Radiation Protection Dosimetry Advance Access published May 17, 2007

Radiation Protection Dosimetry (2007), pp. 1–7 doi:10.1093/rpd/ncm239

TYPE TESTING OF A NEW TLD FOR THE UK HEALTH PROTECTION AGENCY

P. J. Gilvin*, S. T. Baker, T. J. Daniels, J. D. Eakins, D. R. McClure, D. T. Bartlett and C. Boucher
Radiation Protection Division, Health Protection Agency, Chilton, Didcot, OXON OX11 0RQ, UK

Received November 24 2006, revised April 4 2007, accepted April 6 2007

The UK Health Protection Agency is currently commissioning a new personal dosimetry system based on the use of Harshaw™ two-element thermoluminescent dosemeter cards using LiF:Mg,Cu,P. Results of extensive type testing carried out with reference to IEC 61066, "Thermoluminescence Dosimetry Systems for Personal and Environmental Monitoring", have been presented.

INTRODUCTION

In the early 1970s, the then-fledgling UK National Radiological Protection Board undertook a project[1,2] to develop a national dosimetry system that used thermoluminescent dosemeters (TLDs) and was linked to automatic dose record keeping. The dosemeter design[3] featured two discs of polytetrafluoroethylene (PTFE), which incorporated ^{7}LiF:Mg,Ti of thicknesses 0.4 and 0.2 mm. These were fixed in a punched-hole-encoded anodised aluminium card. The plate was enclosed in a polyethylene wrapper, which was labelled with wearer information, the wrapped card being housed in a polypropylene holder. With the card loaded in the holder, the thin disc was positioned behind an open window and the thick disc behind a 720 mg cm^{-2} thickness of polypropylene. Wrapped and labelled cards were sent to customers by post, before being inserted into the holders and distributed to wearers. After use, dosemeters were likewise returned by post. Reading was carried out by contact heating originally in purpose-built readers.

The service rapidly expanded and within a few years was issuing some 350 000 dosemeters per year to a variety of employers in the United Kingdom and abroad. Later developments saw the adoption of a thinner aluminised plastic wrapping material, adaptation of the holder[4] to allow assessment of the newly introduced ICRU personal dose equivalent quantities[5] $H_p(10)$ and $H_p(0.07)$, and an improvement to the annealing regime[6]. Meanwhile, the original readers had been replaced by commercially available hot-contact devices supplied by Vinten Instruments.

During the 1990s, a number of developments occurred in the field of thermoluminescence dosimetry and related methods. Some of these related to business changes, for example, in successive acquisitions of the former Vinten company; some were in the use of alternative TL materials, particularly in LiF:Mg,Cu,P[7–9] and others concerned the development of wholly new methods[10,11]. Meanwhile, there was an increasing interest in the assessment of doses in the 10–100 μSv range. Although the NRPB TLD system continued to work well, and to be successful in intercomparisons[12], it became apparent that, for various reasons including the age of the equipment and the concomitant reliability, the system would have to change. In 2000, NRPB embarked on a project to identify, acquire and commission a new dosimetry system. From April 2005, the functions of the former NRPB were transferred to the Radiation Protection Division of the UK Health Protection Agency (HPA RPD). HPA RPD elected to continue with the project.

Among the attributes required for the new system were:

- a high level of reliability, including maintenance aspects;
- making best use of HPA/NRPB experience and resources;
- making the new system easy for customers to adapt to;
- maintaining the approach of a comprehensive, full-range dosemeter, able to be used in all radiation environments;
- measurement of low doses.

After consideration, a system was selected with the following features:

- Harshaw™ cards and automated '8800' readers, from the Thermo Electron Corporation, USA.
- High-sensitivity ^{7}LiF:Mg,Cu,P material.
- A two-element card, retaining the original NRPB wrapping material and the style (though not the detailed design) of the holder.

*Corresponding author: E-mail: phil.gilvin@hpa-rp.org.uk

The LiF:Mg,Cu,P material was chosen because, although it is subject to a relatively large residual signal, it has the advantage of high sensitivity[7,13].

DOSEMETER DESIGN

The new HPA TLD, therefore, comprises three components: the TLD card, the wrapping material and the holder.

The TLD card is of standard Harshaw™ design[14], with a 0.36-mm thick pellet of ^{7}LiF:Mg,Cu,P in card position ‘2’ and a similar 0.25-mm thick pellet in card position ‘3’. The thick element is used to assess $H_p(10)$, and the thin element $H_p(0.07)$.

The wrapper is a triple laminate, with one layer of polyethylene (50-μm thickness) plus two layers of aluminised polyester (each 12-μm thickness). The total area density is 8.0 mg cm^{-2}.

The holder is of polypropylene, with a rectangular open window to display the printed wearer information. The thin dosemeter element is positioned behind a circular open window of diameter 11 mm, whereas the thick element is positioned behind a filter. The filter comprises a PTFE cylinder of diameter 18 mm and thickness 4.3 mm, surrounded by 2 mm of polypropylene on all sides: the total diameter is therefore 22 mm and the total thickness is 6.3 mm, with a mass thickness of 1130 mg cm^{-2}. This design was produced on the basis, supported by measurements, of calculations carried out by the External Ionising Radiation Dosimetry Group at HPA RPD[15].

Figures 1 and 2 show HPA TLD holder and the Harshaw TLD card. The holder is coloured purple to distinguish it from its predecessors and from other HPA/NRPB types of dosemeter.

TYPE TESTING: DOSIMETRIC TESTS

Type testing of the new HPA dosemeter has been carried out using the standard IEC 61066[16], *Thermoluminescence Dosimetry Systems for Personal and Environmental Monitoring*, as a basis. Irradiations were performed by the Radiation Metrology Group of HPA RPD in accordance with ISO 4037[17]. Tests were selected or adapted as appropriate.

Certain aspects of system performance have already been tested[18,19]. These aspects were:

- time effects (ageing and fading);
- decision threshold[20], including its behaviour with time;
- residual signal;
- the effects of typical laboratory lighting on (unwrapped) TLD cards.

See Refs. (18) and (19) for full details. In summary, this work showed that:

- ageing and fading are negligible for this type of card, in normal laboratory conditions, over 6 months;
- likewise in laboratory conditions, the decision limit remains below 10 μSv for up to 3 months;
- the residual signal on a second read was no more than 1.5% of the primary signal;
- the cards are not sensitive to laboratory lighting.

The type tests remaining to be performed therefore included: dose range; energy and angle dependence of response, for photons and beta radiations; reproducibility; environmental effects and the response to neutron irradiation. Throughout the tests reported subsequently, the manufacturer’s recommended heating cycle was used, as follows: preheat, 165°C for 20 s; acquire, heating rate 15°C s^{-1} up to 260°C, duration 13.33 s; anneal, 260°C for 10 s.

Figure 1. New HPA TLD.

Figure 2. Components of new HPA TLD, including Harshaw™ two-element TLD card using ^{7}LiF:Mg,Cu,P.

Dose range

Lower limits

A sample of 20 calibrated TLD cards were annealed and immediately read out. Applying a Student's-*t* factor of 1.73 appropriate to the 95% confidence level, the decision thresholds[20], L_c, for the dosemeter were found to be 1.6 μSv for $H_p(10)$ and 3.0 μSv for $H_p(0.07)$.

This result is consistent with that obtained in earlier work[18], which also studied the effect upon L_c of extended wearing. Owing to the additional uncertainty arising from increasing natural background dose, the decision threshold was found to approach 40 μSv after 6 months' storage in a typical office environment at HPA's premises in Chilton, Oxfordshire (an area where natural background is somewhat lower than the UK average).

The detection limit[20], L_D, depends upon the behaviour not only of dosemeters that have not been exposed, but also of those that have. The parameter takes into account the inevitable dose received from natural background radiation in a typical wearing period, and seeks to address the question, "what is the smallest dose I can reliably detect?"

A typical relative standard deviation for a group of 20 dosemeters, for doses of 0.1 mSv or greater, is 1.6%. Assuming a relatively low mean monthly dose of 30 μSv from natural background (cosmic ray and terrestrial gamma), then the detection limits—again at the 95% confidence level—are 3.3 μSv for $H_p(10)$ and 6.1 μSv for $H_p(0.07)$.

Note that this quantity does not indicate the magnitude of the measurement uncertainty at low doses: it merely states the value of applied dose that is 95% likely to result in a signal in excess of L_c, the decision limit.

Upper limit

Groups of six TLD cards were given doses between 1 mSv and 1 Sv using the $^{90}Sr/^{90}Y$ sources built into the Harshaw 8800 readers, with doses traceable to the HPA secondary standards laboratory using the dosemeters as transfer devices. Within experimental uncertainty, relative response remained at unity over the whole dose range (see Figure 3).

In further tests in the dose range 1–5 Sv, the reader photomultiplier tubes began to show saturation effects. By plotting calibration curves for the $H_p(10)$ and $H_p(0.07)$ responses, it is possible to arrive at an acceptably accurate (within 10%) measure of $H_p(10)$. Further work will extend the tested range to 10 Sv and will examine the use of neutral-density filters for the assessment of very high doses.

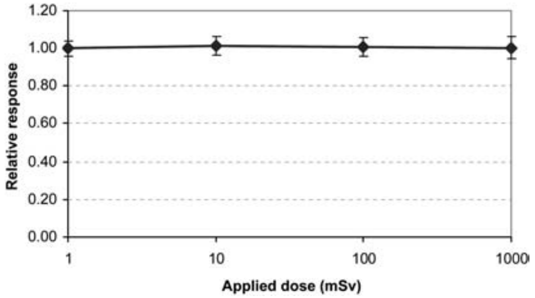

Figure 3. Dose linearity of the HPA TLD, from 1 mSv to 1 Sv.

Energy and angle dependence of response

Energy dependence—photons

Irradiations for the dosimetric type tests were carried out in the secondary standards laboratory of HPA's Radiation Metrology Group, with additional high-energy exposures carried out by PTB, Germany. Groups of six dosemeters were mounted centrally on the front of an ISO water-filled polymethyl-methacrylate (PMMA) slab phantom, 300 × 300 × 150 mm. The radiation qualities were selected from ISO standard 4037-3[17]: X-ray qualities were taken from the ISO narrow series, and the radionuclide sources were ^{137}Cs and ^{60}Co. The high-energy qualities were R-C (mean energy 4.36 MeV) and R-F (mean energy 6.61 MeV). Figure 4 shows the energy dependence of response for normal incidence, normalised to that for ^{137}Cs. The relative response lies within ±25% at all energies, and within ±20% over most of the range. [Note that the conversion coefficients for $H_p(0.07)$ are not available for the two high-energy points.]

Angle dependence—photons

The two lowest photon energies used were selected for testing angle dependence of response: N-20

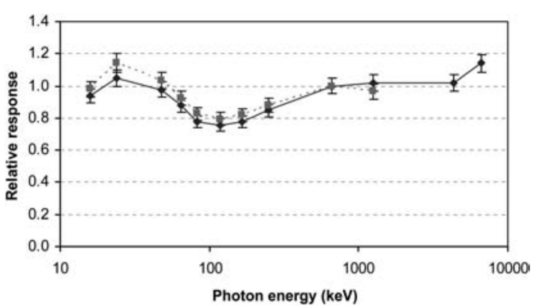

Figure 4. Photon energy dependence of response: $H_p(10)$ (solid line) and $H_p(0.07)$ (broken line).

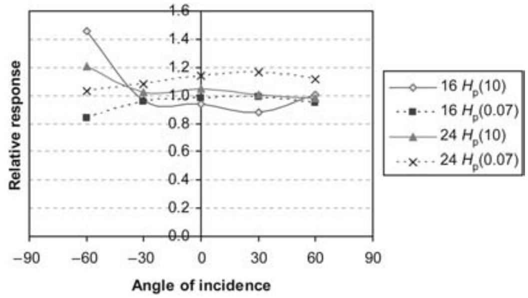

Figure 5. Photon angle dependence of response.

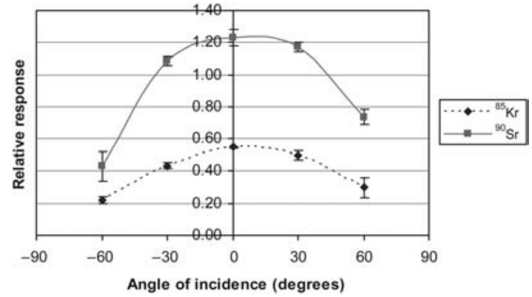

Figure 6. $H_p(0.07)$ beta response of the HPA TLD, normalised to the corresponding response to ^{137}Cs.

(mean energy 16.3 keV) and N-30 (mean energy 24 keV). Dosemeters were irradiated at $\pm 30^\circ$ and $\pm 60^\circ$. Results, normalised to ^{137}Cs at normal incidence, are shown in Figure 5. The lines are shown as a guide; the solid lines refer to $H_p(10)$ responses and the broken lines refer to $H_p(0.07)$; the figures '16' and '24' in the legend refer to the mean energies. Error bars are omitted to retain visibility.

The poorest response occurs for $H_p(10)$ at 16.3 keV and -60°, where there is an overestimate of nearly 50%; otherwise the responses all lie within $\pm 20\%$. The asymmetry in $H_p(10)$ response is considered to be due to differences in backscatter caused by the physical asymmetry of the dosemeter: the backscatter contribution for negative angles comes from photons falling directly on the phantom, to the right of the thick filter as viewed from the front; while the (smaller) backscatter contribution for positive angles comes from photons which have been attenuated by passage through the dosemeter card and holder, to the left of the thick filter as viewed from the front.

Energy and angle dependence—betas

Irradiations were carried out using an Isotrak™ BSS2 secondary standard unit, with beta sources and matched beam-flattening filters traceable to PTB, Germany. The sources chosen were ^{90}Sr/^{90}Y and ^{85}Kr, applied over an angle range from -60° to $+60^\circ$. At the applied dose levels of ~2 mSv, no significant $H_p(10)$ response was found. Figure 6 shows the results for $H_p(0.07)$, normalised to the corresponding response for ^{137}Cs.

The response is adequate for ^{90}Sr/^{90}Y over the angle range -30° to $+60^\circ$ (the negative angles correspond to the wearer's left, for a dosemeter worn on the front of the trunk). At greater angles of incidence, and at the lower energy of ^{85}Kr, the relative response lies outside $\pm 25\%$. For ^{85}Kr ($E_{max} =$ 687 keV), the response at 0° shows an underestimate of $<50\%$.

Eye dosimetry

It is possible, by combining information from the assessments of $H_p(10)$ and $H_p(0.07)$, to use the present dosemeter to assess the quantity[5] $H_p(3)$ for photons. Although ISO 4037-3[17] does not itself provide conversion coefficients from air kerma to $H_p(3)$ for the ISO water-filled slab phantom used in these tests, it is possible to produce an inferred set of coefficients by reference to other work. Grosswendt[21] has published a set of calculated conversion coefficients for a $300 \times 300 \times 150$ mm PMMA slab, for X-ray photons in the ISO narrow series, for $H_p(0.07)$, $H_p(3)$ and $H_p(10)$. It is probable that the 'ratios' between these conversion coefficients are similar to those that would pertain to the ISO 4037-3 set, if the latter contained data for $H_p(3)$.

This approach then provides the energy dependence of response for each of the two dosemeter elements in terms of $H_p(3)$. Predictably, it is found that below ~25 keV the $H_p(10)$ element yields an increasing under-response in terms of $H_p(3)$, while the $H_p(0.07)$ element yields an increasing over-response.

However, by simply averaging the $H_p(10)$ and $H_p(0.07)$ responses, an acceptable response to $H_p(3)$ is achieved, as shown in Figure 7. By means of this

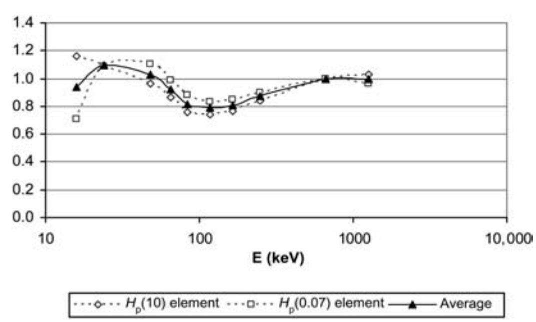

Figure 7. Inferred $H_p(3)$, or eye dose, response of the HPA TLD, for photons, using a simple average of $H_p(0.07)$ and $H_p(10)$.

averaging, the dosemeter is able to measure $H_p(3)$, over the energy range 16.3–1250 keV, to within +10% and −20%.

Dosemeter variability (reproducibility, coefficient of variation, long-term/infrequent)

Coefficient of variation

Twenty TLD cards were subjected to applied doses of 10 mSv using the HPA PDS ^{137}Cs irradiation facility. The mean coefficient of variation for both $H_p(10)$ and $H_p(0.07)$ was 1.6%, with a worst case of 2.6%.

Repeatability

Ten two-element TLD cards were dosed using the TLD reader built-in irradiators, at a level of ~0.5 mSv, and read. The process was then repeated a further nine times. For each of the 20 TLD elements, the mean response was found and, for each of the 10 reads, the modulus of the deviation from the mean was calculated. Over all the 200 results, the mean modulus of deviation was 0.7% and the maximum was 3.4% [see also Ref. (7)].

Residual signal

Five dosemeters were irradiated to dose levels ranging from 100 to 1000 mSv and read out twice. The mean signal on the second read was 1.0% of the first read signal, with no significant difference across the range.

The dosemeter irradiated to 100 mSv required a total of 11 reads to reduce the residual signal to below 25 μSv.

TYPE TESTING: ENVIRONMENTAL EFFECTS

Time effects, ambient

Ageing and fading

The effects of ageing (loss of sensitivity, or 'pre-dose fading') and fading (loss of stored signal, or 'post-dose fading') have been presented in earlier work[18] which compared results for Harshaw™ two-element cards containing LiF:Mg,Cu,P—such as ultimately selected for the HPA service—with those for conventional LiF:Mg,Ti. As expected[7], neither effect was observable, within an uncertainty of 5% at the 95% confidence level, over a period of 6 months.

Elevated temperature and humidity

A dose of 5 mSv was delivered to two groups of eight dosemeters, wrapped and in holders, in the HPA PDS ^{137}Cs calibration facility. One group was next stored in the climatic chamber of the HPA Radiation Metrology Group (model Delta 335, produced by Design Environmental, UK), at 40°C and 90% relative humidity, for 48 h, whereas the other, a control group, was stored in standard laboratory conditions. Both groups were evaluated promptly following exposure.

The mean response $R_{control}$ of the control dosemeters was evaluated and the response ratio $R/R_{control}$ was calculated for each member of the test group. The mean response ratio was 0.99 with a standard error of 9%, with worst-case values of 0.87 (low) and 1.15 (high). The draft standard IEC 61066[16] requires that all values should lie within the range 0.83–1.25; this test is therefore passed.

Light exposure

Laboratory lighting

Studies have been carried out[19] on the effects of standard laboratory and office lighting on bare Harshaw™ TLD cards which use LiF:Mg,Cu,P. No effect was found, even for an 8-h exposure at a distance of 0.6 m from a 58 W fluorescent tube (mean wavelength 366 nm).

Simulated solar exposure

Eighteen dosemeters were given a dose of 5 mSv using the HPA PDS ^{137}Cs irradiation facility. These were divided into three equal groups; all groups were wrapped and one group was loaded into plastic holders. One group was retained under laboratory conditions as a control. The reason for using two test groups, one wrapped and loaded into holders and one wrapped only, was to highlight any effects arising from adventitious heating of the plastic holders. The two test groups of dosemeters were then exposed for 48 h in a SOL 2 solar simulation unit, produced by Dr. Hönle AG of Munich, Germany, and providing a total intensity of 910 W m^{-2}. Full ventilation was used to reduce any heating effect. Following the simulated-sunlight exposure, dosemeters were left for 1 d before processing.

The mean response $R_{control}$ of the control dosemeters was evaluated and the response ratio $R/R_{control}$ was calculated for each member of each of the test groups. Table 1 gives, for each group, the mean relative response, the relative standard error and the worst-case results from individual dosemeters, minimum and maximum. The draft standard IEC 61066[16] requires that all values should lie within the range 0.91–1.11; this test is therefore passed.

Table 1. Results of simulated sunlight exposure, 48 h continuous, 910 W m^{-2}.

Group	Mean relative response	RSE%	Min	Max
Wrapped and loaded in holders	1.01	8.7	0.93	1.10
Wrapped only	0.98	8.5	0.94	1.11

Neutron radiation

A group of six dosemeters were exposed to an Am–Be neutron source fitted with a lead cap to eliminate gamma radiation. The delivered neutron $H_p(10)$ dose was 2.0 mSv. Both the $H_p(10)$ and $H_p(0.07)$ dosemeter elements gave relative responses of ~2%.

Chemical contaminants

Sets of two freshly annealed dosemeter cards were deliberately contaminated with small quantities (~25 mg applied to the sensitive elements) of foreign materials: fine domestic dust, earth and powder detergent. A further set was subjected to a typical cycle in a domestic washing machine. In all cases, the cards were left unwrapped in order to observe worst-case effects.

The worst results resulted from the set contaminated with detergent, where the apparent dose reached 5 mSv. However, in this case, the TL glow curve was of a poor shape and the result was rejected by region-of-interest tests.

In none of the other tests did the apparent dose exceed 0.1 mSv. In particular, exposure to the same detergent in a wash cycle produced a markedly smaller apparent dose than exposure by deliberate contamination.

These tests, on unwrapped cards, emphasise the role of the wrapper in protecting the dosemeter.

CONCLUSION

The new HPA TLD, based on ^{7}LiF:Mg,Cu,P and using Harshaw TLD^{TM} cards and readers, is suitable for a wide range of applications. It exhibits:

- good energy and angle dependence of response for photon and beta radiations;
- a wide dose range;
- negligible neutron sensitivity;
- negligible time-dependence of response;
- negligible sensitivity to heat, humidity and light exposure.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Rolf Behrens of Physikalisch-Technische Bundesanstalt, Germany, for carrying out the high-energy photon irradiations, Mr John Bennett of DSTL Radiation Protection Services, UK, for assistance with the high-dose (>1 Sv) dosimetry and Mrs Marina Khazova, of the Laser and Optical Radiation Dosimetry Group, Radiation Protection Division, HPA, for the use of the solar simulation unit.

REFERENCES

1. National Radiological Protection Board. *A thermoluminescent personal dosemeter compatible with automatic processing and the central recording of dose histories.* NRPB Report NRPB-R16. NRPB, Chilton (1973).
2. National Radiological Protection Board. *The NRPB automated thermoluminescent dosemeter and dose record keeping system.* NRPB Report NRPB-R32. NRPB, Chilton (1974).
3. National Radiological Protection Board. *Technical specification of the NRPB thermoluminescent dosemeter used for the measurement of body dose and skin dose.* NRPB Report NRPB-R64. NRPB, Chilton (1977).
4. Bartlett, D. T., Hessey, J. D., Burgess, P. H., Hill, C. E., McClure, D. R., Steele, J. D. and Watson, P. *A modified design of photon personal dosemeter to measure the ICRU personal monitoring quantity Hp(10).* Radiat. Prot. Dosim. **48**, 209–211 (1993).
5. International Commission on Radiation Units and Measurements. *ICRU report 47: measurement of dose equivalents from external photon and electron radiations.* ICRU, Bethesda, MD, USA (1992).
6. Gilvin, P. J., Steele, J. D., Rose, D. C., Perkins, D. K., Bartlett, D. T., Sandford, D. J., Dutt, J. C. and Hessey, J. D. *Changes in the NRPB body TLD system.* Radiat. Prot. Dosim. **66**, 33–36 (1996).
7. Moscovitch, M. *Personnel dosimetry using LiF:Mg,Cu,P.* Radiat. Prot. Dosim. **85**, 49–56 (1999).
8. Cassata, J. R., Moscovitch, M., Rotunda, J. E. and Velbeck, K. J. *A new paradigm in personal dosimetry using LiF:Mg,Cu,P.* Radiat. Prot. Dosim. **101**, 27–42 (2002).
9. Fantuzzi, E., Monteventi, F., Sermenghi, I. and Uleri, G. *Characterisation of a personal TL photon dosemeter based on two LiF(Mg,Cu,P) detectors in terms of Hp(0.07, α) and Hp(10, α).* Radiat. Prot. Dosim. **85**, 179–182 (1999).
10. Ortega, X., Ginjaume, M., Hernández, A., Villanueva, I. and Amor, I. *The outlook for the application of electronic dosemeters as legal dosimetry.* Radiat. Prot. Dosim. **96**, 87–91 (2001).
11. Akselrod, M. S. and McKeever, S. W. S. *A radiation dosimetry method using pulsed optically stimulated luminescence.* Radiat. Prot. Dosim. **81**, 167–176 (1999).
12. Gilvin, P. J., Dunderdale, J. and Perkins, D. K. *Results for NRPB dosimetry services in the 2000 EURADOS trial performance test.* Radiat. Prot. Dosim. **101**, 243–248 (2002).
13. Nakajima, T., Murayama, Y. and Matsuzawa, T. *Preparation and dosimetric properties of a highly*

sensitive LiF thermoluminescent dosemeter. Health Phys. **36**, 79–82 (1979).

14. See Thermo Electron Corporation web site, http://www.thermo.com/.
15. Eakins, J., Bartlett, D. T., Hager, L., Molinos-Solsona, C. and Tanner, R. *The MCNP-4C2 Design of a Two Element Photon/Electron Dosemeter that uses Magnesium/Copper/Phosphorus Doped Lithium Fluoride*. Radiat. Prot. Dosim.
16. International Electrotechnical Commission. *Thermoluminescence dosimetry systems for personal and environmental monitoring*. IEC 61066 (2006).
17. International Organization for Standardization. ISO 4037-3:1999. *X and gamma reference radiation for calibrating dosemeters and doserate meters and determining their response as a function of photon energy, part 3*. ISO (1999).
18. Gilvin, P. J. *Comparison of time effects, decision limit and residual signal in Harshaw LiF:Mg,Ti and LiF:Mg,Cu,P.* Radiat. Prot. Dosim. doi:10.1093/rpd/ncl118.
19. Baker, S. T. and Gilvin, P. J. *Comparison of the effects of exposure to light in Harshaw LiF:Mg, Ti and LiF:Mg, Cu, P.* Radiat. Prot. Dosim. doi:10.1093/rpd/ncl119.
20. International Organization for Standardization. ISO 11929-7:2005 *Determination of the detection limit and decision threshold for ionizing radiation measurements - part 7: fundamentals and general applications.* ISO (2005).
21. Grosswendt, B. *Coefficients for the conversion of air collision kerma to dose equivalent for the calibration of individual dosemeters in X-ray fields.* Radiat. Prot. Dosim. **40**, 169–184 (1992).