Radiation Protection Dosimetry (2006), Vol. 119, No. 1–4, pp. 248–254
doi:10.1093/rpd/nci692 Advance Access published on July 11, 2006

INVITED PAPER

THE APPLICATION OF LiF:Mg,Cu,P TO LARGE SCALE PERSONNEL DOSIMETRY: CURRENT STATUS AND FUTURE DIRECTIONS

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LiF:Mg,Cu,P is starting to replace LiF:Mg,Ti in a variety of personnel dosimetry applications. LiF:Mg,Cu,P has superior characteristics as compared to LiF:Mg,Ti including, higher sensitivity, improved energy response for photons, lack of supralinearity and insignificant fading. The use of LiF:Mg,Cu,P in large scale dosimetry programs is of particular interest due to the extreme sensitivity of this material to the maximum readout temperature, and the variety of different dosimetry aspects and details that must be considered for a successful implementation in routine dosimetry. Here we discuss and explain the various aspects of large scale LiF:Mg,Cu,P based dosimetry programs including the properties of the TL material, new generation of TLD readers, calibration methodologies, a new generation of dose calculation algorithms based on the use of artificial neural networks and the overall uncertainty of the dose measurement. The United States Navy (USN) will be the first US dosimetry processor who will use this new material for routine applications. Until June 2002, the Navy used two types of thermoluminescent materials for personnel dosimetry, CaF_2:Mn and LiF:Mg,Ti. A program to upgrade the system and to implement LiF:Mg,Cu,P, started in the mid 1990s and was recently concluded. In 2002, the new system replaced the LiF:Mg,Ti and is scheduled to start replacing the CaF_2:Mn system in 2006. A pilot study to determine the dosimetric performance of the new LiF:Mg,Cu,P based dosimetry system was recently completed, and the results show the new system to be as good or better than the current system in all areas tested. As a result, LiF:Mg,Cu,P is scheduled to become the primary personnel dosimeter for the entire US Navy in 2006.

INTRODUCTION

The use of LiF:Mg,Cu,P in large scale dosimetry programs is of particular interest due to the extreme sensitivity of this material to the maximum readout temperature, and the variety of different dosimetry aspects and details that must be considered for a successful implementation in routine dosimetry. Here we discuss and explain the various aspects of large scale LiF:Mg,Cu,P based dosimetry programs including the properties of the TL material, new generation of TLD readers, calibration methodologies, a new generation of dose calculation algorithms based on the use of artificial neural networks, and the overall uncertainty of the dose measurement. The United States Navy (USN) will be the first US dosimetry processor who will use this new material for routine applications.

The USN started a personnel dosimetry program back in 1946. The first dosimeters were based on film technology, and were replaced by thermoluminescence dosimeters (TLDs) in 1975. The USN dosimetry program has been accredited by the US National Voluntary Laboratory Accreditation Program (NVLAP) since this program started in 1984. Currently the USN has three TL based dosimetry programs. The first uses a photon only bulb type design based on a single CaF_2:Mn element (Navy code: DT-526). The phosphor is shielded by a thin lead filter for the purpose of improving the photon energy dependence. The readout is done in a manual reader using ohmic heating. The dose estimation is based on the peak height method rather than on glow curve integration.

The second system, Navy code: DT-702, which is the main topic of this paper, is a recent upgrade to the Navy dosimetry system and implements this relatively new TL material, LiF:Mg,Cu,P. It replaced the previous LiF:Mg,Ti based system, Navy code: DT-648 in 2002. The DT-648 is maintained for emergency or battlefield use but is no longer covered under the NVLAP accreditation. Both of these dosimeters are four-element, used to monitor photon, beta and neutron personnel exposures, and are managed through the USN Dosimetry Center (NDC) located in Bethesda, MD, USA. This is a large scale dosimetry processor, which provides dosimetry for over 250 locations worldwide and processes about 20 000 dosimeters per month. LiF:Mg,Cu,P has superior characteristics as

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compared to LiF:Mg,Ti including, higher sensitivity, better tissue-equivalent response to photons, lack of supralinearity and insignificant fading. As a part of this upgrade, the dosimeter holder was redesigned to improve both the low and high energy photon discrimination and a new dose calculation algorithm was developed based on artificial neural network concepts. The DT-702 was designed to be the central point of the next generation Navy dosimetry system. In the following section we describe the rational of this upgrade, and the remaining of this article is devoted to a full description of the LiF:Mg,Cu,P based dosimetry program.

RATIONAL OF THE UPGRADE

The DT-702 is a four element beta, photon and albedo neutron dosimeter. LiF:Mg,Cu,P phosphors are encapsulated in Teflon® (FEP) and mounted on an aluminum substrate to form a TLD card. The new dosimeter is 10 times more sensitive to photon irradiation as compared to the DT-648 design, has negligible fading over 120 days, is linear up to at least 20 Gy, and has improved photon energy dependence. (More details about the dosimetric characteristics are provided in the following section). On the contrary, the DT-648 without any special low temperature annealing procedures, exhibits noticeable fading, photon energy dependence and supralinearity above 1 Gy. Although corrections can be made to account for these characteristics, the LiF:Mg,Cu,P material used in the DT-702 design, is preferred since fewer and smaller corrections need to be made. The glow curve characteristics of LiF:Mg,Cu,P allow a preheat cycle to be used during readout resulting in a single glow peak, which makes automatic glow curve analysis simpler and more practical. The LiF:Mg,Ti material used in the DT-648, exhibits multiple overlapping peaks, making automatic glow curve analysis more complicated.

The dosimeter holder was also redesigned. Different filter materials and thicknesses were used to enhance photon energy discrimination over the DT-648. A window was placed in the holder that allows the reading of the barcode of the TLD card without opening it. The Mylar window that covers the shallow dose element, is held in place with a sonically welded ring to keep an air and water tight seal to a 40 000 foot altitude in air and to 66 foot depth in water. The belt loops have been redesigned to prevent breakage and reinforcing bars were placed on each side of the holder for added strength and durability.

The dose calculation algorithm has been completely redesigned as well. The DT-702 uses three independent ratios for photon energy discrimination whereas the DT-648 only used one. The DT-702 algorithm uses a neural network approach that is more robust than the decision tree algorithm used in the DT-648. The DT-702 uses one element for shallow and one element for deep dose measurements exclusively, whereas the DT-648 has cross over points where the shallow dose is measured from more than one element depending on the composition of the radiation field. This resulted in larger errors in calculating the shallow dose equivalent. The improved performance of the DT-702 has been demonstrated repeatedly, including in a formal NVLAP proficiency test where the dosimeter passed in all categories by a large margin.

Since the same TLD reader, the Harshaw Model 8800 (Thermo Electron Corporation), is used for both dosimeter types, there was no cost associated with reader replacement and technicians did not require additional training. The switch was practically transparent to the users since the DT-702 is worn and used exactly like he DT-648. A pilot study completed in 2003 for the Naval Reactors, was performed to determine the accuracy of the dose measurements made by the DT-702 as compared to the other dosimeters used by the Navy and some Department of Energy (DOE) facilities. Laboratory tests and field comparisons performed in this study demonstrated that the DT-702 is an accurate and reliable dosimeter and was highly recommended as a replacement for the DT-526, as well as for other dosimeters used at various DOE facilities. This replacement is currently taking place and is scheduled for completion in 2006.

HIGH SENSITIVITY TL MATERIALS: LiF:Mg,Cu,P

The idea of developing a high sensitivity thermoluminescence (TL) material by doping LiF crystals with Mg, Cu and P impurities, was proposed by Nakajima *et al.*(1). The sensitivity of this new preparation was more than 20 times higher as compared to LiF:Mg,Ti (TLD-100), but it lost its high sensitivity after only one use(2,3). In 1984 Wu *et al.*(2) demonstrated that it is possible to prepare high sensitivity LiF:Mg,Cu,P that maintains its high sensitivity during repeated re-use cycles. Initial characterisation(3) of this new preparation has shown promising dosimetric properties and demonstrated that the material can be re-used with little loss of sensitivity (<5% following eight uses). LiF:Mg,Cu,P is now available commercially in several forms, e.g. GR-200 (Beijing Radiation Detector Works, People's Republic of China), MCP-R (Henry Niewodniczanski Institute of Nuclear Physics, Poland) and Harshaw LTD-100H, 600H and 700H (Thermo Electron Corp., USA). The TL characteristics of LiF:Mg,Cu,P that are particularly useful for radiation dosimetry include high sensitivity as compared to LiF:Mg,Ti, almost flat photon energy response, low fading rate and linear dose response. For more details see Ref.(4).

The glow curve of LiF:Mg,Cu,P consists of several overlapping glow peaks. The main peak at ~210°C, known as Peak 4, is the one used for dosimetry applications (the 'dosimetric peak'). The rest of the glow curve consists of a low temperature part in the range of ~70–160°C (Peaks 1, 2 and 3), and a high temperature peak at ~300°C (Peak 5). There is evidence that the glow curve of this material is even more complicated, where Peaks 4 and 5 are each composed of two overlapping peaks(4,5). The TL mechanism in LiF:Mg,Cu,P is currently not well understood, and the reason for the choice of this particular set of impurities (Mg, Cu, P) is not clear. Optical absorption measurements of irradiated LiF:Mg,Cu,P suggest that absorption in the range of 300–400 nm is associated with Mg-related defects, and these defects are responsible for the TL emission at ~200°C (Peak 4)(5). Bilski *et al.*(6) conducted a systematic study to determine the optimum concentration of dopants and their influence on the dosimetric characteristics of LiF:Mg,Cu,P. They made several observations, including: (1) the height of Peak 4 depends on the concentration of Cu and Mg, showing a clear maximum; (2) the intensity of the high temperature peaks increases with increasing Mg and decreases with increasing Cu concentration; (3) the dependence of the height of Peak 4 on the concentration of P behaves like a step function, increasing rapidly above a certain threshold value.

The high sensitivity, combined with its tissue equivalence, is the main advantage of this material in personnel dosimetry applications. The sensitivity of LiF:Mg,Cu,P in the form of powder or chips is ~25 times higher as compared to LiF:Mg,Ti (TLD-100). When LiF:Mg,Cu,P chips are encapsulated into TLD cards, the measured sensitivity (i.e. the detected TL light per unit dose) relative to encapsulated LiF:Mg,Ti drops from 25 to 10. This is in part a result of differences in the encapsulation materials used in the production of the two TLD card types—PTFE films are used to encapsulate LiF:Mg,Ti chips and FEP coated films are used for the production of LiF:Mg,Cu,P cards. In addition, the photon energy dependence of LiF:Mg,Cu,P, is somewhat better as compared to LiF:Mg,Ti. For photons with energy below a few hundred keV, the ratio of the mass energy absorption coefficient of most TL material as compared to air, increases with decreasing energy. TL radiation dosimeters are expected therefore, to over-respond to low energy photons. Both LiF:Mg,Ti and LiF:Mg,Cu,P have the same effective atomic number (8.2), and could therefore be expected to have similar photon energy response. In reality, however, the photon energy dependence of LiF:Mg,Cu,P is considerably different a compared to LiF:Mg,Ti. For example, if the photon energy response is expressed in terms of the TL signal per unit of exposure as a function of energy, the over-response of LiF:Mg,Ti at 30 keV is ∼35% (relative to 662 keV) as compared to only 6% for LiF:Mg,Cu,P. For LiF:Mg,Ti, the overresponse is larger than what could be expected just from the ratio of the mass energy absorption coefficients. The explanation(7) of this phenomena is that some of the microscopic dose distribution within photon induced secondary electron tracks, lies in the supralinear region of the dose response curve. In LiF:Mg,Cu,P no supralinearity is observed, and the dose response is linear-sublinear rather than linear-supralinear as is the case for LiF:Mg,Ti. The photon energy dependence of LiF:Mg,Cu,P indeed is lower than expected just from the ratio of the mass energy absorption coefficients, and is consistent with the lack of supralinearity in this material(8).

The sensitivity and glow curve shape are both dependent on the maximum readout temperature, the heating rate and the pre-irradiation annealing parameters. Short low temperature annealing or 'pre-heat' of 165°C for 10 s prior to readout is capable of removing most of the low temperature peaks. As a result, there is no measurable fading for this material up to at least two months at room temperature. High readout temperatures may result in irreversible reduction or elimination of the main dosimetric peak. This permanent loss of sensitivity resulted in the recommendation, which has been widely accepted, to limit the readout temperature to a maximum of 240°C for bare chips (the maximum is 260°C for encapsulated chips into TLD cards). The maximum readout temperature of 240°C (or 260°C), coupled with the presence of TL glow peaks at temperatures higher than 240°C, has the potential of creating a residual TL problem. Single readout at temperatures below 240°C (260°C) is not capable of removing the residual signal following high dose levels, and multiple readout cycles or 'clearings' are required(9,10). Recent improvements in the preparation process of the Harshaw material at Thermo Electron Corporation has resulted in a decrease of a factor of 2–4 in the residual signal(11).

THE TLD READER

As discussed in the previous section, the TL response of LiF:Mg,Cu,P is sensitive to the readout temperature. Good control of the temperature during the processing is therefore critical to the successful practical application of this material in personnel dosimetry. A reader capable of precise control of the heating regime is an essential component of any LiF:Mg,Cu,P based TLD system. In this section such a reader is described: it uses a linear gas heating technique which combines the advantages of non-contact gas heating and linear ohmic heating. This reader, the Harshaw Model 8800 (Thermo Electron Corporation)(12) incorporates a linear time–temperature controlled hot gas heating technique. This heating method has been in routine use for almost 20 years using LiF:Mg,Ti based dosemeters, and it combines some of the advantages of other commonly used heating techniques, such as contact ohmic heating, constant temperature hot gas and optical heating. In the current TLD system, the heating profile is linear and directly controllable through closed loop feedback to an operator-specified temperature, time and heating rate. There is no mechanical contact with the dosemeter to limit its life, and there are no moving parts in the heating mechanism to wear out or be adjusted. The heating of the dosemeter is reproducible and efficient for both thick and thin TL elements. The reader can use either nitrogen or dry air for heating. The gas enters the system through four flow controls and flow meters to ensure proper flow and pressure. The gas is heated as it flows through electrical resistance heating tubes and is applied to the TL elements through nozzles located close (3 mm) to the TL element encapsulation material. The heating tubes are made of high alloy stainless steel for corrosion resistance, and have thin walls and low thermal mass to enable fast temperature response. Heating rates may be in the range of 1–50°C s^{-1}. The temperature is sensed by individual thermocouples across the end of each nozzle and is sent to a heater control board which compares the measured temperature with that called for by the user defined heating profile (temperature as a function of time). It then adjusts the current in the heating tubes to maintain the temperature of the gas within ±1°C of the specified level. If gas pressure drops below a pre-established value, or if the temperature fails to follow the required heating profile, a controlled shutdown is executed at the end of the read cycle. This closed loop cycle ensures a high degree of accuracy and repeatability of the heating profile, critical to successful application of LiF:Mg,Cu,P to dosimetry. The TL emitted light is measured in parallel from four TL elements heated simultaneously, using four photomultiplier tubes (PMTs) that are thermoelectrically cooled to 10°C. The PMT signal is accumulated via the charge integration technique.

CALIBRATION METHODOLOGY

Next, we describe the methodology for calibrating this system, which in principle is similar to the calibration used for LiF:Mg,Ti personnel dosimetry systems(13). The purpose of the calibration process is to enable the measurement of one type of radiation field, usually ^{137}Cs. The dose algorithm then extends this capability to other radiation types and energies. Let the sensitivity of the dosemeter be defined to be the TL intensity per unit dose, and the sensitivity of the reader to be the amount of charge produced by the photomultiplier tube per unit of light. When the system is not calibrated, both sensitivities are not known. The first step is to establish the sensitivity of the reader. This is done by dividing the dosemeter population into two groups. One group (1–2% of the population) consists of calibration dosemeters used only for calibrating the reader (establishing the reader sensitivity). The second group consists of the field dosemeters (98–99% of the population) used for the actual dose measurements. The reader calibration factor (RCF) for element position i, RCF_i, is defined as follows:

$$\mathrm{RCF}_i = \langle Q \rangle_i / \mathrm{L} \qquad (1)$$

where $\langle \mathrm{Q} \rangle_i$ is the average measured charge for that position when a set of calibration dosemeters is exposed to a known quantity of radiation L. L can be expressed in any convenient units. The RCF maintains a known relationship between the ability of the reader to convert TL photons into charge and the delivered dose. The numerical value of the RCF is mainly dependent on the condition of the reader. It is desirable therefore to perform reader calibration on a regular basis and it is convenient to perform this calibration using a local source that consistently delivers the same amount of radiation every time it is used. The NDC performs this calibration daily using the automatic irradiation systems that are installed in each reader. In this case, L can be expressed in terms of any convenient units.

Since not all TL elements can be manufactured to have exactly the same sensitivity, individual element correction coefficients (ECC) are applied. The method of ECC generation is based on relating the sensitivity of each TL element of the field dosemeters to the mean sensitivity of the calibration dosemeters. The element correction coefficient, ECC_{ij}, for element i ($i = 1 \ldots 4$) in calibration card j is defined as:

$$\mathrm{ECC}_{ij} = \langle Q \rangle_i / \mathrm{Q}_{ij} \qquad (2)$$

where Q_{ij} is the measured charge of element i in card j, and $\langle \mathrm{Q} \rangle_i$ is the average of Q_{ij} over j. Similarly, the element correction coefficient ecc_{ij} for the field cards is defined as:

$$\mathrm{ecc}_{ij} = \langle Q \rangle_i / \mathrm{q}_{ij} \qquad (3)$$

where q_{ij} is the measured charge of element i in field card j. When ECCs are applied to each individual TL element of any of the field or calibration dosemeters, its sensitivity is virtually identical to the mean value of the calibration dosemeters. Let us define the following terms: indicated value: value of the quantity derived from the instrument reading following the application of RCF and ECC or ecc.

L_{ij} is the indicated value of Element i ($i = 1 \ldots 4$) in dosemeter j. For simplicity, in a single dosemeter, the notation L1, L2, L3 and L4 is used for the indicated values of elements 1, 2, 3 and 4, respectively. From Equations 1 and 3, it is easily seen that:

$$L_{ij} = ecc_{ij}q_{ij}/RCF_i \quad (4)$$

Response: quotient of the indicated value divided by the delivered quantity (exposure in case of photon fields, or shallow dose for charged particles). a_{ij} is the response of element i ($i = 1 \ldots 4$) in dosemeter j to radiation field type 'a'. For simplicity, in a single dosemeter, the notation a_1, a_2, a_3 and a_4 is used for the response of Elements 1, 2, 3 and 4, respectively.

The last step of the system calibration consists of establishing the traceability to a calibrated source (usually ^{137}Cs) located at the calibration laboratory. This is done by exposing a small group (5–15) of dosemeters and determining the values of a_1, a_2, a_3 and a_4 as the averages of that group. If the system is calibrated such that the indicated value is the actual ^{137}Cs exposure or dose (as the Navy doses), the values of a_1, a_2, a_3 and a_4 are all equal to unity. At this point, each element is calibrated to measure the exposure, R, given by:

$$R_{ij} = L_{ij}/a_i \quad (5)$$

or using Equation 4:

$$R_{ij} = (ecc_{ij}q_{ij})/(RCF_i a_i) \quad (6)$$

To extend this capability to enable dose measurements from various types of radiation fields and energies, there is a need for the dose algorithm that is described below.

DOSEMETER DESIGN

A special form of LiF:Mg,Cu,P TL chip was introduced by Thermo Electron Corporation (Harshaw) in the form of pressed pellets (3.6 mm in diameter and thickness of 0.4 mm). Similar to LiF:Mg,Ti, this material is available with different thermal neutron sensitivities depending on the concentrations of ^{6}Li, i.e. 7.5, 95.6 and 0.07% corresponding to TLD-100H, 600H and 700H, respectively.

The dosemeter is composed of two parts: a TLD card and a holder. The TLD card consists of four LiF:Mg,Cu,P pellets (TL elements), each of them mounted between two FEP coated films on an aluminum substrate. The holder covers each TL element with its own unique filter, providing different radiation absorption thickness to allow estimation of the various dose components including the shallow, deep and eye dose. When all the TL elements are TLD-700H, the dosemeter is capable of measuring only photon–beta fields. Replacing Element 4 with TLD-600H enables albedo neutron dosimetry as well. There are four filters in the holder of this dosemeter (the Harshaw type 8840): (1) a combination of 255 mg cm^{-2} plastic and 91 mg cm^{-2} Copper; (2) 882 mg cm^{-2} Teflon and 124 mg cm^{-2} plastic; (3) a Mylar window (17 mg cm^{-2}) and (4) a combination of 185 mg cm^{-2} plastic and 1112 mg cm^{-2} Sn. The shallow dose estimation is based on the response of Element 3. The deep dose estimation is based on the response of Element 2. Element 1, shielded by a copper filter, acts as a crude energy spectrometer for low and medium energy photons, taking advantage of the photon attenuation characteristics of the copper. Similarly, when neutrons are absent, Element 4 provides better medium energy photon discrimination.

THE DOSE CALCULATION ALGORITHM

Effective dose algorithms for personnel dosimetry require only limited prior knowledge of the composition of the radiation field(13). In those algorithms, the response of the dosemeter is used to determine the type of radiation field and to apply the appropriate calibration factor to convert the indicated value to the value of the measured quantity (i.e. the dose equivalent). A neural-network(14) dose algorithm was developed for a LiF:Mg,Ti based dosemeter(15), and a similar algorithm was developed for this LiF:Mg,Cu,P multi-element dosemeter(10). In the application of neural networks to personnel dosimetry, the inputs of the training pairs are the TL signals from the various elements, L1, L2, L3 and L4, and the outputs are the deep dose equivalent, shallow dose equivalent and eye dose (eye dose is not used by the Navy algorithm). Elements 1,2 and 3 (L1, L2 and L3) use TLD-700H and the forth element (L4) is a TLD-600H chip. The input/output training sets are generated by exposing dosemeters to a variety of mixed photon–beta fields. The training set consists of a variety of energies as well as mixture types. Increasing the variability of the type of exposures in the training set improves the learning process and usually results in a 'smarter' network, leading to a better and more accurate dose algorithm. During the training process, the TL signals as measured by the TLD reader are provided to the input layer, and the desired outputs (the delivered dose levels) are provided to the output layer of the network. For a four-element dosemeter, the amount of information available as input to the network is very limited. It consists of four indicated values L1, L2, L3 and L4, that form three independent ratios. This small amount of input information limits the capability of the dose algorithm both in terms of accuracy as well as the variability of dose calculation problems that it can handle. To overcome this difficulty, the concept of functional links(16) has been adopted to create a functional link network (FLN) and apply it to the development of a TLD dose algorithm. The functional link concept enables the increase of the dimensionality of the input space (the number of nodes in the input layer). This results in a simple network without hidden layers. The main difference between typical neural network architecture and FLN architecture is that in a typical network the input units transmit the input data without change. The FLN on the other hand applies a transformation (one or more functions) to the input data before distributing them to succeeding layers. The functional link essentially produces multiple data elements from each single input element, where the input elements are used as the arguments of one or more functions. The input to the network used in the commercial (Thermo Electron) algorithm consists of the following element ratios: X1 = L1/L4; X2 = L3/L2; X3 = L3/L1 (For the Navy algorithm, the ratios used are slightly different, X1 = L3/L2, X2 = L3/L1 AND X3 = L2/L4.) The neutron dose is determined by subtracting L1 from L4 and multiplying the result by conversion factors that account for the variation in TLD response as a function of neutron energy. Each of these ratios is passed through four functional links. In addition, there is a 'true' node which is always 'on' and the weight leading from this node provides a constant bias term. The functions used in this network are: $f_i = [\log(x)]_i$, $i = 1 \ldots 4$. The weights associated with the various links are $\{W_{ij}\}$, $i = 1, \ldots 4$ and $j = 1, \ldots 3$. The calibration value used to calculate the dose is given by the following function:

$$a = \sum_{i=1}^{4}\sum_{j=1}^{3} W_{ij} f_i(X_j) + C \tag{7}$$

The network can be typically trained with ~200 dosemeters exposed to a variety of radiation types and compositions. The weighting coefficients are calculated by minimizing the difference between the desired output and the actual output of the network. Equation 7 is linear, i.e. it can be expressed as a linear combination of the logarithmic functions and their powers. This linearity makes it possible to use a variety of multiple regression techniques(17).

OVERALL UNCERTAINTY

The quality assurance procedures associated with this system are described in detail in Ref.(18). But even with the best quality assurance program, there are still several unavoidable uncertainties. In this section we present the sources of these uncertainties and their estimated values. The factors that may affect the overall uncertainty include environmental factors, such as temperature and humidity, fading, residual signals, light sensitivity, contamination, uncertainty in the RCF or in the ECCs and the accuracy of the traceability of the system to a primary standard. A study to determine the overall uncertainty of dose the measurements using this system was recently conducted by the US Navy(19). The results show that the following factors contribute to the overall uncertainty: fading (2.0%), residual signal (0.3%), light sensitivity (2.5%), reader calibration (5.0%), ECC (7.1%) and source traceability (5.0%). By combining all these factors (square root of the sum of squares), a conservative estimate of the overall uncertainty of 10.5% was obtained. This analysis shows that based on the factors considered to contribute to the measurement uncertainty, the propagation of the worse case scenarios results in an overall uncertainty of 10.5%. This does not mean that the measurements are only accurate to within 10.5%, but that a measurement could be off by as much as 10.5% if all the factors that could contribute to the error under normal circumstances, happened to contribute at the same time in the same direction. In practice, the uncertainty is usually much smaller. Typically the actual variation of readings of a set of dosimeters that were exposed to the same dose is only 1–2%.

DISCLAIMER

The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government.

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