On the Set Up of a Thermoluminescent Dosimetric System[1]

Claudio Furetta
Physics Department
University of Rome "La Sapienza"
Piazzale A. Moro 2
00185 Rome, Italy

MX0100255

Introduction

A thermoluminescent dosimetric system consists of several parts as following;

- the passive elements: the TL dosimeters (or detectors).
- a TL reader schematically consisting of a heating element, a PM tube, one or more electronic networks.
- an appropriate algorithm to convert the TL signal (response of the reader) to dose.
- ovens and/or furnaces to be used for thermal treatments of the dosimeters (annealing procedures).
- any other instrumentation which can be used for the right setting up and working for the system and/or for the implementation of the system (i.e. a programme able to deconvolute the glow-curve, to make an automatic estimation of the background, to calculate the average TL values and so on).

For the setting up of the system, one needs to fill up some requirements for initialising, characterising and calibrating the TL material according to the use for. These operations consist of several tests and measurements:

- initialisation procedure,
- determination of the batch homogeneity,

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1 *(invited talk)*

- to choose the reference dosimeters,
- to determine the relative intrinsic sensitivity of each dosimeter,
- the measurement of the determination limit,
- to determine the linearity range of the system and its calibration factor,
- to carry out the reproducibility tests of the reader - (i) stability of the background, (ii) stability of the response - of the calibration factor, and of the dosimeters.
- to study the appropriate annealing procedure in case using a new TL material for which no information in the scientific literature is available.
- to carry out a quality control of the instruments for the thermal treatments of the dosimeters (rise temperature curve, temperature stability, temperature distribution inside oven, etc.).

The present lecture will take into consideration only few of the previous points.

Prerequisites

The following points are very important prerequisites before starting the experimental procedures listed above.

- select dosimeter elements having approximately equal mass.
- reject elements which are imperfect, discoloured or dashed .
- do not handle elements directly; use tweezers (preferably vacuum tweezers) or spatulas for TL powder. Avoid scratching the surfaces of the dosimeters.
- do not leave the dosimeters uncovered in the laboratory. It is better to store the dosimeters in opaque bags or containers.
- some dosimeters are sensitive to sunlight, UV light or develop background effects when exposed to UV light. It is advisable to use tungsten, filtered fluorescent lighting or red lamps and to keep the dosimeters away from direct sunlight.
- keep the dosimeters away from heat and radiation sources during storage. It could be better to store the dosimeters in lead boxes to avoid any background irradiations.
- check periodically the background level of the reader. The background depends on the H.V. applied to the P.M. tube, on its age and on the room temperature: the stability of the TL reader must be checked before and after any reading session.

Initialisation procedure

At first it needs to define a batch of TLDs as the whole number of dosimeters of the same kind of material and activator(s), as obtained from the manufacturer, having the same thermal and irradiation history and, possibly, produced at the same time (this last requirement is not imperative).

Here, we suppose to have just received a new batch of N TLDs and all the dosimeters are supposed to have the same history.

The initialisation procedure is recommended to reduce the possibility of variations in dosimeter performance characteristics during usage.

The first stage of the procedure involves heating dosimeters inside a furnace using the optimum annealing parameters (temperature and time) indicated for the TL material under test. The dosimeters are placed in lidded crucible or in suitable annealing stacks (such as those made from quality stainless steel or electroplated copper). Annealing stacks allow separation and identification of dosimeter elements and are particularly useful if these elements are to be calibrated individually rather than in batches. The annealing stack containing the dosimeters is placed in the furnace, preheated to the required temperature. The actual duration of annealing will be longer than the required annealing time in order to attain thermal equilibrium at the required temperature. This additional time should be determined before all the setting up procedures as it will be indicated in the section concerning the quality control of the furnaces.

After annealing, the dosimeters are cooled in their containers in a reproducible manner. It is imperative to use always the same cooling procedure and that this is reproducible because the glow-curve of the material is strongly affected by the cooling.

The cooling may be accomplished by keeping the furnace door open after the heating has been switched off. In this manner the cooling will be more or less long depending on the starting temperature.

Alternatively, the crucible or annealing stack may be removed from the furnace immediately after the thermal treatment in order to allow the dosimeters to be cooled much faster to room temperature. This can be obtained lying the annealing container on a metal plate .

Tests should be made before initialisation to find the most suitable means of cooling for the user's particular requirements.

It is not recommended to switch to other methods once a cooling procedure has been adopted.

In some case the annealing procedure consists of two subsequent annealings: the first is carried out at high temperature and the second at low temperature. An example is given by LiF:Mg,Ti in the form of TLD-100, 600 or 700, which needs a first annealing at 400°C during 1 hour followed by 2 hours at 100°C (or 24 hours at 80°C). In all the cases where the annealing procedure is formed by two thermal treatments, the first at high temperature followed by one at low temperature, the dosimeters have to be cooled to room temperature at the end of the first annealing and then placed in the preheated oven for the second annealing. There are now several commercial programmed ovens in which the thermal cycles can be programmed at the beginning of the treatment; in this case the low temperature annealing is switched on when the high temperature of the first annealing decreases until the lower temperature of the second one. However, the procedures of heating and cooling have to be always in the same manner.

At the end of the annealing procedure the dosimeters are read to check the intrinsic background signal.

The initialisation procedure is repeated over three cycles. If the backgrounds on the dosimeters have remained low over these cycles, the initialisation is terminated and the dosimeters are ready for the subsequent tests. If backgrounds on the dosimeters are variable, the initialisation can be continued for further two cycles of treatment. If backgrounds continue to remain high or variable the efficiency of the readout system should be checked and/or the dosimeters rejected.

An example of the above initialisation procedure is given for 10 TLD-100. The TLD reader was an Harshaw Mod. 2000 A+B with a heating rate of 5 °C/s. No nitrogen flux was used. Table 1 shows the results obtained. Considering the negligible changes in the average values obtained through the three subsequent cycles (annealing + readout) one can consider the background to be stable and the initialisation ended.

The background values determined for each dosimeter have to be collected (i.e. memorised in a file concerning the batch under test) so that they can be used for the successive tests. In many cases an average background value is considered for the whole batch and then subtracted from each individual reading of the irradiated TLDs. This procedure is valid when the background is very low and constant for the whole batch. In other specific situations, as in radiotherapy where a high accuracy is necessary, an individual background is used and checked periodically to avoid any possible mistakes in the dose determination owing to large variations of the background. Table 2 lists some initialisation procedures.

Table 1
Example of initialisation procedure

TLD No.	1st BKG	2nd BKG	3rd BKG	$\bar{B}$ (a.u.)	%CV
1	0.091	0.087	0.090		
2	0.099	0.101	0.098		
3	0.101	0.098	0.099		
4	0.087	0.091	0.090		
5	0.095	0.087	0.091		
6	0.107	0.095	0.097		
7	0.085	0.090	0.088		
8	0.083	0.087	0.085		
9	0.085	0.088	0.091		
10	0.093	0.091	0.089		
$\bar{B}$	0.093	0.092	0.092	0.092	0.60
%CV	8.60	5.40	5.10		

BKG = background

Table 2 Initialisation procedures for some TL materials	
material	procedure
LiF:Mg,Ti (TLD-100, 600, 700)	4 cycles: 1 h at 400°C + cooling at a constant and reproducible rate + 20 h at 80°C
LiF:Mg,Ti (PTFE)	20-25 h at 300°C + controlled cooling + 20 h at 80°C
BeO (Thermalox 995)	15 h at 1000°C
$CaSO_4$:Dy (TLD-900)	1 h at 700°C
$CaSO_4$:Tm	20 min at 600°C
CaF_2:Dy (TLD-200)	3 h at 500°C
CaF_2:Tm (TLD-300)	3 h at 500°C

Batch homogeneity

This paragraph concerns the methods for the quality control on a new batch of dosimeters just received by an user. Some quality tests can be carried out, each one giving a different precision.

The simplest method is the following. The user screens all the samples by irradiating them with a known dose from a calibrated radiation source showing a good beam uniformity and making sure that all the samples have been inside the irradiation field. Any TL sample outside the specified tolerance limits should be rejected. The TL dosimeters can also be screened at periodic time intervals.

It must be noted that screening can only be used to determine acceptance or rejection of the samples. Indeed, there are two negative aspects of this procedure. Firstly, accepting a large range of responses (i.e. all responses which are within 20 -30% of the mean response), large precision errors are introduced in the dose determination. This is very dangerous when the dosimeters are used in clinical applications. Secondly, the replacement of the rejected TLDs is difficult when the replacement dosimeters come from a different batch: a bias error can be introduced into the whole procedure for the dose assessment.

However, this test remains valid as a first step to know the characteristics of a new TLDs batch.

A quality control concerning the batch homogeneity for TLDs used in personnel dosimetry is suggested in the technical recommendations of the International Electrotechnical Commission (IEC) document. The procedure is given below with some examples.

Procedure for batch homogeneity. (IEC)

All the **N** dosimeters of the same batch have to be annealed according to the annealing procedure used for the type of TL material under test.

At the end of the annealing procedure, all the dosimeters have to be irradiated using a calibrated gamma source under the appropriate electron equilibrium conditions. The given dose depends on the future use of the dosimeters; i.e., a dose of 5 mGy is suitable for personnel dosimetry, while 1 mGy is enough for environmental dosimetry.

Immediately after irradiation the TLDs are read to measure the TL emission (the readout cycle will be chosen as the best one for the particular type of phosphor) of each dosimeter. Let us indicate the values of the TL emission as

M_i with $i = 1, 2, 3, ..., N$

The TLDs are now re-annealed and read again to measure the zero-reading (or the zero dose reading). This value should be the same of that already determined during the initialisation procedure. In case the background levels are higher, the characteristics of the annealing oven must be checked (temperature uniformity inside the oven, correspondence between the temperature set and the actual temperature, etc.). Let us indicate these background values as

M_{0i} with $i = 1, 2, 3, ..., N$

The net readout is then defined as

$M_{i,net}=M_i - M_{0i}$ with $i = 1, 2, 3, ..., N$

In such a series , the maximum and minimum values have to be identified and substituted into the equation

$$\Delta_{max} = \frac{(M - M_0)_{max} - (M - M_0)_{min}}{(M - M_0)_{min}} .100 \leq 30 \qquad (1)$$

where Δ_{max} represents the uniformity index for the given batch. If such expression is not verified, namely the Δ_{max} of the batch is larger than 30, then some TLDs have to be rejected.

Figure 1 shows as an example a histogram obtained from the readings of a batch of 1000 TL dosimeters.

The initial calculation of Δ_{max} gave:

$n = 1000$ $\Delta_{max} = 48.5 > 30$

Since the uniformity index was larger than 30, some TLDs were progressively rejected. The results were:

Rejecting only 2 samples

$n = 1000 - 2$ $\Delta_{max} = 38.7 > 30$ not acceptable

Rejecting 4 samples

n = 1000 - 4 $\Delta_{max} = 33.7 > 30$ not acceptable

Rejecting 6 samples

n = 1000 - 6 $D_{max} = 29.4 < 30$ acceptable.

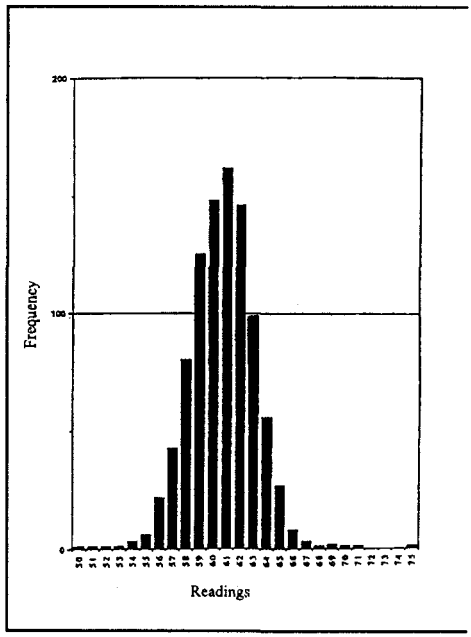

Figure 1. Histogram of 1000 TLDs readings.

Another procedure can be used for this test (not included in the official recommendations). The average value of all readings is evaluated as

$$\overline{M} = \sum_{i=1}^{N} \frac{(M_i - M_{oi})}{N} = \sum_{i=1}^{N} \frac{M_{i_{net}}}{N} \qquad (2)$$

and the two following quantities are evaluated

$\overline{M} - \sigma_p$ and $\overline{M} + \sigma_p$

where σ_P is a predetermined value of the standard deviation. All dosimeters which exhibit a net TL readings outside the previous range are rejected.

It can be noted here that it is not always possible or convenient to reject some dosimeters, i.e. when the batch is limited. In these cases all the samples are kept and their responses are

corrected using the relative intrinsic sensitivity factor (also called individual correction factor) as shown later on.

Any way, it has to be stressed that either some or more samples are rejected or all of the batch samples are considered, the correction factor must be calculated and used to achieve the best uniformity of the batch response.

Another example is reported below. The test has been carried out for a sample of 80 TLDs and the results show its usefulness in some particular cases. It must be noted that the background signal was obtained as an average value and subtracted from each reading. Table 3 lists the net values and the corresponding histogram is given in Fig.2; among them, the responses of two TLDs are evidently abnormal and completely out of the range indicated by the test, so that their rejection is obvious.

Table 3
Example of data for the homogeneity test. The superscripts M and m indicate the maximum and minimum values, respectively. * indicates abnormal readings

Dos.N.	TL	Dos.N.	TL	Dos.N.	TL	Dos.N.	TL
1	8.468^{M}	21	7.601	41	6.765	61	144.9*
2	7.808	22	7.346	42	7.531	62	7.946
3	7.231	23	6.916	43	7.045	63	6.771
4	7.587	24	7.491	44	7.476	64	7.657
5	7.630	25	7.600	45	7.480	65	7.434
6	7.394	26	7.509	46	7.65	66	67.239
7	8.094	27	7.329	47	7.167	67	6.704
8	7.854	28	7.290	48	8.047	68	7.118
9	7.428	29	7.294	49	7.984	69	6.699^{m}
10	7.963	30	7.677	50	8.014	70	7.395
11	7.676	31	8.143	51	6.968	71	8.057
12	8.387	32	8.111	52	8.320	72	7.555
13	8.232	33	7.374	53	7.487	73	6.720
14	7.839	34	6.739	54	8.433	74	7.778
15	7.464	35	7.574	55	7.812	75	6.786
16	7.539	36	7.880	56	7.620	76	7.424
17	7.411	37	7.783	57	7.934	77	7.402
18	7.633	38	7.836	58	7.568	78	7.025
19	8.076	39	172.5*	59	7.872	79	7.580
20	7.085	40	7.912	60	7.167	80	7.334

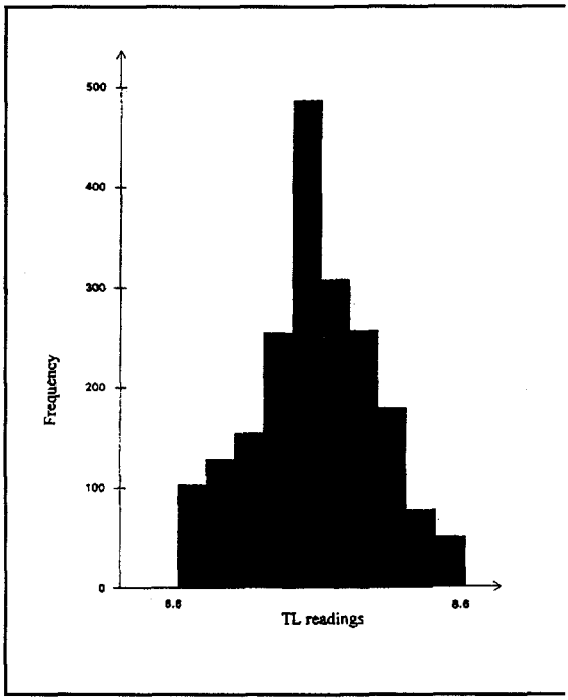

Figure 2. Histogram of 80 readings.

Reference and field dosimeters

The main difference between the so called reference dosimeters and the field dosimeters is caused by their uses.

The sole function of the reference dosimeters is to provide a mean response to which the response of the field dosimeters is normalised in order to produce the individual correction factors. The reference dosimeters can be defined as a sub-batch of dosimeters which has a relative standard deviation smaller than 2-3%: this means that their responses are very close to the average value as defined in the homogeneity test.

The field dosimeters are used to monitor the radiation in all dosimetric applications and to calibrate the TLD readers.

The group of reference dosimeters, in a number of N_r depending on the size of the batch, is chosen from the previous batch itself; i.e. 10 dosimeters over a batch of 100 seems to be a proper sample. Their net TL signal must be much closer to the average value, calculated after an irradiation test, than those of all the samples. They are representative of the whole batch and will never be used for field applications (personnel, environmental or clinical dosimetry).

Only in the case of a very limited batch of dosimeters all of them can be used as reference dosimeters, in the sense that reference and field dosimeters are the same.

After annealing , irradiation and readout, the average value of the response of the N_r reference dosimeters is calculated as follows

$$\overline{M_r} = \frac{\sum_{i=1}^{N_R}(M_i - M_{oi})}{N_r} \qquad (3)$$

The average is associated with the %CV, calculated as

$$\frac{\sigma}{\overline{M_r}}\% \qquad (4)$$

Thermal treatments

General considerations

Before using a thermoluminescent material for dosimetric purposes, it has to be prepared. To prepare a TL material means to erase from it all the information due to any previous irradiation, i.e., to restore in it the initial conditions of the crystal as they were before irradiation. The preparation has also the pupose of to stabilising the trap structure.

In order to prepare a thermoluminescent material for use, it is needed to perform a thermal treatment, usually called annealing, carried out in oven or/and furnace, which consists of heating up the TL samples to a predetermined temperature, keeping them at that temperature for a predetermined period of time and then cooling down the samples to room temperature. It has to be stressed that the thermal history of the thermoluminescent dosimeters is crucial for the performance of any TLD system.

There is a large number of thermoluminescent materials, however the annealing procedures are quite similar. Just few materials, like LiF:Mg,Ti, need a complex annealing procedure.

The thermal treatments normally adopted for the TLDs can be divided into three classes:

initialisation treatment: this treatment is used for new (fresh or virgin) TL samples or for dosimeters which have not been used for long time. The aim of this thermal treatment is to stabilise the trap levels, so that during subsequent uses the intrinsic background and the sensitivity are both reproducible. The time and temperature of the initialisation annealing are, in general, the same as those of the standard annealing.

erasing treatment or **standard annealing** (also called **pre-irradiation annealing**): this treatment is used to erase any previous residual irradiation effect which is supposed to remain stored in the crystal after the readout. It is carried out before using the TLDs in new measurements. The general aim of this thermal treatment is to bring back the traps - recombination centers structure to the former one obtained after the initialisation procedure. It may consist of one or two thermal treatments (in latter case, at two different temperatures).

post-irradiation or **pre-readout annealing**: this kind of thermal treatment is used to erase the low-temperature peaks, if they are found in the glow-curve structure. Such low-temperature peaks are normally subjected to a quick thermal decay (fading) and possibly must not be included in the readout to avoid any errors in the dose determination.

In all cases, value and reproducibility of the cooling rate after the annealing are of great importance for the performance of a TLD system. In general, the TL sensitivity is increased using a rapid cool down. It seems that the sensitivity reaches the maximum value when a cooling rate of 50-100°C/s is used. To obtain this, the TLDs must be taken out of the oven after the pre-set time of annealing is over and placed directly on a cold metal block. The procedure must be reproducible and unchanged during the whole use of the dosimeters.

It must be noted that the thermal procedures listed above can be carried out in the reader itself. This is important for TL elements embedded in plastic cards as the dosemeters used for large personnel dosimetry services. In fact, the plastic cards are not able to tolerate high temperatures and the in-reader annealing is shortened to a few seconds. However, its efficieny is very low when high dose values are involved. The in-reader annealing procedure should be used only if the dose received by the dosemeter is lower than 10 to 20 mGy. Driscoll[1] suggests in this case a further annealing in oven during 20 hours at 80°C for cards holding LiF:Mg,Ti; at this temperature the plastic holder does not suffer any deformation. Any way, excluding cards, for bare TL solid chips or TL materials in powder form, the annealing must be performed in an oven.

The oven used for annealing should be able to keep predetermined temperature oscillations within well specified margins. However, it must be noted that the reproducibility of the annealing procedure, concerning both heating up and cooling down processes, is much more important than the accuracy of the temperature setting.

Temperature overshoots due to the high thermal capacity of the oven walls can be minimised using ovens with circulating hot air. In this way the problem related to a non-ideal thermal conductivity of the annealing trays is also solved.

In some cases, when surface oxidiation of chips is possible (i.e., in the case of carbon loaded chips), it would be advantageous to operate the annealing under inert gas atmosphere. This facility could also reduce any possible contamination.

It would be better to use different annealing ovens depending on the various needs: one of them should be suitable for high temperature annealing, another one for low temperature annealing and a third one for any pre-readout thermal cycles.

As far as are concerned the trays where the TLDs are located for the annealing procedure, the following suggestions may be useful:

- the tray should have between 50 to 100 recesses to accommodate the dosimeters,
- each position in the tray should be identified,
- the tray must be as thin as possible and with a flat bottom surface to get a very good thermal contact,

- the tray material can be ceramic (in particular porcelain), Pyrex and pure aluminium. Ceramic is preferable for its chemical inertia and good thermal conductivity. Good results have also been obtained using Ni-Cu and any light compound not oxidable,
- it should be possible to insert in the tray a thin thermocouple to monitor the actual temperature of the tray as well as that of the dosimeters during the annealing cycle.

The quality control program of the annealing procedure should include the following points:

- determination of the heating rate of the oven from the switch-on time to the steady condition,
- determination of the temperature accuracy and set up of a correction factor which is needed,
- check on the temperature stability,
- check on the temperature distribution inside the oven chamber,
- determination of the heating rate of the tray.

A quality control program concerning the ovens has been suggested by Scarpa[2] and takes into account the various quantities which have to be checked, displayed graphycally in Fig.3. The accuracy is related to the difference between the temperature set and the temperature monitored; the instability of the oven concerns the oscillations of the temperature monitored.

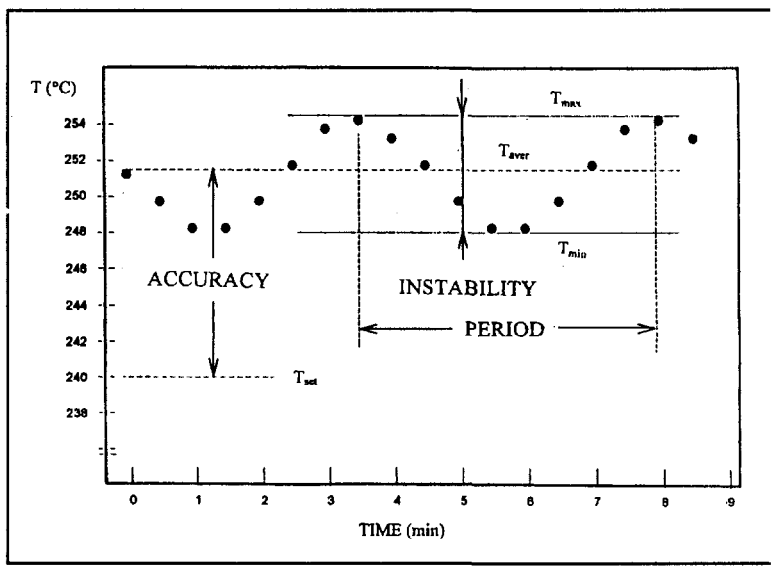

Fig.3. Quantities to be checked for the quality control of the ovens.

Figure 4 shows an example concerning the heating up profile of a muffle oven. Because the heating time is a characteristic of each oven, it must be checked accurately. It is convenient to switch on the oven several hours before use.

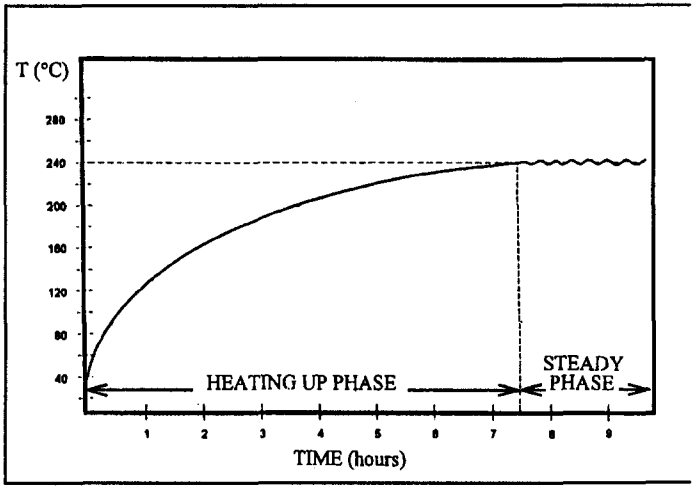

Figure 4. Heating up phase of a muffle oven.

Figure 5 depicts the temperature oscillations during the heating up phase (temperature set at 240°C). Figure 6 shows a typical thermal conditioning for a ceramic tray, inserted in a preheated oven.

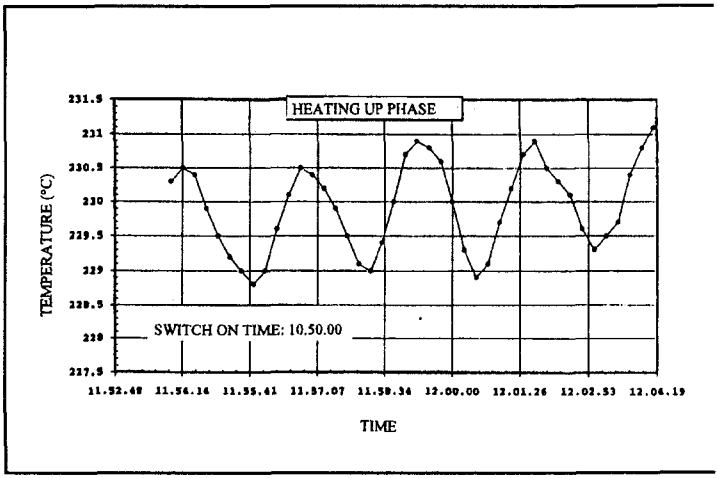

Figure 5. Temperature oscillations during heating up phase.

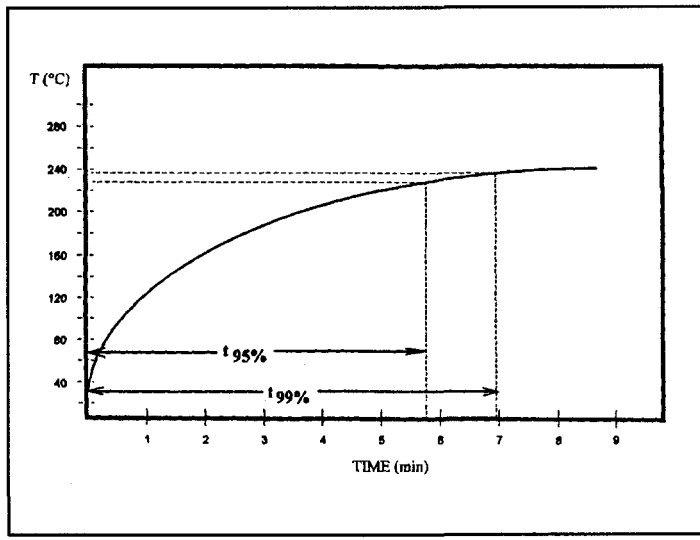

Figure 6. Heating rate of a ceramic tray inserted in a preheated oven.

During the steady phase of the oven the temperature, normally, is not stable. The oscillations around the temperature set are depending on the quality of the oven. This parameter has to be reported in the list of the characteristics of any new oven. As an example, Fig.7 depicts the temperature oscillations during the steady phase (temperature set at 240°C).

Another effect to be taken into account is that one which arises when the door of a preheated oven is opened to put the tray inside; the temperature drops to a lower value and then increases above the pre-set value. An example of this behaviour, measured for an oven without forced air circulation[3], set at a steady temperature of 400°C and an opening time of the door of 60 seconds, is shown in Fig.8. After closing the door, the temperature rises to about 410°C and then, slowly, goes back to the pre-set value in about 30 minutes. Of course, it is not a good procedure to open the oven during the annealing treatment.

According to the previous effects, it is convenient to use at least two different ovens when the TL dosimeters need a complex annealing procedure, as in the case of LiF :Mg,Ti which needs an high temperature annealing followed by a low temperature treatment.

Table 4 (a,b,c) summarise the annealing procedures commonly used for some commercial TL materials.

Annealing study

When a new TL material is going to be used for the first time, it is necessary to perform at first an annealing study which has three main goals:

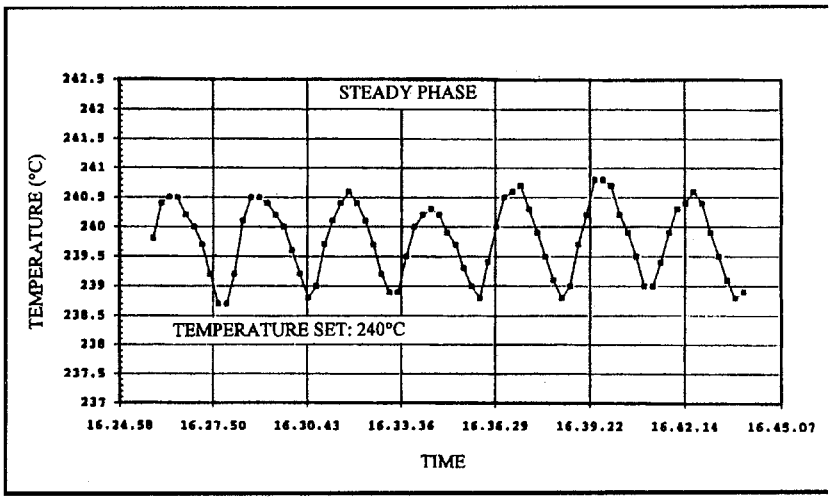

Figure 7. Temperature oscillations in an oven during the steady phase.

- to find the good combination of annealing temperature and time to erase any effect of previous irradiation,
- to produce the lowest intrinsic background and the highest sensitivity,
- to obtain the highest reproducibility for both TL and background signals.

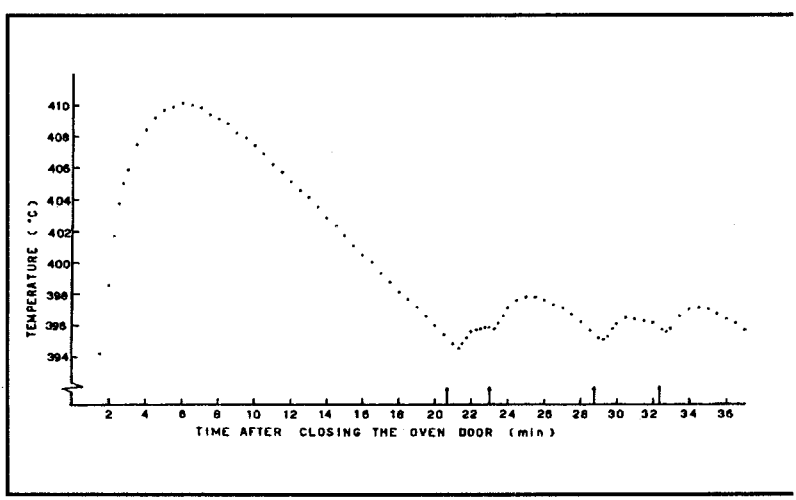

Figure 8. Effect of "open door" on a preheated oven.

The suggested procedures are the following:

1st procedure

1. irradiate 10 TLDs samples to a test dose in the range of the field applications,
2. anneal the irradiated samples at a given temperature (e.g., 300°C) for a given period of time (e.g., 30 minutes),
3. read the samples,
4. repeat steps 1), 2) and 3) increasing the annealing temperature of 50°C each time up to the maximum value at which the residual TL (background) will remain constant as the temperature increases,
5. plot the data as shown in Fig.9. As it can be observed, after a threshold temperature value, i.e., T_c, the residual TL signal remains constant,
6. repeat now the procedure, keeping constant the temperature at the value T_c and varying the annealing time by steps of 30 minutes and plot the results. The plot should be similar to the previous one,
7. choose now the best combination of temperature and time.
8. carry out a reproducibility test to verify the goodness of the annealing, in the sense that background must be unchanged during the test.

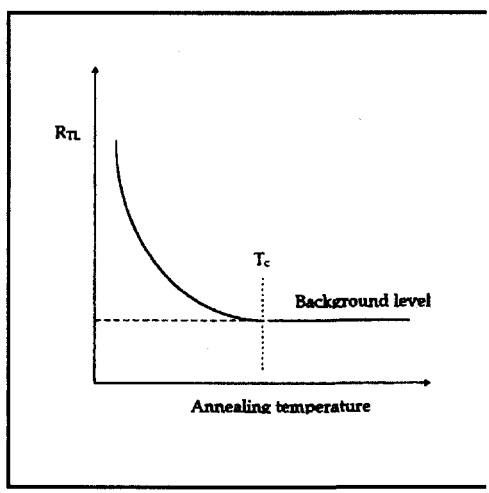

Figure 9.Decrease of TL response, after irradiation, as a function of the annealing procedure.

2nd procedure

This procedure has been suggested by G.Scarpa[4] who used it for sintered Beryllium Oxide. With this procedure both informations concerning annealing and reproducibility are obtained at once. The procedure consists in changing the temperature, step by step, at a constant annealing time. After annealing at a given temperature, the samples are irradiated and then readout. For each temperature 10 samples are used, cycled 10 times. So that each

experimental point in Fig.10 is based on 100 measurements. From the figure it can be seen that the best reproducibility, i.e., the lowest standard deviation in %, is achieved at around 600°C, whereas the absolute value of the TL output is practically constant between 500 and 700°C. The same procedure can be now carried out for a constant temperature and changing the annealing time. Finally, as before, the best combination of time and temperature will give the optimum annealing procedure.

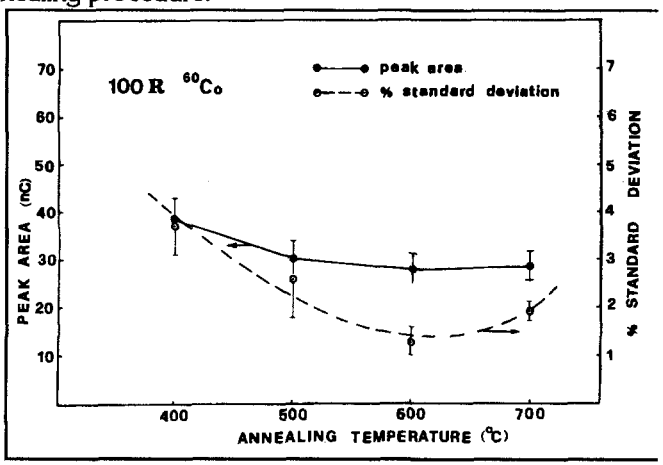

Figure 10.

To be sure that the annealing procedure is useful at any level of dose, it is suggested to repeat the procedure at different doses, according to the specific use of the material.

Table 4.a
Annealing treatments

material	annealingprocedure	
	in oven	in reader
LiF:Mg,Ti (TLD100,600, 700)	1 h at 400°C + 2 h at 100°C [2] or 1 h at 400°C + 20 h at 80°C [2] fast anneal: 15 min at 400°C +10 min at 100°C [3]	30 sec at 300-400°C (+ 20 h at 80 °C in oven) [1]
LiF:Mg,Ti in PTFE (polytetrafluoroethylene)	1 h at 300°C + 20 h at 80°C [5]	30 sec at 300°C (+ 20 h at 80°C in oven)
LiF:Mg,Na (LiF-PTL)	30 min at 500°C + fast cooling [6]	
LiF:Mg,Cu,P (GR-200A)	10 min at 240°C [7-10] or 15 min at 240°C [11]	30 sec at 240°C

CaF_2:Dy (TLD-200)	1 h at 600°C or 30 min at 450°C or 1 h at 400°C + 3 h at 100°C [13,14]	30 sec at 400°C
CaF_2:Tm (TLD-300)	1½ - 2 h at 400°C or 30 min at 300°C [15]	
CaF_2:Mn (TLD-400)	30-60 min at 450-500°C [16]	
$CaSO_4$:Dy (TLD-900)	½ - 1 h at 400°C	
$CaSO_4$:Tm	30 min-1 h at 400°C (PTFE: 2 h at 300°C)	
BeO (Thermalox 995)	15 min at 400 or 600 °C [17,18]	30 sec at 400°C
$Li_2B_4O_7$:Mn (TLD-800)	15 min - 1 h at 300°C	
$Li_2B_4O_7$:Mn,Si	15 min - 1 h at 300°C	
$Li_2B_4O_7$:Cu	15 min - 1 h at 300°C	
$Li_2B_4O_7$:Cu,Ag	15 min - 1 h at 300°C	

Table 4.b
Annealing treatments

material	annealingprocedure	
	in oven	in reader
α-Al_2O_3:C	1 h at 400°C + 16 h at 80°	
CAl_2O_3:Cr	15 min at 350°C	
Mg_2SiO_4:Tb	2 - 3 h at 500°C	
MgB_4O_7:Dy/Tm	1 h at 500-600°C [19, 20]	
MgB_4O_7:Dy,Na	30 min at 700°C + 30 min at 800°C or 2 h at 550°C [22,23]	
CVD Diamond	½ h at 300°C [24]	
$KMgF_3$ (doped with Pb, Cr or Ag)	1 hr at 400°C [25]	
semiconductor-doped Vycor glass	several second at 400°C [26]	

Table 4c
Post-irradiation annealing treatments

material	pre-readout treatment (post-irradiation anneal)	
	in oven	in reader
LiF:Mg,Ti (TLD-100,600,700)	10 min at 100°C	20 sec at 160°C
LiF:Mg,Ti in PTFE (polytetrafluoroethylene)	10 min at 100°C	10-20 sec at 160°C
LiF:Mg,Na (LiF-PTL)		10 sec at 130°C
LiF:Mg,Cu,P (GR-200A)	10 min at 130°C [12]	20-30 sec at 160°C [12]
CaF_2:Dy (TLD-200)	10 min at 110°C or 10 min at 115°C	16 sec at 160°C
CaF_2:Tm (TLD-300)	30 min at 90°C or 10 min at 115°C	16 sec at 160°C
$CaSO_4$:Dy (TLD-900)	20 - 30 min at 100°C or 5 min at 140°C	16 - 32 sec at 120°C
$CaSO_4$:Tm	20 - 30 min at 100°C	16 - 32 sec at 120°C
BeO (Thermalox 995)		1 min at 140°C
$Li_2B_4O_7$:Mn (TLD-800)	10 min at 100°C	
$Li_2B_4O_7$:Mn,Si		20 sec at 160°C
$Li_2B_4O_7$:Cu,Ag		20 sec at 160°C
Al_2O_3:Cr	15 min at 150°C	
MgB_4O_7:Dy/Tm		few sec at 160°C [21]
$KMgF_3$ (doped with Pb, Cr or Ag)	30 - 60 min at 50°C [25]	

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