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The Response of Thermoluminescence Dosimeters to Monoenergetic Photons of Energies between 15 keV and 100 keV.

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## Abstract

Experimental photon energy response curves using monochromatic X-ray sources for the exposures are presented for standard thermoluminescent dosimeters applied in the personnel and environmental monitoring programmes at Risø. The investigation included dosimeters of LiF, $Li_2B_4O_7$:Mn, $CaF_2$:Mn, $CaF_2$:Dy and $CaSO_4$:Dy.

Good agreement between experimental and calculated data has been obtained for small-size (30 milligrams) dosimeters whereas dosimeters of greater masses showed an increa in the response which is ascribed to scattered radiation. Compared to data earlier obtained from the personnel badge using filtered X-rays a decrease of the response of the order of 10-20% was observed for exposures from monochromatic X-rays. The increase of the response of the personnel badge when attached to a phantom and due to scattering from the phantom material amounted to up to 50%.

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Contents

# 1. INTRODUCTION

Energy-dependence studies of the response of thermoluminescence dosimeters to X- and gamma-ray exposures have been the subject of many investigations, see e.g. refs. (1-4). Because of the great variety of dosimeter sizes and shapes studied the investigations often lead to varying results. Simple calculations may give good agreement with experimental data as far as small-size dosimeters are concerned ref. (5). However, for dosimeters composed of several grams of material (including dosimeter cover and filters) exact calculations of the dosimeter response are complicated since corrections for photon energy, scattering and attenuation should be included in the calculations.

The object of the work reported here was to obtain experimental data for the response to monoenergetic photons of standard TL dosimeters used at Risø in our personnel and environmental monitoring programmes and to compare the results with calculated data.

The work was part of a EURATOM comparison programme, and the irradiations were made at CEA, Fontenay-aux- Roses, France

Risø participated with three types of dosimeter packages:

1. LiF -, $Li_2B_4O_7$:Mn - and $CaF_2$:Mn dosimeters kept in 0.2 mm polyethylene bags.
2. LiF -, and $Li_2B_4O_7$:Mn dosimeters kept in the Risø personnel TLD-badge.
3. $CaF_2$:Dy-dosimeters, LiF-dosimeters and $CaSO_4$:Dy powder samples kept in polyethylene and steel containers and used for environmental monitoring.

The dosimeter packages were despatched from Risø 17th May, 1974, and the irradiated samples received again 4th July, 1974. All dosimeter packages were exposed to 250 mR at the following photon energies: 15, 34.5, 48.7, 58.6, 73.7, 96.5 keV and 1.25 MeV ($^{60}$Co), respectively.

# 2. DESCRIPTION OF DOSIMETERS

## 2.1. Dosimeters in Polyethylene Bags

Each dosimeter package contained three of each of the following dosimeters:

LiF, TLD-700 (Harshaw), 24 mg, 3.2 x 3.2 x 0.8 mm chips
$Li_2B_4O_7$:Mn (Risø), 24 mg, 4.55ø x 0.8 mm tables
$CaF_2$:Mn (Harshaw), 28 mg, 3.2 x 3.2 x 0.9 mm chips.

The dosimeters were separately placed in 0.2 mm black polyethylene bags.

## 2.2. Dosimeters in the Risø Personnel TLD badge

The Risø Personnel TLD badge ref. (6) was used for exposures in free air and on the front of a phantom.

The dosimeters were positioned in the TLD badge in the following way:

1 $Li_2B_4O_7$:Mn, 24 mg, tablet (Risø) at skin-dose position
2 $Li_2B_4O_7$:Mn, 24 mg, tablets (Risø) at depth-dose position
1 LiF, 24 mg, (TLD-700) chip (Harshaw) at depth-dose position.

The shielding of the dosimeters is shown in table 1.

Table 1

Dosimeter shielding in the Risø personnel TLD badge.

| | |
|---|---|
| Dosimeter for skin-dose estimation | 19 mg/cm$^2$, Celluloseacetat film<br>5 " " , paint x) layer |
| Dosimeter for depth-dose estimation | 19 mg/cm$^2$, Celluloseacetat film $(C_6H_{10}O_5)_n$<br>5 " " , x) paint layer<br>131 " " , styrene butadien acrylonitril $(C_{15}H_{17}N)_n$<br>270 " " , aluminium |

x) Composition: 0.275 Ti + 0.090 Ca + 0.185 C + 0.025 Al + 0.025 Si + 0.385 O + 0.015 H



## 2.3. Dosimeter Packages Used for Environmental Monitoring

The dosimeter packages used included a 2 mm steel container and a 1 mm polyethylene container each containing identical types of dosimeters.

The dosimeters were:

2 LiF, (TLD-100), 24 mg, 3.2 x 3.2 x 0.8 mm chips (Harshaw)
2 $CaF_2$:Dy, 28 mg, 3.2 x 3.2 x 0.9 mm chips (Harshaw)
2 $CaSO_4$:Dy, 25 mg, powder samples (Harshaw)

The shielding of the dosimeters is shown in table 2.

Table 2

Shielding of dosimeters in packages used for environmental monitoring

| | Steel x) container | Polyethylene container |
|---|---|---|
| LiF and $CaF_2$:Dy | 1576 mg/cm$^2$ steel<br>120 mg/cm$^2$ silastic | 100 mg/cm$^2$ polyethylene<br>120 mg/cm$^2$ silastic |
| $CaSO_4$:Dy | 1575 mg/cm$^2$ steel<br>120 mg/cm$^2$ silastic<br>40 mg/cm$^2$ polyethylene | 140 mg/cm$^2$ polyethylene<br>120 mg/cm$^2$ silastic |

x) Composition: 0.180 Cr + 0.080 Ni + 0.700 Fe + 0.020 Mn + 0.20 P

# 3. EXPERIMENTAL DATA

Using $^{60}$Co gamma-ray photons for the dosimeter calibration the TL response for a given photon-energy E may be expressed by:

$$C_E = \frac{K_E}{0.250 \cdot L_{air}} \times f$$

where $K_E$ is the light yield measured from the exposed (0.250 R) dosimeter, $L_{air}$ the corresponding calibration factor expressed in TL response per 1R $^{60}$Co gamma-ray photons for exposure in air under electronic equilibrium conditions and f a factor correcting for fading. If the dosimeter container used for the experiment has a wall thickness sufficient for establishing electronic equilibrium conditions for $^{60}$Co gamma-ray photons, it may be convenient to present the response data relative to the $^{60}$Co-values, thus simplifying (1) to

$$C_{E,rel.} = \frac{C_E}{C_{^{60}Co}} = \frac{K_E}{K_{^{60}Co}} \qquad (2)$$

Equation (1) was used for dosimeters from group 1 and 2 and equation (2) for dosimeters from group 3. The experimental data are shown in tables 4, 5, and 6 and in figures (1-7). Only $Li_2B_4O_7$: Mn dosimeters were corrected for fading.

The calibration factor $L_{air}$ (used in eq. (1)) was evaluated from the response value $L_{per}$ which is the measured TL-response for 1R $^{60}$Co exposure with the dosimeter placed in a 4.5 mm perspex container. Using Burlin's approach ref. (7) for estimation of dose absorption in dosimeters with sizes comparable with the range of the secondary electrons produced by the primary gamma photons in the wall- and dosimeter material, $L_{air}$ can be obtained from $L_{per}$ according to:

$$\frac{L_{air}}{L_{per}} = \frac{0.869[d \cdot (S/\rho)^{TLD}_{air} + (1-d)(\mu_{en}/\rho)^{TLD}_{air}]}{0.869 \cdot 0.97 \cdot (\mu_{en}/\rho)^{per}_{air}[d \cdot (S/\rho)^{TLD}_{per} + (1-d)(\mu_{en}/\rho)^{TLD}_{per}]}$$

$S/\rho$ is the relative mass stopping power evaluated from ref. (8), $\mu_{en}/\rho$ is the relative mass energy absorption coefficient evaluated from refs. (9-12) and d is a weighing factor determining the relative dose contribution to the dosimeter delivered by the electrons produced in the wall outside the dosimeter. The factor 0.97 refers to the attenuation of $^{60}$Co gamma-ray photons by 4.5 mm perspex. d was calculated from

$$d = \frac{\int_0^g e^{-\beta x} dx}{\int_0^g dx} = \frac{1-e^{-\beta g}}{\beta g}$$



where g is the average path length of the electrons crossing the dosimeter, here equal to the dosimeter thickness for the sintered dosimeters and 8/3 x radius for the cylindrical powder samples. $\beta$ is the effective mass absorption coefficient of the electrons here calculated according to Loevinger (13). Data applied for estimation of $L_{air}$ are shown in table 3.

## 1.2. Calculated data

On the assumption of

a) No fading

b) No LET dependence

c) Complete dosimeter transparency

d) A dosimeter cover sufficient for establishing electronic equilibrium conditions,

the C-values expressed by (1) and (2) may be calculated from

$$C = \frac{0.869(\mu_{en}/\rho)^{c}_{air} \cdot (d \cdot S^{TLD}_{c} + (1-d)(\mu_{en}/\rho)^{TLD}_{c})\, e^{(-\mu x)_c}}{[0.869(d \cdot (S/\rho)^{TLD}_{air} + (1-d)(\mu_{en}/\rho)^{TLD}_{air})]_{^{60}Co}} \; \frac{1-e^{(-\mu x)_{TLD}}}{(\mu x)_{TLD}} \qquad (4)$$

and

$$C = \frac{0.869(\mu_{en}/\rho)^{c}_{air}\,(d \cdot (S/\rho)^{TLD}_{c} + (1-d)(\mu_{en}/\rho)^{TLD}_{c})e^{(-\mu x)_c}}{[0.869(\mu_{en}/\rho)^{c}_{air}\,(d \cdot (S/\rho)^{TLD}_{c} + (1-d)(\mu_{en}/\rho)^{TLD}_{c})e^{(-\mu x)_c}]_{^{60}Co}} \times \frac{1-e^{(-\mu x)_{TLD}}}{(\mu x)_{TLD}} \qquad (5)$$

respectively. In these equations $\mu$ is attenuation coefficient x thickness, and c indicates dosimeter cover. An "average attenuation" thickness calculated from the expression $x = -\frac{1}{\mu}\ln(\frac{1}{r}\int_0^r \exp(-2\mu\sqrt{r^2-y^2})dy)$ was used for the dosimeter thickness of the cylindrical $CaSO_4$:Dy samples with the cylinder radius r. The last term in (4) and (5) is a factor correcting for flux depression caused by the dosimeter material which is only significant for low-energy photons.

For $^{60}$Co photon energies the dosimeter response is highly dependent on the degree of electronic equilibrium present which must be taken into account in the dose calculations for the dosimeters from group 1 and 2 since the dosimeter shields used here are not able to establish complete electron build-up. However, since the electron contamination of the $^{60}Co$ beam at the irradiation position must be very precisely defined to enable exact dose calculations, the $^{60}Co$ data were not included in the investigation for these dosimeters.

Some data evaluated for the calculations are shown in table 3, and the response data calculated according to (4) and (5) are presented in table 4, 5, and 6 and in figures (1-7).

No attempt was made to evaluate theoretical response data for the phantom irradiation.

## 5. DISCUSSION AND CONCLUSION

The investigation covered dosimeters of different masses varying from about 30 milligrams to about 35 grams (with the surrounding material included). Experimental energy-response curves obtained from the small-size dosimeters showed good agreement with energy--absorption calculations when corrections for flux depression caused by the dosimeter and its surrounding material were included (fig. 1). The measured responses from the dosimeters of greater masses were higher than the calculated data (figures (2-7)) which probabl[illegible] or the major part is due to additional dose contributions arising from scattered radiation, ref. (5). Comparisons of the results from the personnel badge with data earlier obtained using filtered X-rays, ref. (6) shows that exposures to monochromatic X-rays give lower (about 10-20%) responses than those obtained from exposures to filtered X-rays. This fact may be explained by differences in the photon quality of the primary and the scattered radiation. It is well-known that dosimeters exposed when attached to a phantom compared with free-air exposures show a considerable increase in the response due to scattering caused by the phantom material. This investigation showed an increase of the response amounting to up to about 50%.

## 6. ACKNOWLEDGEMENTS

The authors wish to thank G. Portal, CEA, France, for carrying out the irradiations and H. Seguin, EC, Luxembourg, for coordinating the intercomparison programme.



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Table 3.

Data used in the calculations of dosimeter responses to $^{60}Co$ gamma-ray exposures.

| | LiF | $Li_2B_4O_7$:Mn | $CaF_2$:Mn | $CaF_2$:Dy | $CaSO_4$:Dy |
|---|---|---|---|---|---|
| Dosimeter composition | 0.268 Li<br>0.732 F | 0.082 Li<br>0.254 B<br>0.658 O<br>0.001 Mn<br>0.005 Si | 0.495 Ca<br>0.484 F<br>0.021 Mn | 0.512 Ca<br>0.486 F<br>0.002 Dy | 0.294 Ca<br>0.235 S<br>0.470 O<br>0.001 Dy |
| Dosimeter thickness ($g/cm^2$) | 0.230 | 0.147 | 0.277 | 0.273 | 0.188 |
| $(S/\rho)^{TLD}_{air}$ | 0.91 | 0.98 | 0.90 | 0.90 | 0.95 |
| $(S/\rho)^{TLD}_{perspex}$ | 0.84 | 0.89 | 0.83 | 0.82 | 0.87 |
| $(\mu_{en}/\rho)^{TLD}_{air}$ | 0.936 | 0.974 | 0.977 | 0.981 | 1.004 |
| $(\mu_{en}/\rho)^{TLD}_{perspex}$ | 0.864 | 0.899 | 0.902 | 0.906 | 0.927 |
| d | 0.32 | 0.44 | 0.27 | 0.29 | 0.25 |
| $\frac{L_{air}}{L_{perspex}}$ | 1.034 | 1.038 | 1.034 | - | - |



Table 4.

Experimental and calculated response data of LiF, $Li_2B_4O_7$:Mn and $CaF_2$: Mn solid dosimeters exposed in 0.2 mm polyethylene bags. Dosimeter response = 1.00 for 250 mR $^{60}Co$ exposure of bare dosimeter free in air and under electronic equilibrium conditions.

| Photon energy (keV) | LiF | | $Li_2B_4O_7$:Mn | | $CaF_2$:Mn | |
|---|---|---|---|---|---|---|
| | Exp. | Theor. | Exp. | Theor. | Exp. | Theor. |
| 15 | 1.08 | 1.06 | 0.79 | 0.80 | 3.32 | 2.70 |
| 34.5 | 1.22 | 1.23 | 0.85 | 0.89 | 10.68 | 11.10 |
| 48.7 | 1.12 | 1.16 | 0.89 | 0.91 | 10.22 | 10.30 |
| 58.6 | 1.14 | 1.12 | 0.92 | 0.94 | 8.62 | 8.60 |
| 73.7 | 1.08 | 1.08 | 0.95 | 0.94 | 5.94 | 5.80 |
| 96.5 | 1.04 | 1.03 | 1.02 | 0.98 | 3.48 | 3.30 |

## Table 5.

Experimental and calculated response data of LiF and $Li_2B_4O_7$:Mn dosimeters exposed in the Risø personnel TLD badge. Dosimeter response = 1.00 for 250 mR $^{60}$Co. exposed to the bare dosimeter free in air and under electronic equilibrium conditions.

| Photon Energy keV | Free in air | | | | | | Phantom | | |
|---|---|---|---|---|---|---|---|---|---|
| | $Li_2B_4O_7$:Mn Skin-dose position | | $Li_2B_4O_7$:Mn Depth-dose position | | LiF Depth-dose position | | $Li_2B_4O_7$:Mn Skin-dose position | $Li_2B_4O_7$:Mn Depth-dose position | LiF Depth-dose position |
| | exp. | calc. | exp. | calc. | exp. | calc. | exp. | exp. | exp. |
| 15 | 0.64 | 0.74 | 0.16 | 0.11 | 0.21 | 0.20 | 0.85 | 0.13 | 0.22 |
| 34.5 | 0.87 | 0.88 | 0.80 | 0.70 | 1.16 | 0.97 | 1.04 | 0.91 | 1.31 |
| 48.7 | 1.02 | 0.91 | 1.01 | 0.81 | 1.26 | 1.06 | 1.00 | 1.16 | 1.55 |
| 58.6 | 0.95 | 0.94 | 1.07 | 0.85 | 1.24 | 1.05 | 1.35 | 1.24 | 1.60 |
| 73.7 | 1.10 | 0.76 | 1.03 | 0.87 | - | 1.00 | 1.51 | 1.37 | 1.53 |
| 96.5 | 1.24 | 0.97 | 0.98 | 0.91 | 1.19 | 0.95 | 1.46 | 1.28 | 1.32 |



## Table 6.

Experimental and calculated response data of LiF, $CaF_2$:Dy and $CaSO_4$:Dy dosimeters exposed in packages used for environmental monitoring. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure given to the dosimeter package at CEA, France.

| Photon energy keV | Steel container | | | | | | Polyethylene container | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LiF | | $CaSO_4$:Dy | | $CaF_2$:Dy | | LiF | | $CaSO_4$:Dy | | $CaF_2$:Dy | |
| | exp. | calc. | exp. | calc. | exp. | calc. | exp. | calc. | exp. | calc. | exp. | calc. |
| 15 | 0.01 | - | 0.03 | - | 0.05 | - | 0.62 | 0.52 | 2.8 | 2.8 | 2.4 | 1.52 |
| 34.5 | 0.03 | - | 0.10 | 0.01 | 0.1 | 0.01 | 1.30 | 1.13 | 10.93 | 9.0 | 13.9 | 10.4 |
| 48.7 | 0.12 | 0.05 | 0.62 | 0.37 | 0.7 | 0.47 | 1.26 | 1.12 | 9.73 | 7.8. | 14.4. | 10.2 |
| 58.6 | 0.26 | 0.19 | 1.41 | 1.14 | 1.8 | 1.47 | 1.14 | 1.08 | 7.84 | 6.6. | 10.8 | 8.7. |
| 73.7 | 0.49 | 0.46 | 2.32 | 1.80 | 3.2. | 2.40 | 1.19 | 1.03 | 8.28 | 3.85 | 8.3 | 6.2 |
| 96.5 | 0.78 | 0.60 | 2.27 | 1.68 | 3.0 | 2.10 | 1.12 | 1.01 | 3.39 | 2.80 | 4.9 | 3.5 |

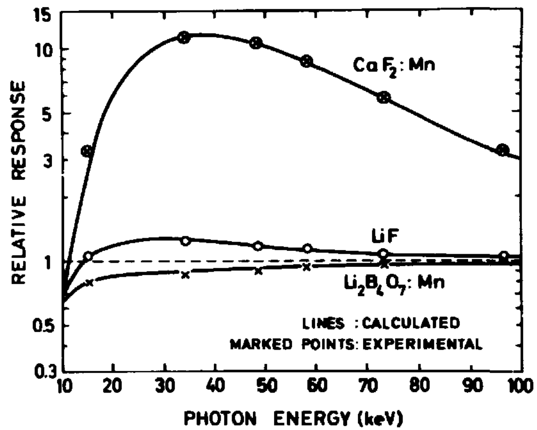


Fig. 1. Experimental and calculated energy-response curves of LiF (TLD-700) $Li_2B_4O_7$:Mn and $CaF_2$:Mn dosimeters exposed in 0.2 mm polyethylene bags. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure of bare dosimeter free in air and under electronic equilibrium conditions.

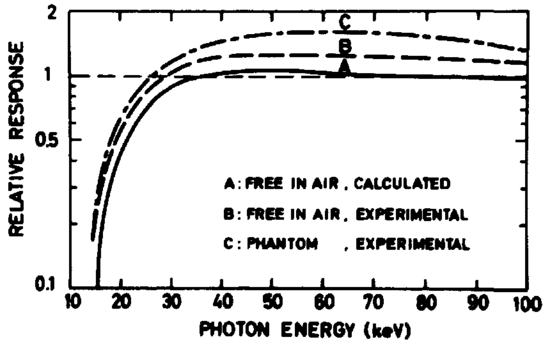


Fig. 2. Experimental and calculated energy-response curves of LiF (TLD-700) chips exposed at depth-dose position of Risö personnel TLD badge. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure of bare dosimeter free in air and under electronic equilibrium conditions.

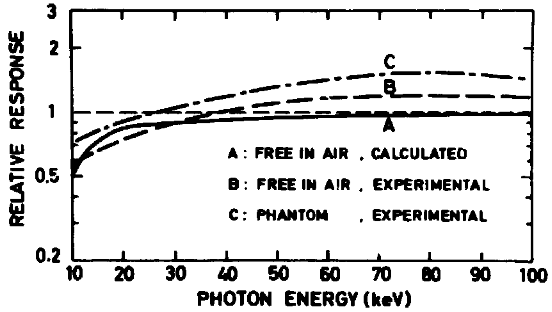


Fig. 3. Experimental and calculated energy-response curves of $Li_2B_4O_7$:Mn dosimeters exposed at skin-dose position of Risö personnel TLD badge. Dosimeter response = 1,00 for 250 mR $^{60}$Co gamma-ray exposure of bare dosimeter free in air and under electronic equilibrium conditions.

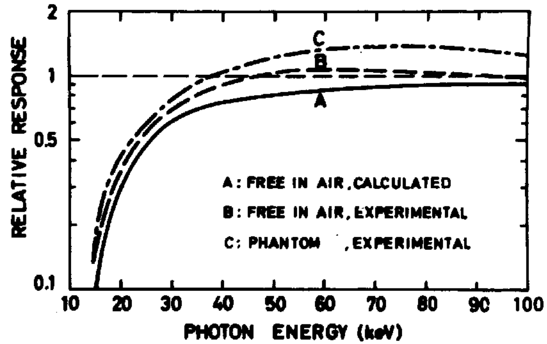


Fig. 4. Experimental and calculated energy-response curves of $Li_2B_4O_7$:Mn dosimeters exposed at depth-dose position of Risö personnel TLD badge. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure of bare dosimeter free in air and under electronic equilibrium conditions.

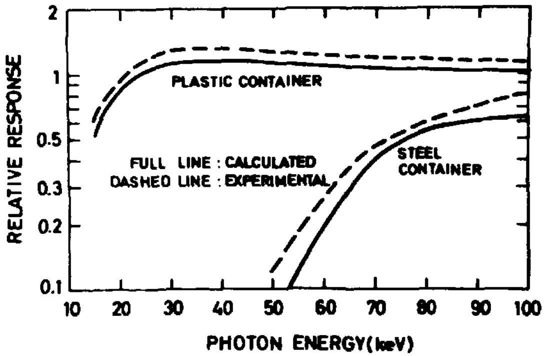


Fig. 5. Experimental and calculated energy-response curves of LiF (TLD-100) chips exposed in dosimeter packages used for environmental monitoring. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure given to the dosimeter package at CEA, France.

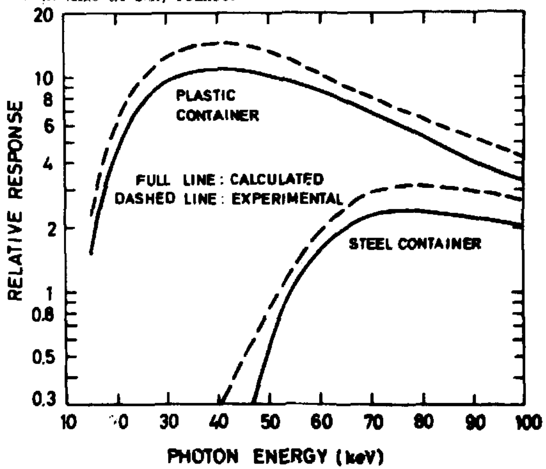


Fig. 6. Experimental and calculated energy-response curves of $CaF_2$:Dy (TLD-200) chips exposed in dosimeter packages used for environmental monitoring. Dosimeter response = 1.00 for 250 mR $^{60}$Co gama-ray exposure given to the dosimeter package at CEA, France.

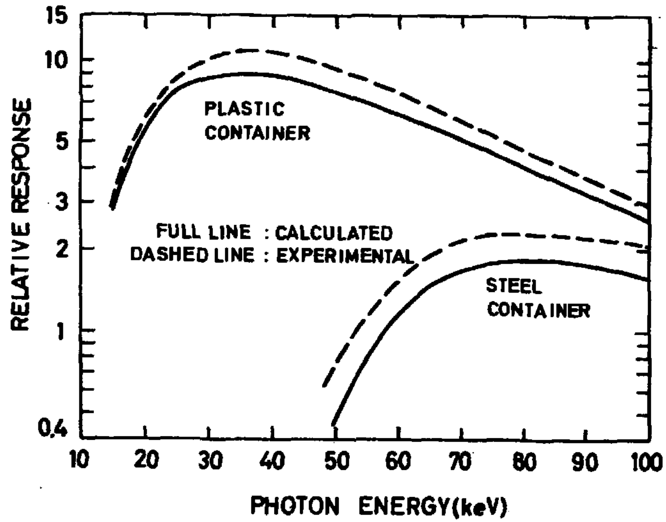


Fig. 7. Experimental and calculated energy-response curves of $CaSO_4$:Dy dosimeter samples exposed in dosimeter packages used for environmental monitoring. Dosimeter response = 1.00 for 250 mR $^{60}$Co gamma-ray exposure given to the dosimeter package at CEA, France.