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*This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

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ABSTRACT

A five-element thermoluminescent dosimeter for beta particles, photons and neutrons has been developed using LiF blocks. One ^7LiF block is shielded to provide interpretation of the one centimeter tissue depth dose. A second ^7LiF block is unshielded to provide the derma dose interpretation. Two ^6LiF and one ^7LiF blocks are used for fast and thermal neutron dose interpretation. The accurate response of the dosimeter to the wide variety of radiation sources at Hanford makes it a good replacement for the Hanford film badge for routine personnel dosimetry.

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I. INTRODUCTION

The phenomenon of thermoluminescence has been studied in great detail by Kocher and Endres at Hanford and other people throughout the world since 1964.^(1,2) Until that time, it had remained essentially a scientific curiosity. In the two or three preceeding years John Cameron at the University of Wisconsin solved the problems of doping lithium fluoride in a manner which provided sufficient sensitivity to radiation so that the material could be used in personnel dosimetry.

Most investigators feel that lithium fluoride (LiF) is the best material to use for personnel dosimetry.⁽³⁾ The beta-photon work conducted at Hanford has been concentrated on nearly pure ^7LiF materials.

The thermoluminescent properties of LiF as measured by Endres⁽⁴⁾ are nearly independent of the incident photon radiation energy, and this property makes it suitable as a replacement for the health physics film badge. The sensitivity of LiF relative to soft tissue is flat within 10 percent for photons from 10 keV to 10 MeV⁽⁵⁾ so that a multi-element array of LiF crystals with suitable filters can act as a simple spectrometer as well as an accurate dosimeter.

*This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

A. Physical Description

This section describes a beta-photon thermoluminescent personnel dosimeter badge to replace the Hanford film badge⁽⁶⁾ for routine personnel monitoring. The dosimeter makes use of the many unique properties of LiF crystals. An exploded view of the dosimeter badge is shown in Figure 1.

The multipurpose card which houses the TL blocks measures 7.8 cm x 3.8 cm x 0.1 cm and weighs 3.6 grams. The LiF TL blocks are contained in Teflon TFE skived tape that is 0.005 cm (12.2 mg/cm^2) on the front side of the block and 0.009 cm (16.0 mg/cm^2) thick on the back and positioned at the center of five 0.95 cm diameter holes in the dosimeter card. The tape on the back side of the card is coated on one side with pressure sensitive silicone polymer adhesive. The adhesive retains the TLD blocks so that when they are placed in the center of these holes, they remain in position. The Teflon TFE tape on the front side is not coated with an adhesive for reasons discussed later. This semi-transparent tape used for securing the blocks allows the thermoluminescent crystals to be read out without removing the blocks from the dosimeter card. The dosimeter card is injection molded from a thermoplastic resin which has a specific gravity of 1.06 and a heat deflection of 130°C . This material was chosen over a metallic holder because of cost and convenience. The plastic card can easily be identified by mechanically punching identification numbers or letters in the card. The whole system lends itself to convenient, automatic processing. The card has been designed to permit insertion into the holder in only one orientation.

The dosimeter holder is injection molded from styrene-butadiene-acrylonitrile (cycolac) and is designed to hold the dosimeter card and the Hanford security credential and appropriate filters for the blocks as shown in Figure 2. The holder measures 8 cm x 4.5 cm x 0.6 cm and weighs 22.5 grams. The 1.27 cm diameter filters are retained in cavities in the holder with an adhesive and covered with mylar tape. When the dosimeter card is inserted into the holder, a snug friction fit is obtained and each TL block is centered between the appropriate filter materials. The physical characteristics of the filter systems are shown in Table I.

TABLE I

FILTER SYSTEM - PHYSICAL CHARACTERISTICS

<u>Filter #</u>	<u>Shield</u>	<u>Diameter in cm.</u>	<u>Thickness in cm.</u>	<u>Total mg/cm²</u>
1	Open Window	0.95	0.0	0
	Teflon TFE Tape		0.005	12
2	Cycolac	1.27	0.089	93
	Aluminum		0.064	173
	Mylar		0.007	7
	Teflon TFE Tape		0.005	12
3	Cycolac	1.27	0.051	53
	Tin		0.102	750
	Mylar		0.007	7
	Teflon TFE Tape		0.005	12
4	Cycolac	1.27	0.051	53
	Tin		0.051	375
	Cadmium		0.051	440
	Mylar		0.007	7
	Teflon TFE Tape		0.005	12
5	Cycolac	1.27	0.051	53
	Tin		0.102	750
	Mylar		0.007	7
	Teflon TFE Tape		0.005	12

At Hanford, an additional thickness of plastic and paper is placed over the filter system and open window in the form of a security credential. The credential is 0.076 cm thick and has a density thickness of 80 mg/cm^2 .

B. Thermoluminescence of Adhesive Coated Teflon Tape

One of the major considerations in the design of a TLD system must be the operating costs involved in processing several thousands of TLDs on a routine basis. When the TLD material is mounted in a permanent housing, then automatic reading and handling makes the operating costs of the system minimal.

One TLD system utilizing a single ^7LiF block has been implemented at Hanford.⁽⁷⁾ This report describes a more complex system utilizing both ^7LiF and ^6LiF blocks which is in the process of being implemented. Both systems use 0.32 cm x 0.32 cm x 0.089 cm LiF blocks sandwiched between two pieces of Teflon tape and mechanically fixed in a two-piece, injection molded, thermoplastic card. Readout is accomplished by positioning the dosimeter card under a photomultiplier tube and heating the TL block with a constant temperature, circular heater 0.55 cm in diameter. The employee identification number is punched in the card so that readout and identification are accomplished without removing the TL blocks from the card.

Considerable attention has to be given to the properties of the card and tape materials. Mechanical properties notwithstanding, the thermal and thermoluminescent properties are of prime importance. A number of plastics were investigated as to their heat deflection and thermoluminescent

response. The criteria for the first Hanford TLD badges were not as stringent as for the second because of the lower readout temperature of ^7LiF (250°C). The heating of the card near the TLD and the heating of the tape were not as critical at this lower temperature. It was found that even the coloring pigments in the card changed the thermoluminescent properties and plastic was selected to minimize this effect. Many brands and types of adhesive coated Teflon tape were tested and the tape with the highest heat deflection and least thermoluminescence was chosen. After some testing of the first TLD system, it became apparent that the Teflon tape was also sensitive to ultraviolet light. This sensitivity was apparent only as a variability in the readings of control cards and was controlled within acceptable limits by storing the cards in the dark and minimizing fluorescent lighting and other ultraviolet exposures during reading and handling procedures.

The second system developed at Hanford included TL blocks of ^6LiF for neutron dosimetry. As indicated in other papers, ^(8,9) the most appropriate readout temperature for neutron induced thermoluminescence is 300°C . When studies began on the prototype badges using this temperature, it was immediately apparent that the thermoluminescence of the tape became more significant and a more detailed study of its properties was in order.

The first discovery during this study was that the thermoluminescence was primarily the property of the adhesive and not the TFE Teflon tape used in the cards. A variety of transparent and semi-transparent tapes and adhesives were investigated and all those adaptable to this application had thermoluminescent properties equal to or greater than the adhesive coated

Teflon tape in use. The response of two pieces of new tape, stuck together, as a function of temperature is shown in Figure 3, Curve A. It can be seen that the adhesive thermoluminescence is not a major problem at heater temperatures up to about 250°C. At temperatures above 250°C, more luminescence is released and the slope is quite steep, making background readings of the TL blocks too large and variable to meet design criteria. The fluorescent spectrum from this Teflon tape adhesive is a broad band emission from 300 nm to 650 nm with the maximum at about 500 nm. This spectrum overlaps the fluorescent spectrum from LiF, which is a broad band emission with a maximum at 400 nm.

A number of other techniques of retention of the TL blocks in the cards were investigated before a successful mockup badge was attained. The compromise assembly was made of one piece of adhesive coated TFE Teflon tape and one piece of plain TFE Teflon tape. This sandwich maintained the mechanical integrity of the block position in the card and made assembling the sandwich much easier. It was found that a complete readout of the TLD could be accomplished without adhesive fluorescence by heating the sandwich on the plain tape side with the heater at a temperature of 300°C for a period of 20 seconds.

The response at various temperatures for an unexposed ^7LiF block in this sandwich are shown in Figure 3, Curve B. These results indicate that during the heating cycle, the temperature differential across the block is never less than 30°C. This difference is enough to preclude most of the readout of the adhesive on the other tape.

Additional studies were made to determine the ultraviolet sensitivity of this adhesive. Cards were exposed for various times to an ultraviolet lamp and read out at various temperatures. Three of these runs are shown in Figure 3, Curve C. These and other handling studies using fluorescent room lights indicate that the ultraviolet induced thermoluminescence of the tape adhesive accounts for about 30 picocoulombs of background for normally handled cards as can be seen by comparing Figure 3, Curves A, B, and C. Studies using a readout temperature of 250°C show that cards processed in normal room light conditions had an average background of 73 picocoulombs, cards processed with no exposure to room light had an average background of 42 picocoulombs and cards exposed to room light on a desk top for about one day had an average background of 147 picocoulombs. Data from earlier experiments with bare TL blocks show that this enhanced response from ultraviolet exposures must come from the thermoluminescence of the tape adhesive. In another experiment, cards were exposed to desk top fluorescent room light for periods of one-half to 4-1/2 hours in half-hour intervals. The average background readings varied from 62 picocoulombs for the half-hour exposure to 80 picocoulombs for the 4-1/2 hours exposure. These results were somewhat random and, when compared to the results of the previous study, indicate that the thermoluminescent response of the adhesive is a slowly varying function of ultraviolet exposure time.

II. BETA AND PHOTON DOSIMETRY

A. Theory and Description

Lithium-7 fluoride crystals are thermal luminescent (i.e., they have centers which can trap charge carriers created by the passage of an ionizing particle without permitting recombination). This property delays the luminescence accompanying the recombination of electrons and holes in the radiation recombination centers. The time of delay is a function of temperature. Another way of looking at the LiF crystal is as an energy integrating device that can store energy imparted by ionizing radiation and then release that energy as optical energy when the crystal is heated to the proper temperature.

The manner in which photons deposit energy in a TL crystal is through the production of energetic secondary electrons and it is the interaction of these secondary particles which account predominantly for the imparting of energy to the TL material. The close relationship of the effective atomic numbers and associated cross sections of LiF and soft tissue is the key to close tissue equivalence of LiF.

The multipurpose dosimeter card has two ^7LiF TL blocks that are isotopically enriched in ^7Li to 99.993 percent for beta and photon dosimetry. The positions of the two blocks (#1 and #2) in the dosimeter card are shown in Figure 1. When the dosimeter card is inserted into the holder, a snug friction fit is obtained and the block in position #1 is located in the open window where it is filtered by only its associated Teflon TFE tape and the security credential. The TLD in position #2 is shielded by an additional 0.089 cm of plastic and 0.064 cm of aluminum. The two blocks

serve as a simple two-element photon-beta particle spectrometer. The 0.089 cm block thickness was chosen to provide adequate sensitivity and to eliminate breakage problems encountered with thinner blocks. The use of the thicker block makes necessary a compromise on the interpretation of the response of block #1 (the "open window"). This will be explained in more detail later in this section.

The thermoluminescent response of block #2 is interpreted as penetrating dose and its shield was designed to correspond to one centimeter of soft tissue for photon energies from 10 keV to 10 MeV as shown in Figure 4. For beta dosimetry, this shield is about 365 mg/cm² thick.

If the photomultiplier tube current is integrated during the readout process, then the dose interpretation is accomplished with the following equations:

$$\text{Penetrating dose} = \frac{R_2}{k_1} \text{ mrad} \quad (1)$$

$$\text{Derma dose} = \text{penetrating dose} + \frac{R_1 - k_2 R_2}{k_3} \text{ mrad} \quad (2)$$

where R_1 and R_2 are the net integrated phototube currents from the #1 and #2 TL blocks and k_1 , k_2 and k_3 are the calibration constants determined by exposures to selected sources.

The sources used are selected to provide spectra of photon and beta radiation which are representative of radiation fields at various Hanford work areas.

B. Photon Energy Response

The photon energy response of the shielded TL blocks is important. The energy response function of #1 TL block within the Teflon envelope and shielded by 0.076 cm of plastic is essentially flat from 100 keV to 1.25 MeV, as shown in Figure 5. The response increases below 100 keV and reaches a maximum at about 35 keV. At this point, the response is about 140 percent of the 1.25 MeV response. At about 16 keV, the response is again equivalent to the response at 1.25 MeV and then it drops sharply to 0.1 relative to 1.25 MeV when the photon energy is 8 keV.

Several filter system designs were studied for possible use in the dosimeter badge to provide a photon response proportional to the one centimeter depth dose in tissue. The filter system chosen was composed of 0.178 cm of plastic plus 0.064 cm of aluminum. Badges were exposed to k-fluorescent x rays, filtered x rays, and gamma rays to experimentally determine the response of this filter-TL block system. Exposures were made at 16, 23, 34, 43, 58, 78, 100, 170, 662, 880 and 1250 keV effective. The response data are shown in Figure 4. At 16 keV, the relative response of the TL block shielded by this filter system is about 35 percent of that at 1.25 MeV. About the same fraction of dose from 16 keV photons will penetrate one centimeter of tissue. Above 16 keV, the response of the filtered TL block system increases and reaches a peak at 43 keV, which is about 135 percent of the response of the system to 1.25 MeV. The penetrating dose evaluation follows the calculated one centimeter tissue dose response quite well. There is a small region around 40 keV where the TL response is greater than that of tissue; this makes the interpretation in a

mixed energy field slightly conservative. It should be pointed out that the penetrating dose as interpreted by this filter system will be somewhat higher than the penetrating dose interpreted from the present Hanford film badge which uses a 0.050 cm thick tantalum filter system. This is especially true in mixed photon fields where photons with energies between 16 and 60 keV are present. An additional advantage of the TL badge is its flat response to high energy photons (> 2 MeV) where pair production in the film and tantalum filter of the Hanford film badge requires a response correction when the high energy component of the photon field becomes significant.

C. Angular Distribution Studies

A variety of laboratory studies were conducted to determine experimentally the beta-photon response of the TLD badge. One series of studies was conducted using the photons from a ^{252}Cf source and a Remab phantom filled with tissue-equivalent fluid. The phantom was placed horizontally on a four-foot high wooden table and the source was attached to a ring stand directly above the chest of the phantom. Badges were taped around the phantom directly below the source, as shown in Figure 6. The source was 71 centimeters from the chest of the phantom. The net response of badges in symmetrical positions were averaged. The response of the TLDs in this arrangement depends only on the number of interactions occurring in the TLD from any direction. The response is, therefore, dependent on source-detector distance, attenuation, angular dependence, and scattering geometry. Ignoring corrections for these factors, the greatest response

is on the front center of the chest. All of these factors become significant at the pocket and side positions. The shielding of the phantom and the source-detector distance become the greatest factors in the reduction of the photon response for badges position on the back of the phantom.

A similar experimental procedure was used to study the angular variation in response of the TLD badge to radiation from a ^{60}Co source placed twenty centimeters from the chest of the phantom (Figure 7). This study was concerned only with the penetrating photon response of the badge and included angles up to 90° from normal both right and left of the center of the chest. The TL block used for penetrating dosimetry is located on the right side of the card and the response should vary depending on the source-detector distance, the effective shield thickness of the filter system as a function of angle, and scattering geometry of the source and phantom. The source-detector distance factor and the reduction in the effective shield thickness make the response greater when the source is to the right of center than at 0° . For angles near 90° to the right, the effective shielding of plastic in the card and holder is slightly larger than the shielding of the filter system and the response drops off. When the source is to the left of center, the source-detector distance and the effective shielding of the badge and filter system continue to increase through 90° . The loss of response on the right side is about 10 percent and the loss on the left side is about 40 percent at 90° .

D. Mixed Radiation Exposures

A dosimeter under field conditions is very seldom exposed to a single monoenergetic source of radiation. It is imperative, therefore, that the dosimeter be capable of accurate dose interpretation of the various kinds and spectra of radiation to which it may be exposed. To study this property of the TLD badge, eleven combinations of 16-keV x-ray, uranium beta, radium gamma and PuF_4 exposures were arranged and two TLD badges were exposed to each combination. It is evident from the data in Table II that the TLD badge does meet the criteria described above. In this table, P stands for penetrating dose and D for derma dose. The dose given in each instance was interpreted from the known exposure.

When ^{90}Sr radiation is used for the derma dose calibration of the TLD badge, the response is about 40 percent lower than the response to radium gamma calibration and about 50 percent higher than the response to uranium beta calibration. However, ^{90}Sr was found to be a good intermediate calibration for mixed fields. The photon-beta contributions for all Hanford sources of exposure tend to average out and interpret well with the ^{90}Sr calibration. In other words, the TLD system will tend to provide an underestimate of a pure low energy beta exposure.

E. Special Field Studies

A number of special studies were conducted at several work locations around the Hanford plant to observe the response of the beta-photon TLD badge and to make comparisons with instruments and the present film dosimeter. Results were evaluated as penetrating and derma dose using the

TABLE II

MIXED DOSE COMPARISONS (mrads)

	<u>Dose Given</u>		<u>TLD</u>	
	<u>P</u>	<u>D</u>	<u>P</u>	<u>D</u>
1	380	710	380	640
2	250	450	270	330
3	120	350	120	250
4	240	340	260	390
5	1140	1310	1020	1020
6	240	410	300	412
7	140	600	160	420
8	240	600	110	760
9	220	350	190	290
10	240	350	190	350
11	70	400	30	350

calibrations previously described. The TLD badge yielded generally consistent results for all of the various exposures. The film generally agreed with the TLD badges and instruments except in those cases where mixed fields of x rays and betas were encountered or photon exposures exceeded the limits of the film.

Another field study was conducted by placing TLD badges on Hanford personnel along with their regular film badges and, in some cases, pencil dosimeters. All of the characteristics of the badges thus far described were observed. The trend for the TLD to show more penetrating dose than the film badge is graphically displayed in Figure 8. A similar

graph of comparisons of derma dose are shown in Figure 9. Several comparisons with Stephens self-reading pencils worn by reactor personnel showed very good correlation with TLD badges worn at the same time.

Some concern has been voiced about the plastic security credential shielding of the TLD in position #1 with respect to beta sensitivity. Subsequent studies indicate that a hole in the credential would increase the beta sensitivity of the TLD about 25 percent and reduce the lower limit of detection of uranium betas from about 50 mrad to 25 mrad. Exposures of these "open window" badges to mixed radiation as described above was repeated and the results showed an insignificant increase in derma dose interpretation compared to the badges with normal security credentials.

For beta-photon dosimetry, the reproducibility (precision) can be maintained within ± 5 percent at the 67 percent confidence level on doses greater than 300 mrad, within ± 15 percent at the 67 percent confidence level on doses down to 100 mrad, and ± 50 percent at the 67 percent confidence level with doses of about 20 mrad. We consider the low level detection limits to be 20 mrad of penetrating radiation and 10 mrad of non-penetrating radiation.

III. NEUTRON DOSIMETRY

A. Theory and Description

The slowing down of neutrons in a human body is due mostly to elastic scattering with hydrogen nuclei and it is the subsequent recoil protons which are responsible for most of the neutron dose delivered to

the body. For neutron energies below 10 MeV, the elastic scattering is nearly isotropic in the laboratory system and, because of the amount of hydrogenous material in the body, the leakage spectrum of neutrons from the body is primarily a thermal spectrum. By monitoring this leakage spectrum of neutrons, a first order measurement can be made of the fast neutron dose delivered to the body.

The Hanford multipurpose neutron dosimeter has three LiF blocks. Two of the blocks are isotopically enriched to 95 percent ^6Li and the third block is enriched to 99.993 percent ^7Li . The positions of the three elements in the dosimeter card are shown in Figure 1. Positions #3 and #4 are ^6LiF blocks and position #5 is the ^7LiF block. Thermal neutrons deposit energy in the ^6LiF block by the nuclear reaction

The alpha and triton particles share the excess energy from this reaction and deposit most of this energy in the TL crystals since the dimensions of the TL blocks are large compared to the range of these particles in LiF.

The bare ^6LiF block responds equally well to backscattered neutrons from the body as well as to the incident neutron current. The incident neutron current can be thought of as consisting of just slow and fast neutrons, ϕ_s and ϕ_f , respectively (see Figure 10). The $^6\text{Li}(n,\alpha)$ cross section (see Figure 11) is about 1000 barns for thermal neutrons whereas it is only 0.3 barns for a 1.0 MeV neutron. Therefore, the ^6LiF TL block is

a relatively poor detector for fast neutrons and for practical applications, the contribution to its thermoluminescence due to fast neutron capture can be ignored. The ^6LiF TL block in position #4 is shielded from incident slow neutrons by placing 0.051 cm of cadmium in front of it. The cadmium totally absorbs all of the incident neutron of energies below 0.4 eV. This cadmium absorption is by an (n,γ) reaction and some of the resulting photons deposit energy in the TL block. If the incident slow neutron were allowed to interact in the TL block, it would deposit 4.78 MeV of energy; whereas if it is absorbed in cadmium and the cadmium photons interact in the TL material, it can deposit only a few eV of energy in the block due to the small mass and low atomic number of the TL material.

The backscattered neutrons that are captured in the ^6LiF blocks are scattered slow neutron (ϕ'_s) and tissue moderated fast neutrons (ϕ'_f). The magnitude of backscattered neutron current density per unit incident fast flux has been calculated by P. S. Nagarajan and D. Krishnan⁽¹⁰⁾ and experimentally measured by J. A. Dennis, J. W. Smith, and S. J. Boot.⁽¹¹⁾ If we ignore photon response, the above discussion can be summarized by writing equations for the relative response of TL blocks #3 and #4.

$$R_3 = n\sigma(E)[\phi_s + \phi'_s + \phi'_f] \quad (3)$$

$$R_4 = n\sigma(E)[\phi'_s + \phi'_f] \quad (4)$$

where R_3 and R_4 are the relative thermoluminescent response of TL blocks #3 and #4, n is a proportionality constant, and $\sigma(E)$ is the $^6\text{Li}(n,\alpha)^3\text{H}$ cross section. The difference between R_3 and R_4 [$n\sigma(E)\phi_s$] can be related to the incident thermal neutron dose

$$\text{Incident slow neutron dose} = \frac{R_3 - R_4}{k_4} \text{ mrad} \quad (5)$$

where k_4 is a calibration constant. By exposing the badge to a source of thermal neutrons, ϕ_f and ϕ'_f , are zero so that Equation (3) and (4) would be

$$R_3 = n\sigma(E)[\phi_s + \phi'_s] \quad (6)$$

$$R_4 = n\sigma(E)\phi'_s \quad (7)$$

The ratio of backscattered thermal to incident thermal neutrons can be defined as a constant:

$$k_5 = \frac{\phi'_s}{\phi_s} = \frac{R_4}{R_3 - R_4} \quad (8)$$

If we subtract that portion of the backscattered neutrons which are due to incident slow neutron ($k_5 \phi_s$) from the bracketed term in Equation (4), then the response of R_4 is proportional to only ϕ'_f . This can then be related to fast neutron dose.

The ^6LiF blocks are also photon sensitive and it is impractical to adequately shield them from all photon radiation. Therefore, a third block of ^7LiF enriched TL material (insensitive to neutrons) is placed in position #5 of the dosimeter card and shielded front and back by 0.102 cm of tin to prevent beta particles and low energy photons from interacting in the TL blocks and possibly causing statistical problems in low neutron dose interpretations. The TL block in position #3 is similarly shielded and the block in position #4 has 0.102 cm of tin on the back and 0.051 cm

of tin on the front between the cadmium and the block. This arrangement makes all three blocks photon equivalent and helps reduce the photon contribution from the activated cadmium in position #4. The fast neutron dose is then interpreted using the following equation:

$$\text{Fast neutron Dose} = \frac{R_4 - k_6 R_5 - k_5 (R_3 - R_4)}{k_7} \text{ mrad} \quad (9)$$

where k_6 is a correction factor for the difference in photon sensitivity between the ^6LiF and ^7LiF TL blocks, and k_7 is a calibration constant.

The constant k_4 is evaluated by solving Equation (5) after known exposures of the badge to thermal neutrons in the Hanford sigma pile. The constant k_5 is evaluated by solving Equation (8) after setting the fast neutron dose equal to zero and evaluating the responses for the same exposures as described above for evaluating k_4 . The constant k_6 is evaluated by solving

$$k_6 = \frac{R_4}{R_5}$$

after exposing the badges to a penetrating photon calibration source. For fast neutron calibration, the badges are attached to a polyethylene phantom. The constant k_7 is then evaluated by solving Equation (9) after exposing the badges to neutrons from a plutonium fluoride calibration source.

Most of the neutron exposures at Hanford are due to neutrons which have a broad energy distribution. Because of this spectral distribution, the neutron badge will tend to average the dose response. Table III illustrates this averaging process on the two dissimilar neutron

TABLE III

MODERATED FISSION SOURCE

<u>Energy Interval</u> <u>MeV</u>	<u>Dose per</u> <u>Energy Interval</u>	<u>Relative</u> <u>Differential</u> <u>Response</u>	<u>Percent</u> <u>Response</u>
$10^{-2} - 5 \times 10^{-2}$	6.8%	0.99	40
$5 \times 10^{-2} - 10^{-1}$	5.1%	0.33	14
$10^{-1} - 5 \times 10^{-1}$	25.4%	0.68	28
$5 \times 10^{-1} - 1.0$	18.2%	0.22	9
$1.0 - 5.0$	45.4%	0.23	9
	<hr/>	<hr/>	<hr/>
	100.0%	2.45	100

BARE FISSION SOURCE

$10^{-2} - 5 \times 10^{-2}$	0.9%	0.13	13
$5 \times 10^{-2} - 10^{-1}$	1.1%	0.07	7
$10^{-1} - 5 \times 10^{-1}$	7.8%	0.21	21
$5 \times 10^{-1} - 1.0$	14.7%	0.18	18
$1.0 - 5.0$	65.4%	0.38	39
$5.0 - 10.0$	10.1%	0.02	2
	<hr/>	<hr/>	<hr/>
	100.0%	0.99	100

spectra⁽¹²⁾ shown in Figure 12 and Figure 13. This shows that the relative response of the TL neutron badge to an unmoderated fission spectrum will be .99 compared to a response of 2.45 for a heavily moderated fission spectrum. It is felt that these spectra represent the extremes of neutron spectra found at Hanford.

Spectral considerations and associated quality factors were studied at a variety of work locations at Hanford and these data are shown in Table IV. The measurements were made with a tissue equivalent proportional counter (TEPC) which measures absorbed dose directly. An average quality factor ($\overline{QF}$) can also be obtained from the TEPC data. These data can then be compared for variations in many of the neutron spectra at Hanford. The range is from 8.5 for a bare ^{252}Cf source to 12.0 for a heavily shielded plutonium storage vault. The average of all these $\overline{QF}$ s is 10.1. The PuF_4 source used for fast neutron calibration has a $\overline{QF}$ of 10.0. The accuracy of these measurements is about $\pm 1 \overline{QF}$ unit so it would seem that the use of PuF_4 as a fast neutron calibration source is justified.

TABLE IV
QUALITY FACTOR MEASUREMENTS

<u>Run</u>	<u>Quality Factor (TEPC)</u>
PuAl Fuel Plates	10.5
234-5 Building	
221	10.6
192	9.1
192-C	8.8
193	9.3
105-KE Building	
Top #23	10.1
Front Face	11.0
308 Building	
Room 208	9.9
Corr #7	10.5
Vent Room (18" Shielding)	12.0
Room C	10.4
^{252}Cf (Bare)	8.5
PuF_4 (Calib)	10.0
	<hr/>
AVERAGE	10.1

B. Fading and Annealing

The general fading and annealing procedures used on the Hanford TLD badge have been discussed in detail elsewhere in this report. However, a few specific items need to be elaborated upon here. The method of deposition of energy due to neutrons is different from that of beta particles and photons as described previously. As a result, deeper traps in the TL material are activated and somewhat higher temperatures are needed to completely empty them. It is generally agreed that 300°C is adequate to readout neutron induced traps. But, because of the heat transfer through the Teflon tape holding the TL blocks, we have found that 300°C for the heater is a minimum and 310°C is more reliable. All other aspects of fading and annealing for TL materials are applicable.

C. Neutron Energy Response

The TL neutron dosimeter must be photon corrected and, as stated above, all three blocks are shielded to provide photon equivalence. The shielding does not allow passage of photons with energies less than about 60 keV and the blocks have a flat response for photons greater than 100 keV, as shown in Figure 14. The neutron energy response was measured using monoenergetic neutrons from a Van de Graaff accelerator. Measurements were made from 100 keV to 5 MeV and the results are shown in Figure 15.

D. Effect of Dosimeter Wearing Position

An experiment was made to determine the effective center of the TL phantom system for fast neutron dose interpretations. If we assume the

center of the detector system (i.e., badge plus phantom) is not at the TL position, then $R = A/(x+a)^2$, where R is the net response of the TLD to fast neutrons, A is the proportionality constant, x is the distance from the surface of the phantom to a point neutron source and a is the distance from the surface of the phantom to the effective center of the detection system. In linear form, $x = (A/R)^{1/2} - a$. If x is plotted versus $R^{-1/2}$, a is the intercept. A ^{252}Cf source was used and data were obtained for six values of x . The intercept was at -4.5 cm. This means the effective center of the detection system is 4.5 cm deep from the surface of the phantom. This effective center is only unique for a bare fission spectrum of neutrons (i.e., the effective detection center is a linear function of the neutron energy). This result confirms previous experiments with various moderator thicknesses versus total response to fast neutrons.

When the TLD neutron badge is worn by a person, the badge is very seldom in contact with the body. Since the fast neutron response depends on backscattered neutrons, a study of the relationship between response and badge-to-phantom distance was made. Sets of three badges each were positioned in front of a chest phantom and exposed to the standard PuF_4 calibration source. Each set was positioned at a different distance from the surface of the phantom. In this study, the phantom was set at 35 cm from the source and, therefore, the badges were at various distances from the source. The results are shown in Figure 16. The response, when the badge is close to the surface, is smaller than one would expect compared to the response at 2 cm due to the effect of the relatively large cadmium shield in the badge. The response increases out to about one

centimeter as the effective shield size decreases. At 3-6 cm, the response drops off similar to an R^{-1} curve. A datum point from 0.56 MeV neutrons produced by our Van de Graaff accelerator and one from a Harwell study⁽¹¹⁾ using 0.120 MeV neutrons fall on this curve.

To better understand the response of the badge in different wearing positions on a human, badges were taped over the breast bone, each shirt pocket position, each side, and across the back of a Remab phantom, as shown in Figure 17. The response of the badges in symmetric positions relative to the neutron source were averaged and corrected for background. For this geometry, the slow neutron current (energies below cadmium cut-off) incident on the phantoms is symmetric with respect to the phantom and is primarily due to thermalization of neutrons in the floor and walls of the room. The maximum fast neutron response is attained when the badge is on the center chest position of the phantom. The response at the front pocket positions is down by a factor of about three because the air filled lung cavities of this phantom cause a smaller fraction of neutrons to be thermalized and scattered back to the badge. No attempt has been made to correct for the radial dependence of the neutron fluence for the data shown in this figure.

A similar set-up was used to expose the badge to neutrons of 4.5, 1.0, and 0.35 MeV generated with the Van de Graaff accelerator. Results are shown in Figure 18. Badges were taped at various positions around the phantom as indicated above. However, the phantom used for these exposures did not have void cavities to represent the lungs.

A similar experiment was used to study the neutron angular response of the badge. A ^{252}Cf source was placed 22 cm from a phantom and adjusted through 90° of arc at $22\text{-}1/2^\circ$ intervals. Two badges positioned at the center of the chest were exposed to 81 mrad of fast neutrons for each exposure. The results were averaged, corrected and plotted in Figure 19. The fast neutron response under these conditions depends primarily on the scattering geometry of the source and phantom. The response decreased by a factor of four at 90° to normal. The thermal neutron response dropped off slowly through all angles. This would indicate that there is scattering of thermal neutrons such that the contribution to the face of the badge is fairly constant.

E. Mixed Radiation and Special Field Studies

As stated in Section II.D., a dosimeter under field conditions is very seldom exposed to a single source of radiation. It is therefore necessary that the TLD badge be capable of accurate neutron dose interpretation when exposed to a variety of different kinds of radiation. To study this property, eleven combinations of 16 keV x-ray, uranium beta, radium gamma and PuF_4 neutron exposures were made using two TLD badges for each combination. These data, shown in Table V, show that the multi-purpose dosimeter provides reasonable dose interpretation for neutrons when mixed combinations of radiations are present.

Another study was conducted by taping TLD and NTA film badges to two-gallon jugs filled with water and placing these jugs in work locations at Hanford. Remmeter readings were made at each location. The TLD badge

TABLE V

MIXED DOSE COMPARISONS

<u>Run</u>	<u>Dose Given (mrad)</u>				<u>TLD mrads</u>	
	<u>16 keV</u>	<u>U_β</u>	<u>PuF₄</u>	<u>Ray</u>	<u>n_s</u>	<u>n_f</u>
1	200	200	100	200	3	74
2	0	200	50	200	2	43
3	50	200	50	50	2	43
4	100	50	100	100	3	91
5	100	100	100	1000	2	124
6	100	100	100	100	2	122
7	100	400	0	100	0	0
8	400	100	0	100	0	0
9	50	100	0	200	0	0
10	100	50	0	200	0	0
11	200	200	0	0	0	0

detected neutrons in every location where neutrons were shown to exist by the neutron remmeter. The NTA film failed to do this in many cases. It was observed in many cases that the NTA film was fogged and fast neutron dose was uninterpretable when the film had been exposed to moderate doses of penetrating and/or non-penetrating radiation. Several incidences of this occurred with derma doses as low as 400 mrads from plutonium fuels. The multipurpose badge on the other hand, yielded interpretable fast neutron data from badges indicating derma doses as high as 3200 mrad. Criticality studies described below indicate accurate fast neutron interpretations in the presence of very high photon exposures. The lower limit

of fast neutron interpretations in high photon radiation fields is a matter of statistics and should be about 10 mrad $\pm$ 100 percent for fast neutrons in a mixed exposure with about 3000 mrad of photons with reading statistics of $\pm$ 5 percent. Exposures of the badge to plutonium fuel sources have been consistent with dose measurements with laboratory instruments.

The next step was to place TLD badges on personnel in the field and compare neutron dose interpretation with the results from their regular film badge dosimeters. Again, the TLD badge was very consistent in responding to neutrons. The results of these field tests are shown in Table VI. The thermal neutron dose interpretation for the two badge systems indicated thermal neutrons where they were known to exist in the field, but the TLD did a more consistent job of responding to fast neutrons. A $\overline{QF}$ of 3 and 10 has been used for thermal and fast neutron results, respectively.

Statistical analysis of the data indicates that the TL neutron dosimeter can consistently detect 0.5 mrad of thermal neutrons and 5 mrad of fast neutrons within $\pm$ 50 percent under ideal conditions.

Exposures simulating a nuclear criticality accident were conducted at the Health Physics Research Reactor at Oak Ridge National Laboratory. The HPRR is a fast burst reactor which can produce a high neutron and gamma dose in a relatively short time ($\sim$ 50 μ sec). Measurements were made of three bursts; one with no shielding between the reactor and dosimeters, one with 11.4 cm of lucite between the reactor and dosimeters, and one with about 5 cm of iron between the reactor and dosimeters. The

TABLE VI

NEUTRON RESULTS FROM FIELD STUDIES

<u>Employee Number</u>	<u>Slow Neutrons (mrem)</u>		<u>Fast Neutrons (mrem)</u>	
	<u>TLD</u>	<u>Film</u>	<u>TLD</u>	<u>Film</u>
1	6	30	0	0
2	9	30	200	0
3	12	40	200	0
4	6	30	0	0
5	3	0	140	0
6	6	30	160	0
7	9	50	180	110
8	36	20	0	110
9	21	0	0	100
10	6	20	180	0
11	3	0	140	0
12	15	0	410	0
13	12	40	260	0
14	15	40	130	0
15	9	30	270	130

fast neutron dose rate at the closest positions to the HPRR was as high as 9×10^6 rads per second. The accompanying gamma exposure rate was about 2×10^7 R per second.

No non-penetrating radiation was observed for any of the burst exposures. Dosimeters were attached to water bottles to serve as phantoms and placed at distances of 3, 4, 5, 6, 9 and 15 meters from the reactor for all three bursts.

No dose rate dependence was observed for any of the burst results with total dose rates as high as 1.1×10^7 rad/sec. Both gamma and neutron dose measurements vary as $1/R^2$, where R is the distance from the reactor, for all three bursts. The results are shown in Table VII for the burst with no shielding. The raw data from each burst indicate the presence of a large flux of thermal neutrons. The thermal neutron flux is so large that the correction $k_5(R_3 - R_4)$ in Equation (9) for thermal neutron effects determined in the Hanford Standard Pile is not acceptable. All results for fast neutron dose were determined without a thermal neutron correction.

TABLE VII

GAMMA AND FAST NEUTRON DOSE RESULTS

Burst #1
 7.7×10^{16} Fissions
 Bare Reactor

Distance (Meters)	Gamma Exposure (R)	Fast Neutron Dose (rads)	<u>Relative Interpretation</u>		
			<u>Photon</u>	<u>Neutron</u>	<u>$1/R^2$</u>
3	91.0	452	1.0	1.0	1.0
4	52.1	262	0.57	0.57	0.56
5	35.8	166	0.39	0.37	0.36
6	24.8	149	0.27	0.26	0.25
9	11.6	61	0.13	0.13	0.11
15	3.4	21.5	0.04	0.05	0.04

For all three bursts, the TLD behind the heavy tin filter used for gamma compensation in the neutron dosimeter showed evidence of high energy gamma radiation. Response behind the tin filter was 20 percent or more above the response behind the aluminum filter. The filters in the neutron section are all photon equivalent so the high energy response does not affect the neutron evaluation. No saturation effects such as occur in film were seen. No super-linear results were observed because the total doses were just below the point where super-linearity begins.

For both bursts with additional shielding, the dose varied as the inverse square of the distance from the reactor. No rate effects were observed. For the lucite shield, the measured neutron dose at three meters was 200 rads compared to 128 rads calculated. This shows an over-response to neutrons in a heavily moderated geometry as indicated earlier in the discussion on bare and moderated geometries. For the burst with about 5 cm of iron, the measured fast neutron dose was 290 rads compared to a calculated 228 rad at three meters from the reactor. In this case, the dosimeter was about 27 percent higher than the calculation.

IV. ANNEALING AND FADING OF ^6LiF AND ^7LiF

The use of ^6LiF and ^7LiF TL materials in personnel dosimetry applications requires a rather detailed knowledge of the annealing and fading properties of these materials. This is especially true if the readout process is to be mechanized by permanently mounting and heating the TL materials in a transparent material of some kind. The only known

transparent materials able to withstand the necessary readout temperature (300-310°C) are several types of Teflon tape. Unfortunately, no plastic material or Teflon tape is presently available that can withstand the accepted annealing temperature for LiF (400°C), and until the problems of annealing and fading of LiF were better understood, the design of a fully automated system was impractical.

The preliminary concepts of the Hanford Multipurpose Dosimeter were conceived after the discovery in 1968 and 1969 that LiF could be read out at the normal reader temperature and held for one month at room temperature. This process would maintain a constant sensitivity of the LiF.

A. Theory

A number of investigators have studied the glow peak structure of LiF^(9,13) and found several peaks present depending on radiation exposure and previous annealing history. If LiF is conditioned before exposure by running it through the standard readout cycle, the resultant glow curve is as shown in Figure 20. The prominent low temperature peak is approximately 80°C and has a room temperature half-life of a few hours. The other peaks have half-lives of six months or longer at room temperature. Some lower temperature peaks also exist but are not shown because they fade within a few minutes after exposure.

When the LiF is conditioned through the standard readout cycle and then held for eight days before exposure to radiation, the glow peak structure is much different even though the TLD is read out soon after

the exposure (see Figure 21). These effects are similar to those observed by Zimmerman, et al.,⁽¹³⁾ although they used different annealing temperatures. Zimmerman studied the behavior of natural LiF using annealing temperatures of 80°C and greater with the annealing time varying from a few minutes to 48 hours. In these studies, the 80°C peak is found to gradually disappear as the annealing time increases. The structure of the high temperature glow peaks also changes with annealing time and temperature. The fraction of the total response due to the higher temperature peaks increases as the annealing time increases even though the overall sensitivity decreases. We have found that the effect of keeping the LiF at room temperature for one month is somewhat similar to the effect of annealing at 80°C for 48 hours. Harris and Jackson⁽¹⁴⁾ have reported similar results in a very detailed study of annealing procedures.

B. Experimental Results

The first experiments which led to the discovery of the room temperature anneal were conducted as a fading study to determine how well LiF holds the trapped electrons at room temperature and only coincidentally revealed additional annealing information. For this fading study, a set of ⁷LiF blocks was read through a modified commercial reader and held eleven days before a series of exposures was begun. Some of the TLDs were given 500 mR of radium gamma exposure on the eleventh day and then held for readout at various times up to 45 days. These results are shown in Table VIII and glow curves in Figures 22a and 22b. Each result is the average of three TLD readings with the background subtracted. The

TABLE VIII

SHORT TERM FADING OF ^7LiF

<u>Set</u>	<u>Day Exposed</u>	<u>Day Readout</u>	<u>Relative Reading</u>
1	11	11	1020
2	11	14	970
3	11	16	975
4	11	18	915
5	11	22	870
6	11	24	930
7	11	26	900
8	11	29	853
9	11	31	847
10	11	33	863
11	11	36	880
12	11	43	820
13	11	45	830

TABLE IX

ROOM TEMPERATURE ANNEALING

<u>Set</u>	<u>Day Exposed After Reader Cycle</u>	<u>Day Readout</u>	<u>Relative Reading</u>
1	14	14	1010
2	18	18	945
3	21	21	1003
4	25	25	947
5	28	28	977
6	32	32	933
7	35	35	910

readings decrease about 20 percent in the 45 days after exposure. From the same set of TLDs, another group was exposed at various times after the original eleven-day holding period and read out within 24 hours. These results which indicate the effect of the room temperature anneal show a decrease in response of only about 10 percent over the 14 to 35 day time interval from the start of the experiment. Again, the exposures were made in groups of three TLDs and the results given in Table IX are the average of the three readings. The glow curve structure shows a rather drastic change from that at 14 days compared to 35 days (see Figure 22c and 22d). After 14 days at room temperature, the 80°C peak is still quite prominent indicating that the shallower trap sites are still available to be populated. But, after 35 days, there is essentially no evidence of the 80°C peak. It appears that most of the effect of annealing is due to a restructuring of the traps. This effect is not really fading though it does affect the fading properties since the dosimeters were not exposed until a relatively short time before they were read out.

The results of this first study suggested a one-month holding period at room temperature between readout and exposure to radiation and the next experiment was so designed. The study was designed to cover a three-month period of time to simulate a quarterly readout cycle of the dosimeters but was later extended to cover more than one year. With a one-month holding period at room temperature, there is no significant 80°C peak in the glow curve even when the exposure is made within 24 hours of readout. This characteristic carried through the full year the experiment was conducted. To further test the anneal procedure, the

dosimeters chosen for the one-year experiment were selected from a group of TLDs that were previously read out over a two-month time span. This simulated a mixture of previous readout histories. They were then held an additional month before the exposures and readout began. The results of this long-term study are shown in Figure 23. A least squares fit to the data from day one to day 371 yielded a slope of 6 to 7 percent per year, which is compatible with results reported in the literature.

These room temperature annealing results were very encouraging and were in agreement with data published by Harris and Jackson.⁽¹⁴⁾ The relatively small decrease in response over a one-year time period led directly to the technique of enclosing the ^7LiF block in a thin Teflon tape holder for convenient automatic processing.

Annealing studies were conducted over a period of four months with ^7LiF blocks enclosed in Teflon tape and mounted in the dosimeter card. The cards were exposed to 320 mR radium gamma and read out again at 250°C and held one month at room temperature. This cycle was repeated four times with ten cards each time. The average relative reading of the ten cards had a range of ± 6 percent with a variation from 425 to 478 reader units. The average of all four sets of readings was 453 reader units, as shown in Table X.

For a fading study, some of the same set of dosimeter cards as used for the annealing study were readout at 310°C and held for one month at room temperature. On the first day after the one-month holding period, all cards (35) were exposed to 320 mR radium gamma radiation and put aside to be read out at intervals for 3-1/2 months. The dosimeter

TABLE X

ONE-MONTH ANNEAL STUDIES

250°C Readout

One-month hold at room temperature

<u>Date</u>	<u>Exposure</u>	<u>Average Relative Reading</u>	
12-8-70	320 mR	443	
1-11-71	320 mR	425	
2-3-71	320 mR	478	Average = 453
3-5-71	320 mR	468	

cards were read out in groups of five each time and the readings were corrected for background. The fading of these dosimeters over the 3-1/2 month period was 12 percent as determined by a least square fit to the data shown in Table XI. The amount of fading is more than desirable but we feel that this is due to reader fluctuations rather than the TLDs themselves since the long term study yielded a fading significantly less severe.

Based on the work of Harris and Jackson,⁽¹⁴⁾ it appears possible to maintain the sensitivity of the LiF by a short anneal process at higher temperature rather than the one-month anneal at room temperature. A group of dosimeter cards were read out at 300°C, and divided into two sets. One set received the standard one-month room temperature anneal; the other set received a short anneal of 60°C for 24 hours and then five days at room

TABLE XI

FADING STUDY
Teflon enclosed ^7Li

<u>Set</u>	<u>Exposed</u>	<u>Readout</u>	<u>Exposure</u>	<u>Relative Reading</u>
1	Day 1	Day 7	320 mR	448
2	Day 1	Day 40	320 mR	424
3	Day 1	Day 47	320 mR	395
4	Day 1	Day 60	320 mR	365
5	Day 1	Day 79	320 mR	404
6	Day 1	Day 92	320 mR	382
7	Day 1	Day 107	320 mR	370

temperature. The dosimeter cards given this short 60°C anneal were then held at room temperature until the other set of cards put through the one-month room temperature anneal were ready. After one month, all the cards were exposed to 500 mR radium gamma radiation. All dosimeter cards were read out on the same day for comparison of sensitivity. This entire monthly cycle was repeated. The cards given the short anneal were about 15 percent less sensitive to the radiation than were those given the standard one-month anneal. The results using the short anneal were statistically more consistent than were the results from cards annealed one month at room temperature.

Another group of dosimeter cards was given the short anneal after a 250°C readout and cycled the same way each month for four months to

determine how reproducible the readout was after exposure to 320 mR radium gamma. Ten dosimeter cards were used for the exposures and three cards were used to determine background. As shown in Table XII, except for the second month, the results are quite reproducible. The average result is 367 with the second month included, and 357 without the second month. The range of the results is +11 and -5 percent with the data from the second month included. Without these data, the range is +1 and -2 percent. The results shown for each month are the average of the ten dosimeter readings minus the background. Thus, the short anneal process seems to give a consistent reading for several dosimeter cycles.

TABLE XII

EXPOSURE - ANNEALING STUDIES

<u>Month</u>	<u>Exposure</u>	<u>Average Relative Reading</u>
1	320 mR	350
2	320 mR	410
3	320 mR	355
4	320 mR	361
5	320 mR	361

Average Result = 367 with Month #2

357 without Month #2

In summary, either the standard readout with a one-month room temperature holding period or a standard readout with a 24-hour 60°C oven anneal with a five-day room temperature holding period will adequately

anneal the multipurpose dosimeter card. We recommend the latter procedure because it will allow the dosimeter cards to be returned to field use faster and the statistical variations appear to be less.

V. CONCLUSIONS

A multipurpose thermoluminescent personnel dosimeter has been developed to replace the Hanford film badge. The dosimeter can be used repeatedly with proper annealing and maintain a constant sensitivity. Its photon energy response and shielding provide the penetrating one centimeter tissue depth dose and total derma dose quite accurately over a wide range of radiation sources and spectra found at Hanford. The calibration and interpretation procedures are simple and do not leave gaps or unreasonable limits for any one kind or mixture of radiation. The badge has a reasonable independence from body wearing position and angle of radiation incidence. The ^7LiF blocks are relatively insensitive to neutrons of any energy so no neutron corrections are necessary for beta-photon dose interpretations.

Most of the neutron exposures at Hanford are due to neutrons which have a broad energy distribution. Because of this fact, the neutron dose interpretation obtained from the multipurpose badge accurately reflects personnel exposure to both fast and thermal neutrons.

Because the TL blocks are read and annealed while in the plastic dosimeter cards, the standard annealing procedures using 400°C cannot be used. Our experimental evidence and that of other authors show that 300°C

is an adequate pre-exposure annealing temperature for precision dosimetry.

At this temperature, we are able to adequately read out and pre-anneal the blocks in the same process. Data indicates that an additional 24-hour 60°C oven anneal with a five-day holding period at room temperature restores the dosimeters to a uniform sensitivity. This process can be repeated indefinitely.

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VIII. FIGURE CAPTIONS

1. An exploded view of the Hanford Multipurpose Dosimeter Card.
2. View of dosimeter holder, security credential and dosimeter card.
3. Curve A is the response of two pieces of adhesive coated TFE Teflon tape. Curve B is the response of a sandwich consisting of one piece of adhesive coated TFE tape, a TLD-700, and a piece of uncoated tape. Curve C is the same as Curve B except exposed to u.v. light.
4. One centimeter shield response compared to one centimeter tissue.
5. The photon energy response function for TLD block in position number one of dosimeter card.
6. Multipurpose TLD phantom distribution - penetrating and derma dose - ^{252}Cf .
7. Multipurpose TLD angular response to ^{60}Co gamma radiation.
8. Penetrating dose comparison - multipurpose TLD vs. film badge.
9. Derma dose comparison - multipurpose TLD vs. film badge.
10. Schematic representation of neutron exposure conditions.
11. The $^6\text{Li}(n,\alpha)$ cross section as a function of neutron energy.
12. Neutron flux density and dose distribution for an unmoderated criticality event.
13. Neutron flux density and dose distribution for a heavily moderated criticality event.
14. The photon energy response function for TLD blocks in position 3, 4, and 5 of the dosimeter card.
15. Fast neutron dose response as a function of neutron energy.

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16. Fast neutron response as a function of the distance between the multi-purpose badge and the surface of a polyethylene phantom.
17. Fast and thermal neutron response as a function of the position of the badge on a Remab phantom.
18. Relative monoenergetic fast neutron response as a function of the position of the badge on a phantom. Data have been normalized to front center position.
19. Fast neutron response as a function of incident neutron angle.
20. Glow curve for ^7LiF after a standard readout cycle.
21. Glow curve for ^7LiF after eight-day holding period.
22. Glow curves for ^7LiF after various annealing and exposure conditions.
23. One-year fading study showing response of ^7LiF exposed after one-month holding period at room temperature.

FIGURE 1. AN EXPLODED VIEW OF THE HANFORD MULTIPURPOSE DOSIMETER CARD.

FIGURE 2. VIEW OF DOSIMETER HOLDER, SECURITY CREDENTIAL AND DOSIMETER CARD

FIGURE 3. CURVE A IS THE RESPONSE OF TWO PIECES OF ADHESIVE COATED TFE TEFLON TAPE. CURVE B IS THE RESPONSE OF A SANDWICH CONSISTING OF ONE PIECE OF ADHESIVE COATED TFE TAPE, A TLD-700 AND A PIECE OF UNCOATED TAPE. CURVE C IS THE SAME AS CURVE B EXCEPT EXPOSED TO U.V. LIGHT.

FIGURE 4. ONE CENTIMETER SHIELD RESPONSE COMPARED TO ONE CENTIMETER TISSUE.

FIGURE 5. THE PHOTON ENERGY RESPONSE FUNCTION FOR TLD BLOCK IN POSITION NUMBER ONE OF DOSIMETER CARD.

FIGURE 6. MULTIPURPOSE TLD PHANTOM DISTRIBUTION - PENETRATING AND DERMA DOSE - ^{252}Cf .

FIGURE 7. MULTIPURPOSE TLD ANGULAR RESPONSE TO ^{60}Co GAMMA RADIATION.

FIGURE 8. PENETRATING DOSE COMPARISON - MULTIPURPOSE TLD VS. FILM BADGE.

FIGURE 9. DERMA DOSE COMPARISON - MULTIPURPOSE TLD VS. FILM BADGE.

FIGURE 10. SCHEMATIC REPRESENTATION OF NEUTRON EXPOSURE CONDITIONS

FIGURE 11. THE ${}^6\text{Li}(n,\alpha)$ CROSS SECTION AS A FUNCTION OF NEUTRON ENERGY.

FIGURE 12. NEUTRON FLUX DENSITY AND DOSE DISTRIBUTION FOR AN UNMODERATED CRITICALITY EVENT.

FIGURE 13. NEUTRON FLUX DENSITY AND DOSE DISTRIBUTION FOR A HEAVILY MODERATED CRITICALITY EVENT.

FIGURE 14. THE PHOTON ENERGY RESPONSE FUNCTION FOR TLD BLOCKS IN POSITION 3, 4, AND 5 OF THE DOSIMETER CARD.

FIGURE 15. FAST NEUTRON DOSE RESPONSE AS A FUNCTION OF NEUTRON ENERGY.

FIGURE 16. FAST NEUTRON RESPONSE AS A FUNCTION OF THE DISTANCE BETWEEN THE MULTIPURPOSE BADGE AND THE SURFACE OF A POLYETHYLENE PHANTOM.

FIGURE 17. FAST AND THERMAL NEUTRON RESPONSE AS A FUNCTION OF THE POSITION OF THE BADGE ON A REMAB PHANTOM.

FIGURE 18. RELATIVE MONOENERGETIC FAST NEUTRON RESPONSE AS A FUNCTION OF THE POSITION OF THE BADGE ON A PHANTOM. DATA HAVE BEEN NORMALIZED TO FRONT CENTER POSITION.

FIGURE 19. FAST NEUTRON RESPONSE AS A FUNCTION OF INCIDENT NEUTRON ANGLE.

FIGURE 20. GLOW CURVE FOR ^7LiF AFTER A STANDARD READOUT CYCLE.

FIGURE 21. GLOW CURVE FOR ^7LiF AFTER EIGHT-DAY HOLDING PERIOD.

FIGURE 22. GLOW CURVES FOR ^7LiF AFTER VARIOUS ANNEALING AND EXPOSURE CONDITIONS.

FIGURE 23. ONE YEAR FADING STUDY SHOWING RESPONSE OF ^7LiF EXPOSED AFTER ONE MONTH HOLDING PERIOD AT ROOM TEMPERATURE.