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THE US NAVAL DOSIMETRY CENTER THERMOLUMINESCENCE DOSIMETRY SYSTEM*

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Abstract - The US Naval Dosimetry Center thermoluminescence dosimetry system is presented. The dosemeter algorithm accounts for individual chip response reader calibration, and particular operational requirements of the Navy. Lower limits of detection are used in the algorithm. Results of the United States National Voluntary Laboratory Accreditation Program are presented. The accuracy of the system is within the required performance criteria.

INTRODUCTION

Operational commitments of the Navy require a dosemeter which can simultaneously measure mixtures of photons, beta particles and neutrons. The United Stave Nuclear Regulatory Commission requires all licensees to have personnel dosimetry devices processed by organisations which have been accredited by the National Voluntary Laboratory Accreditation Program. (NVLAP)[1]. The Los Alamos National Laboratory System was used as a model[2].

The objective of the algorithm is to convert the response of the thermoluminescent materials into values of dose equivalent for penetrating and superficial radiation exposures. The response characteristics of the dosemeter for various photon energies, as well as for neutron and beta radiation fields are parameters which must be quantified and set as terms in the algorithm to calculate the deep and shallow dose equivalents. The algorithm is designed to be effective over: the photon energies from 20 keV to 2 MeV, beta emitters such as ^{90}Sr/ ^{90}Y which are the only high energy beta emitters expected to be encountered in operational use for personnel dosimetry, and fission spectrum neutron energies in the 100 keV to 2 MeV region[3].

The operational requirements demand an issue period of two months or longer since the dosimeters are sent to customers world wide. Terms in the algorithm were developed to correct for fading as well as exposure of the dosimeters in transit and handling. The lower limit of detection has been incorporated to minimize the number of entries which do not correspond to personnel exposure.

DOSIMETRY SYSTEM DESCRIPTION

The thermoluminescent material used is LiF:Mg,Ti manufactured by Harshaw in the form of a solid chip. All four chips are 0.3 cm square; three of the chips. Chip 1, Chip 2, and Chip 4, are 0.04 cm thick as compared to the original 0.09 cm thick Los Alamos design[2] the other. Chip 3, is 0.009 cm thick. Chip 1, Chip 2, and Chip 3 are TLD-700 material; Chip 4 is TLD-600 material. The, chips are placed between two Teflon sheets 0.006 cm thick. The set of few chips is then placed between two aluminum plates for support. This makes a TLD card of dimensions 4.4 cm by 3.2 cm by 0.08 cm. a bar code is placed on the aluminum support for identification. The card is shown in Figure 1.

The holder is made of ABS plastic and is shown in Figure 2. The back is solid and has a belt loop. The latch-groove provides an opening through which a hanger clip can be inserted to allow for an alternative method of attachment to an individual's clothing. In addition to protecting the card, the holder has filters to supply information on the nature of the radiation. Chip 1 has a filtration of 600. mg.cm^{-2} plastic, as compared to the 250 mg.cm^{-2} Los Alamos design[2], to minimize the contribution of high-energy beta emitters. This filtration was used rather than 1000 mg. cm^{-2}so that the size and shape of the badge would be convenient for operational usage. Chip 1 is used to determine deep dose

* The opinions and conclusions expressed in this article are those of the authors and do not necessarily represent the views of the Department of the Navy, or other governmental department or agency thereof. The mention of any commercially available product or equipment does not imply endorsement by any agency of the US Government.

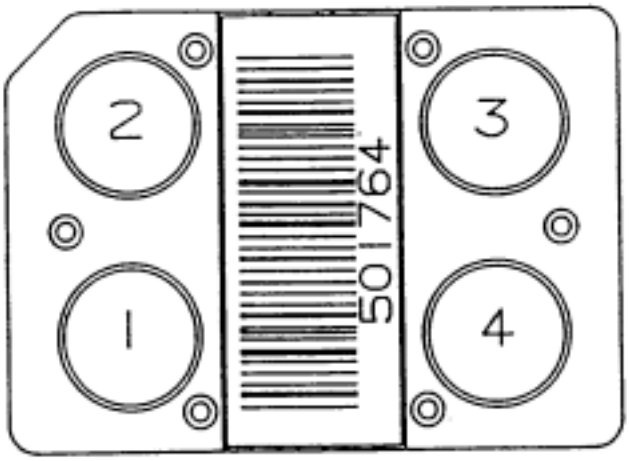

Figure 1. Dosimetry card.

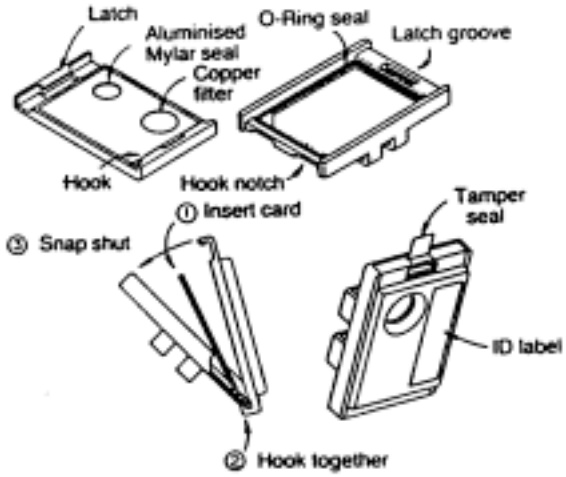

Figure 2. Dosimetry card holder.

equivalent from photons and betas. Chip 2 has 0.11 mm of copper and 242 mg.cm^{-2} plastic filtration and is used to provide information on energy corrections for photon exposures. Chip 3 lies behind a thin aluminised Mylar film, 0.006 cm thick and provides the data from which the shallow dose equivalent is determined. Chip 4 has the same filtration as Chip 1. Chip 1 and Chip 4 together provide information on neutron dose equivalent. In the absence of neutrons, Chip 4 is an excellent photon detector.

The instructions for use of the dosemeter which are supplied to the user include direction to wear the badge in contact with the body to assure proper function as an albedo dosemeter. The angular dependence of response for the dosemeter indicates that it under evaluates the dose equivalent no more than 35% within the 60 degrees of angle from a normal fluence even for the lowest energy tested, M30. Positioning the dosemeter as directed on the front of the body will assure a minimum of error from this factor.

The choice of copper was made since it gives the sharpest change in the low energy region. Tin could be considered but it would not survive the rather harsh environment to which the dose meter is exposed as well as not quite providing the desired response properties.

The response of the TLD chips was measured using the Model 8800 automatic TLD card reader, developed by Harshaw. It utilises a unique hot nitrogen heating technique which avoids contact of the dosemeter with a heating element. This increases the lifetime of the dosemeter card and minimises the infrared signal. A fully controlled heating cycle is required for low dose measurements since the response is dependent on the thermal history of the material as well as the heating rate. The heating cycle chosen for this dosimetry system was: heating rate of 25 C per second to 300^{0}C with a total heating time of 13$^{1/3}$ seconds. Glow curves are provided by the reader for all four chips. The glow curves are used in processing quality control and for investigation of high doses and questionable readings.

DOSIMETRY SYSTEM DEVELOPMENT

The calibration of the reader and the design of the algorithm for determining dose equivalent are based on the average card and so some coefficients must be defined to relate a single card in the dosemeter population to the average response of the system. The element correction coefficients (ECC) were developed by taking the average of the light output readings for all cards for a given chip position on a card and dividing this average into the value of that chip on each card. The ECC provides a card specific correction for the variation of the thermoluminescent response to radiation among the cards.

As the first step in developing the algorithm a set of 350 cards was exposed free-in-air to a uniform field at one time and read on one reader. This process yielded a set of cards with ECCs. The response of each reader for caesium was determined by exposing eight cards for each reader in holders on the ANSI phantom at the National Institute of Standards and Technology and determining the dosemeter response in terms of measured charge per unit deep dose equivalent for Chip 1,2,and 4 and charge per unit shallow dose equivalent for Chip 3. After the ECCs are applied to each card, the average of the response of the eight cards for each of the four chips for each reader yields the reader calibration factor (RCF) for each chip position for that reader. Thirty cards for each reader were then exposed in a radium chamber which provided a uniform exposure. This gave a caesium dose equivalent calibration factor for the radium

chamber. The readers are recalibrated weekly by exposing the set of calibration cards in the chamber. Daily quality control cards, irradiated to a known dose, are used to determine the stability of the readers during processing.

Cards when they are received are examined for broken crystals and physical damage. The cards are then exposed to a dose of 1.5 mSv of gamma radiation. If this differs by more than 30% from the expected response the card is rejected. The card is then exposed to 1 mSv of PuBe neutron radiation to determine the location of the neutron sensitive chip. If its response differs by 30 % from the expected result the card is rejected.

Only consistent sets of dosimetry cards are being admitted to the card population. Cards are exposed in lots of one hundred to radium exposure in a shielded box to a uniform dose of 1.5 mSv of ^{137}Cs dose equivalent and read on three different readers. The data for three thousand cards is accumulated and an average determined. If the average of this set of cards does not differ by more than 5 % from the average of all the previous sets, the batch is considered acceptable. Any cards, which differ by more than 30% from the average, are retested, if they fail to respond to within 30% of the average after retest they are rejected.

CUSTOMER ALGORITHM

The customer requesting dosimetric services supplies information on the nature of the irradiations. For the customer algorithm the calibration exposures can be treated as three separate sets of information and individual algorithms arc developed for the three cases of photon, mixed beta particle and gamma, and mixed neutron and gamma. A mixture of all three types of radiations is not considered likely in the operational conditions which might occur.

The dose equivalents resulting from the photon calibration exposures were calculated by applying the correction factors, $C_{x.d}$ and $C_{x.s}$ to the exposures made on the ANSI phantom. This yields the deep and shallow dose equivalents, H_d and H, respectively. The factors $C_{x.d}$ and $C_{x.s}$ are defined for the energies at which the dosemeter is calibrated by the American National Standards Institute [(4)].

For, the algorithm development the concept of the caesium dose equivalent response. L_i, for chip i is used. This is defined as the value obtained by dividing the charge, q_i, obtained from the reader for chip i by the product of reader calibration factor RCF_i and the element correction coefficient. Conceptually it is the result of a dose equivalent determination where the radiation is known to be ^{137}Cs photons

$$L_i = q_i/(ECC_i RCF_i)$$

The results of the photon calibration are presented in terms of the response of the dosemeter to caesium gamma rays in Table 1. The response of the dosemeter in the region from 70 keV to 662 keV is expected to be rather constant. The $C_{x.s}$ and $C_{x.d}$ vary little in this region and no extraordinary physical effects are likely. The majority of the exposures expected are from multiply scattered photons and medical X rays and so the low energy region is critical. It is also difficult to obtain well characterised fields suitable for calibration of dosemeters other than at those energies specified by the NVLAP tests. A_s and A_d are multiplicative factors applied to correct for the deep and shallow dose equivalent respectively. These are generated by taking the response per dose equivalent of a set of five dosemeters exposed to the X ray fields and dividing by the response to caesium gamma rays:

$$H_d = A_d L_1 \quad (2)$$

$$H_s = A_s L_3 \quad (3)$$

The ratios between the caesium dose equivalents are used to provide an estimate of the energy. Two ratios are used, $L_{1.2,}$ the ratio of Chip 1 behind a thick plastic filter to Chip 2 behind a copper and plastic filter, and, $L_{2.3,}$ the ratio of Chip 2 with the copper and plastic filter, to Chip 3 which has very little filtration. These ratios provide information on the energy and type of radiation to which the dosemeters are exposed. The results presented in Table 1 are an average of the readings of a minimum of five dosemeters for each energy.

When the photon energy is not known and it is known that no beta exposure was possible, the appropriate correction factor is determined using the ratio $L_{2.3}$. For photons, the correction factors of Table 1 are fitted by a quadratic to the ratio $L_{2.3}$. The reading of Chip 1 is multiplied by A_d to correct for the energy response of the thermoluminescent material. Their product is the deep dose equivalent. A_s functions similarly with Chip 3 to yield the shallow dose equivalent. After fitting to the data the factors are given by

$$A_d = 0.46 - 0.33\, L_{2.3} + 0.74\, L^2_{2.3} \quad (4)$$

$$A_s = 0.70 - 1.00\, L_{2.3} + 1.15\, L^2_{2.3} \quad (5)$$

The fits are approximate since there is a rapid variation of response at values of $L_{2.3}$ near one. The differences between the fit and the data can be as high as 15%. The use of higher order polynomials did not improve agreement that much and a fit to $L_{1,2}$ yielded results with variations up to 30%.

To determine the response to mixtures of ^{90}Sr/^{90}Y beta and caesium gamma rays a series of exposures was made to various ratios of these fields. The calibration factors are independent of the gamma to beta ratio within the range of mixtures measured. A

single A_d = 0.96 and A_S = 0.91 to both mixed field and pure beta exposure seem to be adequate.

The relative chip response of gamma to moderated californium neutrons is 0.095. The neutron dose equivalent in the mixed neutron gamma case is obtained by subtracting the reading L_1 from L_4 and multiplying by 0.095 and applying a neutron spectrum correction factor, K. The photon dose equivalent in the mixed neutron and gamma case is L_1:

$$H_n = 0.095(L_4 - L_1)K \quad (6)$$

The deep dose equivalent is the sum of the neutron and gamma components. The spectrum correction factor for neutrons, K, is generated by a survey of sites in operational conditions using an Anderson-Braun remmeter[(x)].

In the photon high dose region, corrections to account for the supralinearity of LiF:Mg,Ti were implemented. The results are presented in Figure 3 in terms of supralinearity correction factor as a function of dose. For the purposes of the algorithm, the correction would not be applied until the dose exceeded one gray. The supralinearity correction can be defined as

$$f(D) = [TL(D)/D]/(TL(D_0)/D_0] \quad (7)$$

where TL(D) is the TL signal corresponding to dose D and $TL(D_0)$ is the TL signal corresponding to D_0 being in the linear region of the TL dose response curve. The line indicated in the fit is used only as a guide. This response results from the reader rather than the thermoluminescent material since supralinearity in LiF:Mg,Ti is not expected to occur below one hundred gray.

Fade factors for the thermoluminescent material were derived experimentally. The cycle for the dosemeter from preparation to receipt and reading is approximately two months. This includes the six weeks it is issued to the person and two weeks in transit. To correct for fade, the readings for photon and beta radiation are multiplied by a factor of 1.1 and the reading of the neutron equivalent dose is multiplied by 1.25.

The dosemeters are sent as a group; some are issued to personnel, some are posted as environmental monitors, and others which are not to be exposed are used as controls. Control values are used to identify exposure not corresponding to occupational exposure caused by handling at the facility and in the mail. The control dosemeters are held by the user in low background areas. The issued dose meters and controls are returned and processed together. If the controls conform to values which have been observed for the facility in previous experience, this amount is subtracted from the dose equivalent read on the personnel or environmental monitor dosemeter. If the control values are abnormal, an investigation is performed and a control value is assigned on this basis.

While the above algorithm will work when the nature of the exposure is known, an additional step must be added when limited information is given on the radiation field type. Criteria for choice of algorithm can be made using the ratios, $L_{4,1}$ $L_{2,3}$ and $L_{1.2}$. The simplest differentiation which can be made is for neutron exposure. Since $L_{4.1}$, is equal to one within 10% for exposures not involving neutrons, this ratio can be used to discriminate doses when the readings of these chips are above background. A case when a dose could be registered and both these chips be at background occurs in beta exposure. The badge shields Chip 1 and Chip 4 from the beta radiation while there can be significant dose to Chip 3. For beta radiation the ratio $L_{2,3}$ defined above lies well below 0.8 and this can be used to differentiate between cases of pure beta particle and neutron exposure.

If the ratio $L_{4.1}$ is within 10% of 1.0, exposure to beta or photon radiation or both is likely. If the ratio $L_{1.2}$ is less than one and the ratio $L_{2.3}$ lies between 0.1 and 0.8 then a beta exposure or mixed beta and gamma exposure is probable. If the ratio $L_{1.2}$ is greater than 0.9 and $L_{2,3}$ is less than 1.1, a photon dose equivalent is assigned.

Ratios not falling into the categories above correspond to conditions which the algorithm is not designed to handle or to errors in the system. The

Table 1. Energy response correction factors for photon exposure.

Energy (keV)	A_d	A_s	$L_{1,2}$	$L_{2,3}$
662	1.00	1.00	1.00	1.00
70	0.71	0.69	0.98	0.95
51	0.57	0.56	1.11	0.81
39	0.54	0.55	1.61	0.53
29	0.48	0.53	2.31	0.34
20	0.40	0.57	5.94	0.11

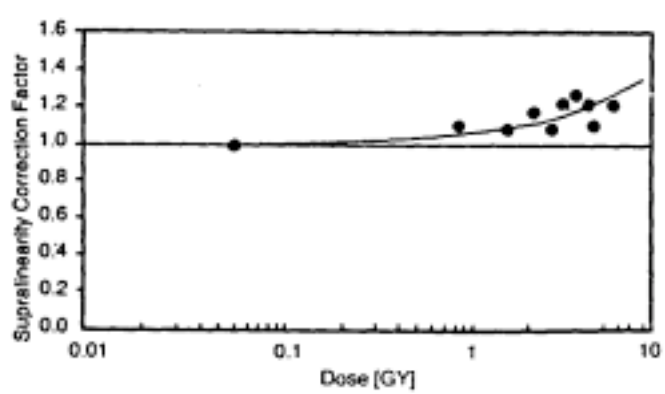

Figure 3. Supralinearity correction.

Table 2. 1988 NVLAP results for the US Naval Dosimetry Center.

Category	Deep or Shallow	Navy dosemeter results $\bar{P}$	S	$\lvert\bar{P}\rvert+S$	NVLAP acceptance criteria
I	D	0.01	0.08	0.09	0.3
II	D	0.05	0.08	0.12	0.3
III	D	−0.23	0.02	0.25	0.5
	S	−0.24	0.05	0.29	0.5
IV	D	−0.13	0.04	0.17	0.5
V	S	−0.17	0.07	0.24	0.5
VI	D	0.01	0.07	0.07	0.5
	S	−0.03	0.07	0.10	0.5
VII	D	−0.10	0.03	0.13	0.5
	S	−0.19	0.04	0.23	0.5
VIII	D	0.01	0.05	0.07	0.5

Table 3. NVLAP categories.

Test category	Range tested
I. Accidents, low energy photons	100-5000 mGy
II. Accidents, high energy photons	100-5000 mGy
III. Low energy photons	0.3-100 mSv
IV. High energy photons	0.3-100 mSv
V. Beta particles	1.5-100 mSv
VI. Photon mixtures	0.5-50 mSv
VII. Mixtures, photons and beta	2-50 mSv
VIII. Mixtures, photons and neutrons	1.5-50 mSv

ratio $L_{4.1}$ is not likely to be less than one unless an element correction factor or reader calibration is incorrect. The correction factor or the reader calibration is questioned if the ratio $L_{1.2}$ is greater than 0.9 and for the same reading $L_{2.3}$ is greater than 1, given that a photon exposure is probable.

The use of the above criteria to determine the nature of the irradiation is not reserved for the case of unknown radiations. The information generated is compared with the data on the type of radiation given in the request for dosimetry services. If there is a discrepancy between the two pieces of information or if the results do not fall into a defined category, the algorithm will mark the result for further investigation.

NVLAP TEST

The NVLAP proficiency test can be used to verify the performance of the algorithm and provide information on the lower limits of detection. The results of the NVLAP Proficiency Test are shown in Table 2, for the categories indicated in terms of the bias of the results measured by the average performance quotient, P, and the standard deviation, S. These quantities are defined in the testing protocol[4] in terms of the set of values reported by the processor under test, O_i, and the corresponding values to which the dosemeters were exposed, E_i. The categories are described in Table 3. The beta particle field for the testis $^{90}Sr/^{90}Y$. The high-energy photon field is ^{137}Cs. The field for Category III (low energy photons) was M50 and the fields for Category VI (photon mixtures) were NIST technique MFG and ^{137}Cs.

$$P_i = (O_i - E_i)/E_i \tag{8}$$

$$\bar{P} = \sum_{i=1}^{n} P_i/n \tag{9}$$

$$S = \sqrt{\sum_{i=1}^{n} (\bar{P} - P_i)^2/n} \tag{10}$$

For the algorithm the lower limit of detection for a dosimetry system L_D is defined to be[9]:

$$L_D = 2\left(\frac{1.75S_u + u^2H_u'}{1 - u^2}\right) \tag{11}$$

$$u = \frac{1.75S}{1 + \bar{P}} \tag{12}$$

where S_0 and H_0 are the standard deviation and the mean of a set of unirradiated dosemeter values made without subtracting a background signal. If these values are calculated for each of the fields of the NVLAP the lower limit of detection for photon and neutron deep dose equivalent is 30 μ Sv and the lower limit of detection for shallow dose equivalent is 200 μSv. In the algorithm, all values below these thresholds are set to zero. These lower limits of detection yield no more than 5 % false positive and 5 % false negative values.

CONCLUSION

A thermoluminescence dosimetry system has been developed which satisfies the operational requirements of the Navy and meets the specifications at the National Voluntary Laboratory Accreditation Program.

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