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THERMOLUMINESCENCE DOSIMETERS CHARACTERIZATION WITH ^{60}Co GAMMA RADIATION AT ENEA CASACCIA RESEARCH CENTER

RT/2025/4/ENEA



ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES,
ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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Abstract

This report presents a study on the characterization of thermoluminescence dosimeters (TLDs) using ^{60}Co gamma radiation at the Calliope Facility and the National Institute of Ionizing Radiation Metrology (INMRI) of the ENEA Casaccia Research Center. It covers thermoluminescence theory and the TLD reading process, followed by dose evaluation and calibration techniques. The dosimeters used, particularly TLD 100, are described in detail, with an explanation of the irradiation process and calibration procedure. Results from low-dose calibration and comparisons with previous INMRI calibrations are presented. Additionally, comparisons between Fricke and TLD dosimetry for short irradiation times and low dose rates are included, along with discussions on shielding. This study aims to enhance the accuracy of dose measurements, especially for small organic samples for possible radiobiological applications.

Keywords: gamma irradiation, ^{60}Co , thermoluminescence dosimetry, calibration.

Riassunto

Questo report presenta uno studio sulla caratterizzazione dei dosimetri a termoluminescenza (TLD) utilizzando radiazioni gamma da Cobalto-60 presso la facility Calliope e l'Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (INMRI) del Centro di Ricerca ENEA Casaccia. Vengono trattati la teoria della termoluminescenza, il processo di lettura del TLD e le tecniche di valutazione della dose e le relative tecniche di calibrazione. I dosimetri utilizzati, in particolare i TLD 100, la procedura di irraggiamento e calibrazione sono descritti nel dettaglio. Vengono presentati i risultati della calibrazione a bassa dose e un confronto con le calibrazioni precedenti effettuate presso l'INMRI. Inoltre, vengono forniti confronti tra dosimetria Fricke e TLD per brevi tempi di irraggiamento e basse dosi, e vengono introdotti i risultati ottenuti nel caso di schermatura. Questo studio mira a migliorare l'accuratezza delle misure della dose, soprattutto per campioni organici di dimensioni ridotte per possibili applicazioni in radiobiologia.

Parole chiave: irraggiamento gamma, cobalto 60, dosimetria a termoluminescenza, calibrazione

INDEX

INTRODUCTION	5
1 THERMOLUMINESCENCE THEORY	5
1.1 IRRADIATION AND READOUT PROCEDURE	6
1.1.1 <i>Randall-Wilkins theory (escape of traps)</i>	7
1.1.2 <i>Reading process and readers</i>	8
1.1.3 <i>Dose evaluation and calibration</i>	10
2 MATERIALS	11
3 METHODS	12
3.1 NATIONAL INSTITUTE OF IONIZING RADIATION METROLOGY (INMRI).....	12
3.2 CALLIOPE	13
3.3 TLD READING.....	14
3.3.1 <i>Calibration</i>	14
4 RESULTS AND DISCUSSION.....	15
4.1 LOW DOSE CALIBRATION CURVE	15
4.2 SHORT IRRADIATION TIME AT LOW DOSE RATE: FRICKE AND TLD DOSIMETRY COMPARISON	16
4.2.1 <i>Lead bunker</i>	17
4.2.2 <i>In air</i>	18
4.3 ADDITIONAL SHIELDING INVESTIGATION	20
CONCLUSION AND FUTURE PERSPECTIVES.....	22
REFERENCES	23

Introduction

Thermoluminescence dosimetry (TLD) is a technique based on the principle that certain materials, when exposed to ionizing radiation, absorb and store energy. This energy can later be released in the form of light (thermoluminescence) upon heating the material. TLDs are widely used in dosimetry due to their small size, accuracy, and ability to provide precise measurements of absorbed radiation. These advantages make TLDs highly suitable for a wide range of applications, including environmental monitoring, radiotherapy and radiation protection.

TLDs work by utilizing specific materials, typically lithium fluoride (LiF), calcium sulfate (CaSO_4), or calcium fluoride (CaF_2), that have the capacity to trap electrons or holes when exposed to radiation. When heated, these trapped charge carriers recombine, emitting light that is proportional to the amount of radiation the material was exposed to. The intensity of this light can be measured and used to determine the absorbed dose. Due to their high sensitivity, TLDs are especially effective at measuring very low doses of radiation, which is relevant in certain radiobiological studies and high-precision applications.

This report presents the preliminary calibration activities of TLD dosimeters conducted as part of a collaboration between the National Institute of Ionizing Radiation Metrology (INMRI) and the Calliope facility at the ENEA Casaccia Research Center. One of the key aspects of this study was the calibration of TLDs at very low doses at the Calliope facility. The Calliope facility is predominantly used for irradiations designed to deliver high doses, with a very wide range of possible exposure times, from just a few minutes to many days. Being a pool-type facility, the source emerges from the water at the start of irradiation and returns to the water once irradiation is complete. The dose rate depends on the position of the sample relative to the source. Shielding effects, which are not negligible during short irradiation tests (less than three minutes) conducted at low absorbed dose values (below 3 Gy), can occur, particularly due to the edges of the pool.

To address this, a detailed study was carried out in the dose range of 0.07 – 2.5 Gy, which is of significant interest for radiobiological applications. The aim was to more accurately assess the dose during short irradiation times and low doses. The measurements were performed under various experimental conditions, including different dose rates and absorbed doses. Specific measurements were also carried out inside the lead bunker of the Calliope facility, focusing on conditions of very low dose and dose rate. One primary objective was to compare the TLD results with those from other commonly used dosimetry systems at the facility, such as the Fricke solution and alanine-Electron Paramagnetic Resonance (alanine-EPR) dosimeters. An additional experiment was conducted to observe the dose trend when the dosimeter container was positioned half behind a lead screen and half without a screen. The results and the theoretical background on TLDs are presented in this report.

1 Thermoluminescence theory

TLDs are highly practical, accurate, and precise tools used for point dosimetry in medical physics applications. These dosimeters have gained widespread use due to their small size, high precision, availability, reusability, and favorable dosimetric characteristics. TLDs rely on thermoluminescence, a process by which certain materials store energy when exposed to ionizing radiation and later release this energy in the form of light upon heating [1]–[5].

The most frequently used thermoluminescent material is lithium fluoride LiF. This material is usually doped with magnesium (and titanium Ti) and is available in three different formulations (from Thermo Fisher Scientific, Inc.) with three levels of $^6\text{Li}/\text{Li}$ ($^7\text{Li}/\text{Li}$) ratio: 7% (93%) for LiF(TLD-100), 96% (4%) for LiF(TLD-600) and 0.01% (99.99%) for LiF(TLD-700).

LiF:Mg,Ti is often used in personnel monitoring because it has an effective atomic number similar to that of tissue. Lithium fluoride has been by far the most commonly used mainly because of its low effective atomic number, only slightly greater than that of tissue and air.

^6Li has a high (n,α) capture cross section for thermal neutrons, while ^7Li is low in this respect.

Thus, in a mixed field of neutrons and γ rays a LiF(TLD-700) dosimeter primarily measures the γ ray dose, while a TLD-100 or TLD-600 dosimeter also responds strongly to thermal neutrons present [6], [7]. Such pairs of LiF dosimeters are widely used in personal neutron dose monitoring.

Thermoluminescent dosimetry is based on the principle that specially prepared crystalline materials have the ability to trap energy deposited by ionizing radiation. The energy stored in these crystals is proportional to the absorbed dose. When the crystal is heated, the stored energy is released in the form of light. The intensity of this light emission provides a measure of the radiation dose.

The thermoluminescent dosimeter consists of a small mass (typically 1 mg to 100 mg) of crystalline dielectric material. This material contains trace amounts of impurities that modify the properties of the crystal lattice, enabling it to perform as a thermoluminescent phosphor.

The impurities within the crystal lattice create two key types of defects:

- *Trap centers*: these are metastable potential traps that capture and hold charge carriers (i.e., electrons and holes) for extended periods;
- *Luminescence centers*: these centers, usually situated close to electron or hole traps, are sites where electron-hole recombination occurs, leading to the emission of light. These centers play a crucial role in the light emission observed during the readout process.

In a perfect crystalline insulator, the conduction and valence bands are separated by an energy gap of several electron volts (eV), and there are no intermediate energy levels within this gap. However, by adding impurities to the crystal, new energy levels are introduced within the band gap, allowing for luminescence.

1.1 Irradiation and readout procedure

TLD functioning principle is based on trap formation during irradiation and electron/hole release during the heating process of the readout, as described in the following.

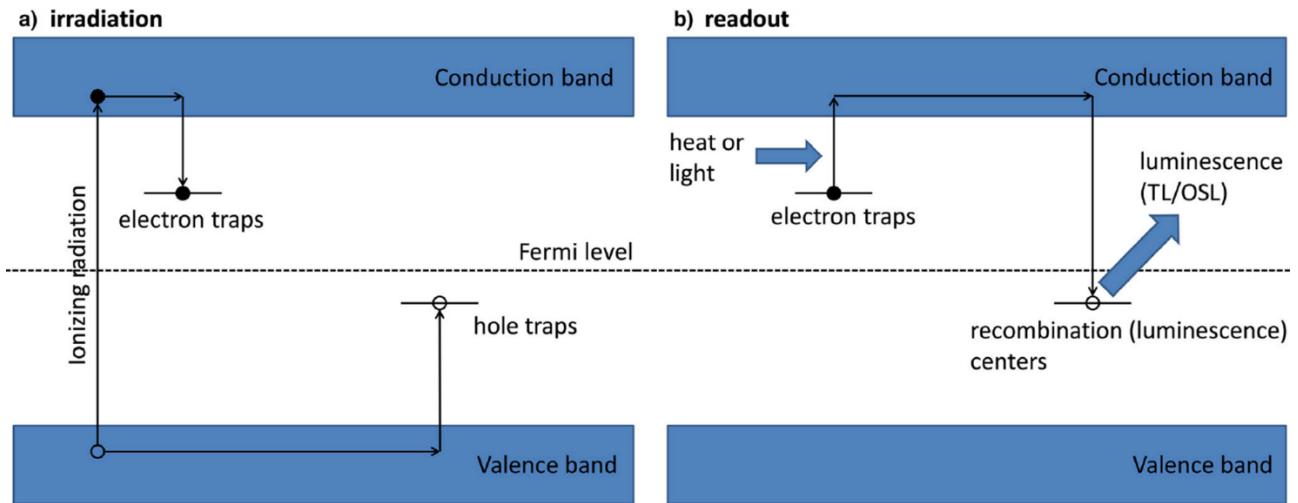


Figure 1. Electron/hole capture during irradiation a) and electron/hole release during readout b) [4].

During exposure to ionizing radiation, the material in the TLD undergoes ionization, creating free electrons in the conduction band and leaving behind holes in the valence band (Figure 1a). These free charge carriers (electrons and holes) can move within their respective energy bands. They either recombine to release energy or get captured by defects, which are the electron and hole traps. The trapped charges, depending on the trap depth, can remain in their trapped states from fractions of a second to thousands of years, allowing the TLD to "remember" the amount of radiation it has been exposed to.

To measure the stored radiation dose, the TLD undergoes a readout process (Figure 1b) composed of two steps:

- *Stimulation*: the TLD is heated, causing the trapped electrons to gain enough energy to move and recombine with the holes. This recombination process occurs at the luminescence centers, resulting in the emission of light.
- *Measurement*: the emitted light is detected by a PhotoMultiplier Tube (PMT), which converts the light into a measurable current or voltage. The intensity of the light is directly proportional to the amount of radiation absorbed by the dosimeter.

1.1.1 Randall-Wilkins theory (escape of traps)

The Randall-Wilkins theory, first proposed in 1945, describes the first-order kinetics for the escape of trapped charge carriers, specifically electrons, from traps in a thermoluminescent (TL) material. This theory provides a mathematical framework for understanding the release of trapped electrons as a function of temperature.

The key equation governing the rate of escape of trapped electrons is given by:

$$P = \frac{1}{\tau} = \nu e^{-\frac{E_{trap}}{k_B T}} \quad (1)$$

Where:

- P is the probability of escape per unit time (s^{-1});
- τ is the mean lifetime of the electron in the trap;
- ν is the frequency factor, which represents the rate at which the trapped charge carriers collide with the escape barrier;
- E_{trap} is the energy depth of the trap (in eV);

- k_B is the Boltzmann constant;
- T is the temperature in Kelvin.

According to the equation, the probability of electron escape increases as the temperature T rises. This relationship implies that increasing the temperature enhances the rate at which trapped electrons escape from their respective traps.

When the temperature is increased in a controlled manner over time (starting from room temperature), the rate of electron escape will initially rise, reaching a maximum at a certain temperature T_{max} . After this peak, as the supply of trapped electrons decreases, the probability of escape and consequently the escape rate will begin to decrease.

Since the intensity of TL is proportional to the rate of electron escape, a corresponding peak in TL brightness will be observed at the temperature T_{max} . This peak represents the temperature at which the maximum number of trapped electrons are released and is a critical parameter in TL dosimetry and material analysis.

In summary, the Randall-Wilkins theory establishes a clear temperature dependence for the escape of trapped electrons, which directly influences the thermoluminescence behavior of materials.

1.1.2 Reading process and readers

TLDs are read by gradually increasing the temperature of the detector while monitoring the emitted TL signal. This process typically results in the creation of a glow curve, where the TL signal is plotted against temperature, or by recording the total TL signal during a portion of the heating cycle. The TL signal can be quantified either by measuring the maximum intensity of a TL peak or by integrating the signal over a specific region of interest.

Different trapping centers within the TLD material have varying energy depths in the bandgap, which necessitate different temperatures for the release of trapped charge carriers. As the TLD is heated, these trapping centers are sequentially stimulated, producing a series of peaks in the glow curve. The temperature corresponding to the maximum of each peak, as well as the maximum TL signal intensity, depends on the rate at which the TLD is heated.

To reduce the impact of fluctuations in the heating rate, the integral of the TL signal (rather than its maximum) is typically used for dose determination. For dosimetry applications, TL peaks with maximum around 200-225°C are preferred, as they offer good stability at room temperature. TL peaks occurring at lower temperatures are associated with shallow trapping levels, which may be unstable at room temperature. Conversely, peaks at higher temperatures can be affected by interference from infrared black-body radiation, leading to spurious signals. These issues can be mitigated by flowing an inert gas, such as nitrogen (N_2) or argon (Ar), over the TLD during the heating process to reduce the occurrence of such interference.

An example of a glow curve for LiF:Mg,Ti (TLD-100) is shown in Figure 2.

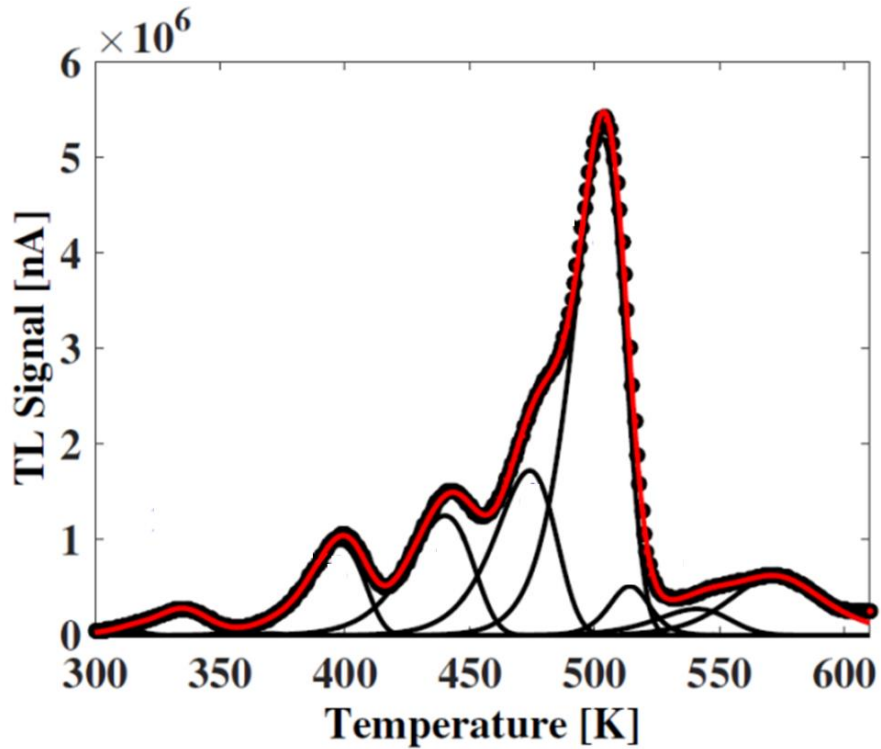


Figure 2. Example of glow curve for LiF:Mg, Ti (TLD-100). Adapted from [8].

During the TLD reading process, the phosphor to be measured is placed in a heater pan at room temperature. It is then heated while the emitted light is measured using a PMT. A schematic diagram of a typical TLD reader is shown in Figure 3.

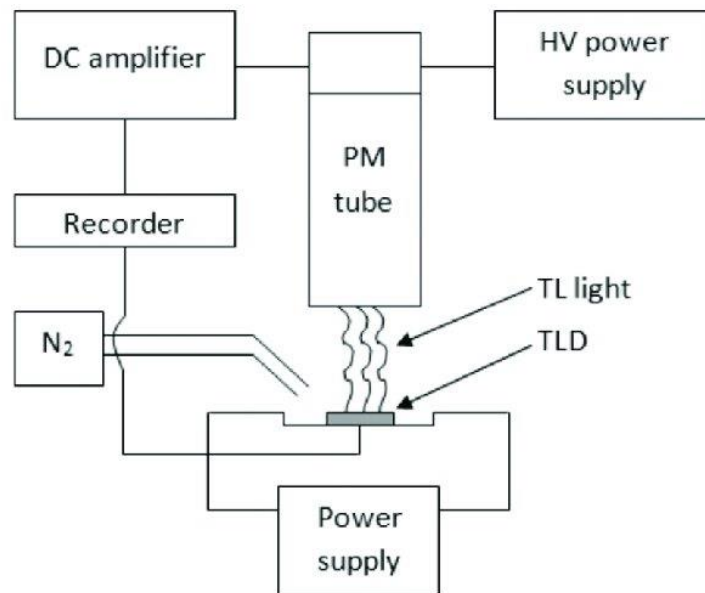


Figure 3. Scheme of a typical TLD reader [9].

The sample may be heated using an ohmically heated pan, which ensures a controlled heating rate. A key part of the process is the final heating step, where the TLD is heated to a high temperature to perform annealing. This step serves to empty the deep traps that were not affected by lower temperature heating, thus ensuring that the TLD is ready for accurate measurements.

Reproducibility of the heating program is crucial for achieving consistent TL dosimetry results. In addition, maintaining constant light sensitivity is essential so that a given TLD light output consistently provides the same reading. To achieve this, the PMT sensitivity must be stable, and the optical system must remain clean. It is also recommended to allow the reader to warm up for at least 30 minutes before beginning measurements to ensure the PMT tube temperature has stabilized. Preheating is typically performed before reading out TLDs to empty the unstable traps that may have accumulated at room temperature.

One of the advantages of TLDs is that they can be reused after removing the original signal through a process called annealing. Annealing releases all trapped electrons, effectively erasing any stored signal in the detector. However, this process also influences the glow curve and sensitivity of the TLD. To ensure consistent sensitivity, it is crucial to follow a standardized annealing procedure. The annealing process involves heating the TLD to a high temperature to eliminate the effects of previous radiation exposure, while the low-temperature component helps restore the original shape of the glow curve, thereby preserving the TLD's sensitivity. With careful and controlled annealing, the sensitivity of each TLD remains relatively unchanged. To further ensure uniform sensitivity, all TLDs in a batch should be annealed together, ensuring their heating and cooling histories are consistent, which in turn helps preserve their relative sensitivities.

1.1.3 Dose evaluation and calibration

For TLDs, the absorbed dose to water D_w is evaluated using the following equation:

$$D_w = M_{corr} N_{D_w} \prod_i k_i \quad (2)$$

where:

- M_{corr} is the corrected reading from the dosimeter,
- N_{D_w} is the calibration coefficient,
- k_i represents a correction factor needed to account for differences between the irradiation conditions of the high precision calibration dosimeters (i.e., the standards used to define N_{D_w}) and the conditions of the experimental dosimeter.

The raw signal M_{raw} represents the number of counts or charge per unit mass collected during the readout process. This raw signal is then converted to the corrected reading M_{corr} by considering background signals M_{bkg} and, if necessary, individual sensitivity correction factors, particularly when batch calibration is used. For most applications, especially in therapeutic settings, the background signal is often negligible compared to the therapeutic doses and does not require correction. If needed, the subtraction of a background signal from the measured one is typically done by reading an unirradiated TLD to identify any common background signal that may be present in both the background and experimental dosimeters.

The calibration coefficient N_{D_w} is a crucial parameter that links the signal from the TLD to the dosimetric property of interest, typically the dose to water. The calibration coefficient is specific to the user's experimental conditions, including geometry, dose level, and other factors. Ideally, this calibration should be based on a cross-calibration with a calibrated ionization chamber, under reference conditions, to ensure traceability. It is important to note that the calibration coefficient is not transferable between different TLD readers or types, as the sensitivities of different readers can

vary by as much as a factor of two, and different batches of TLDs may have substantially different sensitivities. Thus, periodic determination of N_{D_w} is essential for accurate dose measurements.

Since the calibration and experimental conditions are rarely identical, corrections are often required to account for these differences. The correction factors are needed for accurate dose evaluation and strongly depend on the type of TLD used. In general, these factors account for:

- *Linearity correction*: accounts for changes in sensitivity with dose. TLDs show a linear response at low doses, supralinearity at higher doses, and a plateau at very high doses.
- *Fading correction*: TLDs lose signal over time due to the spontaneous escape of trapped electrons at room temperature, a phenomenon known as fading.
- *Beam quality correction*: TLDs response changes depending on the quality of the radiation beam.
- *Angular correction*: addresses any differences in signal due to the angle of incidence of the experimental radiation beam on the TLD compared to the calibration beam's angle of incidence.

In a batch calibration approach, all the dosimeters in the batch are assumed to have uniform characteristics. Fading, energy response, linearity, angular dependence, and other factors are applied uniformly across all elements in the batch, with the calibration coefficient N_{D_w} representing the average system calibration coefficient of the batch. This approach works well when the dosimeters share similar response characteristics.

Alternatively, a more precise method involves determining individual sensitivity factors for each TLD by performing calibration runs. In this case, each TLD is assigned its own sensitivity factor, which is then applied to correct the reading of the dosimeter, ensuring more accurate results for each individual TLD.

TLDs are considered a relative dosimetric technique, meaning that dose assessments are typically performed by comparing the readings from unknown irradiation scenarios to a known dose delivered to a subset of TLDs from the same batch. The known dose should be delivered using a radiation quality similar to that expected in the measurement, and the irradiation should occur simultaneously with the unknown exposure to avoid potential fading issues.

2 Materials

The TLDs used in this study are Thermo Scientific TLD-100 [10], which are composed of Lithium Fluoride (LiF) doped with Magnesium (Mg) and Titanium (Ti) (LiF:Mg, Ti). These TLDs are square chips with dimensions of 3.2 mm × 3.2 mm × 0.89 mm.

The TLDs are inserted into a cylindrical holder made from Polymethylmethacrylate (PMMA), a material chosen for its clarity, durability, and compatibility with radiation measurement systems. The PMMA holder is designed to accommodate up to 20 TLD chips, providing flexibility in dosimeter usage and ensuring a sufficient number of samples for accurate dose assessments. A picture of the dosimeter with a focus on the cylindrical holder for TLD and a technical scheme of the dosimeter are shown in Figure 4.

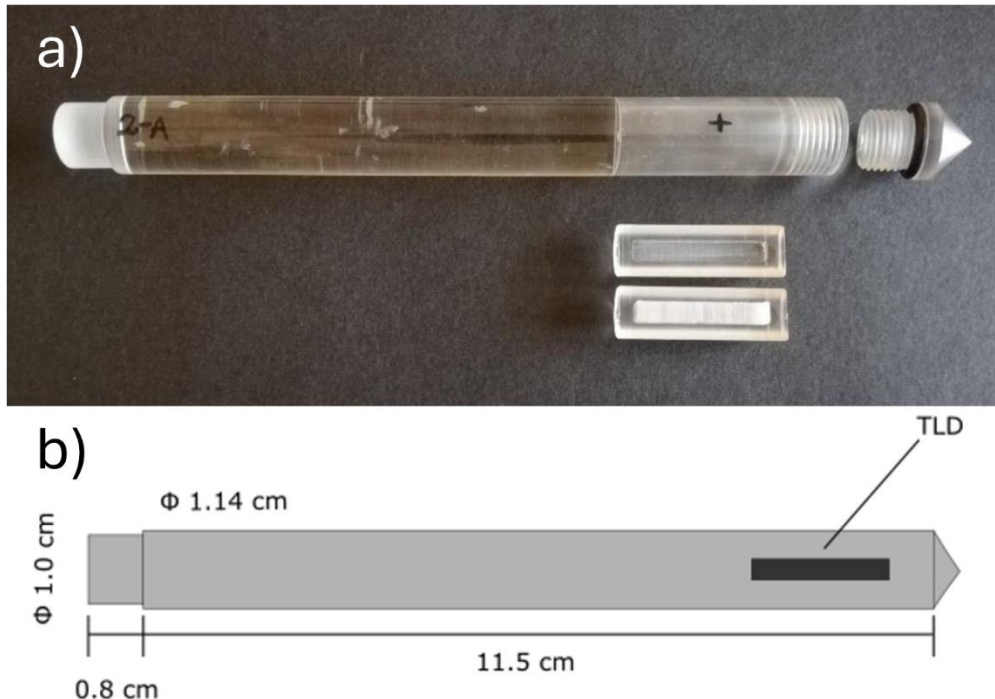


Figure 4. a) The dosimeter highlighting the cylindrical holder for TLDs (sensitive volume: $3.2 \times 3.2 \times 0.89$ mm) and b) a technical drawing of the dosimeter, showing dimensions.

The sensitive volume of the dosimeter is defined by the TLD chips contained within the PMMA holder, with the centre of the TLDs serving as the reference point for all absorbed dose measurements. To further enhance positioning accuracy, the reference point is marked on the walls of the dosimeter, providing clear guidance for its alignment during dosimetric evaluations. For this study, the dosimeter signal was evaluated by calculating the average value of 10 TLD chips.

3 Methods

3.1 National Institute of Ionizing Radiation Metrology (INMRI)

The Italian National Institute of Ionizing Radiation Metrology (ENEA-INMRI) is responsible for developing and providing the Italian national Standards and dissemination of the units of measurement in the ionizing radiation sector, as established in 1991 by the Act No. 273. ENEA-INMRI is located at the Casaccia Research Centre.

TLDs were calibrated in terms of absorbed dose to water D_w in the ENEA-INMRI reference ^{60}Co γ -beam, used for calibration of radiotherapy dosimeters in terms of absorbed dose to water.

For irradiation, TLD were positioned in a water phantom of size $30 \times 30 \times 30$ cm³ at 5 cm depth and 100 cm source distance. A picture of the irradiation setup is shown in Figure 5.

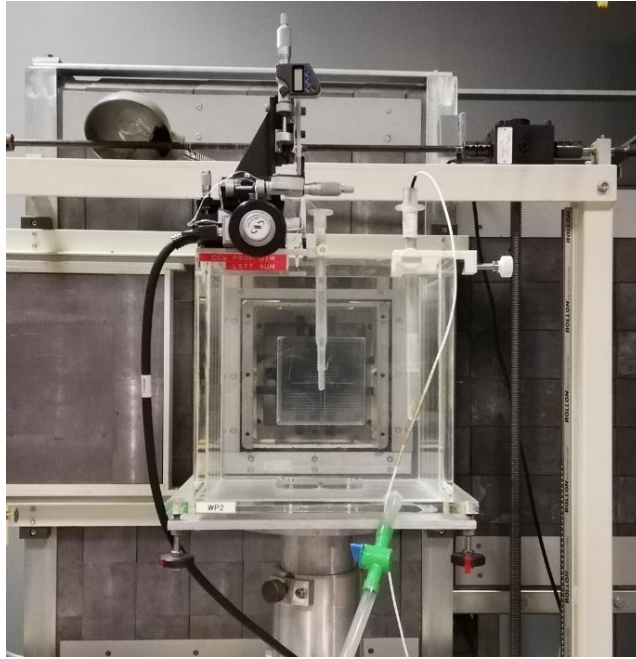


Figure 5. Irradiation setup for TLD calibration at INMRI. In this picture, the ^{60}Co source is positioned behind the water phantom.

At this distance the radiation field size was $10 \times 10 \text{ cm}^2$ and the lateral uniformity of the beam was better than 0.5% in a region $3 \times 3 \text{ cm}^2$ centered on the beam axis.

The absorbed dose rate at the irradiation depth was measured by means of a Farmer type ionization chamber with traceability to the Italian National Standard of absorbed dose to water [11].

3.2 Calliope

The Calliope facility, located at the ENEA Casaccia Research Center, is a pool-type gamma irradiation facility equipped with a ^{60}Co radioisotope source array (mean energy 1.25 MeV) [12]. The irradiation cell has dimensions of $7.0 \times 6.0 \times 3.9 \text{ m}^3$ and houses a source rack with 25 source rods in a planar geometry (Figure 6).



Figure 6. a) Calliope source rack in the pool and b) source rack within the irradiation cell (picture acquired by remote camera).

The maximum licensed activity for the Calliope plant is $3.7 \cdot 10^{15} \text{ Bq}$ (100 kCi) and, positioning a sample at different distances with respect to the source rack within the irradiation cell, it is possible to perform irradiation at different dose rate values; in particular, the maximum available dose rate is approximately 5 kGy/h (January 2025).

The steel platform, shown in Figure 6b, is installed to enable samples positioning close to the irradiation source and to perform irradiation at high dose rate values. At Calliope facility it is also possible to perform irradiation tests in different environmental conditions. A dosimetric and characterization laboratory is also available at the facility. The dosimetric systems used include the Fricke solution [13], alanine-EPR, Red Perspex, TLD, RADFET and online dose rate sensors, suitable for different dose ranges. The Fricke solution, which is used as absolute dosimeter, serves as the reference for calibrating the other systems. The process of calibration involves irradiating relative dosimeters at the same locations where dose rates are measured using the Fricke system.

3.3 TLD reading

The reading of TLD was performed with a manual reader (Harshaw Model 3500 Thermo Scientific [14]). After irradiation, the TLD were read after a preheating cycle conducted at 100°C for 10 minutes.

Each TLD chip was placed on the metal plate for heating. The reading was managed by the Windows Radiation Evaluation and Management System (WinREMS™) software, that allows to set the parameters of heating cycle and signal acquisition (heating rate 10°C/s, minimum temperature 60°C, maximum temperature 300°C and acquire time 33 s, as recommended by TLD reader's manual). The result of reading was the glow curve and the signal considered was the integrated charge (nC) collected from TLD reader, proportional to absorbed dose.

After reading, TLDs were treated with an annealing cycle at 400°C for 1 hour and at 100°C for 2 hours followed by cooling at room temperature, to be recycled. In general, TLD were annealed 10-15 days before the irradiation.

3.3.1 Calibration

For this study, a batch of 200 TLDs was characterized. The absorbed dose to water values D_w reported in this report were determined using the relation:

$$D_w = M_i E_{CCi} N_{Dw} \quad (3)$$

where M_i is the signal of the i -th chip in a dosimeter in nC (which in this study consists of 10 or 20 chips, as specified in the following section), E_{CCi} is the element correction coefficient of the i -th chip (adimensional) and N_{Dw} is the calibration coefficient (in Gy/nC). The element correction coefficient E_{CC} is a correction factor that relates the luminescence signal of each chip to the average signal of all chips in the same batch exposed to the same dose:

$$E_{CCi} = M/M_i \quad (4)$$

where E_{CCi} is the E_{CC} of i -th chip, M is the mean signal of the chips of the same batch and M_i is the signal of i -th chip. The calibration coefficient N_{Dw} allows conversion of the thermoluminescence signal into the absorbed dose to water. It is specific to the batch response and is evaluated as:

$$N_{Dw} = D_{ref}/M \quad (5)$$

where D_{ref} is the dose delivered to TLDs and M is the average signal of the TLDs.

The batch was characterized at ENEA-INMRI, where the values of E_{CC} for each TLD were determined along with the value of N_{Dw} . Specifically, to obtain these coefficients, the TLDs were exposed to 2 Gy in the ENEA-INMRI reference ^{60}Co γ -beam, which is traceable to the Italian Primary Standard of D_w [11].

4 Results and discussion

4.1 Low dose calibration curve

For the calibration of TLDs in the absorbed dose range of 0.07–2.5 Gy, 9 dosimeters, each consisting of 10 TLD chips, were irradiated in different positions and for different irradiation times. After irradiation, the 10 TLDs in each dosimeter were measured, and the signal values corresponding to each individual chip (M_i) were acquired. An example of the screen displayed after reading a TLD with the WinREMS™ software, showing the curve, is presented in Figure 7.

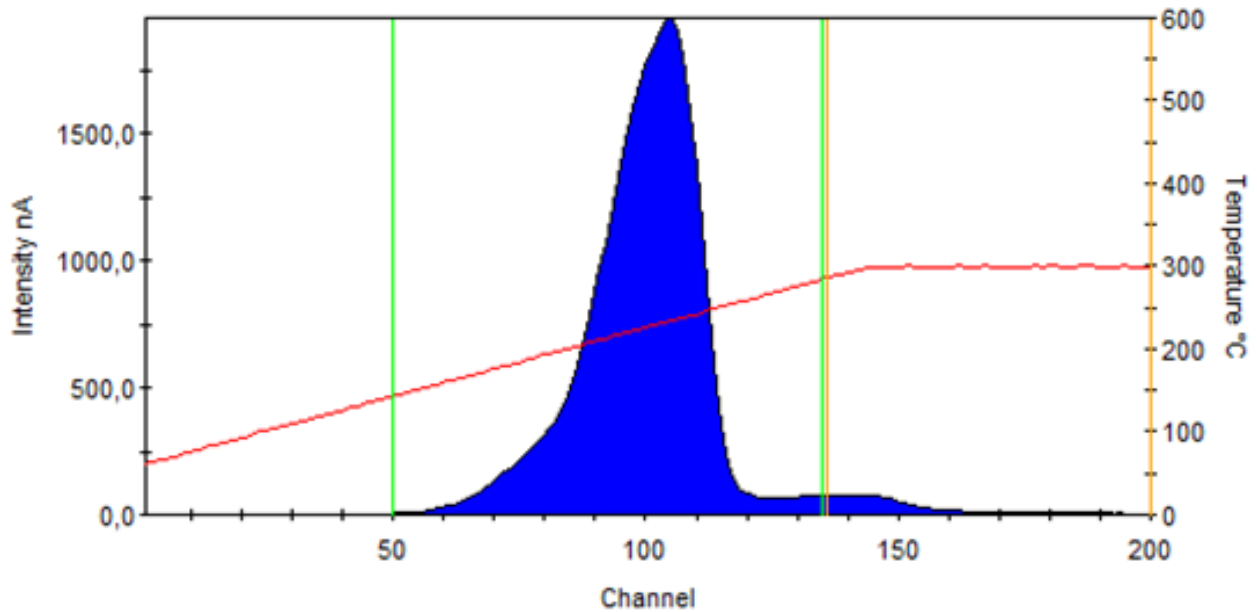


Figure 7. Example of a TLD chip reading using WinREMS™ software.

The M_i value was then multiplied by the corresponding E_{CCi} value of the chip obtained during the characterization at INMRI. The mean value of $M \cdot E_{CC}$ for the 10 TLDs in a dosimeter was recorded for all 9 irradiated dosimeters and are reported in Table 1 along with the irradiation condition and absorbed dose values provided by the Calliope facility.

Dosimeter	Dose rate (Gy/h)	Irradiation time (h)	Dose delivered (Gy)	$M \cdot E_{CC}$ (nC)	Standard deviation
#1	0.29	0.23	0.0685	321.8	1.9%
#2	0.29	0.33	0.0980	470.1	1.9%
#3	0.29	0.50	0.147	700.2	1.8%
#4	0.29	0.67	0.196	937.3	1.4%
#5	0.82	0.67	0.548	2672	1.2%
#6	2.61	0.33	0.868	3904	1.2%
#7	2.61	0.50	1.31	6082	1.0%

#8	4.30	0.47	2.00	$1.038 \cdot 10^4$	1.8%
#9	4.30	0.58	2.51	$1.317 \cdot 10^4$	1.0%

Table 1. Irradiation conditions and absorbed dose of dosimeters (10 TLD chips) provided by the Calliope facility. The values of $M \cdot E_{CC}$ correspond to the mean values of the ten chips in the dosimeter. The standard deviation refers to the ten measurements from the ten TLDs in the dosimeter.

To obtain the calibration curve, the absorbed dose values of Table 1 were plotted as a function of the obtained $M \cdot E_{CC}$ values (Figure 8).

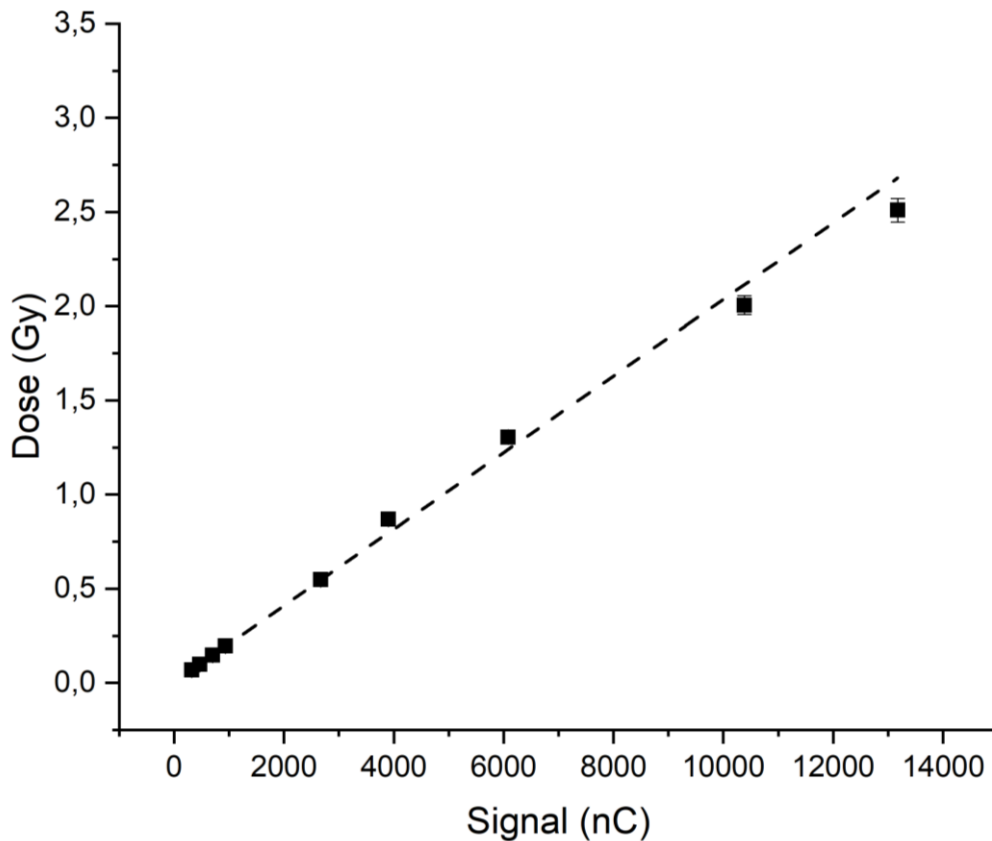


Figure 8. Calliope calibration curve for TLDs. Absorbed dose determined at the Calliope facility as a function of the TLD signal multiplied by the correction coefficient ($M \cdot E_{CC}$). The slope of the linear fit, corresponding to N_{Dw} , is equal to $(2.03 \pm 0.05) \cdot 10^{-4}$.

Analogously, a calibration curve for the same batch of TLDs was also obtained with the ^{60}Co source at INMRI, and this curve is in good agreement with the one obtained at Calliope.

4.2 Short irradiation time at low dose rate: Fricke and TLD dosimetry comparison

One of the main objectives of this study was to evaluate the agreement between the dose provided by TLDs and those obtained with the dosimetry systems most commonly employed at the Calliope facility [12] (Fricke solution and alanine-EPR dosimeters) at very low absorbed dose values (<3 Gy). For this purpose, TLDs were irradiated in two different positions, corresponding to two different dose rates determined by the Fricke solution. Specifically, one dosimetric point was positioned within a lead bunker inside the Calliope irradiation cell, and the other in air. The details and results obtained from these two experimental conditions are presented in the following subsection.

4.2.1 Lead bunker

The first dosimetric point analyzed was positioned within a lead bunker and was characterized by a dose rate of 2.56 Gy/h. A picture of the lead bunker and an image of the dosimeters positioned on a sample holder inside the lead bunker are shown in Figure 9.

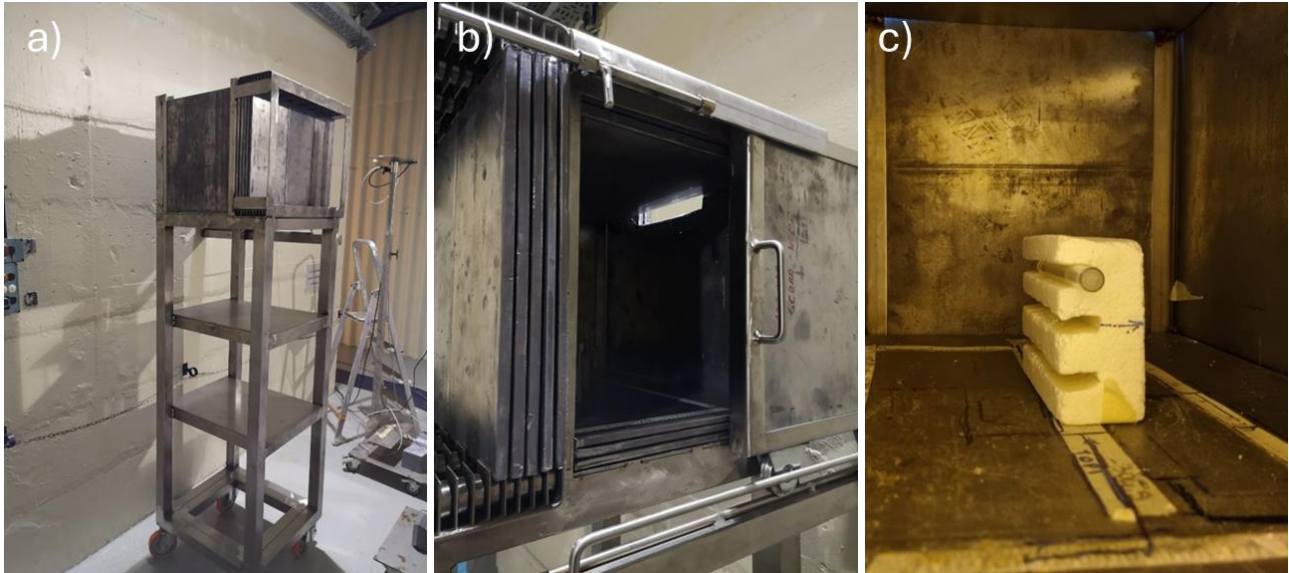


Figure 9. Pictures of: a) the lead bunker inside the Calliope irradiation cell for low dose rate irradiation, b) a detailed view of the inside of the bunker, and c) dosimeters on a sample holder inside the lead bunker.

Six dosimeters, each consisting of 10 TLD chips, were irradiated for varying times in the absorbed dose range (0.06 – 0.2 Gy). The irradiation time and the absorbed dose values provided by the Calliope facility (D_{Calliope} , calculated with Fricke solution) and those obtained from the TLD measurements (D_w , as per Equation 3) are presented in Table 2.

Dosimeter	Irradiation time (s)	D_{Calliope} (Gy)	D_w (Gy)
#1b	91	0.065	0.066
#2b	129	0.092	0.092
#3b	147	0.104	0.105
#4b	177	0.126	0.126
#5b	236	0.168	0.169
#6b	291	0.207	0.214

Table 2. Irradiation time of dosimeters irradiated inside the Calliope lead bunker, and dose values obtained at Calliope (D_{Calliope}) and by measuring TLD chips (D_w refers to the average value of the ten chips in a dosimeter). The error associated with D_{Calliope} is 2.5%, and the error associated with D_w is approximately 4%.

The corresponding trend of dose obtained using Fricke dosimeter and TLDs as a function of the irradiation time is shown in Figure 10.

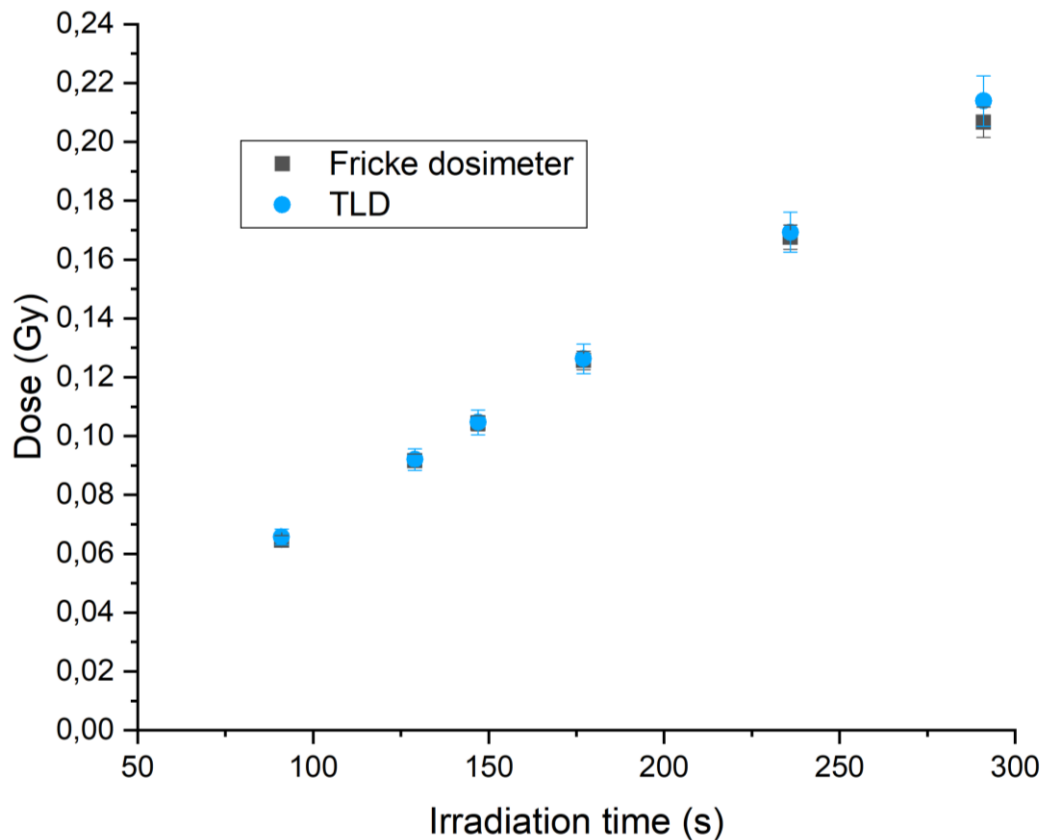


Figure 10. Absorbed dose of dosimeters irradiated within the lead bunker at Calliope facility (dose rate of about 2.5 Gy/h) obtained with Fricke solution (black squares) and TLDs (light blue dots).

The comparison between the dose values obtained using TLDs and those provided by the Fricke solution demonstrates good agreement. The measured doses with TLDs closely match the values calculated by the Fricke dosimeter, with minimal deviation.

4.2.2 In air

The second dosimetric point analyzed was in air, characterized by a dose rate of approximately 52.4 Gy/h. A picture of the dosimeters positioned on a sample holder in the in-air irradiation configuration is shown in Figure 11.



Figure 11. Picture of dosimeters on a sample holder in the in-air irradiation condition.

Six dosimeters, each consisting of 10 TLD chips, were irradiated for varying times in the absorbed dose range (0.6 – 4.5 Gy). The irradiation time and the absorbed dose values provided by the Calliope facility (D_{Calliope} , calculated with Fricke solution) and those obtained from the TLD measurements (D_w , as per Equation 3) are presented in Table 3.

Dosimeter	Irradiation Time (s)	D_{Calliope} (Gy)	D_w (Gy)
#1c	90	1.311	0.605
#2c	118	1.719	1.041
#3c	150	2.185	1.548
#4c	178	2.593	2.052
#5c	237	3.452	3.134
#6c	291	4.306	4.255

Table 3. Irradiation time of dosimeters irradiated in air, and dose values obtained at Calliope (D_{Calliope} , calculated with Fricke solution) and by measuring TLD chips (D_w refers to the average value of the ten chips in a dosimeter). The error associated with D_{Calliope} is 2.5%, and the error associated with D_w is approximately 4%.

The corresponding trend of dose obtained using Fricke dosimeter and TLDs as a function of the irradiation time is shown in Figure 12.

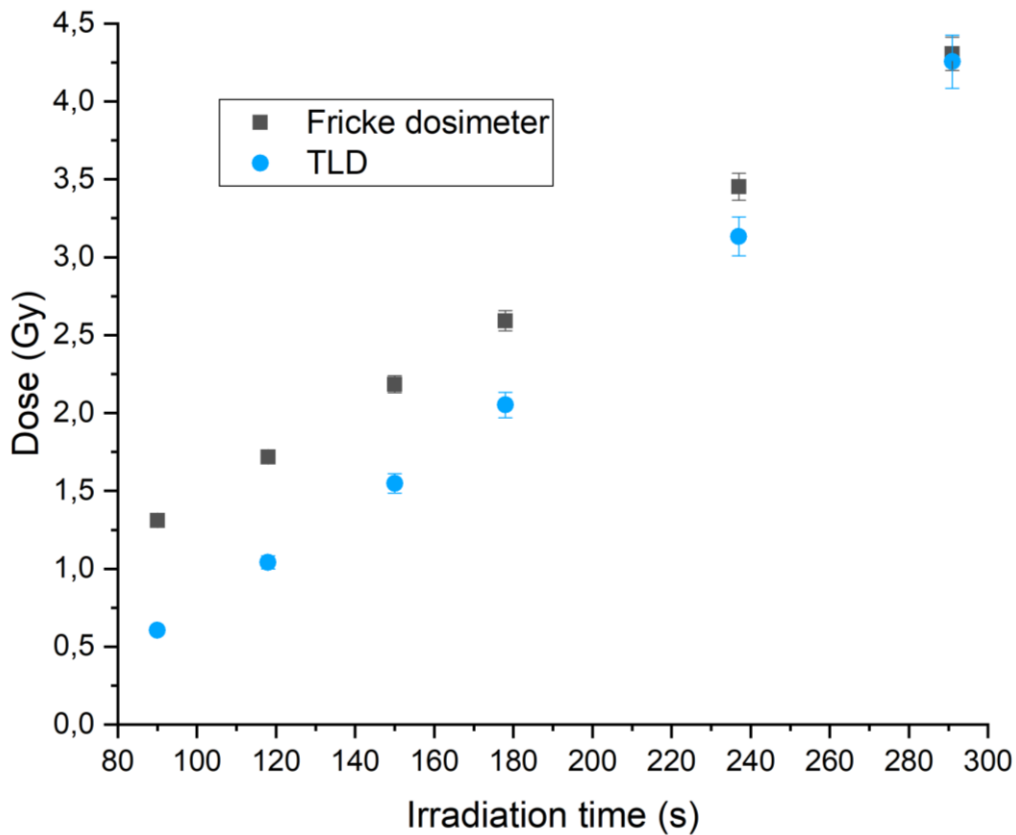


Figure 12. Absorbed dose of dosimeters irradiated in air at Calliope facility (dose rate of about 54 Gy/h) obtained with Fricke solution (black squares) and TLDs (light blue dots).

The comparison between the doses measured by the TLDs and those provided by the Calliope facility in air shows a noticeable discrepancy between the two methods. While the TLD measurements generally follow the expected trend, the differences between the $Dose_{Calliope}$ and D_w , considering their respective errors (2.5% for $Dose_{Calliope}$ and approximately 4% for D_w), may be attributed to the effects of the rising and lowering of the ^{60}Co source rack in the pool-type Calliope facility. This discrepancy is likely due to the very short irradiation times required to reach the studied dose range at this particular dose rate of approximately 50 Gy/h. As shown in Table 3, as the irradiation time increases, the results become more consistent and compatible. Therefore, further analysis is needed to assess the impact of this source behavior on irradiations at low doses and very short irradiation times.

4.3 Additional shielding investigation

The results in this section refer to the dose rate inside the lead-shielded bunker. Given the strong agreement with the results obtained from conventional dosimeters used at the Calliope facility, we decided to further investigate this aspect at the same dosimetric point. Specifically, an additional study was conducted to observe how the dose varied when the dosimeter was positioned behind a lead shield, both partially and fully.

For this investigation, dosimeters containing 20 TLD chips were used. Three scenarios (illustrated in Figure 13) were analyzed: irradiation within the bunker at a dose rate of approximately 2.4 Gy/h without additional shielding (Figure 13a), irradiation with 5 cm of lead shielding covering half of the dosimeter (Figure 13b), and irradiation with 5 cm of lead shielding covering the entire dosimeter (Figure 13c).

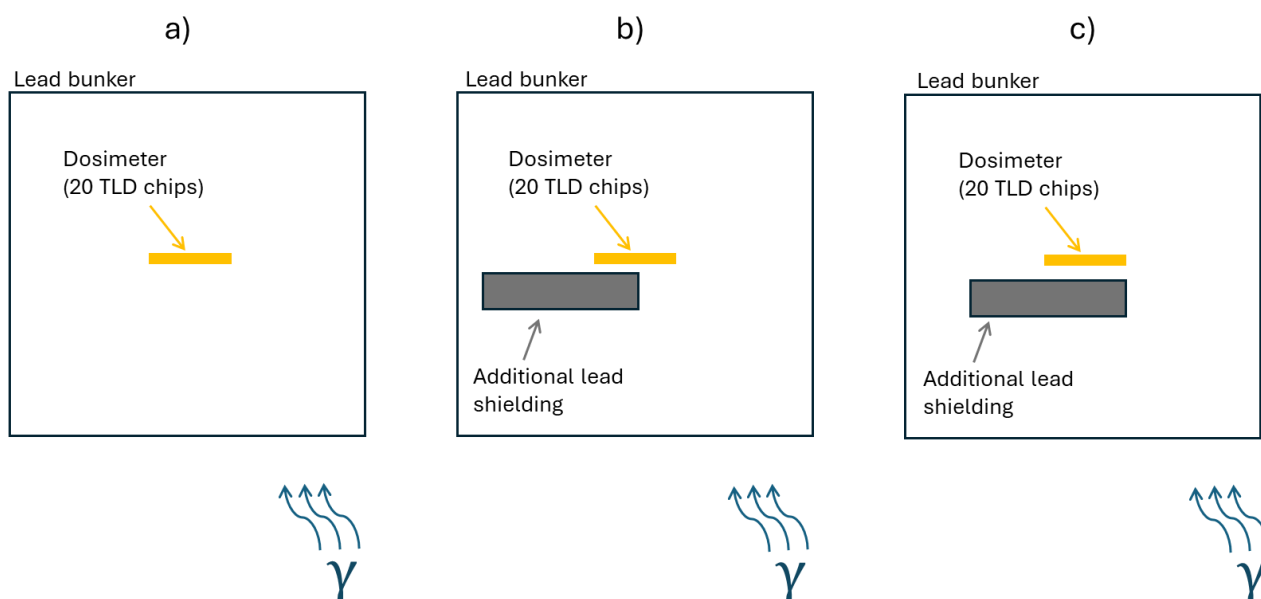


Figure 13. Top view schematics of the three dosimeter irradiation configurations within the lead bunker: a) no additional shielding, b) 5 cm of lead shielding covering half of the dosimeter, and c) 5 cm of lead shielding covering the entire dosimeter.

To explore the shielding effect, relevant for applications like radiobiology that may require partial shielding of organic samples, the trend of dose delivery to individual TLD chips as a function of their position within the dosimeter was analyzed for all three configurations shown in Figure 13. The results are shown in Figure 14.

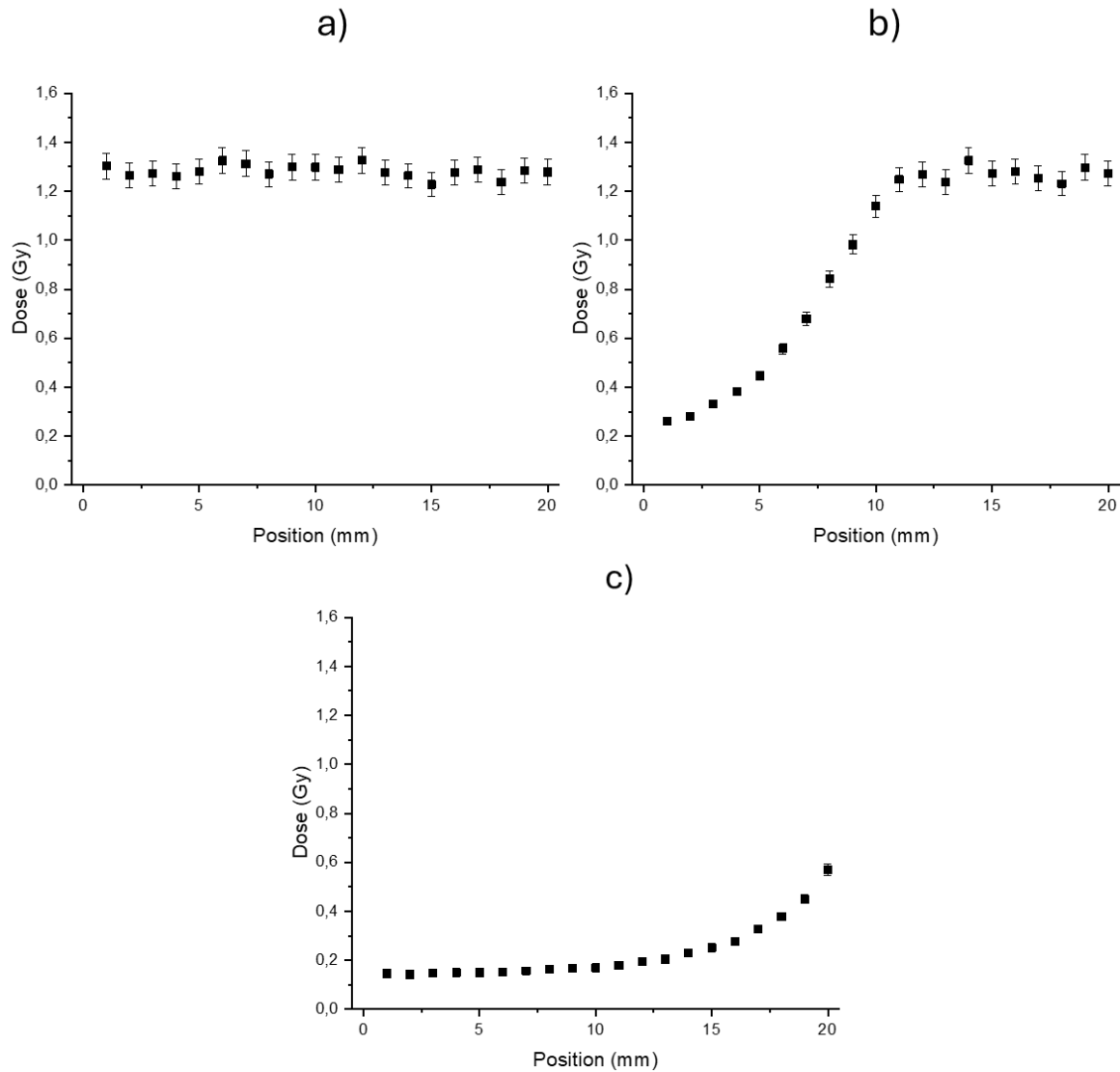


Figure 14. Dose delivered to individual TLD chips within the dosimeter as a function of their position for the three irradiation configurations: a) no additional shielding, b) additional 5 cm of lead shielding covering half the dosimeter, and c) additional 5 cm of lead shielding covering the entire dosimeter.

The results reveal a shadowing effect caused by the lead shielding, likely due to the position of the bunker relative to the ^{60}Co source. In the absence of additional shielding, the dose is fairly homogeneous across the TLD chips (Figure 14a). However, when half of the dosimeter is shielded (Figure 14b), a partial shadowing effect is observed, leading to reduced dose delivery to the chips located behind the shielded portion. Specifically, the dose exhibits a gradual increase across the shielded half of the dosimeter. Considering the lead shield is positioned between 0 and 10 mm, the chip at 0 mm shows a completely shielded dose, while the dose increases in a gradient towards the chip at 10 mm, which, despite being behind the lead, reads a dose similar to the chips not located behind the shield. This dose gradient effect is also evident when the entire dosimeter is shielded (Figure 14c). Considering that the bunker where the dosimeter is positioned is slightly shifted to the left relative to the source, the dose detected by the TLDs increases as they move towards the center of the source. Specifically, the dose increases gradually from 0 mm (where the dosimeter is fully shielded) to 20 mm, where the shielding becomes less effective due to the geometry of the setup. As the dosimeter moves further from the shielded edge, the dose increases until it reaches a point where the shielding is no longer fully effective, resulting in a gradual reduction in dose attenuation.

These findings highlight that lead shielding effectively reduces radiation exposure in specific areas, especially at lower doses, and demonstrates the excellent sensitivity of the dosimeters, which are particularly useful for radiobiological studies.

Conclusion and future perspectives

This study demonstrates that thermoluminescence dosimetry (TLD) is a precise and reliable technique for low-dose measurements, making it particularly valuable for radiobiological applications. The calibration curves obtained at both the Calliope facility and INMRI show strong agreement, confirming the reliability and accuracy of TLDs for low-dose measurements in the Calliope irradiation facility and further validating their use alongside established dosimetric systems.

The comparison between TLDs and Fricke dosimetry systems revealed good agreement, particularly at low dose rates, where both methods provided consistent results. However, discrepancies were observed at higher dose rates, likely due to the very short irradiation times and the complex geometry of the Calliope facility.

The shielding investigation further highlights the sensitivity of TLDs in detecting dose variations, demonstrating a clear dose gradient under partial and full lead shielding. This behavior is particularly useful in scenarios requiring partial shielding, such as radiobiological studies.

The next steps include the calibration of TLDs for higher doses, up to 10 Gy, to extend the applicability of this technique to a broader dose range. Additionally, further investigation into the behavior of the source will be conducted to better understand the discrepancies observed during very short irradiation times and to improve the precision of dose measurements under these conditions.

Overall, the findings underscore the effectiveness of TLDs in various experimental setups and reinforce their utility for precise dose measurements in challenging irradiation conditions.

Future works will focus on expanding the application of TLDs to mixed gamma-neutron fields, using materials such as TLD-100, TLD-600, and TLD-700. Calibration campaigns will be developed for various irradiation environments, including reactors and neutron accelerators, to improve the accuracy of TLDs in complex radiation fields. These efforts will aim to optimize TLD calibration for mixed radiation types, enhancing dose measurements where traditional methods may be less effective.

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