Radiation Protection Dosimetry
Vol. 101, Nos. 1–4, pp. 211–216 (2002)
Nuclear Technology Publishing

EVALUATING TWO EXTREMITY DOSEMETERS BASED ON LiF:Mg,Ti or LiF:Mg,Cu,P

L. Z. Luo, K. J. Velbeck and J. E. Rotunda
Saint-Gobain Crystals and Detector
6801 Cochran Road
Solon, OH 44139, USA

Abstract — Evaluation of a new extremity dosemeter is presented. The dosemeter is a passive device that is easy to wear and features a permanent individual numerical ID with barcode, a watertight case, an automatic TLD reader and database management software. Two dosemeters were studied; the first consists of a 100 $mg.cm^{-2}$ ^{7}LiF:Mg,Ti (TLD-700) chip and a 42 $mg.cm^{-2}$ cap, the other consists of a 7 $mg.cm^{-2}$ layer of ^{7}LiF:Mg,Cu,P (TLD-700H) powder and a 5 $mg.cm^{-2}$ cap. Sensitivity, repeatability, lower limit detection, angular responses and energy responses for these dosemeters are studied and presented. The dose calculation algorithm is developed and its dosimetric performance accuracy is compared with the standard ANSI N13.32–1995, Performance Testing of Extremity Dosemeters.

INTRODUCTION

Extremity dosimetry has evolved to the state where rugged, individually barcoded dosemeters with self-contained human and machine-readable identification can be manufactured. The associated TLD readers can read the barcodes in process and relate the reported dose to the dosemeter ID and the wearer of the ring, providing a continuous chain of custody. The Saint-Gobain Harshaw TLD DXTRAD system is an example of this technology. The dosemeters are sealed in a finger-ring-shaped container that is watertight, cold and hot sterilizeable to 140ºC, and opaque to light. With the introduction of LiF:Mg,Cu,P and the improvements in reader performance in recent years, a thin-layer, high-sensitivity, non-fading dosemeter can be produced.

The dosemeters and system will be described. Testing results based on the ANSI N13.32–1995 'Performance Testing of Extremity Dosemeters'(1) and ISO 12794:2000–02–15 standard 'Individual Thermoluminescence Dosemeters for Extremities and Eyes'(2) are reported.

DOSEMETER DESCRIPTION

The TLD materials for the extremity rings are manufactured at Saint-Gobain Crystals and Detectors (SGCD) and are available in pressed pellet and powder forms. The solid material in this study is a 3.0 mm diameter by 0.38 mm pressed pellet(3) made of TLD-700 (^{7}LiF:Mg,Ti). The powder material is a monolayer of 50–90 micron grains of TLD-700H (^{7}LiF:Mg,Cu,P). The manufacturing techniques used to produce these materials have been refined to the point that very consistent performance is obtained from batch to batch. In addition, the residual signal has been reduced and the re-use performance improved in the TLD-700H material. The TLD material is supported by Kapton film and is surrounded by a metal ringlet with integral identification in the form of human readable numerals and a barcode.

The standard ring cap used with the TLD-700 material is a single injection moulded piece with its entrance window having a thickness density of 42 $mg.cm^{-2}$. The beta window version, used with the TLD-700H, has a thin aluminium layer sputtered onto Polysulfone film to seal out moisture and to shield the TLD area from UV light. The ring cap assembly is made by injection moulding around the thin window. The resulting thickness density of the entrance window is 5 $mg.cm^{-2}$. The ringlets containing the TLD material are guaranteed for 50 re-uses. The ring cap and finger ring container are disposable after one use.

EQUIPMENT AND PROCEDURES

The TLDs were read on a Harshaw Model 8800PC Automatic TLD reader(4). This reader features non-contact hot nitrogen gas heating with a programmable, linearly ramped time temperature profile. Glow curves were recorded using a maximum temperature of 300ºC for the TLD-700 and 255ºC for the TLD-700H. Both dosemeters use a heating rate of 15ºC.s^{-1}. All measurements were carried out in subdued (low UV intensity) lighting.

The Harshaw TLD-700 and TLD-700H dosemeters were tested using the ANSI N13.32–1995, 'Performance Testing of Extremity Dosemeters'(2) and ISO 12794:2000–02–15 'Individual Thermoluminescence Dosemeters for Extremities and Eyes'(3) standards.

For the energy response test and the angular dependence tests, the dosemeters were assembled in their ring format and irradiated using a 19 mm diameter PMMA finger phantom. Irradiations were performed at Battelle Pacific Northwest Laboratories. Other tests were perfor-

Contact author E-mail: Ling.Z.Luo@Saint-gobain.com

med using the irradiator installed in the reader, which is a ^{90}Sr source, referenced to ^{137}Cs.

ISO STANDARDS TESTING

The tests described in this section were conducted in accordance with ISO standard 'Individual Thermoluminescence Dosemeters for Extremities and Eyes'. Element Correction Coefficients (ECCs) were applied to all dosemeters to normalise sensitivity. The following is a short description of each test, including procedures and results.

Batch homogeneity

Ten dosemeters were prepared, irradiated to 15 mSv ^{137}Cs equivalent and read. The test was repeated a total of 10 times. The criteria require that the maximum coefficient of variation shall not exceed 15% at the 99.5% confidence interval, $(s_{Ei}+I_i)/\bar{E}i) \leq 15\%$, where s_{Ei} is the standard deviation of ten dosemeters at the i^{th} read, $\bar{E}i$ is the mean of the evaluated value and Ii is the half-width of the confidence interval. The results show 5% for the TLD-700H dosemeter and 2% for the TLD-700 dosemeter. Both are under the required limit of 15%.

Reproducibility

Ten dosemeters were dosed to 15 mSv ^{137}Cs equivalent and read and the cycle repeated a total of 10 times. The criteria require that the coefficient of variation of the evaluated value shall not exceed 10% for each dosemeter separately. This is expressed as $(s_{Ej}+Is_j)/\bar{E}_j \leq 10\%$, where s_{Ej} is the standard deviation, $\bar{E}_j$ is the mean of the evaluated value, and Is_j is the half-width of the confidence interval. The maximum coefficient of variation at the 99.5% confidence interval was 3% for the TLD-700H dosemeter and 1% for the TLD-700 dosemeter. Both are under the required limit of 10%.

Detection threshold

Ten dosemeters were cleared by reading three times, recording the value of the last reading. The criteria require that the detection threshold shall not exceed 1.0 mSv. The detection threshold is defined as $\bar{E}$+Ii $\leq$1.0 mSv, where $\bar{E}$ is the mean of the evaluated value and Ii is the half-width of the confidence interval. The results show a detection threshold of 0.04 mSv for the TLD-700H dosemeter and 0.01 mSv for the TLD-700 dosemeter. Both are under the required limit of 1.0 mSv.

Self-irradiation

The criteria require that after a storage period of 60 days, the zero point shall not exceed a value of 2 mSv. The equation used is $(\bar{E}+Ii)-C_B \leq 2$ mSv where $\bar{E}$ is the mean of the evaluated value, C_B is the background radiation during storage, and Ii is the half-width of the confidence interval. Ten dosemeters were stored in a lead house for 30 days. The results show a self-irradiation of 0.1 mSv for both the TLD-700H and the TLD-700 dosemeters. If the value of these readings is doubled to reflect 60 days, the resulting values still fall well under the 2 mSv limit. Note that 30 days were used instead of 60 because of time constraints.

Residual signal

Part 1

A group of ten dosemeters was exposed to 100 mSv (10 rem). The Detection threshold test was then repeated. The criteria require that the detection threshold shall not exceed 2.0 mSv. The results show a detection threshold of 0.11 mSv for the TLD-700H dosemeter and 0.03 mSv for the TLD-700 dosemeter. Both dosemeters clearly passed the test.

Part 2

The response shall not change by more than 10% at a dose level of about 2 mSv. The criteria used is $0.90 \leq (\bar{E} \pm I_i) / C \leq 1.10$. The results show a low of 1.01 and a high of 1.04 for TLD-700H and a low of 0.93 and a high of 0.94 for TLD-700. Both are within the limits of 0.90 and 1.10. The graph in Figure 1 shows a typical residual signal relative response for up to 10 reads after the original irradiation. LiF:Mg,Cu,P typically shows a higher residual than LiF:Mg,Ti.

ADDITIONAL TESTING

Photon energy response

Both dosemeter types were irradiated in finger ring holders at Battelle Pacific Northwest Laboratories on a 19 mm diameter PMMA finger phantom to obtain a photon energy response. See Figure 2.

The radiation techniques used were M30, M60,

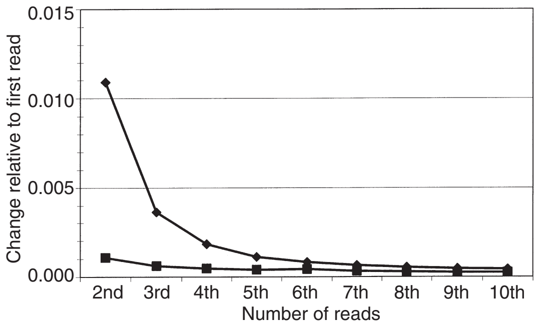

Figure 1. Relative response of re-reads. Original dose = 100 mSv ^{137}Cs equivalent. ◆, LiF:Mg,Cu,P; ■, Lif:Mg,Ti.

M100, M150, H150 moderately and heavily filtered X rays, and ^{137}Cs, and ^{60}Co radioactive sources. Both dosemeter types show good flatness over the energy range with TLD-700H having only a 20% over-response at most due to the near tissue equivalence of the TLD material.

Beta energy response

Both dosemeter types were irradiated in finger ring holders at Battelle Pacific Northwest Laboratories on a 19 mm diameter PMMA finger phantom to obtain a depleted beta energy response. See Table 1. The radiation techniques used were ^{147}Pm, ^{204}Tl, ^{90}Sr/^{90}Y, and uranium slab. The thin window dosemeter responded down to the 230 keV energy level at ^{147}Pm.

Angular response

Both vertical and horizontal response tests were performed for the following angles: 0°, 30°, 60° and 85°, with 180° added for the vertical test. In the vertical test, the dosemeter ring is mounted on a vertical finger phantom. The radiation source is in the plane of the ring, with 0 ° being perpendicular to the TL element. The phantom is rotated about its own axis from 0° to 180°. In the horizontal test, the dosemeter ring is mounted on a horizontal finger phantom with the TL element to the side. The radiation source is in the plane of the finger, with 0 ° being perpendicular to the TL element. The phantom is rotated about a vertical axis through the ring from 0° to 85°.

Photon irradiations using M30 and M150 moderately filtered X rays, a ^{137}Cs radioactive source and beta irradiations using ^{204}Tl and ^{90}Sr/^{90}Y were performed for each angle. The results are shown in Tables 2 and 3. Both dosemeters respond well to high-energy photons at all angles. The response to low-energy photons and betas falls off at higher angles due to the attenuation caused by the holder and ultimately due to the density of the finger phantom.

Reuse

Both dosemeter types were read about 350 times with periodic irradiations of about 10 mSv once every 10 reads. Data from the readings just after each irradiation were compiled. The graph in Figure 3 shows the percentage change in signal over the 350 re-uses. For both dosemeter types, the decrease in sensitivity was about 10% over the 350 re-uses. Any change due to the reader was subtracted out. (This would be due mainly to dust accumulation on the optics during the lengthy test.)

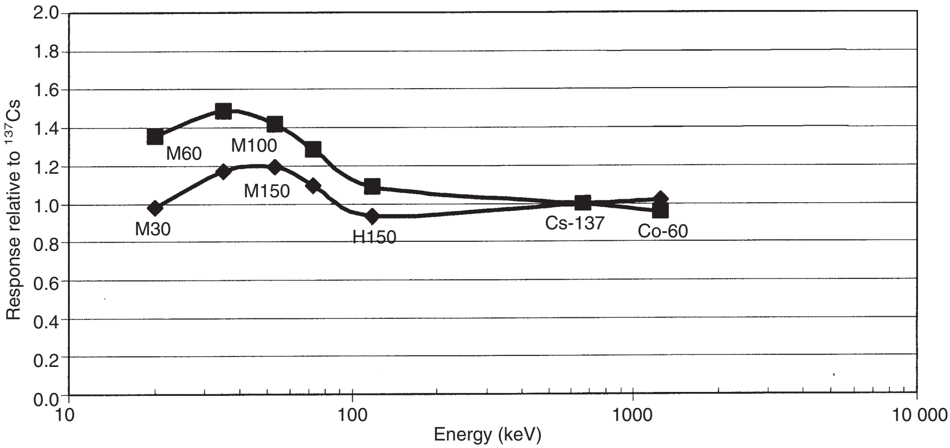

Figure 2. Photon energy dependence. ◆ — LiF:Mg,Cu,P; ■ — LiF:Mg,Ti.

Table 1. Beta energy response.

Beta source	Energy	Response relative to ^{137}Cs TLD-700H	Response relative to ^{137}Cs TLD-700
^{90}Sr/^{90}Y	2.27 MeV max.	1.3	1.0
Uranium slab	2.27 MeV max.	0.8	0.6
^{204}Tl	760 keV max.	0.7	0.2
^{147}Pm	230 keV max.	0.3	–

Light exposure (effect on response)

A group of 15 dosemeters was dosed to 6.6 mSv. Ten dosemeters (group 1) were placed under a fluorescent light and the remaining five dosemeters (group 2) were placed in a dry, dark room for seven days. The performance is tested by taking the ratio of the two groups ($\bar{E}_{group1}/\bar{E}_{group2}$) ± I, where $\bar{E}$ is the mean of the evaluated value and I is the half-width of the confidence interval. The results show a low of 0.93 and a high of 0.96 for TLD-700H and a low of 0.88 and a high of 0.93 for TLD-700. A fluorescent lamp containing two 15 watt bulbs was used at a distance of 4 cm, giving a measured light of 5.3 × 10^4 lx (5000 foot-candles).

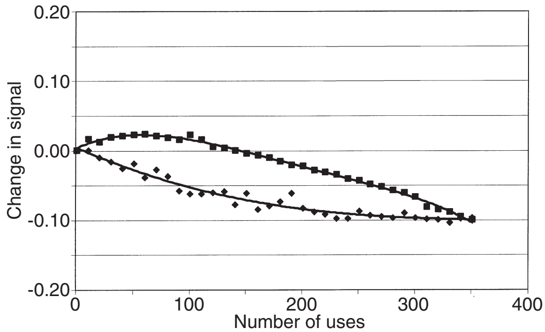

Figure 3. Re-use. ◆ — LiF:Mg,Ti; ■ — LiF:Mg,Cu,P.

Humidity test

A group of 15 dosemeters was dosed to 6.6 mSv. Ten dosemeters (group 1) were placed in a humid environment, (22ºC, 95% relative humidity), and the remaining five dosemeters (group 2) were placed in a dry, dark room for seven days. Values of ($\bar{E}_{group1}/\bar{E}_{group2}$) ± I were computed, where $\bar{E}$ is the mean of the evaluated value and I is the half-width of the confidence interval. The results show a low of 1.0 and a high of 1.05 for TLD-700H, and a low of 0.95 and a high of 1.01 for TLD-700. Both are within ±5%.

Table 2. Angular dependence of LiF:Mg,Cu,P.

Angle (degrees)	Response normalised to 0°				
	^{137}Cs 662 keV average	M150 70 keV average	M30 20 keV average	^{90}Sr 2.27 MeV max.	^{204}Tl 230 keV max.
Vertical 0°	1.00	1.00	1.00	1.00	1.00
Vertical 30°	1.00	1.01	0.94	0.89	0.79
Vertical 60°	0.97	0.99	0.66	0.44	0.30
Vertical 85°	0.94	0.91	0.26	0.23	0.09
Vertical 180°	0.90	0.70	0.18	0.00	0.01
Horizontal 0°	1.00	1.00	1.00	1.00	1.00
Horizontal 30°	1.00	1.04	0.96	0.81	0.71
Horizontal 60°	0.99	1.00	0.73	0.44	0.32
Horizontal 85°	0.97	0.94	0.24	0.20	0.10

Table 3. Angular dependence of LiF:Mg,Ti.

Angle (degrees)	Response normalised to 0°				
	^{137}Cs 662 keV average	M150 70 keV average	M30 20 keV average	^{90}Sr 2.27 MeV max.	^{204}Tl 230 keV max.
Vertical 0°	1.00	1.00	1.00	1.00	1.00
Vertical 30°	0.99	1.00	0.95	0.85	0.71
Vertical 60°	0.95	0.96	0.81	0.38	0.23
Vertical 85°	0.93	0.83	0.18	0.15	0.04
Vertical 180°	0.82	0.66	0.17	0.00	0.00
Horizontal 0°	1.00	1.00	1.00	1.00	1.00
Horizontal 30°	0.99	1.03	0.97	0.88	0.72
Horizontal 60°	0.98	1.00	0.81	0.42	0.23
Horizontal 85°	0.93	0.82	0.20	0.14	0.04

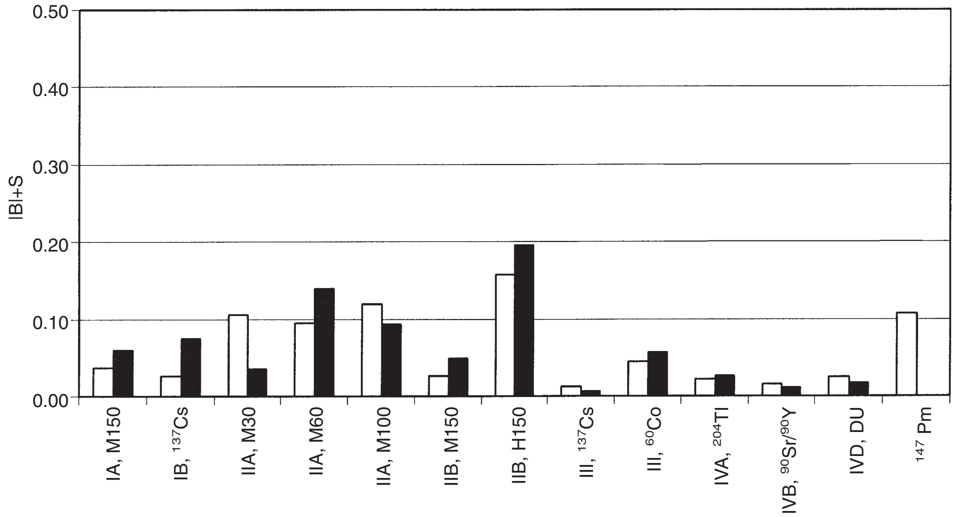

Figure 4. Performance DXT-RAD extremity, |B| + S. □, LiF:Mg,Cu,P; ■, LiF:Mg,Ti.

Table 4. Radiation test categories.

Category	Description	Delivered dose	Tolerance levels B+S	B	S
I. High dose category					
A. Low-energy photons	M150(70 keV avg.)	5 Sv	0.3	none	none
B. High-energy photons	^{137}Cs(662 keV)	5 Sv	0.3	none	none
C. General, low- and high-energy photons	M150(70 keV avg.)	5 Sv	0.3	none	none
II. Low-energy photons					
A. General					
M30	20 keV (avg.)	20 mSv	0.5	0.35	0.35
M60	34 keV (avg.)	20 mSv	0.5	0.35	0.35
M100	51 keV (avg.)	20 mSv	0.5	0.35	0.35
M150	70 keV (avg.)	20 mSv	0.5	0.35	0.35
H150	117 keV (avg.)	20 mSv	0.5	0.35	0.35
B. M100	51 keV (avg.)	20 mSv	0.5	0.35	0.35
M150	70 keV (avg.)	20 mSv	0.5	0.35	0.35
H150	117 keV (avg.)	20 mSv	0.5	0.35	0.35
III. High-energy photons					
^{137}Cs	662 keV	20 mSv	0.5	0.35	0.35
^{60}Co	1.25 Mev	20 mSv	0.5	0.35	0.35
IV. Beta Particles					
A. Low-energy only ^{204}Tl	0.76 MeV (max.)	20 mSv	0.5	0.35	0.35
B. High-energy only ^{90}Sr/^{90}Y	2.3 MeV (max.)	20 mSv	0.5	0.35	0.35
C. General ^{90}Sr/^{90}Y or ^{204}Tl			0.5	none	0.35
D. Slab uranium	2.3 MeV (max.)	20 mSv	0.5	0.35	0.35
Additional (not in standard)					
^{147}Pm	230 keV(max.)	20 mSv	0.5	0.35	0.35

ALGORITHM DEVELOPMENT

The development of the dose algorithm was empirical and based on results from actual readings. The irradiations were performed on radioactive and X ray standard sources at Battelle Pacific Northwest Laboratories. Only single fields were used to characterise the dosemeters for energy response. The outline in Table 4 shows the radiation types and delivered doses referenced to the appropriate ANSI 13.32 standards category. A delivered dose of 5.0 Sv was used for the high dose category and 20 mSv for all other tests. For each field, background controls were subtracted. Fade and supralinearity corrections were applied for TLD-700 dosemeters. Note that for TLD-700H there are no supralinearity corrections required over the range tested. Also, fade is almost negligible (3% in three months using reader preheat). The resultant readings were normalised to ^{137}Cs to produce a correction factor for each radiation type. The concept of superposition was used by combining single field responses between multiple fields. Linear regression was used to determine correction factors for general cases, such as general low-energy photons.

RESULTS (ALGORITHM)

After developing the algorithm, the raw data were re-inserted into the algorithm and the following results obtained. Criteria, including B (bias) and S (standard deviation), based on the ANSI 13.32 standard, are shown in the graph in Figure 4. The resultant bar graph shows that all categories are well within the B+S limits. In addition the separate B and S value limits were met.

CONCLUSION

The pelletised and powder versions of the TLD-700 and TLD-700H materials perform well with respect to the type tests to which they were subjected. They also performed well by staying within the bias and standard deviation limits set in the ANSI N13.32–1995 standard. Both dosemeter types would be suitable candidates for extremity dose-reporting applications, with the thin-window version being more suitable for low-energy, non-penetrating radiation and in general. The residual signal of TLD-700H is still higher than would be desired, but has improved from previous efforts[5] and can be further reduced by successive re-reads. The self-contained dosemeter barcode makes chain of custody tracking possible even when the sensitive element is separated from its ring case. Associated TLD readers can read the ring identification codes automatically. The small, rugged, water-tight, sterilizeable packages make these dosemeters excellent candidates for practical use in the majority of health and medical environments.

REFERENCES

1. American National Standards Institute. *Performance Testing of Extremity Dosemeters*. HPS N13.32–1995
2. International Organization for Standardization. *Nuclear Energy — Radiation Protection — Individual Thermoluminescence Dosemeters for Extremities and Eyes*. ISO 12794 : 2000–02–15
3. Velbeck, K. J., Zhang L., Green R. and Tomlins, P. *Performance and Test Results of Harshaw Pelletised LiF:Mg,Ti TLD Material*. Radiat. Prot. Dosim. **84**, 243–246 (1999).
4. Moscovitch, M., Szalanczy, A., Bruml, W. 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).
5. Yuen, P. S., Freedman, N. O., Frketich, G. and Rotunda, J. *Evaluation of Bicron NE MCP DXT-RAD Passive Extremity Dosemeter*. Radiat. Prot. Dosim. **85**, 187–195 (1999).