be consistent for all dosimeters. An annealing device must be regularly calibrated to insure that the temperature does not vary. With a longer heating cycle and proper quality assurance procedures, the separate anneal should eliminate sensitivity differences among groups of dosimeters and reduce variability caused by fluctuations in heater temperatures.

APPENDIX A

CHIP ACCEPTANCE AND SCREENING PROCEDURES

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CURRENT PROCEDURES

Batches of TLD material entering the Hanford personnel dosimetry system receive multiple screenings to insure that their sensitivities do not differ significantly from sensitivities of TLDs already in use. Accepted batches are fabricated into badges and rescreened for out-of-position chips.

Samples of 200 or more TLDs randomly selected from each new batch are annealed along with samples of 20–25 chips from an original reference set of TLD material and 20–25 chips from another set used in special studies. The chips are spread in vicor dishes and placed in a 400°C furnace under a nitrogen atmosphere for 1 hour, then transferred to a 100°C oven. After 2 hours, TLDs are placed in a low-background storage cave, where they are held for at least 24 hours. All transfers of heated chips are performed under dim light to avoid ultraviolet sensitization of the LiF.

After annealing, the samples are loaded into cardboard holders and irradiated with 250 mR gamma from ^{137}Cs (off-phantom) followed by 5 mrem thermal neutrons from a D_2O moderated PuBe source. A hot gas reader is normally used to compare light outputs. If the laboratory planchet reader is used, sample sizes are reduced. Sample means and standard deviations are calculated for each group. The exposure/readout process is repeated twice to simulate the effects of reader annealing.

Batches are accepted if the sample mean falls within 5% of both reference sample means and the sample standard deviation is less than $\pm 10\%$ for TLD-700 or $\pm 15\%$ for TLD-600s. When the mean or standard deviation does not fall within acceptable limits, the batch sample and reference samples are reannealed and rescreened; the laboratory anneal will often stabilize chip responses sufficiently for samples to pass a second screening. If a sample is accepted after a second anneal and screening, the entire batch is annealed before use. Rejected batches are returned to the manufacturer.

Chips from discontinued badges receive a different screening prior to reuse. To reduce wear on reference TLDs, recycled batches are screened for outliers without any comparison to reference samples. Individual TLDs with light outputs differing from the group mean by greater than 10% for TLD-700s or greater than 15% for TLD-600s are discarded.

Accepted batches of new and old TLDs are fabricated into badges. New dosimeter inserts receive a mixed gamma-thermal neutron irradiation followed by readout at U.S. Testing. Accidental placement of TLD-600s in position 1, 2 and 5 or TLD-700s in positions 3 and 4 can be detected through large differences in chip response. Badge inserts with incorrectly positioned TLDs are returned for proper reassembly.

CONCLUSIONS

Based on observed variances in chip response of samples from the personnel dosimetry pool, the current screening process is effective. However, one of the steps seem unnecessary. Repeated irradiations and laboratory readouts during the screening do not simulate the routine reader anneal. Changes in chip responses during the repeated readouts reflect differences in chip handling procedures rather than intrinsic changes in the TLD material. Eliminating this step would save wear on the reference standards as well as time.

A complete screening of the TLDs after fabrication into badges would not be difficult. Under the current screening process, only the outliers in the sample are detected. Outliers in the remainder of the batch generally escape notice. A simple screening algorithm could identify outliers as well as misplaced chips at the time of dosimeter insert acceptance. No extra readout time would be required, and problems due to chip flyers would be reduced. This would not replace the laboratory screening, which is necessary to compare batch response and precision to reference standards; however, the final screening could provide a final quality control check on the dosimeters being introduced into the program.

APPENDIX B

AUDIT CORRECTIONS TO DATE FOR 1981

DOSE ADJUSTMENTS, JAN-MAY 1981, READER 2

Month	Run	Correction Factors ^(a)			
		Nonpenetrating (C ₂ and C ₃)	Penetrating (C ₁)	Thermal Neutron (C ₄)	Fast Neutron (C ₅ , C ₆ , C ₇)
Jan	Monthly	1.24	1.17	1.35	0.72
Feb	Monthly	1.11	1.08	1.07	1.20
Mar	Monthly	1.06	1.25	1.20	1.29
Mar	Quarterly	1.18	1.15	1.34	1.16
Apr	Monthly	1.16	1.08	1.29	1.25 ^(b)
May	Monthly	1.00	1.07	1.29	1.12

(a) Correction factors were supplied by M. K. Winegardner, PNL.

(b) Calculated but discarded due to large variance in audit badge readings (a value of 1.00 was used).

Audit corrections reflect the ratio of the doses given to audit badges versus audit doses calculated using personnel dosimetry calibration.

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