

## Research Article

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**Investigation of TLD-700 energy response to low energy x-ray encountered in diagnostic radiology**

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**Abstract:** The aim of this work is to study the energy dependence of thermoluminescent dosimeter (TLD-700) for low energy X-ray beams encountered in conventional diagnostic radiology. In the first step, we studied some characteristics (reproducibility and linearity) of TLD-700 chips using a  $^{137}\text{Cs}$  source, and selected TLD chips with reproducibility better than 2.5%. Then we determined TLD-700 energy response for diagnostic radiology X-ray qualities, and investigated its influence on air kerma estimate. A maximum deviation of 60% can be obtained if TLDs are calibrated for  $^{137}\text{Cs}$  radiation source and used in diagnostic radiology fields. However, this deviation became less than 20% if TLDs chips are calibrated for the reference x-ray radiation quality RQR5 (recommended by the IEC 61267 standard). Consequently, we recommend calibrating this kind of TLD detector with RQR5 diagnostic radiology X-ray quality. This method permits to obtain a good accuracy when assessing the entrance dose in diagnostic radiology procedures.

**Keywords:** energy response; TLD-700; diagnostic radiology; X-ray beams

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**1 Introduction**

Ionizing radiation is used for diagnostic and therapeutic purposes in medicine. This encompasses a wide range of different radiation doses and most applications make use

of photons either in the form of x rays (diagnostic radiology, radiotherapy) or gamma rays (nuclear medicine, radiotherapy) [1].

The main objective of dosimetry in a clinical environment is radiation protection. The radiation protection principles are applied in the design of medical facilities and for the minimization of the exposure of medical staff, many of whom are required to wear personal dosimeters. While no limit value was specified to restrict the dose to patients in medical procedures, radiation protection principles still apply in the context of optimization of procedures<sup>1</sup>. Important applications in the field of diagnostics encompass quality assurance in mammography [2], dose assessment in procedures with relatively high exposures such as CT scanning [3] and prolonged fluoroscopic procedures [4].

Thermoluminescent (TL) dosimeters (or TLD) are widely used in medical and health physics, due to a large number of their advantages (tissue equivalence, small dimensions, easy handling, reusability, sensitivity). Many TLD materials are based on the LiF, which has been doped with small quantities of Mg and Ti, and denoted by LiF:Mg,Ti [5]. They can be found under different commercial names: TLD-100, TLD-600 and TLD-700.

The knowledge of TLD energy response is necessary to estimate the uncertainty of any personal dosimetry system, and an experimental method is considered as the most reliable option [6].

The characteristics of TL materials have been intensively studied and published [7–9]. McKeever *et al.* [10] summarized characteristics of both LiF: Mg, Ti and LiF:Mg, Cu, P and provided extensive references to the original literature describing these materials.

TLD energy response studies exist in the literature for a variety of applications. Mobit *et al.* [11] performed Monte Carlo study of the quality dependence of LiF TLD in kilovoltage photon beams for radiotherapy dosimetry studies. Kearfott *et al.* [12] observed an energy response of LiF TL ribbon for low energy x-rays. Kron *et al.* [6], studied

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<sup>1</sup> IAEA, Safety Series 115, International Basic Safety Standards for protection against ionizing radiation and for the safety of radiation sources, Vienna, 1996.

energy response of LiF for low energy synchrotron radiation. Muhogora *et al.* [13, 14] studied energy response of LiF chips for typical ISO 4037 X-ray beams<sup>2</sup> and some diagnostic qualities. Davis *et al.* [5] studied the energy response of standard TLD-100 and high-sensitivity TLD-100H TL dosimeters for photon beams with mean energies from about 25 to 1100 keV.

The majority of these studies has concerned the LiF in different forms (chips, rods or ribbon) with mono-energetic x-ray beams, and only a few studies involved broad x-ray spectra like those encountered in diagnostic radiology [12, 15]. However, only few works were published concerning TLD-700 energy response. Lakshmanan *et al.* [16] have studied the energy dependence of sensitized LiF for x-rays produced by high voltage from 80 to 250kV (with effective photon energy from 29 to 133keV) and <sup>60</sup>Co. Bakshi *et al.* [17] have studied the energy response of some TLD dosimeters for low energy synchrotron radiations. More recently, other works were published, but they concerned another kind of dosimeters and the study was at high energy [18–20].

However, all the performed studies agreed that TL dosimeters have noticeable photon energy dependence at energies below a few hundred keV [21–23].

This work is a part of a study concerning the feasibility of using only one kind of TLD dosimeter (TLD-700) in a dosimetry service provider for assessing x and gamma doses received by workers in all fields (industry, research, radiotherapy and diagnostic radiology) and in a mixed field (gamma and neutrons) when they are associated with TLD-600.

The work presented here is devoted to the energy response study of TLD-700 dosimeters. The concerned X-ray qualities are those recommended by the International Electrotechnical Commission for calibration of instruments used to estimate entrance dose in conventional diagnostic radiology<sup>3</sup>.

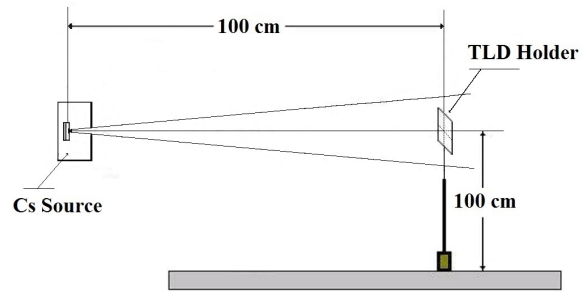


Figure 1: Setup for TLD irradiation with <sup>137</sup>Cs source.

## 2 Methodology

The study was carried at the Secondary Standard Dosimetry Laboratory (SSDL) of Algiers. The first step was devoted to the study of the TLD-700 characteristics: the reproducibility and the linearity. The reproducibility is by far the most important characteristic requested in any measuring instrument in all fields. A dosimeter which is not reproducible (or has a bad reproducibility), cannot be used reliably for dose assessment nor for any other kind of measurement. Therefore, it was the first characteristic we investigated.

To be able to investigate the influence of other parameters, it is advisable to select TLDs that have the best reproducibility.

### 2.1 TLD-700 characteristics determination

TLD-700 dosimeters are manufactured by BICRON-NE HARSHAW (USA) in different forms (chips, powder and rods). In our laboratory, we have TLD-700 chips with the following dimensions: 3.2mm × 3.2mm × 0.89 mm.

These chips are produced in batches, and their characteristics can vary from one batch to another, and even can vary from one chip to another in the same batch. Before their first use, it is necessary to determine their characteristics (reproducibility, linearity, energy dependence, angular dependence, sensitivity and fading).

In our case, we have focused our study on reproducibility, linearity and energy dependence (for X-ray qualities used in diagnostic radiology). The setup used for the irradiation with <sup>137</sup>Cs source is presented in Figure 1.

<sup>2</sup> ISO 4037-1:1997, X and gamma reference radiation for calibrating dosimeters and doserate meters and for determining their response as a function of photon energy- Part 1: Radiation characteristics and production methods.

<sup>3</sup> International Electrotechnical Commission, Medical diagnostic X-ray equipment-Radiation conditions for use in the determination of characteristics, CEI/IEC no.61267, 1994 (replaced by 2005 version).

### 2.1.1 Reproducibility

For this study, we took a batch of 100 TLD-700 chips and studied their reproducibility as follows:

The chips were annealed at 400°C in a high-temperature oven for one hour. After the high-temperature annealing, the chips were rapidly cooled to room temperature. After approximately 30 minutes, they were annealed for a second time at 200°C in an oven for two hours, and were again rapidly cooled to room temperature. The chips were then irradiated at a known dose. After the irradiation, and prior the readout, the chips were annealed at 100°C in an oven for 12 minutes. This post-irradiation annealing empties the low temperature traps and reduces the effects of the fading on the thermo luminescence (TL) signal. The chips were evaluated using a TLD reader (Victoreen 2800), by applying a pre-heat temperature of 140°C for 10 seconds (to empty the low temperature traps), followed by a reading time of 15 seconds (increasing temperature up to 240°C). For this step, we have used the following equipments:

- An oven for TLD annealing (CARBOLITE 2700)
- TLD reader (Victoreen 2800)
- Irradiation source of  $^{137}\text{Cs}$  (BUCHLER OB6)
- Nitrogen flux (5 cm<sup>3</sup>/s)

During the irradiations, the TLD chips were positioned in a PMMA holder (rectangular plate with 72 holes of 5 mm diameter and covered with a PMMA sheet of 3mm thickness). The holder used is illustrated in Figure 2.

All chips were marked (numbered from 1 to 100), irradiated and evaluated using the above mentioned cycle. We repeated the entire cycle (annealing, irradiating and reading) five times, and determined the mean reading (charge in nC) and the corresponding standard deviation for each TLD chip (all readings have been corrected for TLD reader background reading). The results obtained are illustrated in Figure 3.

We found that about 70% of all TLD chips have reproducibility better than 5%, and only 20% of them have reproducibility better than 2.5%.

For the remaining studies, we decided to select TLD chips with reproducibility better than 2.5%.

From the TLDs having a reproducibility better than 2.5%, we have selected ten TLD chips (chips having following numbers: N7, N8, N9, N11, N17, N31, N34, N42, N44 and N55).

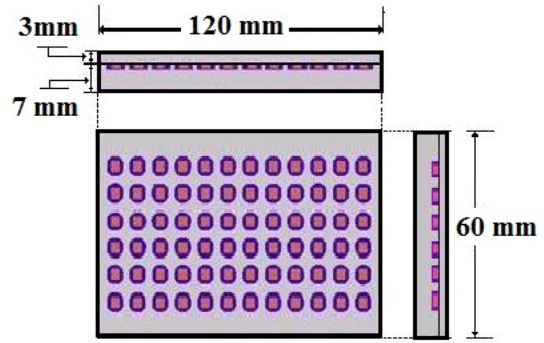


Figure 2: Details of the holder used for TLD irradiation.

### 2.1.2 Linearity

Doses received by patients undergoing conventional diagnostic radiology examination are low and likely does not exceed 10cGy. Therefore, we decided to study the response of selected TLDs for doses ranging from 0.5 to 10 cGy, using the same irradiation source of  $^{137}\text{Cs}$ . The obtained curves are illustrated by the Figure 4.

From the Figure 4 we have found that variation of TLD reading versus received dose can be fitted with a linear equation in the form:

$$\text{Reading}(nC) = A * \text{Dose}(cGy) + B, \quad (1)$$

where:

*Reading*(nC): represents the charge registered by the TLD reader (corrected for background reading of the TLD reader),

*Dose*(cGy): represents the dose communicated to TLD chips,

*A*: represents the slop of the line and

*B*: represents the TLD reading without any irradiation (TLD background).

Equation (1) can be rearranged as follow:

$$\text{Dose}(cGy) = [\text{Reading}(nC) - B]/A, \quad (2)$$

$$\text{Dose}(cGy) = [\text{Reading}(nC) - B] * Fc, \quad (3)$$

where *Fc* is the calibration factor in (cGy/nC) units.

The last form (Equation 3) is more useful for dose estimate from TLD reading (and is what is used in practice).

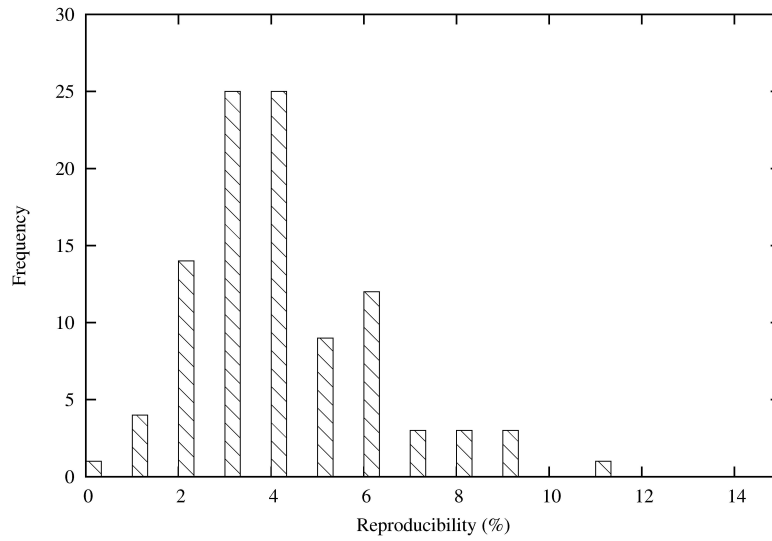


Figure 3: Reproducibility of TLD-700.

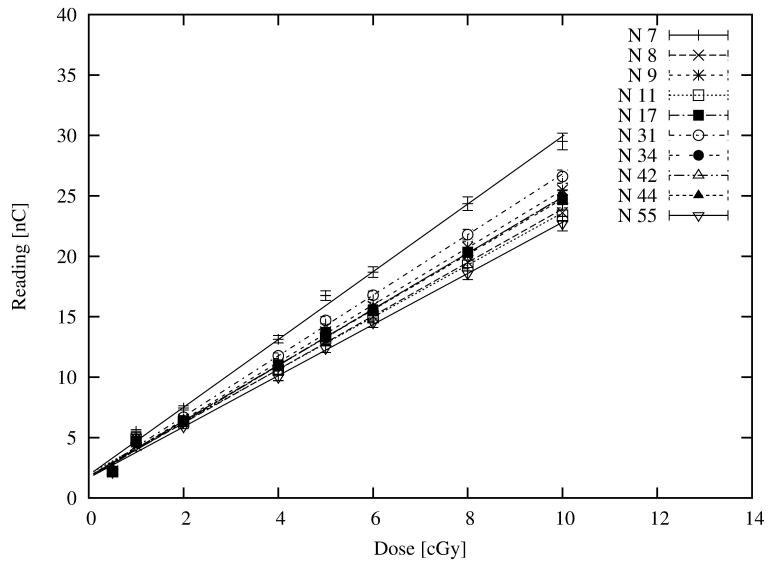


Figure 4: Study of TLD-700 response for <sup>137</sup>Cs versus dose.

**Table 1:** Characteristics of RQR x-ray qualities (from PTB and SSDL).

X-ray Qualities	Tension (kV)	Added filtration (mmAl)	1 <sup>st</sup> HVL (PTB) <sup>a</sup> (mmAl)	1 <sup>st</sup> HVL (SSDL) (mmAl)	Std Dev <sup>b</sup> (%)
RQR2	40	2.8	1.44	1.46	1.39
RQR3	50	2.5	1.8	1.81	0.56
RQR4	60	2.5	2.11	2.1	-0.47
RQR5	70	2.4	2.35	2.35	0
RQR6	80	2.5	2.65	2.69	1.51
RQR7	90	2.4	2.97	2.99	0.67
RQR8	100	2.4	3.28	3.31	0.91
RQR9	120	2.5	3.95	3.94	-0.25
RQR10	150	2.5	4.96	4.9	-1.21

<sup>a</sup> These qualities were reported in calibration certificate of A3 ionization chamber (Issued by PTB in 2005).  
<sup>b</sup> Std Dev (%) = 100 \* [HVL(SSDL)-HVL(PTB)]/HVL(PTB)

## 2.2 Energy response

To determine the energy response of selected TLD-700 dosimeters it is necessary to irradiate them with the same dose for each X-ray quality. The same batch of TLD was irradiated free in air at 5cGy using developed diagnostic X-ray qualities and <sup>137</sup>Cs source. X-ray qualities used are those specified by IEC-61267 standard namely the RQR series. Their characteristics are specified in Table 1 where HVL is the Half Value Layer defined as the thickness of a specified absorber (in our case Al), when positioned between the x-ray generator and the detector used, give an air kerma rate equal half its initial value (without attenuator). The setup used for the irradiation with RQR x-ray qualities is illustrated in Figure 5.

## 3 Results and discussion

The air kerma response of TLD chips for <sup>137</sup>Cs and X-ray quality,  $Q$ , are given by Equation 4 and Equation 5 respectively.

$$R_{Cs} = \left( \frac{I}{D} \right)_{Cs} \quad (4)$$

$$R_Q = \left( \frac{I}{D} \right)_Q, \quad (5)$$

where  $I_{Cs}$  and  $I_Q$  are the corrected output from the TLD reader for <sup>137</sup>Cs and X-ray beam quality  $Q$ , and  $D$  is the reference air kerma ( $D = 5\text{cGy}$ ).

By taking the ratio  $R_Q$  of the measured air kerma response for X-ray quality  $X$  to the measured air kerma response for <sup>137</sup>Cs source  $R_{Cs}$ , we obtain the relative energy

response of TLD chips,  $S(Q)$ , given by the Equation 6. We have represented  $S(Q)$ , the relative energy response in Figure 6.

$$S(Q) = \frac{R_Q}{R_{Cs}}. \quad (6)$$

In Figure 6 we have represented the normalized energy response  $S(Q)$  of the selected TLD chips versus the HVL of the investigated X-ray beam qualities. We estimated the influence of this quantity (energy dependence) on the estimated air kerma by using Equation (7).

$$\Delta K_{air}(\%) = 100[S(Q) - 1]. \quad (7)$$

In Table 2, we have summarized data for each selected chip, by giving lowest highest and mean value of its relative energy response for X-ray beam qualities investigated (taking the response for <sup>137</sup>Cs source as the reference value).

From Figure 6 and Table 2, without taking in account the energy dependence of TLDs, we deduced that relative error on air kerma can reach 60%, and only three chips (N7, N8 and N55) have a relative error less than 20%. All others chips have a relative error between 20% and 60% (when calibrated for <sup>137</sup>Cs).

For calibration purposes, it is a common use to calibrate a detector or an instrument for one reference radiation beam quality and to determine a correction factor for others radiation qualities to count for energy dependence.

For the calibration of instruments used in diagnostic radiology, the RQR5 quality was considered as the reference radiation beam. We determined the relative response of TLDs using RQR5 X-ray quality as reference beam for calibration and obtained results illustrated by Figure 7. For each selected chips we calculated the lowest, the mean

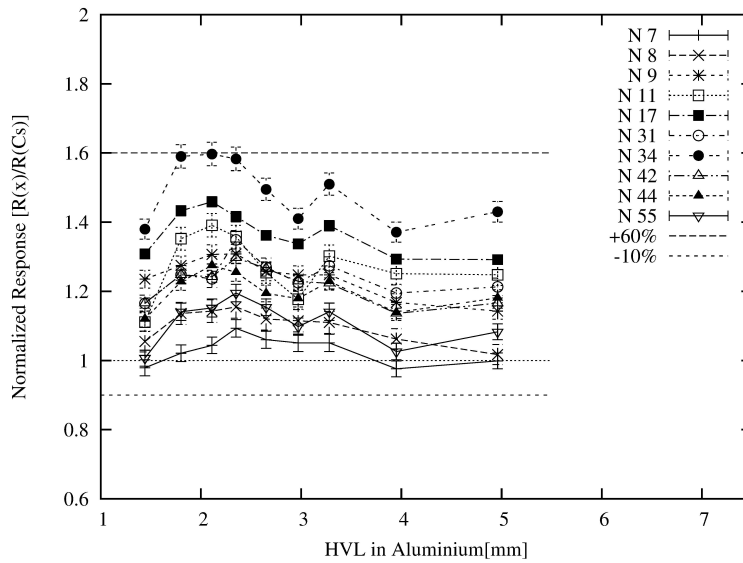


Figure 5: Setup for TLD irradiation with x-ray qualities.

Table 2: TLD-700 Relative Response normalized to <sup>137</sup>Cs.

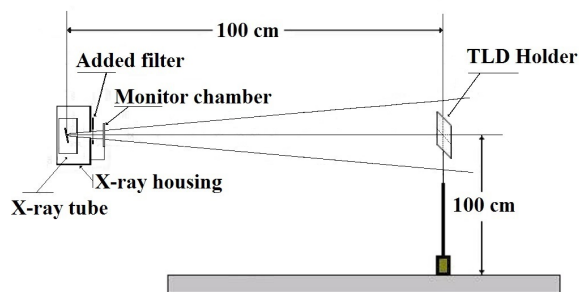
TLD	TLD Relative Response*			Air Kerma Relative error (%)**		
	Min	Max	Mean	Min	Max	Mean
N7	0.976	1.093	1.03	<b>-2.40</b>	9.3	3.04
N8	1.017	1.155	1.101	1.7	15.5	10.14
N9	1.143	1.308	1.243	14.3	30.8	24.33
N11	1.111	1.391	1.272	11.1	39.1	27.16
N17	1.292	1.459	1.366	29.2	45.9	36.56
N31	1.165	1.349	1.242	16.5	34.9	24.17
N34	1.371	1.597	1.485	37.1	<b>59.7</b>	48.51
N42	1.136	1.297	1.219	13.6	29.7	21.92
N44	1.12	1.275	1.2	12	27.5	20
N55	1.007	1.195	1.111	0.7	19.5	11.08

\* Relative energy response of TLD-700 chips calculated on investigated x-ray qualities  
 \*\* Indicated values represent 100\*(Relative Response - 1) in %

**Table 3:** TLD-700 Relative Response normalized to RQR5.

TLD	TLD Relative Response*			Air Kerma Relative error (%)**		
	Min	Max	Mean	Min	Max	Mean
N7	0.893	1	0.943	-10.7	0	-5.72
N8	0.881	1	0.954	-11.95	0	-4.64
N9	0.874	1	0.951	-12.61	0	-4.94
N11	0.818	1.024	0.936	<b>-18.19</b>	2.43	-6.37
N17	0.912	1.03	0.964	-8.76	<b>3.04</b>	-3.56
N31	0.864	1	0.92	-13.64	0	-7.96
N34	0.866	1.009	0.938	-13.39	0.88	-6.18
N42	0.876	1	0.94	-12.41	0	-6
N44	0.892	1.016	0.956	-10.76	1.59	-4.38
N55	0.843	1	0.929	-15.73	0	-7.05

\* Relative energy response of TLD-700 chips calculated on investigated x-ray qualities  
 \*\* Indicated values represent  $100 \times (\text{Relative Response} - 1)$  in %

**Figure 6:** TLD-700 Free-in-air energy response normalized to  $^{137}\text{Cs}$  (versus HVL).

and the highest value of its relative energy response for X-ray beam qualities investigated (taking the response for RQR5 X-ray quality as the reference value). The obtained results are summarized in Table 3.

From Table 3, without taking in account the energy dependence of TLDs, we deduced that relative error on air kerma did not exceed 20% for all selected chips when they are calibrated for RQR5 diagnostic radiology quality.

From Figure 7 we found that TLD chips have similar energy response (the same behavior). The greatest sensitivity is situated around RQR4 X-ray quality (2.57mmAl). The lowest sensitivity is situated around RQR2 X-ray quality (1.42mmAl). Also, we notice that all relative response of selected chips lies between 0.8 and 1.1 which give an absolute relative error on air kerma of less than 20%.

## 4 Conclusion

TLD dosimeters are widely used for dose estimate in diagnostic radiology, and it is also well known that they have an energy dependence for low energy x-rays. So, it is recommended that these dosimeters are calibrated for adequate X-ray qualities (those recommended by national and international standards), and to have some knowledge about the x-ray quality at the work places where they are intended to be used. Differences between air kerma estimated using the calibration factor for  $^{137}\text{Cs}$  and air kerma obtained taking in account the energy dependence can reach 60%. The best accuracy on air kerma estimates can be obtained by taking in account TLD energy dependence, and determining characteristics of X-ray qualities effectively used at diagnostic radiology units.

If TLD-700 are intended to be used for dose estimate in diagnostic radiology, we recommend calibrating TLD dosimeters for RQR5 beam quality which ensure a maximum error on air kerma estimate less than 20% (if the x-ray qualities at working place are comparables to diagnostic radiology qualities recommended by IEC61267 standard).

However, since the recommended accuracy limits in personnel dosimetry of external radiation are -33% to +50% near dose limits and -50% to +100% for low doses [24], the studied TLDs can be used for personnel dosimetry to estimate dose received in conventional diagnostic radiology.

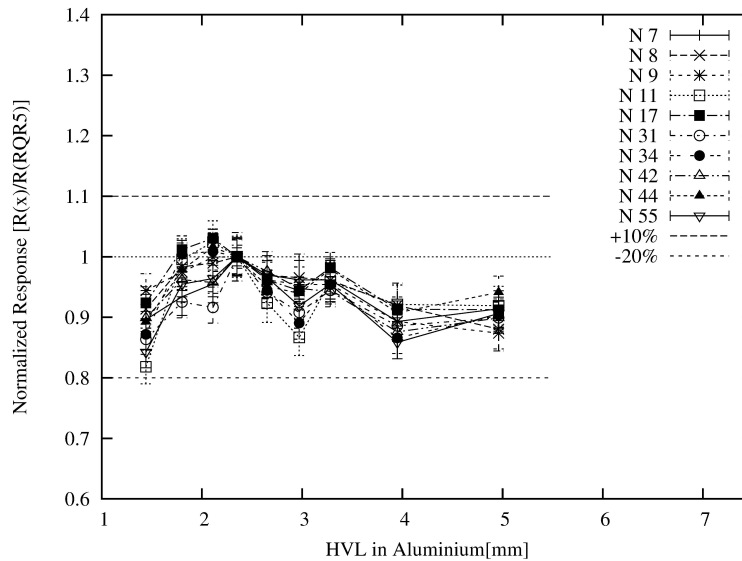


Figure 7: TLD-700 Free-in-air energy response normalized to RQR5 (versus HVL).

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