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PERSONNEL DOSIMETRY USING LiF:Mg,Cu,P

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Abstract — Significant advances have been made in recent years in the development of new and improved thermoluminescent (TL) materials for applications in personnel and environmental dosimetry. One of the most promising new TL materials is LiF:Mg,Cu,P. This paper provides an up-to-date review of the main dosimetric properties of LiF:Mg,Cu,P, emphasising recent improvements in the preparation of this material. An attempt is made to focus on the TL characteristics that are particularly useful for personnel monitoring, although most are relevant to environmental dosimetry as well. Advantages of LiF:Mg,Cu,P include high sensitivity as compared to LiF:Mg,Ti, almost flat photon energy response, low fading rate and linear dose response. The lack of supralinearity at higher dose levels is particularly useful for accident dosimetry, and eliminates the source of error usually associated with the application of supralinearity corrections. The main drawbacks are still the relatively high residual signal and the loss of sensitivity for high readout temperatures. This does not limit the usefulness of LiF:Mg,Cu,P for low dose levels typical to personnel or environmental dosimetry, but may be a limiting factor for high dose applications such as clinical dosimetry.

INTRODUCTION

The idea of developing a high sensitivity thermoluminescence (TL) material by doping LiF crystals with Mg, Cu and P impurities, was first proposed by Nakajima *et al* in 1978[1]. The sensitivity of this new TL material was more than 20 times higher as compared to LiF:Mg,Ti (TLD–100), but it was reported to lose 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 [in short LiF(MCP)] 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 (less than 5% following eight uses). LiF(MCP) is now available commercially in several forms, for example, GR–200 (Beijing Radiation Detector Works, People's Republic of China), MCP-N (Henry Niewodniczanski Institute of Nuclear Physics, Poland) and the recently developed new Harshaw TLD materials, TLD-100H, 600H and 700H (Bicron/NE, USA). The TL characteristics of LiF(MCP) 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. As a result, this material has attracted the attention of both basic scientists who study the physical mechanism involved in the TL process, and dosimetry practitioners who use it in various radiation monitoring applications. This article presents an up-to-date review of the main dosimetric properties of LiF(MCP), emphasising recent improvements in the preparation of this material. An attempt is made to focus on the TL characteristics that are particularly useful for personnel monitoring, although most are relevant to environmental dosimetry as well. The full potential of this new material still needs to be explored, and based on current knowledge, the better applications of LiF(MCP) to radiation dosimetry are yet to come.

GLOW CURVE

The glow curve of LiF(MCP) consists of several overlapping glow peaks. The main peak at approximately 220°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 approximately 70–160°C (Peaks 1, 2 and 3), and a high temperature peak at approximately 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 thermoluminescence mechanism in LiF(MCP) is currently not well understood, and the reason for the choice of this specific set of impurities (Mg, Cu, P) is not clear. Optical absorption measurements of irradiated LiF(MCP) suggest that absorption in the range of 300–400 nm is associated to Mg-related defects, and these defects are responsible for the TL emission at approximately 200°C (Peak 4)[6]. Recently, Bilski *et al*[7] conducted a systematic study to determine the influence of the different impurities and their concentrations on the dosimetric characteristics of LiF(MCP). They made several observations that may shed some light on the effect of the different impurities on the TL properties of this material. These include: (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 (0.15 mol%); and (4) the optimum concentration of dopants is in the following range: Mg $\approx$ 0.2 mol%, P = 1.0 − 3.0 mol%, and Cu = 0.02 − 0.05 mol%. Although the work by Bilski *et al* is a big step in the right direction, further studies are certainly needed to understand, and perhaps even control the dosimetric properties of this important material.

GENERAL DOSIMETRIC CHARACTERISTICS

The dosimetric characteristics of LiF(MCP) are discussed in detail in Reference 4. In this section a brief summary is provided of the main TL properties that are important to personnel monitoring. The high sensitivity, combined with its tissue equivalence, is the main advantage of this material in personnel dosimetry applications. The sensitivity of LiF(MCP) is approximately 25 times higher as compared to LiF:Mg,Ti (TLD-100). It is important to note, however, that the measured sensitivity depends not only on the TL properties of the material itself, but also on the spectral response of the light detection system. Both LiF(MCP) and LiF:Mg,Ti have the same effective atomic number (8.2), and could therefore be expected to have a similar photon energy response. In reality, however, the photon energy dependence of LiF(MCP) is considerably different as compared to LiF:Mg,Ti. For example, if the photon energy response is expressed in terms of TL signal per unit of exposure as a function of energy, the over-response of LiF:Mg,Ti at 30 keV is approximately 35% (relative to 662 keV) as compared to only 6% for LiF(MCP)[8]. This discrepancy can be explained as a microdosimetric ionisation density effect[9]. The decreased TL efficiency of LiF:Mg,Cu,P at the lower photon energies is a result of local saturation (decrease) of the TL efficiency in microscopic volumes along the tracks of the secondary electrons. This local microdosimetric saturation, in turn, is a result of the lack of supralinearity and early saturation in the dose response curve of LiF(MCP). The dose response curve of LiF(MCP) is linear–sub-linear rather than linear–supralinear–sub-linear. The lack of supralinearity is a particular advantage in accident personnel dosimetry where the dose levels can exceed 1 Gy, reaching the supralinear region of LiF;Mg,Ti. The linearity range extends from 1 μGy up to 10 Gy where sub-linearity starts.

The sensitivity and glow curve shape are both dependent on the maximum readout temperature, 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 temperature annealing of 400°C (as used in LiF:Mg,Ti) results in irreversible elimination of the main dosimetric peak and causes some increase in the high temperature peaks of LiF(MCP). This permanent loss of sensitivity resulted in the recommendation, which has been widely accepted, of a pre-irradiation anneal of this material at 240°C for 10 min (standard annealing) and to limit the readout temperature to a maximum in the range 240°C to 260°C. The maximum readout temperature of 240°C, coupled with the presence of TL glow peaks at temperatures higher than 260°C, has the potential of creating a residual TL problem. Single readout at temperatures below 260°C is not capable of removing the residual signal following high dose levels, and multiple readout cycles or 'clearings' are required (for more information, see last section). This is still the main drawback of LiF(MCP), although it does not limit the usefulness of this material for low dose levels typical of personnel or environmental dosimetry, but may be a limiting factor for higher dose applications such as accident or clinical dosimetry.

A PERSONNEL DOSIMETRY SYSTEM BASED ON LiF:Mg,Cu,P

A new type of high sensitivity LiF(MCP) TL chip was recently introduced by Bicron/NE (Harshaw)[8,10] 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. For use in personnel dosimetry, the TLD pellets are encapsulated in thin FEP coated film and mounted in a standard Harshaw aluminium substrate to form a TLD card. As described in the previous section, the TL response of this material is extremely sensitive to the readout temperature. Good control of the temperature during the processing of LiF(MCP) is therefore critical to successful practical application in personnel dosimetry. A reader capable of precise control of the heating regime is an essential component of any LiF(MCP) 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[11]. The TLD badge design and the associated calibration and dose algorithm are also presented here.

The reader incorporates a linear time–temperature controlled hot gas heating technique. There are currently several commercially available TLD readers that are based on this heating technique, including the Harshaw Models 8800, 6600, 5500 and 4500 readers. This heating method has been in routine use for more than 10 years using LiF:Mg,Ti based dosemeters. It combines some of the advantages of other commonly used heating techniques, such as contact ohmic heating, constant temperature hot gas, and optical heating. The traditional advantage of ohmic heating is its direct and programmable temperature control, that enables reproducible

and flexible control over heating times, rates and temperatures in all portions of the readout cycle. There is some high temperature infrared signal, but it is predictable and can be easily subtracted. Ohmic heating is also capable of handling large mass dosemeters, enabling good low dose performance. However, the contact of the hot finger used to heat the dosemeter limits its useful life. The hot finger pressure must be checked and adjusted periodically to ensure proper thermal contact in order to eliminate incomplete readout if the pressure is too low or damage to the dosemeter if it is too high. In the optical heating method, the readout cycle is fast, however there are dosemetric limitations. The TL elements must be thin and small, resulting in reduced sensitivity. Furthermore, the control of the temperature is difficult, and linear heating is not practical. A third technique, constant temperature hot gas, combines some advantages of the above heating methods; however, the temperature increase as a function of time is not linear. This results in uncontrolled and unpredictable glow curve shape. It is believed that controlled temperature hot gas heating is the preferred method for use with LiF(MCP) since it combines all the advantages of the above systems. 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 air for heating the TL elements. The gas enters the system through one, two or four (depending on the specific system design) flow controls and flow meters to ensure proper flow and pressure. Solenoid valves are incorporated to eliminate gas flow to those TL elements which are not to be read. 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 to 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(MCP) to dosimetry. The TL emitted light is measured using several photomultiplier tubes (PMT) that are thermoelectrically cooled to 12°C. The PMT signal is accumulated via the charge integration technique.

The TLD system consists of a reader and a set of multi-element dosemeters. The dosemeter is composed of two parts: a TLD card and a holder. The TLD card consists of four LiF(MCP) pellets (TL elements), each of them mounted between two FEP coated films on an aluminium 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 one of the elements with TLD-600H enables albedo neutron dosimetry as well. There are four filters in the holder of this dosemeter (the Harshaw type 8825): (1) a combination of 242 mg.cm^{-2} plastic and 91 mg.cm^{-2} Copper; (2) 1000 mg.cm^{-2} plastic; (3) an open window (17 mg.cm^{-2}); and (4) a combination of 242 mg.cm^{-2} plastic and 240 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 energy photons, taking advantage of the photon attenuation characteristics of the copper. Similarly, element 4 provides medium energy photon discrimination.

Next, the methodology for calibrating this system, which in principle is similar to the calibration used for LiF:Mg,Ti personnel dosimetry systems[12], is described. 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 for element position i, RCF_i, is defined as follows:

$$RCF_i = \langle Q \rangle_i / L \quad (1)$$

where $\langle Q \rangle_i$ 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. The numerical value of the RCF is mainly dependent on the condition of the reader.

Factors which could affect the value of the RCF include: the cleanliness of the optical components, the stability of the high voltage applied to the photomultiplier tube, and geometrical effects such as the position of the dosemeter in the readout chamber. It is desirable therefore to perform reader calibration on a regular basis. It is convenient to perform this calibration using a local source, not necessarily calibrated in terms of absolute quantity (i.e. dose or exposure) but consistently delivering the same amount of radiation every time it is used. In this case, L can be expressed in terms of irradiation time, for example, the amount of radiation delivered during a period of one second by a given source with specific geometry to a dosemeter located at a set distance from the source. This source is called the local or reference source.

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 . . .4) in calibration card j is defined as:

$$ECC_{ij} = \langle Q \rangle_i / Q_{ij} \quad (2)$$

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

$$ecc_{ij} = \langle Q \rangle_i / q_{ij} \quad (3)$$

where q_{ij} is the measured charge of element i in field card j. When element correction coefficients 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 reader calibration factor (RCF) and element correction coefficient (ECC or ecc). L_{ij} is the indicated value of Chip i (i=1 . . .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 . . .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 Chips 1, 2, 3 and 4, respectively.

The last step of the system calibration consists of establishing the link 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. 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 dose algorithms. Effective dose algorithms for personnel dosimetry require only limited prior knowledge of the composition of the radiation field. 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 dose algorithm was recently developed for a LiF:Mg,Ti based dosemeter[13], and a similar dose calculation algorithm is envisioned for this LiF(MCP) multi-element dosemeter (still under development). The following briefly describe the basic ideas behind this algorithm.

In short, neural networks[14] are a family of computational methods inspired by the functionality of living neurons, that are fundamentally different from conventional computing algorithms. Conventional algorithms follow exactly a pre-determined pattern of instructions. This means that for the same input the result of a conventional algorithm will always be the same. A neural network, on the other hand, has the capability to learn from its own experience. The neural network is shown many times what the solutions to a certain problem should be (for different conditions), and the network essentially produces its own solution for similar (but not exactly the same) conditions. The basic component of a neural network is a node, and the network typically consists of an input layer of nodes, an output layer and possibly one or more hidden layers in between. The network can be fully or partially connected, where each link between the nodes carries a specific weight. The total input to each node is the sum of all the individual inputs coming from other nodes, and it responds by sending an output signal related to the input. This output is multiplied by a weighting factor and then transmitted to the nodes in the next layer. The input is propagated this way through the network and produces a set of numbers representing the solution at the output layer. The actual intelligence of the network lies in the value of the weighting factors. These factors are determined by training the network using a variety of input/output data pairs. The weights are being continuously updated by a learning algorithm until the network learns to associate between the input and the appropriate output. The learning algorithm is based on least squares to minimise the network error defined as the difference between the actual output and the desired output.

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, shallow and eye dose. 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[15] 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 choice of the exact functional form and the number of functions is difficult and there is no systematic method that can be used to make this decision. Different problems require different network architecture and the preferred approach is the one that actually works. For a LiF:Mg,Ti based four-element dosemeter, the functional link method described below was found to produce excellent results in terms of accuracy and precision. The input to the network consists of the following element ratios: X_1 = L1/L4; X_2 = L3/L2; X_3 = L3/L1. 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, . . .4. The weights associated with the various links are $\{W_{ij}\}$, i=1, . . .4 and j=1, . . .3. The calibration value used to calculate the dose is given by the following function:

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

The network can be typically trained with approximately 200 dosemeters exposed to a variety of radiation types and compositions. The weighting coefficients are calculated by minimising 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[16].

RECENT TEST RESULTS

This section discusses the results of some recent tests, designed to determine the usefulness of the system described above for practical personnel dosimetry.

The manufacturer recommended heating profile for these cards include a pre-readout low temperature reader anneal ('pre-heat') of 10 s at 165°C, followed by a linear increase in the temperature at a rate of 15°C.s^{-1} up to 260°C. The temperature is held constant at this value (260°C) for an additional 7 s to ensure a complete glow curve reading. A post-readout reader anneal for 10 s at 260°C completes the read cycle. The effect of the 'pre-heat' cycle is to eliminate the low temperature peaks as shown in Figure 1[8]. Repeatability studies of these TLD cards by applying this heating profile in a hot gas TLD reader (the Harshaw Model 8800) show loss of sensitivity of approximately 10% following 1000 uses. This figure, of 0.01% sensitivity loss per use, is comparable to the sensitivity loss of LiF:Mg,Ti (TLD-100, 600, 700)

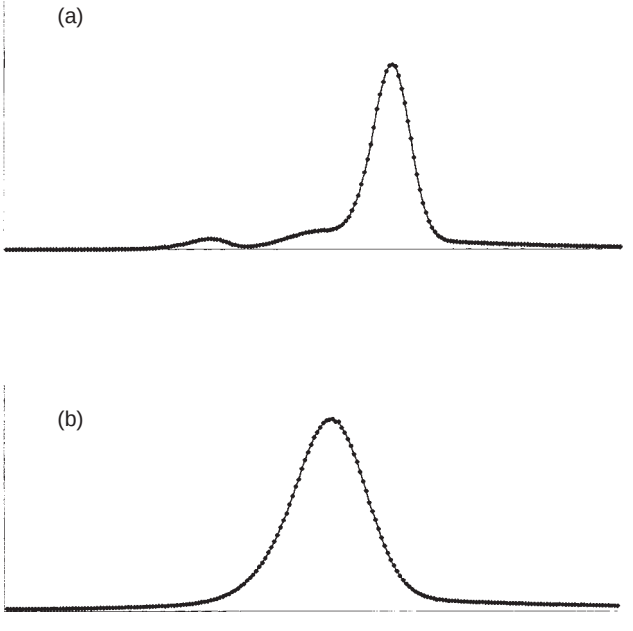

Figure 1. (a) Glow curve of LiF:Mg,Cu,P (TLD-700H) using linear hot gas heating at a heating rate of 15°C.s^{-1} up to a maximum temperature of 260°C. (b) The low temperature peaks are eliminated by applying a pre-readout low temperature reader anneal ('pre-heat') of 10 s at 165°C[8]. (Different temperature scales are used in (a) and (b).)

using the same hot gas readout technique[11]. In addition to the sensitivity, the glow curve shape is another important parameter that needs to be considered when testing the repeatability of TLD materials. Shift in the peak position, or increase in the width of the glow curve, may indicate some change in the property of the TL material, or inefficient heat transfer due to damaged encapsulation. Visual inspection of the glow curves produced during these repeatability studies clearly shows consistent glow curve shape with no visible changes, even following more than 1000 read cycles (Figure 2)[10].

The sensitivity of this new material is approximately 25 times higher than the sensitivity of TLD-100, with a batch homogeneity of 8% (one standard deviation). Once encapsulated in a TLD card however, the relative sensitivity drops to 10. The reason for this sensitivity decrease is that the heating applied to the chip during manufacturing (the encapsulation process) increases the temperature to 280–290°C for short periods of time. This results in permanent loss of sensitivity of the phosphor. The other important dosimetric characteristics of this new preparation of LiF(MCP) are similar to those discussed in previous sections.

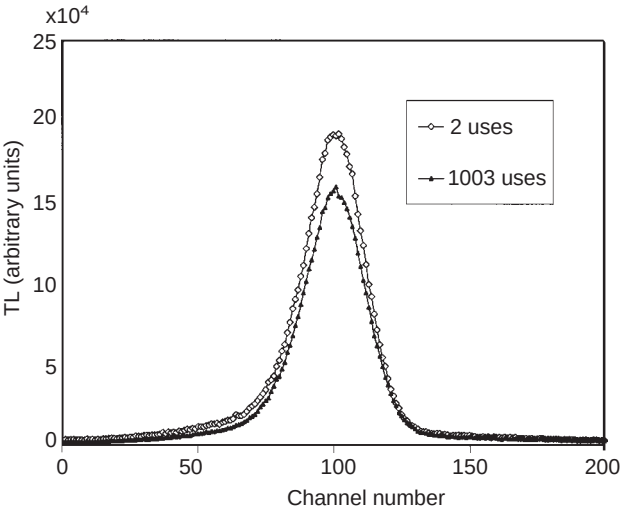

Figure 2. Glow curves of LiF:Mg,Cu,P (TLD-600H) following 2 and 1003 read cycles using linear hot gas heating[10].

Further tests were conducted, with some modifications, at the US Naval Dosimetry Center[17] to determine compliance with the international standard IEC 1066. Here is a summary of the results with a brief statement for each test criteria:

(1) *Batch homogeneity*: The maximum difference in sensitivity between any two dosemeters in a batch should be less than 30%. The result for this test was 5%, indicating compliance with a large margin.
(2) *Repeatability*: The coefficient of variation CV (associated to the relative standard deviation) for repeated evaluation of a dosemeter or of a group of dosemeters, should be less than 7.5%. Results of this test show compliance with the standard, with CV values in the range of 2–4%.
(3) *Linearity*: Deviations from linearity should be less than 10% over the range of 0.5 mSv to 1 Sv. In all cases, deviation from linearity was shown to be less than 5%.
(4) *Detection threshold*: The detection threshold is approximately twice the standard deviation of the results of repeated evaluations of an unexposed dosemeter. The standard requires that the detection threshold should not exceed 100 μSv. Test results revealed a detection threshold of only 5 μSv, again exceeding the requirement of the standard by a large margin. This low detection threshold of LiF(MCP) is further demonstrated in Figure 3[17], which shows

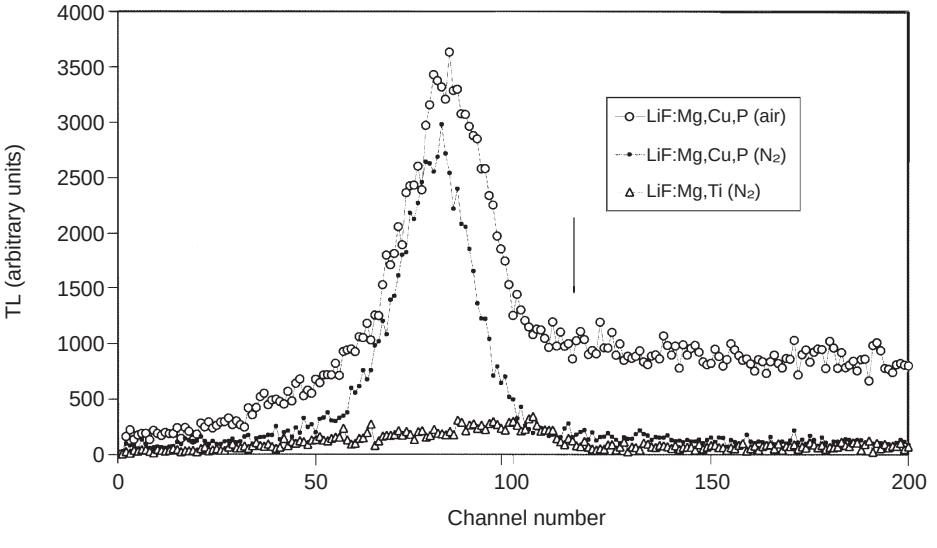

Figure 3. Glow curves of LiF:Mg,Cu,P (TLD-700H) and LiF:Mg,Ti (TLD-700) following a dose level of 10 μSv, including TLD-700H read using hot air heating, TLD-700H read using hot nitrogen heating, and TLD-700 read using hot nitrogen heating[17].

a 10 μSv glow curve of this material. Glow curves are shown for air and nitrogen heating, and compared to a glow curve of LiF:Mg,Ti read using hot nitrogen. It is clear that even at this low dose level, the TL signal of LiF(MCP) is easily distinguished from the noise even when air is used for heating (although the background is higher for air).

(5) *Self irradiation*: The standard requires that the self irradiation following a storage period of 30 days should be less than 100 μSv. The test shows no measurable self irradiation, indicating that the self irradiation is below the detection threshold of 5 μSv.

(6) *Residual signal*: Following delivered dose of 0.1 Sv, the detection threshold should not exceed 100 μSv and the response should not change by more than 10% following irradiation at a dose level of 2 mSv. To be able to pass this test, the dosemeters had to be reader annealed (subjected to a readout cycle) eight additional times following the initial read cycle (see Figure 4[17] that shows the residual signal in TLD-700H as a function of the number of read cycles ('clearings') following various dose levels). With these additional 'clearings', the dosemeters were able to read 2 mSv to within 2.8%.

(7) *Light sensitivity*: This test has two parts. (i) Light induced signal: following light exposure of 1000 $W.m^{-2}$ for a period of 24 h, the 'zero point' response of the dosemeter should not change by more than 100 μSv. The test result showed light sensitivity of only 20 μSv. LiF:Mg,Ti encapsulated in PTFE and exposed to light under the same conditions did not pass this test, with light sensitivity equivalent to 300 μSv. Since the phosphor itself is not sensitive to light, the reported light sensitivity of LiF:Mg,Ti is most likely the result of the sensitivity of the PTFE encapsulation. (ii) Light induced fading: after light exposure for one week, the response of irradiated dosemeters shall not change by more than 10% as compared to storage in the dark. The bare LiF(MCP) cards did not pass this test due to possible light induced fading effects. Therefore, care must be exercised when using this material for personnel dosimetry, by avoiding light exposure of TLD cards outside their holders.

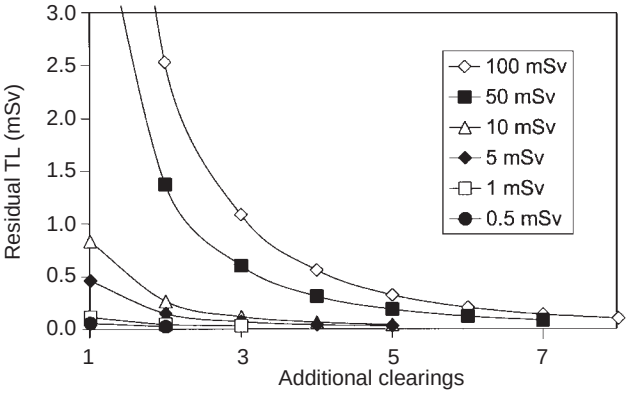

Figure 4. Residual signal in LiF:Mg,Cu,P (TLD-700H) as a function of the number of read cycles ('clearings') following various dose levels including: 0.5, 1, 5, 10, 50, and 100 mSv[17].

Although not yet widely used for personnel dosimetry, these test results clearly demonstrate the potential of LiF(MCP) to replace LiF:Mg,Ti in large scale personnel dosimetry programmes.

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REFERENCES

1. Nakajima, T., Maruyama, Y., Matsuzawa, T. and Koyano, A. *Development of a New Highly Sensitive LiF Thermoluminescence Dosimeter and its Applications*. Nucl. Instrum. Methods **157**, 155–162 (1978).
2. Wu, D. K., Sun, F. Y. and Dai, H. C. *A High-sensitivity LiF Thermoluminescent Dosimeter — LiF(Mg,Cu,P)*. Health Phys. **46**, 1063–1067 (1984).
3. Dewerd, L. A., Cameron, J. R., Wu, D. K. and Das, I. J. *Characteristics of a New Dosemeter Material: LiF(Mg,Cu,P)*. Radiat. Prot. Dosim. **6**, 350–352 (1984).
4. McKeever, S. W. S., Moscovitch, M. and Townsend, P. D. *Thermoluminescence Dosimetry Materials: Properties and Uses* (Ashford, UK: Nuclear Technology Publishing) (1995).
5. Chen, T. C. and Stoebe, T. G. *Influence of Annealing on Kinetic Trapping Parameters in LiF:Mg,Cu,P Thermoluminescent Phosphors*. Radiat. Meas. (in press).
6. McKeever, J., Macintyre, D., Taylor, S. R., McKeever, S. W. S., Horowitz, A. and Horowitz, Y. S. *Diffuse-reflectance and Transmission Measurements on LiF:Mg,Cu,P Powders and Single-crystals*. Radiat. Prot. Dosim. **47**, 123–127 (1993).
7. Bilski, P., Budzanowski, M. and Olko, P. *Dependence of LiF:Mg,Cu,P (MCP-N) Glow Curve Structure on Dopant Composition and Thermal Treatment*. Radiat. Prot. Dosim. **69**, 187–198 (1997).

8. Bicron-NE. *LiF:MCP Product Specification*. Publication No DOSM-H-D-0298-001 (1998).
9. Olko, P., Bilski, P. and Michalik, V. M. *Microdosimetric Analysis of the Response of LiF Thermoluminescent Detectors for Radiations of Different Qualities*. Radiat. Prot. Dosim. **52**, 405–408 (1994).
10. Bicron/NE. *High Sensitivity TL Chips (LiF:Mg, Cu,P) — Formal Test Program and Results*. Publication No DOSM-C-V-0797-001 (1997).
11. Moscovitch, M., Szalanczy, A., Bruml, W., Velbeck K. J. and Tawil R. A. *A TLD System based on Gas Heating with Linear Time–Temperature Profile*. Radiat. Prot. Dosim. **34**, 361–364 (1990).
12. Moscovitch, M. *Dose Calculation Algorithms in Personnel Dosimetry*. Radiat. Prot. Dosim. **47**, 373–380 (1993).
13. Moscovitch, M. and Rotunda, J. E. *Multi-element Dosimetry System using Neural Network*. US Patent No 5,572,028 (1996).
14. Clark, J. W. *Neural Network Modelling*. Phys. Med. Biol. **36**, 1259–1317 (1991).
15. Freeman, J. A. *Simulating Neural Networks with Mathematica* (Addison-Wesley) (1994).
16. Neter, J., Wasserman, W. and Kutner, M. H. *Applied Linear Statistical Models*, 2nd edn (Homewood, Illinois: Irwin) (1985).
17. Cassata, J. R. *Type Testing and Characterization of Harshaw Copper Doped Material*. In: Harshaw/NE TLD User Symposium, San Diego, CA, 23–27 March 1998.