Research Article

Performance testing of locally manufactured commercial soda–lime–silicate glass in Saudi Arabia for low-dose radiation in γ-ray field

Fathi Djouider[1]

Received: 8 December 2019 / Accepted: 6 May 2020 / Published online: 15 May 2020

Abstract
In this study, the thermoluminescence dosimetric performances of a locally produced soda–lime–silica glass by the *Saudi Arabian Glass Company* Limited (SAGCO) were examined to evaluate its potential use in low-dose γ-ray field. The samples were homogenously irradiated to different doses using a cesium-137 source. Some important characteristics of these glass dosimeters were investigated: The thermoluminescent glow curve exhibited a main peak at about 200 °C, the dose response curve showed a good linearity in the low-dose range 0–500 mGy, and the lowest detection dose was found to be 0.30 mGy. No substantial change (less than 6%) in the response of the dosimeters was found within incident angles of irradiation between ± 60°. A post-irradiation heating at 160 °C for 15 min before readout was found to be the most appropriate procedure for the elimination of the initial rapid fading.

Keywords Thermoluminescence dosimetry · Window glass dosimeter · Glow curve · Dose response · Post-irradiation fading

1 Introduction

Thermoluminescence (TL) is a one of the most used techniques in radiation dosimetry [1, 2]. Having an amorphous structure, glass material is quite resistant to radiation damage. Nevertheless, ionizing radiation can generate within this structure electron–hole pairs which can be trapped inside the glass matrix and become a defect [3]. When heated, the electron–hole recombines, and light is emitted. The extent of the released light is generally proportional to the radiation dose absorbed by the glass material. In the last few decades, commercial specific type of glasses has been examined either for their intrinsic thermoluminescence [4, 5] or their dosimetric characteristics [6–9]. They showed very promising performances in dosimetry audits because of their handling advantages and low cost [10].

In this study, we aimed to assess the thermoluminescent performances of a commercial window glass material locally produced by the *Saudi Arabian Glass Company Limited* (SAGCO) in Jeddah, Saudi Arabia. We focused particularly in the reproducibility, angular dependence and the post-irradiation stability, with regard to its potential use in routine radiation personal and environmental dosimetry.

2 Materials and methods

2.1 Glass material

The 1-mm-thick glass sheets, produced by the *Saudi Arabian Glass Company*, were manually cut, using a pen cutter, into chips of dimensions 3 mm × 3 mm to fit into the TL reader. The masses, measured with the Mettler Toledo AT

✉ Fathi Djouider, fdjouider@kau.edu.sa | [1]Nuclear Engineering Department, King Abdulaziz University, PO Box 80204, Jeddah 21589, Kingdom of Saudi Arabia.

SN Applied Sciences (2020) 2:1079 | https://doi.org/10.1007/s42452-020-2874-1

201 electronic balance, were in the range 57.3–78.2 mg with a mean mass of 68.0 ± 7.2 mg. This quiet large dispersion of the chips weigh was expected due to unavoidable inaccuracies during the manual cutting of the chips. Prior to irradiation, chips were checked for any physical damage and cleaned with a solvent made of 50% methanol-50% acetone to remove any surface impurities and allowed to dry in air.

The elemental analysis and the surface micromorphology of the powdered glass specimen were probed, at the Nano-Technology Center, King Abdulaziz University (Jeddah, Saudi Arabia), by an energy-dispersive X-ray spectroscopy system (Oxford-Instruments, UK).

2.2 Irradiation facility and procedure

The irradiations of the glass samples were carried out in the Nuclear Engineering Department of King Abdulaziz University using the ^{137}Cs γ-source of 1 Ci activity. A 2×2 cm^2 plastic card, fitted with four small compartments each hosting one glass chip, was taped with transparent electrical tape at the center of a thin polystyrene backing board. This latter was positioned at 30 cm from the γ-source. The absorbed dose rate in air at 30 cm from the source, measured with LiF:Mg, Ti (TLD-100) chip which was used as reference dosimeter in this work, was about 40 mGy h^{-1}. The total dose each glass chip received was determined by the duration of exposure. Irradiations were carried out at 25–30 °C room temperature and 60–70% relative humidity.

2.3 Annealing procedure

To reduce the background radiation, all the glass chips used in this work were subject to an optimum annealing temperature and time of 300 °C for 4 h by placing them in a TLD oven (Thermolyne 10500—Sybron).

2.4 TLD reader

The TL measurements were taken by using the Harshaw 3500 (Thermo Fisher Scientific Inc, USA) thermoluminescence reader. The TL glass was placed on the planchet and heated at a constant rate of 10 °C s^{-1} in the range 80–340 °C, which include the main peak (~ 200 °C) of the glass glow curve and then stabilized at that temperature for few seconds for the readout. The planchet was then allowable to cool down to 40 °C, to start the next TL glass readout. Each measurement was normalized to the mass of the glass chip.

Table 1 Chemical composition of the oxide components present in the glass sample

Element	Oxide compound	Concentration (wt%)
Carbon	$CaCO_3$	5.07
Oxygen	Present in all compounds	56.82
Sodium	Na_2O	9.11
Magnesium	MgO	2.35
Aluminum	Al_2O_3	0.45
Silicon	SiO_2	23.30
Potassium	K_2O	0.48
Calcium	CaO, $CaCO_3$	2.42

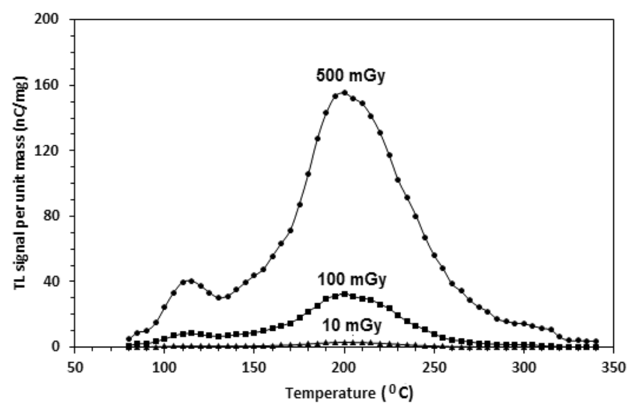


Fig. 1 TL glow curves of the glass chips irradiated at three different doses. The readout was taken 2 h after irradiation

3 Results and discussion

3.1 Characterization of the glass specimen

Energy-dispersive X-ray spectroscopy (EDS) provided the elemental composition of the oxide components present in the soda–lime glass sample used in this work (Table 1). Silicon, sodium and calcium were the major components.

3.2 Radiation-induced glow curve

Ionizing radiation causes defects such as vacancies and interstitials atoms in the glass network and induces free electrons and holes, which are then trapped in these defects [11, 12]. The profile of the radiation-induced glow curves of three glass chips was obtained by exposing them to doses of 10, 100 and 500 mGy, respectively. Figure 1 illustrates the TL glow curves (TL signal normalized to the mass of the chip vs heating temperature) of the three glass samples in the temperature range 80–340 °C. A heating rate of 10 °C s^{-1} was found to produce an optimal glow curve by minimizing the thermal quenching and the shifting of the glowing peaks toward high temperatures [13].

As the heating temperature increases, the 500 mGy glow curve presents two peaks corresponding to different energy electron trap depths. The main glow peak of high-energy trap, at about 200 °C, was used for dosimetric purposes. The small glow peak of low-energy trap is at approximately 110 °C. The specific profile of this glow curve was almost dose-independent in the dose range studied in this work (0–500 mGy). A change in the peak positions and the profile of the glow curve were observed beyond a dose of 500 mGy. Since the position of the main peak in the TL glow curve of the glass is dose-independent within the dose range used here, it is more likely that the thermoluminescence properties of the trapping centers are not altered by the radiation dose. The same behavior has been observed by other workers in different glass materials used as TLD [14, 15].

3.3 Dose response curve

The TL response per unit of mass (nC mg^{-1}) of the glasses exposed to different doses of ^{137}Cs gamma radiation is shown in Fig. 2. A set of four chips was taken for each dose, and the average reading was recorded. These results clearly show a good linearity charge measurement vs absorbed dose (linear regression coefficient was 0.9994) with a sensitivity factor of 0.311 nC mg^{-1} mGy^{-1}. This linearity is a very good indicator of the suitability of the type of glass used in this work for low-dose dosimetry.

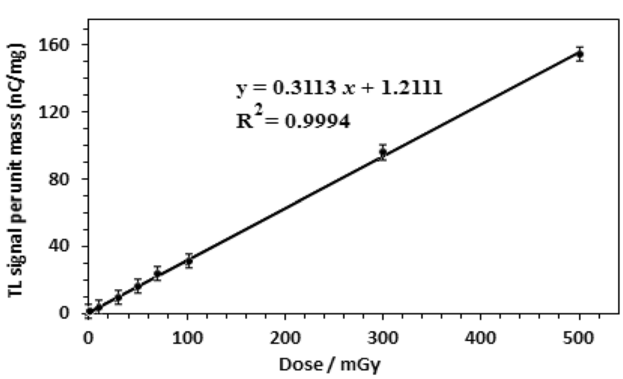


Fig. 2 Dose response curve of the glass chip as functions of γ-ray doses ranging from 1 to 500 mGy. Points are experimental; the line is calculated by least square fitting method. Error bars represent one standard deviation

3.4 Effect of annealing temperature and time

The choice of the optimum annealing temperature and time was dictated by the desire of getting the highest sensitivity of the TL glass. Variation in TL response for different annealing temperatures and times is shown in Fig. 3 where we can see that 300 °C and 4 h and a heating rate of 10 °C s^{-1} are the optimum parameters for annealing before any irradiation.

3.5 Reproducibility of the glass chips TL response

Forty chips detectors were randomly selected from a common batch. They were submitted to the same sequential annealing (300 °C for 4 h)—irradiation—reading cycle for an irradiation dose of 100 mGy. Readout was taken 2 h after the irradiation. This same cycle was repeated ten times. The mean value of the each of the forty glass chips

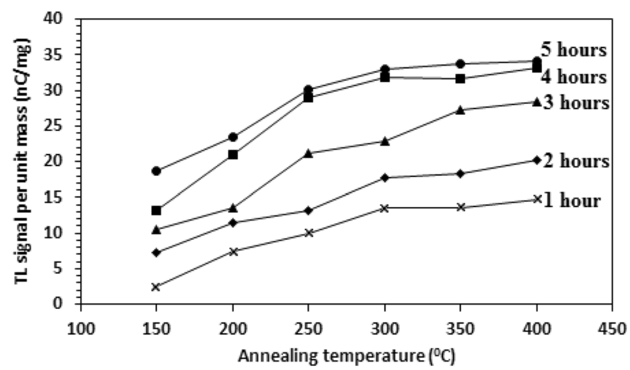


Fig. 3 Effect of the annealing temperature and annealing time on the TL signal

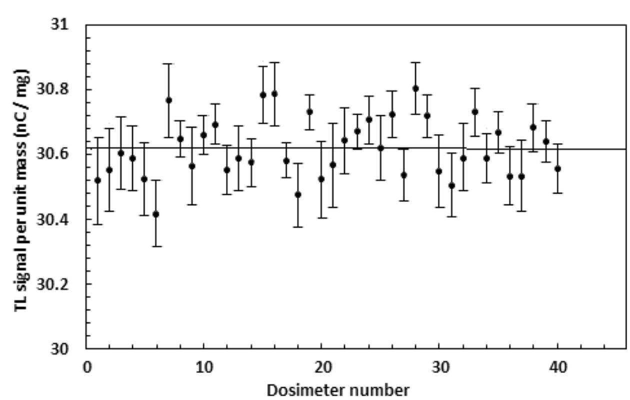


Fig. 4 Reproducibility of the forty glass chips irradiated to 100 mGy. The central line shows the mean value of the reading of all measurements, and the error bars show $\overline{x}+1\text{sd}$ and $\overline{x}-1\text{sd}$. The standard deviation of the mean response values for each glass chips was between 0.057 and 0.134 with an average of 0.089

responses for each cycle was calculated with its standard deviation (Fig. 4). The standard deviation of the mean response values for each glass chips was between 0.057 and 0.134 with an average of 0.089.

3.6 Reproducibility in dose measurements

To assess their dose reproducibility, five batches of glass chip dosimeters each were irradiated to five different test doses (measured with TLD-100) namely 10, 30, 50 70 and 100 mGy, respectively. The results were obtained after eight identical cycles: annealing—irradiation—readout. Figure 5 shows that the standard deviation of the dosimeters laid between 0.38 and 0.98% with an average of 0.61%. Table 2 gives the statistical analysis of the measured dose reproducibility.

The % of variation in the measured mean dose at 95% confidence level lies in the range 0.77–1.47% (with an average of 1.06%). These results show a very good reproducibility of the type of glasses used in this work.

3.7 Coefficients of variation

To assess the reproducibility of replicate measurements of the same TLD, the coefficient of variation $CV_i(\%)$ for the response of the *i*th glass chip dosimeter is used [16]. This coefficient is given by the equation

$$CV_i(\%) = \frac{\sigma}{\bar{M}_i} \times 100 \quad (1)$$

where $\bar{M}_i$ is the average of the ten reading values of the *i*th glass chip dosimeter and σ is the standard deviation of these readings. As it can be seen from Fig. 6, values of CV_i for all the glass chips are below 0.45%.

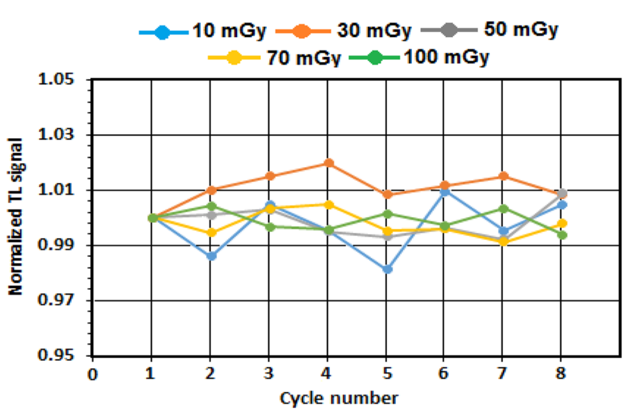


Fig. 5 Reproducibility of five batches of glass chips irradiated to five different doses. The standard deviation of the dosimeters laid between 0.38 and 0.98%

Table 2 Average reading and uncertainty in measurement at 95% confidence level have been calculated for response of the glass detector at different doses of irradiation

Test dose (mGy)	Average dose measured (mGy)	% standard deviation in dose measurement	Dose interval at 95% confidence level (mGy)
10	10.19	0.98	10.07–10.22
30	29.45	0.66	29.31–29.62
50	49.16	0.56	48.97–49.35
70	70.970	0.46	70.2–70.97
100	99.71	0.38	99.03–99.97

3.8 Batch homogeneity: generation of ECC coefficients

To compare the response of each glass dosimeter to the average response of a batch comparable chips, the element correction coefficient (ECC) is introduced. It is the ratio of the thermoluminescent response of a given glass chip to the average TL response of all glass chips when irradiated to the same dose, that is

$$ECC_i = \frac{\overline{TL_{resp}}}{\left(TL_{resp}\right)_i} \quad (2)$$

where $\overline{TL_{resp}}$ is the average of the net readings of all glass chips and $\left(TL_{resp}\right)_i$ is the net reading of the *i*th glass chip. The TL response obtained from a single glass chip is then multiplied by the ECC to determine the corrected response of this glass chip. Forty glass chips of a same batch were irradiated to a dose of 100 mGy, and the ECC of each individual glass chip was computed. The percentage deviation of element correction coefficients was all less than 0.7% (Fig. 7).

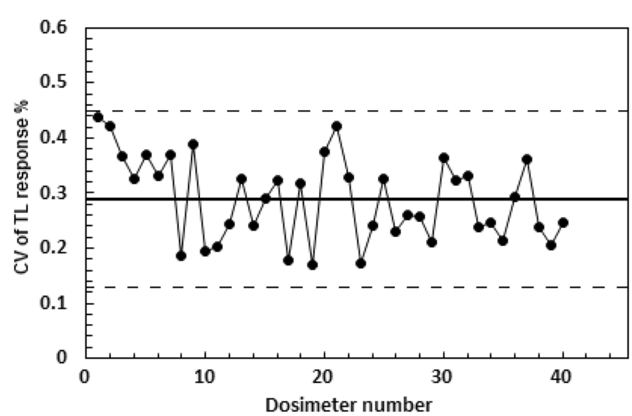


Fig. 6 Coefficient of variation (CV %) for the TL response of each dosimeter

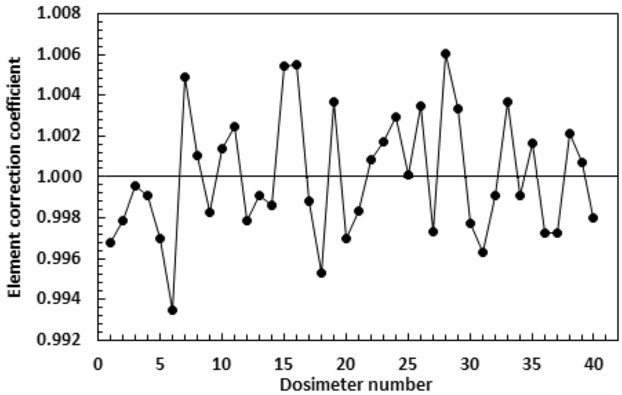


Fig. 7 Reproducibility for five different doses of four samples for ten cycles of annealing—irradiation—readout

3.9 Angular dependence of the glass response

The angular dependence of the glass dosimeter response was examined by positioning the chips at angles between 0° and 90° in steps of 10° increment in both clock- and anticlockwise. Angles were measured sideways from the beam axis. All the glass chips were subject to fixed dose of 30 mGy. The TL signals were normalized to the reading obtained at angle 0°. Figure 8 shows that no substantial change (less than 6%) in the response of the dosimeters was found within incident angles of irradiation between ± 60°.

3.10 Lowest dose detection threshold (LDDT)

The lowest dose detection threshold (LDDT), i.e., the smallest dose that can be distinguished significantly from a zero dose, is obtained from the readout of the signal of an unirradiated glass detector. This threshold is mainly governed by the magnitude of the natural radiation background. Other factors such as the signal produced by the dark current of the photomultiplier tube, the black-body radiation from glass chip and any other non-radiation-induced thermoluminescence can affect it [17]. The LDDT, expressed in unit of absorbed dose, can be taken as three times the standard derivation of the intrinsic background readings [18] and calculated using the following equation:

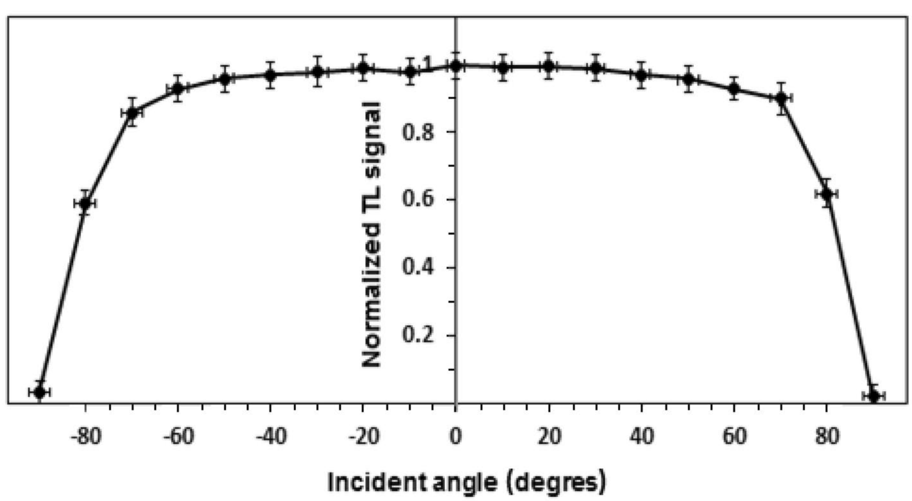
$$LDDL = 3 \times \sigma_{BG} \times SF^{-1} \quad (3)$$

where σ_{BG} is the standard deviation at zero dose of the average of eight glass dosimeters (0.032 nC mg^{-1}) and SF = 0.311 nC mg^{-1} mGy^{-1} determined from Fig. 2. The lowest dose detection threshold was found to be 0.300 mGy.

3.11 Post-irradiation fading

The post-irradiation fading of a TL dosimeter, i.e. loss of signals during storage following an irradiation, is a troublesome issue that is important to quantify in order to precisely correlate the TL readout with the actual radiation dose. This fading is caused by the spontaneous depopulation of its thermally unstable phosphorescent shallow trapping centers at room temperature even if the detector is kept in a dark place [11, 19, 20]. For dosimetry purposes, the glass detectors require a long-term post-irradiation stability. A post-irradiation heating of the glass detectors can substantially reduce fading due to the removal of the lower temperature peaks [11]. The protocol, we followed for studying the effect of post-irradiation heat treatment on the behavior of the glass TLD, consists of irradiating a batch of glass detectors to a dose of 30 mGy and then straightaway subjected to different preheat treatments ranging from lower temperature of 100 °C to higher temperature of 160 °C for 15 min. The choice of

Fig. 8 Angular dependence of the glass dosimeters. Error bars represent one standard deviation



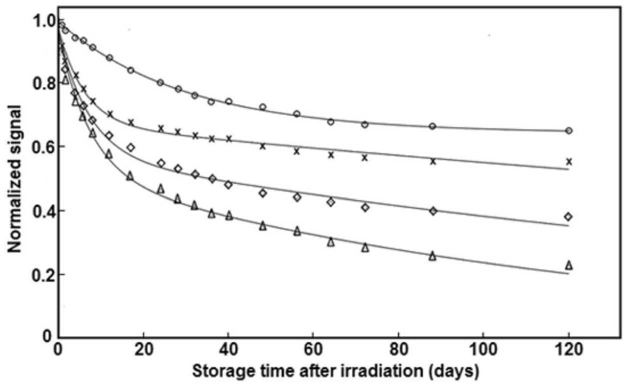


Fig. 9 Decay profiles for first-order post-irradiation preheat fading of the TL glass. The signals data were normalized to the first measurement. Points are experimental, and lines are calculated using the nonlinear fitting method. (open circle): 160 °C, (times): 140 °C, (diamond): 120 °C, (triangle): 100 °C

Table 3 Values of the fitting parameters of Eq. 4

Temperature (°C)	*a*	*b*	*c*	*d*	R^2
160	0.3464	0.333	0.6435	1.763×10^{-5}	0.9987
140	0.2995	0.1643	0.6696	0.001979	0.9883
120	0.3832	0.1374	0.5729	0.004055	0.9867
100	0.4346	−0.1352	0.5191	0.007866	0.9931

this temperature range was mainly guided by two criteria: depopulating the low-temperature glow peak at 110 °C while maintaining a minimum loss of intensity of the main dosimetric peak at 200 °C. They were then stored in a dark place at room temperature until readout. Subjected to a post-irradiation preheating procedure, the fading of the TLD decreases with increasing preheat temperature (Fig. 9) because of the elimination of the lower energy electron trap. The post-irradiation fading can be described by the sum of two first-order exponential decay functions

$$y = ae^{-bx} + ce^{-dx} \tag{4}$$

where the first term of the right member of Eq. 2 describes the rapid fading, observed in the 20 first days due to the small glow peak at 110 °C, followed by a much slower decline in the subsequent days which is described by the second part of the right member of Eq. 4. The values of the fitting parameters are given in Table 3. Therefore, to improve the post-irradiation stability, and before the readout, the irradiated glass must initially be heated to a temperature of 160 °C to eliminate the small glow peak (at 110 °C) which is largely accountable for the fading characteristic of the glass detector.

Decreases of about 6% and 18% were observed over a week and a month of storage times, respectively, when the detectors have been subject to a post-irradiation heating of 160 °C for 15 min. These results are promising when compared to the 60% fading obtained by Harvey and his co-workers over a month for commercially available LiF and $CaSO_4$-based TLDs [21] and similar to the 16% fading over a month storage for the commercial glass beads used as dosimeters in radiotherapy [22] or the 18% fading obtained with commercial window glass dosimeters [11]. Knowing the fading profile vs time and the time interval between irradiation and readout, a fading correction factor should be applied for dose assessment. However, if the glass dosimeters are read within 2 days post-irradiation, the fading correction is negligible.

4 Conclusion

In this work, we investigated the TLD dosimetric characteristics of the low-cost locally produced window glass for γ-field irradiation. This material exhibited a very good linearity ($R^2 = 0.9994$) in the low-dose interval 0–500 mGy used in this work. It also showed a very good reproducibility in dose measurement, with a standard deviation lying between 0.38 and 0.98%, for the 10, 30, 50, 70 and 100 mGy doses. In addition, several other key TLD parameters were also evaluated: glow curve, angular dependence, lowest detection threshold and post-irradiation stability. In conclusion and besides the lesser know how constraint in application of the procedure, this study indicates that soda–lime is a promising material for low gamma-radiation TL dosimetry.

Acknowledgements The present study was partially supported by the Department of Nuclear Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

Compliance with ethical standards

Conflict of interest The author can confirm that this manuscript does not contain any conflict of interest.

References

1. Meghzifene A, Dance DR, Mclean D, Kramer H (2010) Dosimetry in diagnostic radiology. Eur J Radiol 76:11–14. https://doi.org/10.1016/j.ejrad.2010.06.032
2. DeWerd LA, Liang Q, Reed JL, Culberson WS (2014) The use of TLDs for brachytherapy dosimetry. Radiat Meas 71:276–281. https://doi.org/10.1016/j.radmeas.2014.05.005
3. Hegde V, Prabhu N, Wagh A, Sayyed MI, Agar O, Kamath SD (2019) Influence of 1.25 MeV gamma rays on optical and luminescent features of Er^{3+} doped zinc bismuth borate glasses. Res Phys 12:1762–1769. https://doi.org/10.1016/j.rinp.2019.02.003

4. Zacharias N, Beltsios K, Oikonomou A, Karydas AG, Bassiakos Y, Michael CT, Zarkadas C (2008) Solid-state luminescence for the optical examination of archaeological glass beads. Opt Mater 30:1127–1133. https://doi.org/10.1016/j.optmat.2007.05.036
5. Pagonis V, Mian S, Mellinger R, Chapman K (2009) Thermoluminescence kinetic study of binary lead-silicate glasses. J Lumin 129:570–577. https://doi.org/10.1016/j.jlumin.2008.12.016
6. Caldas LVE, Teixeira MI (2004) Colored glasses for high dose dosimetry using the thermoluminescent technique. Radiat Prot Dosim 111:13–15. https://doi.org/10.1093/rpd/nch352
7. Moffatt JE, Spooner NA, Creighton DF, Smith BW (2012) Luminescence properties of common glasses for application to retrospective dosimetry. Radiat Meas 47:851–856. https://doi.org/10.1016/j.radmeas.2012.03.020
8. Bartolotta A, Brai M, Caputo V, D'Oca MC, Longo A, Marrale M (2011) Thermoluminescence response of soda lime glass irradiated with photon and electron beams in the 1–20 Gy range. Radiat Meas 46:975–977. https://doi.org/10.1016/j.radmeas.2011.03.005
9. Marrale M, Longo A, Bartolotta A, Basile S, D'Oca MC, Tomarchi E, Cirrone GAP, Di Rosa F, Romano F, Cuttone G, Brai M (2012) Thermoluminescence response of sodalime glass irradiated with proton and neutron beams. Nucl Instrum Methods B 292:55–58. https://doi.org/10.1016/j.nimb.2012.10.003
10. Izewska J, Andreo P, Vatnitsky S, Shortt KR (2003) The IAEA/WHO TLD postal dose quality audits for radiotherapy: a perspective of dosimetry practices at hospitals in developing countries. Radiother Oncol 69:91–97. https://doi.org/10.1016/S0167-8140(03)00245-7
11. Farah K, Kovács A, Mejri A, Ben Ouada H (2007) Effect of post-irradiation thermal treatments on the stability of gamma-irradiated glass dosimeter. Radiat Phys Chem 76:1523–1526. https://doi.org/10.1016/j.radphyschem.2007.02.065
12. Nordlund K, Zinkle SJ, Sand AE et al (2018) Primary radiation damage: a review of current understanding and models. J Nucl Mater 512:450–479. https://doi.org/10.1016/j.jnucmat.2018.10.027
13. Spooner NA, Franklin AD (2002) Effect of the heating rate on the red TL of quartz. Radiat Meas 35:59–66. https://doi.org/10.1016/S1350-4487(01)00109-3
14. Debnath R, Chaudhuri AK, Luthra JM, Vaijapurkar SG, Bhatnagar PK (1995) High temperature thermoluminescence of γ-irradiated copper activated silica glass and its application to dosimetry. J Lumin 65:279–282. https://doi.org/10.1016/0022-2313(95)00076-3
15. Abdel-Kader A, Higazy AA, Elkholy MM, Farag HI (1993) Thermoluminescence dosimetry in the pGy range of neodymium-doped tellurite-phosphate glass. J Mater Sci 28:5133–5137. https://doi.org/10.1007/BF00570052
16. Oliver L, Candela-Juan C, Palma JD, Pujades MC (2017) Comparison of the dosimetric response of 4-elements OSL and TL passive personal dosimeters. Radiat Meas 107:128–135. https://doi.org/10.1016/j.radmeas.2017.09.001
17. Tengku TNH, Bahri K, Wagiran H, Hussin R, Hossain I, Kadni T (2014) Thermoluminescence properties of $CaO–B_2O_3$ glass system doped with GeO_2. Radiat Phys Chem 102:103–107. https://doi.org/10.1016/j.radphyschem.2014.03.029
18. Caldas LVE, Teixeira MI (2002) Commercial glass for high doses using different dosimetric techniques. Radiat Prot Dosim 101:149–152. https://doi.org/10.1093/oxfordjournals.rpd.a005957
19. Kitis G, Polymeris GS, Pagonis V, Tsirliganis NC (2013) Anomalous fading of OSL signals originating from very deep traps in Durango apatite. Radiat Meas 49:73–81. https://doi.org/10.1016/j.radmeas.2012.11.011
20. Rodrigues AA, Caldas LVE (2002) Commercial plate window glass tested as routine dosimeter at a gamma irradiation facility. Radiat Phys Chem 63:765–767. https://doi.org/10.1016/S0969-806X(01)00637-5
21. Harvey JA, Haverland NP, Kearfott KJ (2010) Characterization of the glow-peak fading properties of six common thermoluminescent materials. Appl Radiat Isot 68:1988–2000. https://doi.org/10.1016/j.apradiso.2010.04.028
22. Jafari SM, Bradley DA, Gouldstone CA, Sharpe PHG, Alalawi A, Jordan TJ, Clark CH, Nisbet A, Spyrou NM (2014) Low-cost commercial glass beads as dosimeters in radiotherapy. Radiat Phys Chem 97:95–101. https://doi.org/10.1016/j.radphychem.2013.11.007

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.