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Dose Algorithm Determination
for the Los Alamos National
Laboratory Personnel
Dosimetry System

Janna Patterson

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Dose Algorithm Determination for the
Los Alamos National Laboratory
Personnel Dosimetry System

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A thesis submitted to the faculty of the University of North Carolina in
partial fulfillment of the requirements for the degree of Master of
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Janna Marie Patterson: Dose Algorithm Determination for the
Los Alamos National Laboratory Personnel Dosimetry System

ABSTRACT

One of the most important aspects of a TLD dosimetry system is the dose algorithm used to convert the signals from the badge reader to an estimate of a worker's dose. It is now more important than ever to have an accurate algorithm to estimate dose well below regulatory limits. Dosimetry systems for DOE laboratories must meet minimum performance standards based on DOELAP criteria. The purpose of this paper is to describe the development of a dose algorithm for a new TLD dosimeter that has been developed at Los Alamos National Laboratories. It is expected that DOELAP testing will start in 1995. Initial results indicate that the system will be able to exceed the minimum performance criteria by a large margin. The enhanced ability of the dosimeter to determine beta, gamma, and neutron energies makes it very useful in the various radiation fields encountered at the laboratory.

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TABLE OF CONTENTS

LIST OF TABLES	v
LIST OF FIGURES.....	vi
LIST OF ABBREVIATIONS.....	vii
I. Introduction	1
A. Background.....	1
B. TLD Phosphors.....	2
C. TLD Dosimeters	5
D. Research Outline	6
II. Dosimetry System.....	9
A. Physical Description and Properties.....	9
B. TLD Reader	13
1. Reader characteristics.....	16
2. TLD and reader calibrations.....	18
III. DOELAP Requirements.....	21
A. Irradiation Categories.....	21
B. Angular Dependence	22
C. Lower Limit of Detectability.....	24
IV. Supporting Studies.....	27
A. Reproducibility.....	28
B. Residual Signal.....	30
C. Fading	32
D. Background.....	36
V. Algorithm Determination.....	41
A. Neutron Dose.....	44
B. Beta Dose.....	46
C. Gamma Dose	50
D. LANL Irradiator Comparison.....	56
VI. Conclusions.....	58
A. Supporting Studies.....	58
B. Dose Algorithm Determination.....	60
APPENDIX A: SUPPORTING STUDIES.....	63
APPENDIX B: DOELAP STUDIES	85
APPENDIX C: LANL IRRADIATOR STUDIES.....	91
APPENDIX D: DOSE ALGORITHM.....	94
REFERENCES.....	99

LIST OF TABLES

Table 1: New Dosimeter Phosphors.....	12
Table 2: New Dosimeter Filtration.....	12
Table 3: DOELAP Irradiation Beams	23
Table 4: Percent Relative Standard Deviation for Dose on the Beta/Gamma Card.....	29
Table 5: Percent Relative Standard Deviation for Dose on the Neutron Card.....	29
Table 6: Residual Signal (mrem) on the Beta/Gamma Card ...	30
Table 7: Residual Signal (mrem) on the Neutron Card	31
Table 8: Residual Correction Factors.....	32
Table 9: Background Correction Factors.....	40
Table 10: Correction Factors for Background and Residual Signal.....	43
Table 11: C _x Conversion Factors.....	51

LIST OF FIGURES

Figure 1: Dose/Response Relationship for LiF:Mg,Ti and LiF:Mg,Cu,P	4
Figure 2: New Dosimeter Design	9
Figure 3: New Dosimeter Shielding Case.....	10
Figure 4: TLD System 8800 Card Reader.....	14
Figure 5: Sample Glow Curve.....	16
Figure 6: Sample TTP	18
Figure 7: LD and LC Curves	25
Figure 8: Fading on Beta/Gamma Card.....	34
Figure 9: Fading on Neutron Card with ^{137}Cs Irradiation	35
Figure 10: Fading on Neutron Card with ^{252}Cf Irradiation.....	36
Figure 11: Background Signal on Beta/Gamma Card.....	37
Figure 12: Background Signal on Neutron Card.....	38
Figure 13: Neutron Dose Determination.....	45
Figure 14: Gamma Energy Dependence	47
Figure 15: Gamma Response On E2, Low and High Energy	48
Figure 16: Gamma Response On E3, Low and High Energy	48
Figure 17: Beta Dose Determination.....	49
Figure 18: Shallow Gamma Dose, Low Energy.....	53
Figure 19: Shallow Gamma Dose, High Energy	53
Figure 20: Eye Level Gamma Dose, Low Energy.....	54
Figure 21: Eye Level Gamma Dose, High Energy	54
Figure 22: Deep Gamma Dose, Low and High Energy	55
Figure 23: LANL and Battelle Irradiation Comparison.....	57

LIST OF ABBREVIATIONS

B	bias
Cd	cadmium
DOE	Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
ECC	element correction coefficient
L	fractional tolerance level
LANL	Los Alamos National Laboratories
LC	critical level
LD	detection level
LLD	lower limit of detection
NVLAP	National Voluntary Laboratory Accreditation Program
PMT	photomultiplier tube
r^2	Pearson product moment correlation coefficient
RCF	reader calibration factor
S	standard deviation
TLD	thermoluminescent dosimeter
TTP	time temperature profile
Z	effective atomic number

I. Introduction

A. Background

There is an ongoing effort to make personnel radiation monitoring methods more accurate and able to detect smaller and smaller doses. One system used for detecting radiation is a thermoluminescent dosimetry (TLD) system. This method uses thermoluminescent materials that interact with radiation and store the deposited energy. The energy is released from the TLD element as a light signal when it is heated. The light signal is analyzed and an approximate dose is determined. A second heating in an oven clears most of the residual signal from the TLD elements. After this annealing procedure, the TLD is ready to be used again.

At Los Alamos National Laboratories (LANL), a new dosimeter has been developed. In order to use this dosimeter at a Department of Energy (DOE) laboratory, the processing laboratory must be certified by the Department of Energy Laboratory Accreditation Program (DOELAP) for Personnel Dosimetry Systems. This program is very similar to the National Voluntary Laboratory Accreditation Program (NVLAP) that is used by non - Department of Energy laboratories.

DOELAP was developed to regulate laboratories that process dosimeters for DOE laboratories. This program provides some

uniformity between the laboratories and defines "minimum levels of acceptable performance."⁽¹⁾ Laboratories must be able to determine deep and shallow doses within a certain degree of accuracy to become certified.

B. TLD Phosphors

One of the most widely used phosphors for TLD dosimeters is lithium fluoride doped with magnesium and titanium (LiF:Mg,Ti). Lithium, in its natural form, is approximately 92% ^7Li and 8% ^6Li ⁽²⁾. In this state, the phosphor is commonly referred to as TLD-100. When the phosphor is enriched with either the ^7Li isotope or the ^6Li isotope, it is referred to as TLD-700 or TLD-600 respectively. These three TLD elements respond identically to gamma and beta radiation, but respond differently to neutron radiation. The ^7Li isotope has almost no cross-section for neutrons while the ^6Li isotope has a high thermal neutron cross-section. This makes the TLD-600 phosphor a good neutron dosimeter.

One of the newest and most exciting TLDs to be developed is LiF:Mg,Cu,P (GR-200). It improves on some of the deficiencies encountered with LiF:Mg,Ti. The sensitivity of LiF:Mg,Cu,P to radiation is its most impressive feature. It is reportedly 30 times more sensitive than LiF:Mg,Ti⁽³⁾. With a greater sensitivity, lower doses can be determined. GR-200 enriched with either the ^7Li or ^6Li isotope is called GR-207 or GR-206, respectively.

There are several properties that make a material a good TLD. One of the most important properties is the effective

atomic number (Z) since this number dictates the response of the material to radiation. The most desirable situation is to have the Z number equivalent to the Z number of the human body, around 7. LiF:Mg,Ti has a Z number of 8.2 and overresponds at low radiation energies by approximately 30%⁽⁴⁾. This overresponse is due to the photoelectric effect. Most materials now in use experience this phenomenon. The effective Z number of LiF:Mg,Cu,P is the same as LiF:Mg,Ti, 8.2, but it doesn't have the same response to low energy gammas. At 30keV, GR-200 underresponds by 10%⁽⁵⁾ as opposed to the overresponse seen with LiF:Mg,Ti. This is seen because the efficiency of LiF:Mg,Cu,P decreases with increasing X-ray energy⁽⁶⁾.

Another desirable property for a TLD is a linear response in relation to exposure level. Ideally, the relative response of the material would not change. LiF:Mg,Ti has a supralinear response at high dose levels while LiF:Mg,Cu,P underresponds. The major difference between the two deviations from linearity is the maximum linear dose. LiF:Mg,Ti is linear up to about 100 röntgens (R) where the linearity of LiF:Mg,Cu,P extends to about 1000 R. Another difference between the two TLD materials is the shape of the dose/response curve as it deviates from linearity (Figure 1). This figure shows LiF:Mg,Ti irradiated with a: ^{60}Co , b: 50keV X-rays, c: 20keV X-rays and LiF:Mg,Cu,P irradiated with ^{60}Co . The curve defined for LiF:Mg,Ti is very difficult to characterize whereas the LiF:Mg,Cu,P curve has a simpler

relationship. This makes an extrapolation easier with LiF:Mg,Cu,P in an accident situation.

Figure 1: Dose/Response Relationship for LiF:Mg,Ti and LiF:Mg,Cu,P⁽⁵⁾

The most limiting factor in the use of LiF:Mg,Cu,P is its temperature sensitivity. If the temperature of the TLD crystal exceeds 245°C during annealing, there is a permanent loss of sensitivity. Because of this temperature restriction, there is a relatively high residual signal left on the crystal after the initial

heating. It is therefore important to find a balance between a high residual signal and a sensitivity loss.

C. TLD Dosimeters

The current dosimeter design for LANL consists of a single card with four TLD elements to measure a combined beta, gamma, and neutron field. Three of the elements are TLD-700 and will not react with neutron radiation. One of the TLD-700 elements is covered by a copper filter to eliminate beta radiation and provides a gamma dose. The second TLD-700 element, covered by a thin plastic window, detects beta and gamma radiation. The beta dose is determined by subtracting the gamma dose from the total signal on the second TLD element. The third and fourth TLD elements are a TLD-700, 600 pair that are covered by plastic shielding to eliminate the beta signal. This pair is used to determine the neutron dose in a similar manner as the beta dose determination. The third TLD-700 element is needed because equal shielding is required over the pair used to detect neutrons. Without equal shielding, the gamma response on the TLD-600 element would be different from the response on the TLD-700 element.

One of the major limitations with this four element design is the lack of ability to make energy determinations. Element response is dependent on the incident radiation energy. Without knowing the radiation energy, the energy/response ratio is unknown and the dose can not be determined accurately. Some gamma energy determination is possible using the two heavily

shielded TLD-700 elements. No energy determination is possible for beta and neutron radiation. An attempt to overcome this problem is with the use of correction factors to estimate the radiation energy. This does not lead to a large error if the radiation fields are fairly constant and well known. However, LANL has many sources of radiation and a single factor can not mimic all the different fields accurately. A dosimeter that can estimate energy in a mixed beta, gamma, and neutron radiation field is both practical and necessary in this environment.

The signal from a radiation dosimeter is converted to an estimation of a worker's dose using a mathematical dose algorithm. The dose algorithm presented in this study is a refinement of the algorithm developed by Stanford and McCurdy⁽⁷⁾ and is inspired by others⁽⁸⁻¹⁰⁾. Their dosimetry system used a four element dosimeter to discriminate between gamma and beta radiation. The system used two TLD elements to determine the average energy and amount of dose received from gamma radiation, while the third and fourth TLD elements were used in a similar way for beta radiation. Stanford and McCurdy report good results from their NVLAP proficiency testing. One of the limitations of their dosimeter is that it does not have the ability to detect neutron radiation.

D. Research Outline

The primary goal of this research was to perform experiments on a new TLD dosimeter design that is going to be used by LANL in the near future. This dosimeter uses the new

GR-206 and GR-207 phosphors in a badge design capable of detecting beta, gamma and neutron radiation as well as estimating the energies of the radiations. The experiments performed contributed to the development of a dose algorithm for the new dosimeter. The main set of tests involved the irradiation of the dosimeter to known doses with known radiation types and energies. Based on these results, mathematical algorithms were developed that related the energy of the radiation to signal ratios between certain TLD elements. By estimating the radiation energies from the TLD, a more accurate dose estimation can be made.

In addition to the main experiments, other supporting experiments were performed to characterize the new dosimeter. These included a reproducibility study, a residual study, a background study, and a fading study. A reproducibility study was performed to examine whether the signals from TLD elements were the same given the same radiation dose. Even after a card is annealed, the entire signal can never be removed. This residual signal needs to be known for accurate dose determination. Since there is a tendency for a signal on a TLD to fade over time, a fading experiment was performed. A background study was performed in conjunction with the fading study since a signal due to cosmic radiation will also be induced on the dosimeter in addition to the worker's dose.

In order to fully understand the performed experiments, the design of the dosimetry system will first be described in detail. The characteristics of the dosimeter, how it is read and how the

dosimeter and the reader are calibrated will be discussed. The performance of the dosimeter will be judged against DOELAP standards. In order to meet DOELAP requirements, it is necessary to develop an algorithm. The standards that the algorithm will be judged against are discussed.

II. Dosimetry System

A. Physical Description and Properties

The new dosimeter for LANL was developed by Jeffrey Hoffman, Team Leader, Personnel Dosimetry Operations, LANL and by Michael Mallett, Measurements Technology Support, LANL. The dosimeter consists of two cards, each containing four TLD elements to measure a combined beta, gamma, and neutron radiation field (Figure 2).

Figure 2: New Dosimeter Design

The first card is used to detect beta and gamma radiation with two elements devoted to each radiation type. Elements 1 and 4 are used for gamma detection and are both covered by 600 mg/cm² of ABS plastic. This amount of shielding effectively blocks all the beta radiation. An illustration of the shielding case is shown in Figure 3. Element 1 is a CaF₂:Mn phosphor and

Figure 3: New Dosimeter Shielding Case

element 4 is a GR-207 phosphor. Since the CaF tends to overrespond at lower radiation energies and the LiF:Mg,Cu,P tends to underrespond, a ratio of the signals from the two elements gives an indication of the average gamma energy. Elements 2 and 3 are used to detect beta radiation. Element 2 is covered by one layer of mylar (5 mg/cm^2) and element 3 is covered by two layers of mylar (10 mg/cm^2). Both of the beta elements are GR-207 phosphors. The difference in the shielding thickness allows the determination of the average energy of the beta radiation using signal ratios. As the radiation energy increases, the ratio of element 3 to element 2 ($E3/E2$) approaches one. A relationship can be developed which relates the ratio of dose/element 3 (dose/ $E3$) to the average energy of the radiation. The average energy is determined with the ratio of $E3/E2$. A summary of the TLD elements is presented in Table 1. The radiation sensitivity mentioned in Table 1 is dependent on both the phosphor and the dosimeter shielding that is presented in Table 2.

The second card is used exclusively for neutron detection. Elements 5 and 8 are TLD-600 and elements 6 and 7 are TLD-700. LiF:Mg,Cu,P is not used with this card since the increased sensitivity to beta and gamma radiation is not needed. One of the important aspects in detecting neutrons is determining the energy of the incident radiation. Every neutron source emits neutrons with a spectrum of energies. The neutrons may also be reduced in energy, or moderated, before reaching the worker. Dose is therefore determined using the average neutron energy.

Table 1: New Dosimeter Phosphors

TLD Element	Phosphor	Designation	Radiation Sensitivity
1	CaF ₂ :Mn	TLD-400	γ
2	LiF:Mg,Cu,P (Li ⁷)	GR-207	β, γ
3	LiF:Mg,Cu,P (Li ⁷)	GR-207	β, γ
4	LiF:Mg,Cu,P (Li ⁷)	GR-207	γ
5	LiF:Mg,Ti (Li ⁶)	TLD-600	γ, n
6	LiF:Mg,Ti (Li ⁷)	TLD-700	γ
7	LiF:Mg,Ti (Li ⁷)	TLD-700	γ
8	LiF:Mg,Ti (Li ⁶)	TLD-600	γ, n

Table 2: New Dosimeter Filtration

TLD Element	Front Filter	Back Filter
1	ABS Plastic: 600 mg/cm ²	ABS Plastic: 185 mg/cm ²
2	Mylar: 5 mg/cm ²	ABS Plastic: 185 mg/cm ²
3	Mylar: 10 mg/cm ²	ABS Plastic: 185 mg/cm ²
4	ABS Plastic: 600 mg/cm ²	ABS Plastic: 185 mg/cm ²
5	ABS Plastic: 185 mg/cm ²	ABS Plastic: 185 mg/cm ² Cadmium: 461 mg/cm ²
6	ABS Plastic: 185 mg/cm ²	ABS Plastic: 185 mg/cm ² Cadmium: 461 mg/cm ²
7	ABS Plastic: 185 mg/cm ² Cadmium: 461 mg/cm ²	ABS Plastic: 185 mg/cm ²
8	ABS Plastic: 185 mg/cm ² Cadmium: 461 mg/cm ²	ABS Plastic: 185 mg/cm ²

When neutrons have a fairly low energy, referred to as thermal neutrons, they will react with TLD-600. The response of the

element decreases by a factor of 100 as the neutron energy increases up to 15 MeV⁽¹¹⁾. However, the body of the worker can act as a moderator for the high energy neutrons. After moderation, the now lower energy neutrons can leave the body and interact with the dosimeter from the back. These neutrons are called albedo neutrons. It is important to know whether the signal on the TLD is caused by incident thermal neutrons or by albedo neutrons. For this reason, the dosimeter is divided into two pairs. Elements 5 and 6 are used together to detect thermal neutrons. This pair has a cadmium (Cd) back plate that will eliminate the albedo neutron signal. Elements 7 and 8 have a top cover of Cd to eliminate the thermal neutron signal. Since both TLD-600 and TLD-700 react identically to gamma radiation, the gamma induced signal on the TLD-600 elements can be removed by a simple subtraction of the TLD-700 signal from the TLD-600 signal leaving a pure neutron signal. A ratio of the two filtered neutron signals will indicate the average neutron energy.

B. TLD Reader

The TLD reader system used at LANL is a HARSHAW/Filtrol TLD System 8800 Card Reader™ (Figure 4) using the REMS© software package. This system has the ability to process 1400 cards before reloading. Before a group of cards is read, and periodically during the reading process, two system checks are performed. The first is the photomultiplier tube (PMT) noise check. The system measures the light signal while the reader is empty and will stop the operation if the signal is too high since

Figure 4: TLD System 8800 Card Reader⁽¹²⁾

that would indicate a light leak in the system. It will also stop if the signal is zero since there should always be some dark noise in the system. The second check is the monitoring of a reference light source. The operation will stop if the signal from the reference source is not within the specified bounds for that source.

In addition to the instrument system checks, the reader performance can be monitored with quality control cards. These are cards that have been irradiated to a known amount of ^{137}Cs . They are randomly mixed with regular cards during the reading process. The reader will recognize a quality control card and will expect a certain output signal. Operations will stop if the signal from any of the TLD elements is outside the range defined by the operator.

To process a card, the reader identifies each card with a bar code reader. If the code can not be read, the operator can manually enter the card's number or the card is placed aside without being read. This protects the information on the card from being lost. If the card can be read, it is taken into the PMT housing where it is heated using hot nitrogen gas. The output signal is measured using a photomultiplier tube and the information is sent to a computer where the dose algorithm is applied and the final doses are determined.

1. Reader characteristics

There are two main characteristics of the card reader that need to be considered, the glow curve and the time temperature

profile (TTP). When a TLD is heated, the signal is seen as a glow curve. A sample is shown in Figure 5. This curve is a relative signal as a function of time. A glow curve is a measure of the TLD light output as a function of time or temperature. The curve has the shape of a single peak but may actually be composed of five or more overlapping peaks. The peaks correspond to the different energy levels of the trapped radiation energies. The radiation energy that was trapped at lower energy states is very unstable and will appear first in the glow curve. These peaks are not used in dose determination because of their instability. The sample glow curve represents the time after the preheat. Either the area or height of the peak can be used to determine the dose. Each phosphor type has its own unique glow curve shape.

Figure 5: Sample Glow Curve

The glow curve is an important characteristic to be considered when deciding on a phosphor to use in dosimetry. The main peak needs to be removed at a temperature above room temperature, but not at a temperature that will damage the elements in the process of removing the signal. The signal from

the phosphor must also be emitted at a wavelength readable by the card reader. LiF:Mg,Cu,P's main dosimetric peak occurs at 220°C with a wavelength between 400 and 490nm⁽¹³⁾. This is well within the capabilities of the HARSHAW reader.

The time temperature profile (TTP) controls the reader's temperature, rate of heating, and heating time for each element. A sample TTP is shown in Figure 6. The first part of the profile is the preheat which will eliminate the unstable low temperature peaks in the glow curve. The temperature is then steadily increased until the maximum temperature is reached and held. During this time, the main signal is read and the card is annealed. The relative temperature is displayed on the glow curve in Figure 5.

Each type of phosphor has its own heating cycle customized to its properties. Finding the correct TTP for each phosphor is an exacting science. If the maximum temperature is too high, a thermal signal can be induced on the phosphor. This would cause a high residual signal. If it is too low, the original signal will not be removed completely, also leaving a residual signal. If the preheat is too short, the low temperature peaks may be recorded as part of the dosimetric signal producing an artificially high dose estimation. If it is too long, some of the main signal could be lost.

2. TLD and reader calibrations

When a batch of TLDs is manufactured, each TLD element will have different response to a given amount of radiation.

Figure 6: Sample TTP

Data Acquisition	Environment #1 (8800 ANNEALED)		6-Sep-1994 8:14 am	
Time Temp Profile	Harshaw TLD-REMS		S-23672.014	
Date Edited	26-Jul-1994	Edited by	A	
Calibrated	03-Aug-1994	Reread	none	
Profile	2	Title	6776 cards	

	(i)	(ii)	(iii)	(iv)
roi1 [	1 , 10]	[1 , 10]	[1 , 10]	[1 , 10]
roi2 [	11 , 100]	[11 , 100]	[11 , 100]	[11 , 100]
roi3 [	101 , 190]	[101 , 190]	[101 , 190]	[101 , 190]
roi4 [	191 , 200]	[191 , 200]	[191 , 200]	[191 , 200]
Calibration Region [	1 , 200]	[1 , 200]	[1 , 200]	[1 , 200]
Preheat temperature	150	150	150	150 °C
time	3	3	3	3 sec
Temperature rate	30	30	30	30 °C/sec
Maximum	300	300	300	300 °C
Acquire time	20	20	20	20 sec
Anneal temperature	300	300	300	300 °C
time	0	0	0	0 sec
Calibration factor	0.340	0.339	0.363	0.317 nC/mrem
Average PMT noise	0.1268	0.1352	0.1297	0.1066 nC
Average Reference light	604.83	436.66	657.02	420.29 nC
Next	Previous	Undo	Restore	Report
				Return

Differences in the dopant amounts, cracks in the crystal, and many other minor differences will give the TLD elements different responses. For this reason, elemental correction coefficients (ECC's) are assigned to each TLD element in each card.

The card reader drifts in its ability to read a signal over time. Therefore, the instrument has a reader correction factor (RCF) for each element location. To develop these correction factors, some of the cards are designated as calibration cards. The calibration cards have the smallest signal deviation from the

mean response of the group. To determine which cards will be used for calibration, a large group of cards is irradiated using a ^{137}Cs irradiator. When the cards are read, they are assigned a temporary, calibration ECC. The ECC for element i in card j is given as:

$$\text{ECC}(i, j) = \frac{Q(i)}{Q(i, j)} \quad (1)$$

where $Q(i)$ = the average signal for each element i in all cards, and
 $Q(i, j)$ = the signal from element i in card j .

The calibration cards are the cards with ECC's closest to one. For the selected calibration cards, the temporary ECC's are retained. The RCF for the machine is now be determined. The calibration cards are exposed to a ^{137}Cs source again and then read. The RCF is defined as

$$\text{RCF}(i) = \frac{\sum [Q(i, j) \cdot \text{ECC}(i, j)]}{k \cdot D} \quad (2)$$

where k = the number of calibration cards, and
 D = the given dose.

The RCF has units of nano-Coulombs/milli-rem since the output signal has units of nano-Coulombs. Once the reader is calibrated, the ECC's for the rest of the cards are determined.

The cards are exposed to the ^{137}Cs source and read. The ECC for element i in card j is calculated by the equation

$$\text{ECC}(i,j) = \frac{\text{RCF}(i) \cdot D}{Q(i,j)} \quad (3)$$

Normally, the ECC's will not have to be recalculated for the life of the card. If damage occurs, a new ECC is determined or the card is taken out of use. All of the elements are calibrated using a ^{137}Cs source since all of the elements are sensitive to gamma radiation. The RCF is recalculated at least once a month or whenever a quality control card indicates a problem with the reader.

The neutron cards are also calibrated with a gamma source. It would be more accurate to calibrate the two neutron sensitive elements with neutron radiation and the two gamma sensitive elements with gamma radiation. Due to limitations of the equipment, two different calibration sources can not be used on the same card. Since the neutron sensitive elements are also sensitive to gamma radiation, all calibrations are done with ^{137}Cs .

III. DOELAP Requirements

A. Irradiation Categories

To become DOELAP accredited, laboratories must be able to determine deep and shallow doses within a certain degree of accuracy. This is done with the use of a certified irradiation facility. Dosimeter processing laboratories send a group of dosimeters, at least five for each irradiation category plus five more for controls, to the irradiation facility to be exposed. The delivered doses are then reported to DOE but not to the laboratory. The laboratory processing the dosimeters will know only if the badges were exposed to neutrons or if they were involved in a high dose category. The doses determined by the laboratory are then reported to DOE where the accuracy of the dose determination is assessed. To determine the accuracy of the dosimetry system, the bias (B) and the standard deviation (S) of each group is calculated. The bias and standard deviation are defined by the equations

$$B = \frac{m - \mu}{\mu} \quad (4)$$

and

$$S = \frac{\sigma}{\mu} \quad (5)$$

where m = dose determined by the laboratory,
 μ = the delivered dose, and
 σ = the standard deviation in the category.

The accuracy of a laboratory's dosimetry system is assessed using the fractional tolerance interval (L). The fractional tolerance interval is calculated by the equation

$$L = |B| + t_{\alpha, n-1} \cdot S \quad (6)$$

where t = the statistical t test,
 n = number of dosimeters, and
 α = confidence level.

The categories for DOELAP irradiations are low-energy photons, high-energy photons, beta particles and neutrons. In addition there are mixture and high dose categories. The sources for these irradiations are shown in Table 3. The fractional tolerance level must be below 0.3 for categories I-VI and below 0.4 for category VII.

B. Angular Dependence

Most tests on dosimeters are performed with radiation that is incident to the dosimeter. This is rarely the case in practical situations. Typically, as the angle between the dosimeter and the radiation source increases, the recorded dose decreases. This is partially due to the improper geometry of the dosimeter

and the blocking of the radiation by the worker. Beta radiation detection could be inhibited if the betas pass through the plastic part of the dosimeter shield instead of through the mylar windows. The angular dependence problem is magnified when the worker is between the radiation and the badge. In this

Table 3: DOELAP Irradiation Beams⁽¹⁴⁾

Category	Source	Energy (keV)
I. Low-energy photons, high dose	X-ray: M150	70
II. High-energy photons, high dose	¹³⁷ Cs beam	662
III. Low-energy photons	X-ray: M30	20
	S60	36
	M150	70
	H150	120
	K17	15-20
	Monoenergetic ²⁴¹ Am beam	55-65 59
IV. High-energy photons	¹³⁷ Cs	662
V. Beta particles	²⁰⁴ Tl	760 (Max)
	⁹⁰ Sr / ⁹⁰ Y	2,300 (Max)
	Uranium	2,300 (Max)
VI. Neutrons	²⁵² Cf, moderated	
	²⁵² Cf, unmoderated	
VII. Mixtures	Categories III & IV	
	Categories III & V	
	Categories IV & V	
	Categories III & VI	
	Categories IV & VI	

situation, the beta dose would not be recorded and the gamma radiation signal would be reduced due to attenuation of the radiation. Neutron dose determination would be affected since the thermal neutrons would be absorbed by the worker. The dosimeter would therefore record only the albedo neutron signal and would incorrectly assess the neutron dose.

For DOELAP certification, angular dependence needs to be determined for categories III-VI excluding uranium. The dosimeter response is measured in two rotational planes from -85° to $+85^{\circ}$ with an exposure of approximately 500 mrem. This test does not have to be part of a test series and does not have to be performed utilizing a certified irradiation laboratory. In fact, there are no minimum performance standards. While angular dependence is a very important consideration, it is too difficult to counteract without increasing costs by at least a factor of two. It would require more than one dosimeter per person, placed on opposite sides of the body, and many workers would not bother placing a second dosimeter on their back. Until a better method for counteracting this variable is developed, it will have to be recognized as a limitation of the system.

C. Lower Limit of Detectability

The lower limit of detectability (LLD) of a counting system is probably the most misunderstood concept in the field of dosimetry. There are actually two important quantities to be considered. One is the critical level (LC) and the other is the

detection level (L_D) (Figure 7). The critical level is where, given a reading, you have a confidence level of $1-\alpha$ that the reading is not due to background. In the figure, the part of the background (B) curve above L_C represents α . The detection level is an activity that has a confidence level of $1-\beta$ of being recognized as a true signal using L_C as a determination point⁽¹⁵⁾. The part of the L_D curve below L_C is β . Alpha and beta are confidence levels that can be set by the user depending on how much confidence is needed in interpreting the results. L_D and L_C are determined by the standard deviations of the readings and the chosen α and β levels. The lower limit of detectability referred to by DOE LAP is L_D . To determine L_D mathematically, two groups of dosimeters

Figure 7: L_D and L_C Curves

are allowed to build up a background signal equivalent to a typical time a dosimeter is out in the field. One of the groups is then irradiated to a dose "significantly greater than the estimated lower limit of detectability"⁽¹⁾. L_D is calculated from the equation

$$L_D = \frac{2 \left[t_{\alpha, n-1} \cdot S_0 + \left(\frac{t_{\alpha, n-1} \cdot S_1}{H_1} \right)^2 \cdot H_0 \right]}{1 - \left[\frac{t_{\alpha, n-1} \cdot S_1}{H_1} \right]^2} \quad (7)$$

where H_0 = the mean dose equivalent for the unirradiated dosimeters,
 H_1 = the mean dose equivalent for the irradiated dosimeters,
 S_0 = the standard deviation for the unirradiated dosimeters, and
 S_1 = the standard deviation for the irradiated dosimeters.

It is common practice to report any readings below L_D as a zero dose, although this is a very inaccurate practice. Assuming an α of 0.05, any reading over L_C has a 95% chance of representing a true dose. Even using a zero point of L_C or lower creates a bias when a worker's dose is averaged over the year. If all readings are recorded, including the negative ones, a better total and average should result over time.

IV. Supporting Studies

Before an algorithm can be developed for a dosimetry system, there are several supporting studies that must be performed. The initial studies are reproducibility, angular dependence, and lower limit of detectability. These studies do not alter the dose algorithm but they must have results within certain tolerance ranges. The importance of the angular dependence and the lower limit of detectability were discussed in the previous section. Preliminary work performed by Michael Mallett at LANL indicated that these properties of the badge would be adequate. The angular dependence and the LLD experiments were not performed due to a lack of time and a change in the card holder design. The new card holder will have a different configuration making the angular dependence of the dosimeter impossible to determine accurately at this time. In depth studies of these two properties will take place when the new holders arrive.

The other supporting studies are residual, background build up, and fading. The results of these tests are used to adjust the signal from the card reader before the dose algorithm is applied. After a card is read and annealed, there is a residual signal left on the card. When the card is used again, the residual is subtracted from the signal on the cards. A difficulty with thermoluminescent dosimetry is that the signal on the TLD

elements tends to fade over time. If the fading is significant, there can be a large underestimation of the true dose. Another deterrent to accurate dose estimation is background radiation. While background radiation does give a dose to the worker, it is not considered an occupational dose and is removed from the reading. These adjustments need to be made to the signal for an accurate dose estimation.

A. Reproducibility

The reproducibility study was performed at three different dose levels with seven cards for each level. The cards were irradiated at 50, 100, and 200 mrem with a ^{137}Cs irradiator and the signals were allowed to fade for 24 hours. The 24 hour waiting period is used because the $\text{CaF}_2:\text{Mn}$ phosphor experiences significant fading during the first day. By not reading the cards for 24 hours, the initial fading is accounted for in the calibration. The cards were then read on the Harshaw TLD reader and annealed. This procedure was repeated twice at the same dose levels. The average for each set of seven cards was calculated for each trial. The relative standard deviations for the averages of the three trials was calculated. The results are presented in Tables 4 and 5.

The average percent relative standard deviation for the beta/ gamma card is 2.9% and for the neutron card it is 3.2%. Using a range of $\pm 2\sigma$, a 10 mrem dose would produce a signal in the range of 9.4 to 10.6 mrem for the beta/gamma card and 9.4 to 10.6 mrem for the neutron card. It is assumed from these

Table 4: Percent Relative Standard Deviation for Dose on the Beta/Gamma Card

Delivered Dose (mrem)	TLD Element			
	1	2	3	4
50	2.9	1.3	0.9	1.9
100	3.1	5.8	3.4	2.2
200	1.2	5.5	3.8	2.6

Table 5: Percent Relative Standard Deviation for Dose on the Neutron Card

Delivered Dose (mrem)	TLD Element			
	5	6	7	8
50	3.0	2.4	4.4	5.2
100	1.4	1.5	3.7	5.3
200	1.5	2.2	3.2	4.5

results and from the common use of the phosphors on the neutron card that the reproducibility for neutron radiation is also acceptable. Though the standard deviations were small, the ECC's used on the beta/gamma cards varied quite a bit indicating a non-uniformity between the cards. It is preferable to have cards with the same sensitivity. When the phosphors are mass produced, it is expected that the ECC's will be closer to one. This slight deviation in the readings indicates that the cards will operate within reasonable tolerances during normal operations.

B. Residual Signal

The residual signal experiment was performed in conjunction with the reproducibility study. When the cards were finished annealing for that study, they were re-read with no added dose. The results are given in Tables 6 and 7. It can be seen that there is a slightly higher residual with a higher initial dose. The residual on elements 2, 3, and 4 changed by a factor of two between the 50 mrem delivered dose and the 200 mrem delivered dose. The residual change for the rest of the elements was not as pronounced. Since typical doses at LANL are less than 50 mrem, the residual for a delivered dose of 50 mrem was used in the dose algorithm. On the neutron card, all four elements are expected to have the same residual since they are composed of the same materials. The difference in isotopic concentration should not change the residual signal. Elements two, three, and four on the beta/gamma card should have the same residual for the same reason as the neutron elements. The residual results for these identical elements will be averaged to determine a working residual reading. Element one

Table 6: Residual Signal (mrem) on the Beta/Gamma Card

Delivered Dose (mrem)	TLD Element			
	1	2	3	4
50	3.2	1.5	1.7	1.4
100	4.8	2.2	2.5	1.9
200	3.6	3.4	3.4	3.1

Table 7: Residual Signal (mrem) on the Neutron Card

Delivered Dose (mrem)	TLD Element			
	5	6	7	8
50	2.3	2.5	2.3	2.5
100	2.3	2.5	2.2	2.6
200	2.6	2.7	2.4	2.6

has its own residual since its phosphor is unique in the card. The large residual signal is due to the signal that is stored in the phosphor at 390°C. It is difficult to completely empty this trap using the standard annealing procedure. Chakrabarti *et al*⁽¹⁶⁾ have discovered that exposure to a 337 nm nitrogen laser light can significantly reduce the residual signal from that trap. The residual correction factors used for the dose algorithm are presented in Table 8.

There is one point of caution when using neutron sensitive phosphors. If they are exposed to a high neutron dose, the residual may be much higher. This is due to the neutron reaction in the phosphor. Thermal neutrons react with ^6Li by way of a $^6\text{Li}(n,\alpha)^3\text{H}$ reaction⁽¹⁷⁾. At high doses, there will be a large production of tritium. The tritium will keep producing a signal on the card until it has decayed. This is why a neutron source was not used in this experiment. Any moderate neutron dose would produce a tritium residual that would complicate the measurement of the signal residual. A significant neutron dose would make the card useless as a dosimeter and it would therefore cease to be used.

Table 8: Residual Correction Factors

TLD Element	Correction Factor (mrem)
1	3.2
2,3 and 4	1.5
5,6,7 and 8	2.4

C. Fading

The fading experiment was designed to measure the signal loss over three months. This time period was chosen because it exceeds the typical time between the issuance of the dosimeters and their subsequent reading, six to eight weeks, at LANL. For the study, 35 beta/gamma cards (7 groups of 5 cards) were irradiated with approximately 250 mrem of ^{137}Cs . After 24 hours, the first group was read to determine the initial dose. Every two weeks, another group of cards was read. The neutron cards were subjected to the same study using 30 cards (6 groups of 5 cards) irradiated with moderated ^{252}Cf . In addition, 21 neutron cards (7 groups of 3 cards) were irradiated with ^{137}Cs to determine if there was a difference in the signal fading characteristics of gamma and neutron radiation. Due to miscommunication, the neutron cards with the ^{252}Cf irradiation were not started at the same time as the other fading studies. It was decided to shorten this part of the experiment by two weeks so that the three experiments would end at the same time. This still provided fading characteristics for 2.5 months, two weeks more than the minimum required.

The results from this study are shown in Figures 8 through 10. All error bars in this paper represent a 2σ deviation. The line fits were done using a least squares fit. By observation, it can be seen that there is very little fading. All but two of the fading slopes are statistically equal to zero at a 95% confidence interval. Confidence intervals were calculated for the slopes using the equations⁽¹⁸⁾:

$$\hat{\beta}_1 \pm t_{1-\alpha/2, n-1} \hat{\sigma}_{\hat{\beta}_1} \quad (8)$$

and

$$\hat{\sigma}_{\hat{\beta}_1} = \frac{\sum_{i=1}^N (Y_i - \hat{Y}_i)^2}{(N-2) \sum_{i=1}^N (X_i - \bar{X})^2} \quad (9)$$

where

- N = the number of dosimeter,
- Y_i = the dose at point i ,
- $\hat{Y}_i$ = the equation estimation of dose at point i ,
- X_i = the number of days at point i ,
- $\bar{X}$ = the average number of days, and
- $\hat{\beta}_1$ = the slope of the line.

Elements seven and eight on the neutron card have statistically significant fading after gamma irradiation. These results are subject to speculation since elements six and five are made of the same phosphor respectively and should therefore have the same fading characteristics. Element three on the beta/gamma card shows a statistically significant positive "fade". This is not

Figure 8: Fading on Beta/Gamma Card

Figure 9: Fading on Neutron Card with ^{137}Cs Irradiation

Figure 10: Fading on Neutron Card with ^{252}Cf Irradiation

D. Background

Since background radiation is not considered part of the occupational dose, the background signal on the TLD is subtracted. It was possible to combine the background determination study with the fading study. After each fading group was read, it was secured in an area free of radiation sources. At the end of the study, all groups were re-read showing a build up of the background signal every two weeks for a period of three months. The results of the background experiment are shown in Figures 11 and 12.

The fitted lines were calculated with a forced y-intercept equal to the calculated residual signal. There is good agreement between the data points and the least square fitted lines. The Pearson product moment correlation coefficient (r^2) is a measure

Figure 11: Background Signal on Beta/Gamma Card

Figure 12: Background Signal on Neutron Card

of the linear relationship between x and $y^{(18)}$. A perfect linear fit has an r^2 equal to 1. On the neutron card, the agreement between elements five and eight and between elements six and seven are very good. The minimum r^2 value is 0.951. An average background accumulation rate between the two pairs will be used in practice since they are made of the same phosphor. An average of all four elements can not be used since there is background neutron radiation.

The agreement on the beta/gamma card is not as high as the neutron card. The minimum r^2 value is 0.882. Elements two, three, and four are all made of the same phosphor and should therefore have the same background slope. Using equations 8 and 9 and a 95% confidence interval, the background for elements two and three was not the same. One possible reason for this fluctuation is that elements two through four are made of the new phosphor, LiF:Mg,Cu,P . These were made especially for LANL by Harshaw for the small number of cards that were ordered for testing purposes. It is possible that there is a greater variability in the concentration of the phosphor constituents in this type of situation. There could have also been a shift in the RCF after the last calibration. This would cause all the readings for one element to be too high or too low. Dirt obscuring the light signal leading into one of the PMT would cause low readings for one element by blocking some of the light released by the element. In practice, the background for elements two, three, and four should be averaged. Element one should not be included in the average since it is a different

phosphor. The background correction factors used are presented in Table 9.

It can be seen in Table 9 that there are different background responses for different elements. The background readings shown in this table represent the response of the element to the background radiation and are not a measure of the true background dose. Elements 2, 3, and 4 are made of the same phosphor and therefore accumulate the same amount of background. All four elements are calibrated to ^{137}Cs and have the same response at that energy. At lower energies, the CaF element tends to overrespond. Since the background rate on element 1 is higher than on the other elements, it can be surmised that the average energy of the background radiation is less than that of ^{137}Cs . The background signal on elements 5 and 8 are higher than the signal on elements 6 and 7 because 5 and 8 are recording the background neutron radiation.

Table 9: Background Correction Factors

TLD Element	Correction Factor (mrem)
1	$0.379 \cdot d$
2, 3, and 4	$0.283 \cdot d$
5 and 8	$0.437 \cdot d$
6 and 7	$0.232 \cdot d$

where d = # days since last reading

V. Algorithm Determination

A proper algorithm is essential for accurate dose determination. It is a mathematical conversion from the signals on the TLD dosimeter to a dose estimate to the worker. To determine the conversion factors, signals from known doses need to be measured. This is done with the use of a testing laboratory of the type mentioned in the DOELAP requirements. This experiment was conducted with the assistance of Battelle Pacific Northwest Laboratories, Richland, WA. Gamma and X-ray irradiations were requested for irradiation types K17 (17keV), M30 (20keV), S60 (36keV), ^{241}Am (59keV), M150 (70keV), H150 (120keV), ^{137}Cs (662keV) and beta irradiations were requested for ^{204}Tl (760keV), and $^{90}\text{Sr}/^{90}\text{Y}$ (2.3Mev). Doses of 300 mrem were requested for all except ^{204}Tl where a 500 mrem dose was requested. Five badges for each irradiation type plus five control badges were shipped to Battelle in prototype badge holders. All dosimeters were returned by Battelle with the irradiations completed except the K17 irradiations. An error on their part required a second shipment of badges for the K17 irradiation including Cs and control badges.

Upon the return of the cards, they were removed from their holders and washed with alcohol. This was done to remove any dirt that would inhibit the readings. The cards were then read

after a recalibration of the reader. The background experienced by these cards would not be consistent with the previously calculated background. This difference is experienced because the cards were mailed to another location for a significant period of time. The background experienced at the other location would not be identical in either the amount or in the radiation type distribution as the background in Los Alamos. Since the control cards that were sent were not irradiated, they could be used to estimate the background and the residual signal on the other cards. This was done by subtracting the average readings for each element on the control cards from the signal read on the other cards.

The signals were then normalized to the Cs readings. If there is consistent instrument calibration between Battelle and LANL, the readings on all eight Cs irradiated elements will be 300 mrem. To adjust for calibration differences, the readings on the Cs irradiated elements were adjusted to be exactly 300 mrem. The same adjustment was applied to all other readings. This procedure will account for any calibration differences as well as any reader miscalibration.

One of the algorithm's main functions is the ability to determine radiation energies. To determine the energies, two separate elements for each radiation type are needed. The response on these two elements will be different for a given energy either because of a shielding difference or a difference in the material of the element. Regardless of the total delivered dose, the ratio of the two elements will remain the same. This

ratio can then be used as an independent variable representing energy for dose determinations. The delivered dose can be determined by examining the magnitude of the signal of one of the elements in addition to the previously mentioned ratio.

Calibration curves were then created for use in the algorithm. These curves have the independent variable (x) as the radiation energy represented by the energy ratio. A second ratio of the dose over one of the elements is used for the dependent variable (y). The use of these ratios for the variables produces an interesting result. For any radiation energy, there will be a single y value regardless of total dose. The dose is then determined by multiplying the resultant y value by the magnitude of the element signal used in the dose ratio. If the dose was used alone as the y value, there would only be one dose for each radiation energy.

The first step in the algorithm is to adjust the readings to account for background, fading, if any, and the residual signal. This is done by subtracting the correction factor given in Table 10. Now the separate doses can be determined.

Table 10: Correction Factors for Background and Residual Signal

TLD Element(s)	Correction Factor (mrem)
1	$0.379 \cdot d + 3.153$
2, 3, and 4	$0.283 \cdot d + 1.538$
5 and 8	$0.437 \cdot d + 2.398$
6 and 7	$0.232 \cdot d + 2.398$

where d = number of days since last reading

A. Neutron Dose

With the new LANL badge design, an entire card is used solely for neutron dose determination. The irradiations for determining the neutron dose were performed prior to the start of this project. To determine the neutron dose, the gamma component of the signal must first be removed from the neutron sensitive elements. TLD-600 and TLD-700 have the same elemental composition, therefore a subtraction without conversion is possible. The signal from element six is subtracted from element five and element seven is subtracted from element eight since these pairs have the same shielding. The modified signal ratios of element eight (E8n) to element five (E5n) is used to estimate the average energy of the radiation. The element used in the dose ratio is E8n. This element is used instead of element 5 because element 8 detects the albedo neutrons. If the neutron energy is very high, there will be very little response on element five which would make it difficult to determine dose. The neutron dose relationship is shown in Figure 13. The y-error bars for this graph were based on a 5% error in the delivered dose and represent errors of 1σ . All of the following graphs will assume no error in the delivered dose and will represent errors of 2σ . This curve was created by Jeffrey Hoffman using a ^{252}Cf source. The energy of the radiation was changed by shielding the source with varying amounts of Lucite. The same energy will produce the same ratio of E8n/E5n.

Figure 13: Neutron Dose Determination⁽¹⁹⁾

The dose is then determined using the equation:

$$\text{dose} = \left[0.107 \exp\left(\frac{0.531 \cdot E_{8n}}{E_{5n}}\right) \right] \cdot E_{8n} \quad (10)$$

B. Beta Dose

The next step in the algorithm is to determine the beta dose. However, to do this, some aspects of the gamma dose must be determined. The elements that record beta radiation are also sensitive to gamma radiation. To determine the gamma response on the beta sensitive elements, two and three, the energy of the gamma radiation needs to be known. The energy is determined using the ratio E_1/E_4 since elements one and four are sensitive only to gamma radiation. However, there is one difficulty. At very low energies, the ratio E_1/E_4 rolls over with respect to energy (Figure 14). This relationship was determined using the Battelle irradiation results. The data for all Battelle irradiations can be found in appendix B. A method is needed to determine if the dose is due to very low energy gammas. This can be accomplished with the neutron card. The two TLD-700 elements are covered by two different thicknesses of front shielding. Element 6 has a plastic cover while element 7 has the plastic cover plus a cadmium shield. Lower energy gammas will have a larger response on element 6 since they will have more attenuation on element 7. A ratio of E_7/E_6 would indicate if there are low energy gammas present by the value of the ratio. This would only need to be done if the E_1/E_4 ratio was greater than 7.5.

Figure 14: Gamma Energy Dependence

After it has been determined whether there are high or low gamma energies present, the gamma signal can be separated from the beta signal on the beta sensitive elements. To determine the gamma response on elements 2 and 3, a relationship is needed between those elements and elements 1 and 4 since the experimental signal on elements 2 and 3 will represent both beta and gamma radiation. This relationship is used because elements 1 and 4 are sensitive to gamma radiation exclusively. Curves showing the gamma response on elements two and three for both high energy and low energy gammas are presented in Figures 15 and 16. Using the signals for elements 1 and 4, a resultant for the gamma signal on elements 2 and 3 can be determined. First the ratio of $E1/E4$ is calculated, this is the x value. The y value is determined from the fit equation on the graph. The gamma response on the elements is then calculated

Figure 15: Gamma Response On E2, Low and High Energy

a: Low Gamma Energy

b: High Gamma Energy

$$y = 0.001x^3 - 0.018x^2 + 0.081x + 0.935$$

Figure 16: Gamma Response On E3, Low and High Energy

a: Low Gamma Energy

b: High Gamma Energy

$$y = 0.001x^3 - 0.007x^2 + 0.016x + 0.990$$

Figure 17: Beta Dose Determination

by multiplying the y value by $E4$. The gamma signal on elements 2 and 3 can then be subtracted from the experimental signal on elements 2 and 3 resulting in the beta component of the signal. After the subtraction is completed for both elements, the corrected signals are used to determine the beta dose. By using the corrected ratio $E3\beta/E2\beta$, the dose can be determined using the straight line fit given in Figure 17.

One of the limitations with the beta dose determination is the limited number of sources used to determine the relationship. More sources would provide a more detailed fit equation. Another difficulty is the large uncertainty with the ^{204}Tl data point. The error bars show that the dose can take on a large range of values. Another set of experiments should be performed to better define the algorithm and to reduce the size of the error bars.

C. Gamma Dose

The determination of the gamma dose is simplified once the decision between high and low energies has been determined. One part of the DOELAP standard requires the determination of the gamma dose at different depths in the body. This is done because the lower energy gammas impart more energy to the skin of the worker than to the inner organs. Therefore, dose determinations are made at three different depths, 0.007cm, 0.3cm and 1.0 cm. These depths represent doses to the skin, the lens of the eye, and to the organs. To determine the doses delivered to these different depths, conversion factors (C_x) are used to convert the delivered exposure, expressed in röntgens, to absorbed dose, expressed in rems, in that depth of the body. These C_x values are given in Table 11. The values for the shallow and deep conversions are taken from DOE Standards⁽¹⁾ and are usually applied by the irradiating facility. People working in dosimetry are being asked by DOE to determine doses at the lens of the eye, yet no conversion factors are available at this time. The values for the eye depth dose presented in Table 11 are interpolations from the other two values. These conversion factors were used on the reported doses from Battelle when the testing dosimeters were returned.

In all the gamma dose determinations, the ratio $E1/E4$ will be used as an energy reference and will be the x value in the fit equations. Equations will be developed to relate $E1/E4$ to a dose

Table 11: C_x Conversion Factors⁽¹⁾

Irradiation Source (keV)	C _x Conversion Factor rem / röntgen		
	Shallow Dose	Lens of Eye	Deep Dose
K17 (17)	1.08	0.87	0.38
M30 (20)	1.08	0.89	0.45
S60 (36)	1.15	1.13	1.07
²⁴¹ Am (59)	1.47	1.49	1.54
M150 (70)	1.41	1.43	1.47
H150 (120)	1.41	1.41	1.41
¹³⁷ Cs (662)	1.03	1.03	1.03

ratio as discussed previously. The dose is then determined by multiplying the resultant by the element in the dose ratio. The gamma dose relationships were developed using the data obtained from Battelle Laboratories.

There are two dose ratios that can be used to determine the shallow dose. The first and preferred ratio is to use the dose/E² ratio for the low gamma energies and dose/E⁴ ratio for the high gamma energies. The determination between high and low gamma energies was determined during the beta dose determination. The dose/E² ratio should not be used for gamma dosimetry if there is a beta dose on the card. The beta dose is significant if it is greater than an administratively determined value. No value has been set at this time. If there is a beta dose, the ratio dose/E⁴ is also used for the low energy gammas. It is preferable to use element two because the shielding is closer to the 7mg/cm² value defined for the shallow depth. The values of 0.007cm and 7mg/cm² are used interchangeably when

referring to the human body because there are approximately 1000 mg per 1 cm³. At the higher energies, there is no difference in the response between elements two and four. It is therefore better to use element four to ensure that beta radiation is not interfering with the dose determination. These relationships, with their curve fits, are presented in Figures 18 and 19. There was one difficulty encountered with the low energy gamma dose determination. Because the energies are so low, it is difficult to accurately expose the dosimeters. The two points that are close together in Figure 18 represent energies of 17 and 20 keV. The difficulty in performing K17 irradiations is the most probable cause for the shift. DOE is considering removing the K17 irradiation category from the testing requirements.

The determination of the eye dose is done in the same way as the shallow dose. The ratio of dose/E3 can be used for the lower energies or alternately dose/E4 for the same reasons mentioned above. The ratio of dose/E4 is used for the high energies. These graphs are presented in Figures 20 and 21.

There is only one ratio needed for the deep dose calculation, the dose/E4 ratio, since the E4 element is covered by 600mg/cm² of shielding. This shielding depth eliminates most of the beta signal and is close to the depth for deep dose determination. These relationships are presented in Figure 22.

Figure 18: Shallow Gamma Dose, Low Energy **Figure 19:** Shallow Gamma Dose, High Energy

Figure 20: Eye Level Gamma Dose, Low Energy **Figure 21: Eye Level Gamma Dose, High Energy**

$$y = 0.003x^3 - 0.059x^2 + 0.309x + 0.750$$

Figure 22: Deep Gamma Dose, Low and High Energy

a: Low Gamma Energy

b: High Gamma Energy

The slope of the curve for the low energy gamma deep dose is positive. This is due to the fact that the shielding represented by the deep dose is greater than the shielding over element 4. Therefore the dose is decreasing faster than the response on element 4 as a function of energy. This causes the positive slope. The low energy gamma curves for the shallow and eye level doses have a negative slope. For these dose levels, the dose does not change very much with energy but the response on element 4 decreases with decreasing energy. Since element 4 is in the denominator, a positive slope is produced. A summary of the dose algorithm is presented in appendix D.

One of the difficulties encountered in the course of the experiments was a possibility of sensitivity losses in the LiF:Mg,Cu,P elements. These losses can be observed by

comparing the two sets of data from Battelle in appendix B. Both sets of Cs irradiations were performed with the same cards. The first irradiation produced higher readings than the second irradiation in elements 2, 3, and 4. Element 1 with the CaF phosphor was not affected. The losses could not be reproduced but they occurred at various times. It is unclear at this point what was causing the losses or even if the losses were real. It is possible that the problems occurred with the irradiation or in the reading process.

D. LANL Irradiator Comparison

LANL recently obtained and calibrated equipment that could perform some of the required irradiations for DOELAP certification. Irradiations from M30 (20keV), S60 (36keV), M150 (70keV), and H150 (120keV) were performed at LANL and compared to the results from Battelle. A comparison graph is shown in Figure 23. The two curves indicate that there is agreement with the relationship between energy and the $E1/E4$ ratio. However, the value of the ratio from the cards irradiated by the LANL facility is lower than the ratio from the cards irradiated by Battelle for the same energy. The lower ratio for LANL would be caused either by element 1 reading lower, element 4 reading higher, or a combination of the two. One interesting point to note is that the ratios between the two facilities seem to be different by the same amount. This shift is most likely caused by the reading of the cards rather than the irradiation of the cards. A problem with the irradiation energy would shift the curve to the

left or the right. Differences with the irradiation dose would not affect the $E1/E4$ ratio. This shift cannot be explained with the possible sensitivity losses in elements 2, 3, and 4. That would have caused the LANL readings to be higher than the Battelle readings.

Figure 23: LANL and Battelle Irradiation Comparison

VI. Conclusions

A. Supporting Studies

The results that were obtained from the supporting studies indicated that there were no significant problems with the new dosimeter. The reproducibility study indicated that the cards have a small enough deviation to be usable with dosimetry operations. It is also thought that when the cards are mass produced, there will be greater consistency between like elements. One area that demonstrates this problem is the ECC numbers. The neutron cards which contain phosphors commonly in use had ECC's ranging from 1.2 to 0.8. The beta/gamma cards which contain the new phosphor had ECC's ranging from 2.0 to 0.7. These large numbers indicate a wide variability between the beta/gamma cards. Even though the ECC's correct for the variability, small deviations in the readings are multiplied. It is believed that when the cards are ordered in large quantities, there will be greater consistency between the cards.

The residual signal found on the cards was not very large and should not pose a problem in dose determinations. The highest residual was found on the CaF element. This element is used solely for gamma energy determination and should therefore not have as much effect on dose determination. The signal from the CaF element is used most when the gamma energy is very low. At these energies, the CaF element has a

very large signal even with low doses. The residual would therefore be insignificant. Since the residual found on a card is dependent upon the signal originally placed on the card, a second round of studies should be undertaken. These studies would have original doses that were lower than performed here. It is expected that the residual signal would be constant at lower doses. Another way to determine the residual signal would be to read and anneal the card a few times without irradiations in between. It is unknown whether the residuals obtained by these two procedures would be the same. The first method would be closer to normal conditions and is therefore the preferred method.

The results from the fading study were the most unexpected of all the results. Theoretically, a linear curve should have been seen. One of the curves had a statistically positive fade, some had no fade, and others had a statistically negative fade. There is a second method to determine the fading characteristics of phosphors. This method would stagger the irradiations on the cards and have all of the cards read at once. The first method ensures that the cards are all irradiated with the same dose and the second method ensures that the instrumentation reads all the cards in the same manner. The first method was chosen since it could be combined with the background study and there were a limited numbers of cards available. One of the problems with this study was that the TTP for the beta/gamma cards was altered slightly during the experiment. However, this can not explain the deviations in the data. Even with the difficulties and

the inconsistencies, the fading observed was very small for all the elements. This amount of fading is not considered significant for the typical doses encountered. It would also be very difficult to accurately determine the amount of fading that had occurred. There would be quite a difference in the fading if the dose was received at the beginning or at the end of the issuing period. In an accident situation where the fading could be significant, the badges are always read immediately.

The background study produced good results that were consistent with expectations. A second study could be undertaken to discover two things. One question is what caused the difference in the background rates between the elements in the beta/gamma card. This is a very important question since it can influence the accuracy of the results. Another question that should be answered concerns the seasonal variation of the background. It is possible that the summer months are high or low months for background radiation. If one relation is to be used, it should be the average dose for the year. For more accurate results, background levels for each of the months could be determined and used accordingly during field usage.

B. Dose Algorithm Determination

Overall, the development of the dose algorithm was successful. The ratios between the element signals provided a good energy relationship. One of the difficulties that still needs to be overcome is the ability to recognize low energy gammas. There are two problems with the suggested method of using the

neutron card. Many people at LANL do not work in areas that have neutron radiation. It would be more cost efficient to not issue them a neutron card. The badge would remain the same but the slot for the neutron card would remain empty. Another difficulty occurs when there is beta radiation. The shielding for elements five and six is not thick enough to stop high energy beta particles. While this does not affect the neutron dose determination, it would interfere with the low energy gamma determination. To determine the gamma energy, a regressive algorithm would have to be applied. If the shielding was thickened to eliminate the beta signal, there would be a decrease in the sensitivity for thermal neutron detection.

The LANL irradiations showed the same curve shape for the E1/E4 ratio as Battelle but with a lower ratio value. If LANL's irradiator was just calibrated too low, the ratio would remain the same. For this type of error, one element would produce signals that are too high or too low. A shift in the RCF for one of the elements could account for this result. A second experiment should be undertaken to see if the results can be reproduced.

A problem with the sensitivity of the LiF:Mg,Cu,P elements was experienced during the experiments. This became very apparent during the DOELAP irradiations. When the second group of cards was sent for the K17 irradiation, a group was sent for Cs irradiation in order to normalize the data. These cards were the same cards that were sent with the initial irradiation group. The cards were returned with a significantly lower signal though they were irradiated to the same dose level. It was

thought that the maximum temperature in the TTP was set too high and caused the sensitivity loss. The TTP being used was suggested by the manufacturer and had been extensively tested by them⁽²⁰⁾. Slight changes in the TTP did not stop the apparent sensitivity losses. The glow curve became elongated when the maximum temperature was lowered, indicating that the signal was not being completely removed. Attempts to reproduce the loss were not successful though they were experienced at other times through the experiment. At the beginning of these studies, the cards had already been used for other tests. The sensitivity question should be studied when new cards are available. The sensitivity loss could be induced before the cards go into production if there is a loss occurring. If they are calibrated after the loss, no difference should be seen as long as there are no future losses.

Work that still needs to be done is the determination of the lower limit of detection and the angular dependence. While these studies are not integral in the algorithm itself, they are required for DOELAP certification. A sensitivity study should be done to determine if a sensitivity loss is occurring. If the neutron card is going to be used to distinguish high and low gamma energies, a relationship must be established.

APPENDIX A: SUPPORTING STUDIES

Reproducibility Study, beta/gamma cards, readings in mrem

Reading 7/31/94

50 mrem dose

Element 1	Element 2	Element 3	Element 4
54.63	54.74	57.32	59.03
54.99	52.80	57.17	59.30
55.43	51.53	55.26	58.78
55.37	51.40	55.91	58.75
54.31	56.52	60.09	91.36
55.38	51.09	54.66	58.20
55.18	54.94	55.96	58.43

100 mrem dose

Element 1	Element 2	Element 3	Element 4
106.3	101.7	112.5	114.5
105.2	112.8	124.1	128.4
101.3	114.2	121.9	125.3
103.7	112.6	122.8	126.6
103.0	112.2	126.6	128.0
101.7	112.6	123.3	128.4
106.8	112.8	122.6	126.4

200 mrem dose

Element 1	Element 2	Element 3	Element 4
208.7	229.1	246.2	251.5
210.3	227.3	245.8	252.6
209.8	230.0	246.2	249.2
210.0	227.6	245.6	243.0
210.3	227.5	238.1	253.7
209.4	224.7	242.3	255.4
208.4	227.5	244.6	252.9

Reproducibility Study, beta/gamma cards, readings in mrem

Reading 8/4/94

50 mrem dose

Element 1	Element 2	Element 3	Element 4
53.34	55.01	57.69	58.04
53.13	52.42	55.45	57.66
52.99	57.26	60.16	59.33
53.26	53.49	56.23	58.06
53.10	52.14	56.47	57.46
52.10	54.02	57.62	57.89
52.37	54.18	58.18	58.44

100 mrem dose

Element 1	Element 2	Element 3	Element 4
105.0	123.9	129.1	131.8
96.07	122.1	131.1	133.7
97.17	124.2	132.5	133.0
100.0	125.1	129.8	132.7
95.84	125.1	130.1	132.1
100.3	121.5	131.1	133.7
102.9	110.6	115.4	115.1

200 mrem dose

Element 1	Element 2	Element 3	Element 4
206.9	247.9	262.0	267.9
205.5	245.6	257.4	266.8
206.6	247.6	255.5	266.8
207.2	250.9	259.3	251.5
205.9	251.7	262.8	262.0
206.5	249.8	261.8	266.4
203.9	246.9	262.1	262.6

Reproducibility Study, beta/gamma cards, readings in mrem

Reading 8/9/94

50 mrem dose

Element 1	Element 2	Element 3	Element 4
52.64	55.02	57.22	56.40
52.37	53.35	56.40	56.77
52.29	57.24	60.49	58.06
52.14	54.19	56.14	56.14
51.96	52.84	56.74	56.29
51.36	55.55	57.65	56.93
51.59	54.71	58.46	57.44

100 mrem dose

Element 1	Element 2	Element 3	Element 4
104.0	126.2	129.9	130.7
94.37	125.5	132.1	132.9
94.99	125.7	135.7	134.4
97.32	127.6	132.5	132.7
93.83	127.8	131.8	130.6
98.22	124.9	134.4	134.6
102.5	112.0	107.1	114.8

200 mrem dose

Element 1	Element 2	Element 3	Element 4
206.3	252.7	264.8	267.4
204.5	248.8	261.0	266.8
204.9	251.0	259.5	265.9
206.2	254.3	263.0	247.2
204.5	257.5	267.4	259.1
205.4	253.7	265.4	263.4
204.1	249.7	265.6	261.7

Reproducibility Study, neutron cards, readings in mrem

Reading 7/14/94

50 mrem dose

Element 5	Element 6	Element 7	Element 8
56.65	56.18	55.75	56.07
55.82	55.37	53.38	54.49
55.24	53.59	53.46	52.68
55.31	52.95	54.52	54.26
55.29	52.96	54.23	54.89

100 mrem dose

Element 5	Element 6	Element 7	Element 8
106.6	104.7	105.2	105.8
106.7	104.2	103.8	105.1
106.1	103.5	106.3	107.7
106.7	104.8	105.2	107.3
107.1	104.0	106.0	107.3

200 mrem dose

Element 5	Element 6	Element 7	Element 8
208.7	206.6	207.9	208.9
209.4	206.5	207.1	209.0
210.2	209.5	209.5	207.2
209.8	208.0	208.6	208.8
211.5	211.5	207.1	208.6

Reproducibility Study, neutron cards, readings in mrem

Reading 7/21/94

50 mrem dose

Element 5	Element 6	Element 7	Element 8
53.52	53.24	50.21	50.89
53.62	53.68	48.90	50.61
53.27	51.57	50.33	50.26
54.28	52.24	49.16	49.70
53.49	51.42	50.38	49.52

100 mrem dose

Element 5	Element 6	Element 7	Element 8
105.7	101.8	98.41	99.16
106.7	103.7	98.86	99.39
106.0	103.6	98.30	101.0
106.1	103.9	96.22	97.90
105.3	102.2	98.19	99.45

200 mrem dose

Element 5	Element 6	Element 7	Element 8
213.0	210.0	193.6	199.6
209.7	206.7	196.3	196.5
208.8	207.5	197.2	197.1
205.7	207.4	196.6	197.6

Reproducibility Study, neutron cards, readings in mrem

Reading 8/4/94

50 mrem dose

Element 5	Element 6	Element 7	Element 8
54.12	52.98	51.14	50.41
51.73	51.93	50.63	49.19
51.08	51.86	51.57	51.03
51.60	51.27	50.77	49.48
52.72	51.38	51.75	48.21
51.62	52.47	51.58	48.23
53.70	49.93	51.51	49.13

100 mrem dose

Element 5	Element 6	Element 7	Element 8
101.9	99.53	98.55	94.92
102.3	100.8	100.0	95.19
103.8	100.6	99.12	97.00
105.1	103.7	99.91	97.94
105.3	100.6	100.0	97.33
101.9	101.4	98.59	94.44
105.9	100.9	104.1	97.47

200 mrem dose

Element 5	Element 6	Element 7	Element 8
205.4	201.7	199.2	189.8
203.7	199.6	197.9	188.4
201.6	199.5	199.3	192.8
206.4	199.5	198.9	191.5
204.2	199.3	193.2	188.2
203.5	199.4	200.5	191.4
203.6	202.4	195.2	192.9

Residual Study, beta/gamma cards, readings in mrem

Reading 8/3/94

50 mrem initial dose

Element 1	Element 2	Element 3	Element 4
3.088	1.892	1.517	1.287
4.211	1.608	1.906	1.414
2.912	1.836	1.862	2.061
4.243	1.437	2.077	1.208
3.470	1.992	2.080	2.569
3.105	1.852	2.860	2.126
2.802	1.817	2.073	1.576

100 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.678	1.989	2.730	1.711
7.278	2.927	2.508	2.072
6.270	2.678	2.369	1.574
5.946	1.964	3.016	1.630
6.537	2.389	3.180	1.919
7.062	3.022	2.980	2.700
3.077	1.819	3.032	3.097

200 mrem initial dose

Element 1	Element 2	Element 3	Element 4
4.400	4.316	3.395	2.473
3.629	4.047	3.821	2.446
3.724	4.000	4.555	2.467
4.478	3.439	3.178	5.045
4.075	3.131	3.781	4.216
4.208	2.869	3.927	3.500
3.145	3.662	3.652	3.052

Residual Study, beta/gamma cards, readings in mrem

Reading 8/5/94

50 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.107	1.265	1.606	1.197
2.370	1.285	2.040	1.454
2.889	1.448	1.490	1.640
3.486	0.9951	1.601	1.002
2.522	1.433	1.395	1.488
3.603	1.219	1.318	0.9064
3.601	1.328	1.154	0.9691

100 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.484	1.353	2.246	2.401
5.044	2.453	2.531	2.358
5.252	2.059	2.547	1.655
4.669	1.613	2.331	1.402
4.900	2.123	1.936	1.482
5.624	2.380	2.132	1.717
2.410	1.806	2.594	1.631

200 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.712	3.240	3.026	2.772
3.383	2.373	3.553	3.355
3.403	2.686	3.011	3.557
3.560	3.024	2.465	3.580
3.029	3.321	3.728	2.232
2.926	3.269	3.268	2.312
3.819	3.860	2.827	2.225

Residual Study, beta/gamma cards, readings in mrem

Reading 8/8/94

50 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.813	1.446	1.214	1.146
3.938	1.264	1.449	1.187
2.954	1.564	1.504	1.621
3.871	1.177	1.501	1.094
3.261	1.486	1.485	1.594
2.495	1.409	1.774	1.384
2.451	1.539	1.545	1.233

100 mrem initial dose

Element 1	Element 2	Element 3	Element 4
2.739	1.966	2.240	1.695
5.896	2.413	2.022	1.815
5.167	2.222	1.883	1.637
4.698	1.882	2.223	1.623
5.427	2.182	2.468	1.762
4.932	2.526	2.318	2.343
2.933	1.562	2.131	2.328

200 mrem initial dose

Element 1	Element 2	Element 3	Element 4
4.560	4.099	3.062	2.589
3.465	3.566	3.223	2.598
3.369	3.584	3.806	2.508
3.670	3.278	2.640	3.688
3.540	2.870	3.304	3.831
3.538	2.696	3.267	3.159
3.133	3.505	3.288	2.836

Residual Study, neutron cards, readings in mrem

Reading 7/15/94

50 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.461	3.158	2.188	2.982
2.559	2.590	2.106	2.300
2.280	2.762	2.355	2.114
2.455	2.466	2.404	2.885
2.665	2.589	2.362	3.167

100 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.629	3.129	2.056	3.664
2.515	2.404	1.097	3.247
2.419	2.301	2.402	2.851
2.554	2.904	2.335	2.827
2.736	2.339	2.321	3.692

200 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.706	3.295	3.357	3.650
2.652	2.918	3.348	2.459
3.237	3.082	2.562	2.780
3.715	2.774	2.393	2.637
3.410	3.407	2.613	3.324

Residual Study, neutron cards, readings in mrem

Reading 8/5/94

50 mrem initial dose

Element 5	Element 6	Element 7	Element 8
1.902	1.917	2.187	1.825
1.847	2.618	2.059	2.021
2.058	2.142	1.996	2.384
1.943	2.215	1.787	2.028
2.006	2.318	1.910	3.307
1.723	1.941	2.179	2.415
3.259	2.812	2.707	2.072

100 mrem initial dose

Element 5	Element 6	Element 7	Element 8
1.996	3.243	4.975	2.363
1.822	2.084	1.891	1.858
2.451	2.105	1.848	2.071
2.013	1.952	2.021	2.639
1.952	2.602	1.813	2.441
1.702	1.931	1.899	1.786
2.040	2.406	1.813	1.665

200 mrem initial dose

Element 5	Element 6	Element 7	Element 8
1.940	2.295	2.010	2.160
1.938	2.059	2.159	2.740
2.360	2.397	2.147	2.694
2.518	2.047	1.918	2.081
1.831	2.172	2.033	2.353
1.988	2.613	1.885	2.628
1.913	2.254	1.902	1.962

Residual Study, neutron cards, readings in mrem

Reading 8/8/94

50 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.615	2.298	2.172	1.937
2.020	2.300	2.291	2.495
2.246	2.489	2.340	2.922
2.261	2.319	2.040	2.178
2.498	2.935	2.186	2.349
2.312	2.844	2.535	2.441
3.076	2.636	3.309	2.640

100 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.447	2.604	2.138	2.007
2.126	2.240	2.065	2.178
2.530	2.552	2.141	2.588
2.330	2.188	2.295	2.854
2.622	2.297	2.109	2.443
2.068	2.196	2.057	2.038
2.300	3.094	5.357	2.444

200 mrem initial dose

Element 5	Element 6	Element 7	Element 8
2.690	2.751	2.375	2.417
2.292	2.651	2.435	3.051
2.154	2.466	2.289	2.493
2.742	2.359	2.258	2.210
2.912	2.470	2.723	2.662
2.431	2.351	2.329	2.707
2.384	2.362	2.007	2.092

Fading Study, beta/gamma cards, readings in mrem

Initial Reading, same day as exposure 6/13/94

Element 1	Element 2	Element 3	Element 4
263.7	274.1	281.9	274.9
261.4	273.7	278.7	274.0
265.7	272.7	278.5	271.5
262.7	275.3	272.5	271.3
261.0	274.9	274.5	268.1

Group 1, read 6/14/94

Element 1	Element 2	Element 3	Element 4
256.0	266.8	279.4	292.9
255.3	266.8	280.3	265.6
252.6	268.7	277.0	273.9
253.5	264.8	277.3	272.7
251.7	270.3	278.3	273.8

Group 2, read 6/29/94

Element 1	Element 2	Element 3	Element 4
254.4	279.2	284.3	273.1
251.3	279.4	281.7	273.1
249.9	278.5	279.2	274.6
249.3	277.0	278.6	271.4
250.4	274.6	280.8	269.4

Group 3, read 7/12/94

Element 1	Element 2	Element 3	Element 4
255.3	279.0	287.2	263.7
263.8	274.8	319.0	276.2
241.7	278.8	292.6	264.1
250.2	266.1	285.2	260.9
236.5	282.8	291.4	264.8

Fading Study, beta/gamma cards, readings in mrem

Group 4, read 7/26/94

Element 1	Element 2	Element 3	Element 4
248.3	277.2	294.8	269.1
250.4	284.2	289.0	266.7
248.8	286.6	287.4	272.9
239.4	280.8	286.5	270.5
248.7	286.0	291.9	265.5

Group 5, read 8/9/94

Element 1	Element 2	Element 3	Element 4
311.4	295.1	347.5	316.9
309.7	303.2	352.9	326.8
289.6	300.9	321.7	327.6
303.8	309.4	325.0	334.8
287.1	316.4	337.0	339.2

Group 6, read 8/23/94

Element 1	Element 2	Element 3	Element 4
282.5	288.5	302.8	286.0
277.5	292.0	304.8	292.9
293.2	284.7	343.1	295.9
280.1	273.3	321.1	274.4
279.9	267.3	324.4	270.8

Group 7, read 9/2/94

Element 1	Element 2	Element 3	Element 4
317.2	297.4	334.9	298.2
309.1	311.9	350.2	298.1
285.3	282.1	291.6	258.5
290.7	270.5	313.3	257.0
288.4	266.1	307.5	247.4

Fading Study, neutron cards with Cf irradiation, readings in mrem

Group 2, read 6/29/94

Element 5 Element 6

245.4	245.7
241.1	242.6
244.4	260.6
255.8	253.7
254.3	267.4
257.7	253.0
246.7	252.2
255.4	246.6

Group 3, read 7/12/94

Element 5 Element 6

251.7	262.0
255.4	246.7
274.9	262.0
258.1	250.3
265.7	264.0

Group 4, read 7/26/94

Element 5 Element 6

251.3	233.7
249.1	243.5
253.6	246.3
253.8	267.6
248.6	255.0

Group 5, read 8/9/94

Element 5 Element 6

270.8	254.5
283.0	247.9
261.5	246.3
242.0	231.0
252.4	221.2

Group 6, read 8/23/94

Element 5 Element 6

347.9	276.0
358.3	237.0
335.0	250.0
330.0	250.6
378.3	256.1

Group 7, read 9/2/94

Element 5 Element 6

270.2	221.8
257.7	208.3
246.6	209.6
240.0	218.8
257.9	217.4

Fading Study, neutron cards with Cs irradiation, readings in mrem

Group 1, read 6/14/94

Element 5	Element 6	Element 7	Element 8
205.9	198.1	203.5	201.8
204.1	197.4	200.1	198.9
204.5	197.5	201.6	201.2

Group 2, read 6/29/94

Element 5	Element 6	Element 7	Element 8
201.6	197.6	203.5	197.0
205.9	202.4	205.1	198.0
206.2	203.9	205.7	198.5

Group 3, read 7/12/94

Element 5	Element 6	Element 7	Element 8
216.2	211.4	208.2	205.4
210.9	206.7	215.0	205.8
224.8	211.0	216.6	219.0

Group 4, read 7/26/94

Element 5	Element 6	Element 7	Element 8
231.6	223.2	196.6	218.2
220.6	207.2	195.2	216.4
220.9	226.2	201.3	199.0

Group 5, read 8/9/94

Element 5	Element 6	Element 7	Element 8
232.9	208.6	207.4	192.7
219.5	218.9	219.6	206.4
234.9	212.9	212.3	196.1

Fading Study, neutron cards with Cs irradiation, readings in mrem

Group 6, read 8/23/94

Element 5	Element 6	Element 7	Element 8
297.3	265.2	687.9	209.3
293.8	275.3	701.8	206.5
287.3	280.1	767.1	212.2

Group 7, read 9/2/94

Element 5	Element 6	Element 7	Element 8
228.2	207.1	187.2	194.0
222.6	201.4	186.0	190.0
235.6	201.2	184.1	192.3

Background Study, beta/gamma cards, readings in mrem

Group 1, 85 days

Element 1	Element 2	Element 3	Element 4
34.79	20.80	30.13	28.88
34.77	20.34	29.89	28.06
34.77	20.04	29.62	29.21
35.11	20.33	31.75	28.48
35.84	20.28	29.40	26.21

Group 2, 70 days

Element 1	Element 2	Element 3	Element 4
28.27	21.39	27.64	22.59
28.23	21.77	27.11	23.72
28.39	20.10	26.45	23.06
29.33	19.60	27.38	23.89
37.15	22.29	31.83	29.45

Group 3, 57 days

Element 1	Element 2	Element 3	Element 4
23.71	12.73	15.15	12.55
24.31	14.57	14.67	13.08
24.76	13.15	15.04	12.89
24.88	13.79	14.94	13.22
22.58	12.19	13.70	11.91

Group 4, 43 days

Element 1	Element 2	Element 3	Element 4
17.31	10.06	11.70	9.80
19.47	11.34	12.57	10.34
19.54	10.16	11.58	9.82
18.91	10.50	11.80	9.28
20.69	11.44	12.22	10.45

Background Study, beta/gamma cards, readings in mrem

Group 5, 29 days

Element 1	Element 2	Element 3	Element 4
14.15	11.44	12.24	13.29
16.17	11.36	11.05	11.79
15.12	11.57	12.06	10.56
15.11	11.30	12.40	10.87
15.56	10.22	11.93	9.98

Group 6, 15 days

Element 1	Element 2	Element 3	Element 4
9.32	7.98	7.23	6.14
9.81	6.28	7.78	5.90
8.88	7.98	7.16	6.63
8.80	6.14	7.48	5.90
9.21	7.86	7.39	7.44

Group 7, 5 days

Element 1	Element 2	Element 3	Element 4
4.25	2.44	4.04	4.01
3.76	3.83	3.83	3.36
5.08	3.43	3.62	3.86
4.14	3.71	5.24	4.96
4.16	3.29	4.93	3.51

Background study, neutron cards, readings in mrem

Group 2, 70 days

Element 5	Element 6	Element 7	Element 8
36.09	20.66	20.26	29.66
29.87	18.34	17.01	26.22
33.18	19.58	17.77	27.94
38.60	18.80	19.45	32.33
43.61	18.85	16.90	40.82
37.47	17.77	16.93	40.83
36.78	18.59	17.54	36.89
39.52	18.39	17.25	35.59
45.82	19.68	17.36	39.65
47.35	17.73	16.83	30.47
45.11	20.04	22.14	33.13

Group 3, 57 days

Element 5	Element 6	Element 7	Element 8
27.10	16.33	15.16	22.51
23.45	15.59	15.06	22.59
24.96	15.53	14.39	22.60
25.24	16.01	13.50	21.82
28.41	15.53	14.01	23.10
25.06	15.95	14.19	23.56
24.36	16.04	14.25	22.38
26.07	16.29	14.20	23.73

Background study, neutron cards, readings in mrem

Group 4, 43 days

Element 5	Element 6	Element 7	Element 8
20.51	12.89	11.24	19.18
19.73	13.43	12.07	19.80
19.96	12.27	11.68	18.51
19.99	12.69	11.90	18.01
20.16	13.49	11.81	18.84
19.78	13.21	12.36	18.29
19.25	12.95	11.37	17.98
22.88	13.69	11.79	18.81

Group 5, 29 days

Element 5	Element 6	Element 7	Element 8
14.95	9.92	9.14	14.86
16.54	10.06	8.94	13.00
14.43	9.99	8.66	13.66
14.26	9.68	8.49	13.20
14.29	10.28	8.59	12.88
15.13	9.68	9.059	12.88
14.40	9.72	8.40	12.36
16.05	10.38	8.74	12.74

Group 6, 15 days

Element 5	Element 6	Element 7	Element 8
11.35	6.08	6.97	10.32
10.81	8.72	9.70	8.83
8.78	6.80	6.38	8.28
8.71	7.24	6.05	7.74
13.46	8.11	7.26	12.59
10.21	6.34	7.09	9.98
10.17	6.67	7.51	10.74
12.47	6.87	6.76	14.39

Background study, neutron cards, readings in mrem

Group 7, 5 days

Element 5	Element 6	Element 7	Element 8
3.18	2.82	2.70	4.37
4.34	3.30	3.23	3.05
4.64	4.31	3.51	3.86
3.70	2.85	2.79	6.09
4.12	2.66	2.32	4.51
4.87	2.75	2.06	3.90
4.16	2.36	2.23	3.83
5.80	4.67	2.88	5.72

APPENDIX B: DOELAP STUDIES

Controls

	Element 1	Element 2	Element 3	Element 4
	12.03	8.89	8.47	7.80
	11.99	8.21	8.56	7.63
	12.92	8.70	8.54	7.59
	12.46	8.84	8.42	7.70
	14.57	8.71	8.39	7.63
average	12.79	8.67	8.48	7.67
std. dev.	1.06	0.269	0.073	0.081

Category III. Low Energy Photons, M30, E = 20 keV

	Element 1	Element 2	Element 3	Element 4
	3726	575.0	535.7	384.6
	3745	603.3	551.6	371.3
	3695	592.9	537.4	385.1
	3773	589.9	545.2	398.2
	3764	596.7	563.7	379.5
average	3741	591.6	546.7	383.8
std. dev.	31.26	10.52	11.43	9.80
normalized	3407	576.3	578.0	421.6

Category III. Low Energy Photons, S60, E = 36 keV

	Element 1	Element 2	Element 3	Element 4
	4366	427.5	397.3	356.2
	4394	423.3	389.1	367.1
	4349	421.0	402.3	340.1
	4438	425.5	386.1	362.9
	4349	418.6	402.7	352.9
average	4379	423.2	395.5	355.9
std. dev.	37.66	3.53	7.59	10.41
normalized	3989	412.2	418.1	390.9

Category III. Low Energy Photons, M150, E = 70 keV

	Element 1	Element 2	Element 3	Element 4
	2639	312.7	292.5	273.9
	2642	315.7	297.0	292.3
	2644	312.0	298.1	288.5
	2587	317.1	300.5	288.9
	2786	319.5	309.4	283.3
average	2660	315.4	299.5	285.4
std. dev.	74.54	3.11	6.25	7.18
normalized	2423	307.3	316.6	313.5

Category III. Low Energy Photons, H150, E = 120 keV

	Element 1	Element 2	Element 3	Element 4
	1038	241.7	231.7	206.0
	1146	246.9	236.8	227.1
	1100	248.0	247.9	235.2
	1049	239.5	239.6	215.8
	1118	247.6	251.3	233.1
average	1090	244.8	241.5	223.5
std. dev.	45.84	3.88	8.04	12.32
normalized	993.2	238.4	255.3	245.5

Category III. Low Energy Photons, ^{241}Am , E = 59 keV

	Element 1	Element 2	Element 3	Element 4
	3105	333.8	314.4	290.2308
	3017	314.5	311.8	301.0308
	3033	303.4	305.5	306.3308
	3222	335.5	305.8	299.0308
	3241	344.2	321.1	314.3308
average	3123	326.3	311.7	302.2
std. dev.	104.1	16.77	6.50	8.93
normalized	2845	317.9	329.6	331.9

Category IV. High Energy Photons, ^{137}Cs , $E = 662 \text{ keV}$

	Element 1	Element 2	Element 3	Element 4
	325.5	304.3	282.6	272.2
	322.5	298.1	282.5	280.0
	325.3	304.8	286.1	264.8
	331.6	311.1	279.5	265.5
	341.8	321.4	288.1	282.9
average	329.3	308.0	283.8	273.1
std. dev.	7.72	8.82	3.37	8.23
normalized	300	300	300	300

Category V. Beta Particles, ^{204}Tl , $E = 0.76 \text{ Mev (max)}$

	Element 1	Element 2	Element 3	Element 4
	1.02	271.6	382.2	0.159
	1.21	286.5	413.3	0.551
	1.63	378.3	437.6	0.564
	1.62	312.6	337.9	0.340
	1.17	267.8	362.3	0.494
average	1.33	303.4	386.7	0.422
std. dev.	0.278	45.44	39.67	0.172
normalized	1.22	295.5	408.8	0.464

Category V. Beta Particles, $^{90}\text{Sr}/^{90}\text{Y}$, $E = 2,300 \text{ Mev (max)}$

	Element 1	Element 2	Element 3	Element 4
	11.80	367.7	351.8	13.92
	11.20	374.0	337.5	12.11
	10.48	400.9	352.8	12.23
	11.69	383.7	372.5	13.44
	11.60	397.2	371.4	14.74
average	11.36	384.7	357.2	13.29
std. dev.	0.538	14.34	14.77	1.12
normalized	10.35	374.8	377.6	14.60

Category III. Low Energy Photons, K17, $E = 15\text{-}20 \text{ keV}$
(done separately)

Controls

	Element 1	Element 2	Element 3	Element 4
	6.07	4.04	3.72	3.36
	6.12	3.87	3.86	3.56
	6.53	4.08	3.62	3.35
	6.37	3.98	3.78	3.36
	7.18	3.87	3.82	3.30
average	6.45	3.97	3.76	3.38
std. dev.	0.448	0.096	0.092	0.100

Category IV. High Energy Photons, ^{137}Cs , E = 662 keV

	Element 1	Element 2	Element 3	Element 4
	338.1	280.3	258.0	239.9
	340.2	274.8	254.4	245.2
	341.8	278.8	258.6	247.0
	337.9	282.7	258.7	240.7
	355.5	295.8	264.5	250.3
average	342.7	282.5	258.9	244.6
std. dev.	7.33	7.98	3.62	4.36
normalized	300	300	300	300

Category III. Low Energy Photons, K17, E = 15-20 keV

	Element 1	Element 2	Element 3	Element 4
	4971	663.1	613.9	429.1
	5147	666.3	636.3	473.3
	5215	706.4	666.8	479.9
	5268	708.8	663.5	490.1
	5012	674.3	661.3	458.1
average	5123	683.8	648.4	466.1
std. dev.	128.0	22.14	22.75	23.72
normalized	4484	726.1	751.4	571.6

APPENDIX C: LANL IRRADIATOR STUDIES

Controls

	Element 1	Element 2	Element 3	Element 4
	4.24	2.28	3.21	2.35
	4.33	2.87	4.34	3.18
	4.77	3.25	3.68	2.66
	4.90	2.90	3.33	4.46
	4.34	3.40	4.16	2.60
average	4.52	2.94	3.74	3.05
std. dev.	0.296	0.433	0.496	0.845

Category III. Low Energy Photons, M30, E = 20 keV

	Element 1	Element 2	Element 3	Element 4
	3187	468.5	467.4	356.5
	3114	476.2	475.4	379.9
	2860	480.7	479.9	367.5
	3174	486.3	485.5	383.4
	3183	480.8	480.0	378.1
average	3104	478.5	477.6	373.0
std. dev.	139	6.64	6.75	11.00
normalized	2827	466.1	504.9	409.8

Category III. Low Energy Photons, S60, E = 36 keV

	Element 1	Element 2	Element 3	Element 4
	4256	385.6	389.5	403.1
	4053	365.2	359.8	396.9
	4252	389.7	381.8	386.5
	4437	404.0	389.2	408.9
	4382	390.6	395.8	417.0
average	4276	387.0	383.2	402.4
std. dev.	148	14.02	14.00	11.61
normalized	3895	377.0	405.1	442.1

Category III. Low Energy Photons, M150, E = 70 keV

	Element 1	Element 2	Element 3	Element 4
	2312	269.3	275.4	287.0
	2272	276.5	270.9	282.3
	2446	272.7	264.0	294.1
	2223	240.5	259.4	289.3
	2267	268.7	271.7	276.7
average	2304	265.5	268.2	285.8
std. dev.	85.41	14.34	6.45	6.66
normalized	2099	258.6	283.6	314.0

Category III. Low Energy Photons, H150, E = 120 keV

	Element 1	Element 2	Element 3	Element 4
	808.8	205.8	215.1	222.5
	838.5	207.4	206.5	219.8
	879.4	207.8	212.8	228.9
	850.8	204.3	210.8	233.6
	752.9	200.8	200.5	202.1
average	826.1	205.2	209.1	221.3
std. dev.	48.12	2.83	5.77	12.06
normalized	752.5	199.9	221.0	243.1

APPENDIX D: DOSE ALGORITHM

Flow Chart (Equations follow)

Equations

$$\text{Neutron dose} = \left[0.107 \cdot \exp \left(\frac{0.531 \cdot (E8 - E7)}{E5 - E6} \right) \right] \cdot (E8 - E7) \quad (11)$$

$$E2\gamma = \left[0.001 \cdot \left(\frac{E1}{E4} \right)^3 - 0.018 \cdot \left(\frac{E1}{E4} \right)^2 + 0.081 \cdot \left(\frac{E1}{E4} \right) + 0.935 \right] \cdot E4 \quad (12)$$

$$E3\gamma = \left[0.001 \cdot \left(\frac{E1}{E4} \right)^3 - 0.007 \cdot \left(\frac{E1}{E4} \right)^2 + 0.016 \cdot \left(\frac{E1}{E4} \right) + 0.990 \right] \cdot E4 \quad (13)$$

$$E2\gamma = \left[-0.119 \cdot \left(\frac{E1}{E4} \right) + 2.287 \right] \cdot E4 \quad (14)$$

$$E3\gamma = \left[-0.113 \cdot \left(\frac{E1}{E4} \right) + 2.219 \right] \cdot E4 \quad (15)$$

$$\text{Beta dose} = \left[2.433 \cdot \left(\frac{E3 - E3\gamma}{E2 - E2\gamma} \right) - 1.674 \right] \cdot (E3 - E3\gamma) \quad (16)$$

High energy gamma, deep dose

$$= \left[0.002 \cdot \left(\frac{E1}{E4} \right)^3 - 0.047 \cdot \left(\frac{E1}{E4} \right)^2 + 0.265 \cdot \left(\frac{E1}{E4} \right) + 0.783 \right] \cdot E4 \quad (17)$$

High energy gamma, lens of eye dose

$$= \left[0.003 \cdot \left(\frac{E1}{E4} \right)^3 - 0.059 \cdot \left(\frac{E1}{E4} \right)^2 + 0.309 \cdot \left(\frac{E1}{E4} \right) + 0.750 \right] \cdot E4 \quad (18)$$

High energy gamma, shallow dose

$$= \left[0.003 \cdot \left(\frac{E1}{E4} \right)^3 - 0.064 \cdot \left(\frac{E1}{E4} \right)^2 + 0.327 \cdot \left(\frac{E1}{E4} \right) + 0.737 \right] \cdot E4 \quad (19)$$

Low energy gamma, deep dose

$$= \left[0.072 \cdot \left(\frac{E1}{E4} \right) + 0.036 \right] \cdot E4 \quad (20)$$

Low energy gamma, with significant beta, lens of eye dose

$$= \left[0.215 \cdot \left(\frac{E1}{E4} \right) + 3.014 \right] \cdot E4 \quad (21)$$

Low energy gamma, with significant beta, shallow dose

$$= \left[-0.335 \cdot \left(\frac{E1}{E4} \right) + 4.260 \right] \cdot E4 \quad (22)$$

Low energy gamma, without significant beta, lens of eye dose

$$= \left[-0.097 \cdot \left(\frac{E1}{E4} \right) + 1.762 \right] \cdot E3 \quad (23)$$

Low energy gamma, without significant beta, shallow dose

$$= \left[-0.182 \cdot \left(\frac{E1}{E4} \right) + 2.631 \right] \cdot E2 \quad (24)$$

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