



Standard Practice for Application of $\text{CaF}_2(\text{Mn})$ Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments¹

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1. Scope

1.1 This practice describes a procedure for measuring gamma-ray absorbed dose in $\text{CaF}_2(\text{Mn})$ thermoluminescence dosimeters (TLDs) exposed to mixed neutron-photon environments during irradiation of materials and devices. The practice has broad application, but is primarily intended for use in the radiation-hardness testing of electronics. The practice is applicable to the measurement of absorbed dose from gamma radiation present in fields used for neutron testing.

1.2 This practice describes a procedure for correcting for the neutron response of a $\text{CaF}_2(\text{Mn})$ TLD. The neutron response may be subtracted from the total response to give the gamma-ray response. In fields with a large neutron contribution to the total response, this procedure may result in large uncertainties.

1.3 More precise experimental techniques may be applied if the uncertainty derived from this practice is larger than the user can accept. These techniques are not discussed here. The references in Section 8 describe some of these techniques.

1.4 This practice does not discuss effects on the TLD reading of neutron interactions with material surrounding the TLD to ensure charged particle equilibrium. These effects depend on the surrounding material and its thickness, and on the neutron spectrum (1).²

2. Referenced Documents

2.1 ASTM Standards:³

- E 170 Terminology Relating to Radiation Measurements and Dosimetry
- E 666 Practice for Calculating Absorbed Dose from Gamma or X Radiation
- E 668 Practice for Application of Thermoluminescence Do-

simetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronics

E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics

E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics

E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E 1854 Practice for Assuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts

F 1190 Guide for Neutron Irradiation of Unbiased Electronic Components

3. Terminology

3.1 Definitions:

3.1.1 *absorbed dose*—see Terminology E 170.

3.1.2 *exposure*—see Terminology E 170.

3.1.3 *kerma*—see Terminology E 170.

3.1.4 *linear energy transfer (LET)*—the energy loss per unit distance as a charged particle passes through a material. Electrons resulting from gamma-ray interactions in a material generally have a low LET. Heavy charged particles resulting from neutron interactions with a material generally have a high LET.

3.1.5 *neutron sensitivity $m(E)$* —the ratio of the detector reading, that is, the effective neutron dose, to the neutron fluence. Thus,

$$m(E) = \frac{M(E)}{\Phi(E)} \quad (1)$$

where:

$\Phi(E)$ = the neutron fluence, and

$M(E)$ = the apparent dose (extra light output) in the TLD caused by neutrons of energy E .

4. Significance and Use

4.1 Electronic devices are typically tested for survivability against gamma radiation in pure gamma-ray fields. Testing their response against neutrons is more complex since there is invariably a gamma-ray component to the neutron field. The

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² The boldface numbers in parentheses refer to the list of references at the end of this standard.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

gamma-ray response of the device is subtracted from the overall response to find the response to neutrons. This testing thus requires a determination of the gamma-ray exposure in the mixed field. To enhance the neutron effects, the field is sometimes selected to have as large a neutron component as possible.

4.2 $\text{CaF}_2(\text{Mn})$ thermoluminescent detectors are often used to monitor the gamma-ray dose for this type of testing. Since they are exposed along with the device under test to the mixed field, their response must be corrected for neutrons. In a field rich in neutrons, the uncertainty in the TLD response grows, but this may be unimportant since the gamma-ray effects on the device under test may be relatively small. In fields with relatively few neutrons, the TLD response may be used to make a relatively large correction for gamma response on the device under test. Under this condition, the relative uncertainty in the TLD response shrinks.

4.3 This practice gives a means of estimating the response of $\text{CaF}_2(\text{Mn})$ to neutrons. This neutron response is then subtracted from the measured response to give the response to gamma rays. The procedure has relatively high uncertainty because the neutron response of $\text{CaF}_2(\text{Mn})$ may vary depending on the source of the material, and this procedure is a generic calculation applicable to $\text{CaF}_2(\text{Mn})$ independent of source. The neutron response given in this practice is a summary of responses reported in the literature. The associated uncertainty envelops the range of results reported, and includes the variety of TLDs used as well as the uncertainties in the determination of the neutron response as reported by various authors.

4.4 Should the user find the resulting uncertainties too large for his purposes, the neutron response of the particular TLDs in use must be determined. This practice does not supply guidance on how to determine the neutron response of a specific batch of TLDs.

4.5 Neutron effects on electronics under test are usually reported in terms of 1 MeV equivalent fluence (E 722). Neutron effects of TLDs, as discussed here, are reported in units of absorbed dose, since they are corrections to the gamma-ray dose.

5. Exposure Procedure

5.1 Determine the neutron and gamma-ray environments. Calculate the relative neutron response of the TLDs. If this response is negligible, document this result. No further measurements are required for the purpose of neutron sensitivity of the TLDs.

5.2 Expose the TLD along with the device under test (see Practice E 1854 and Guide F 1190). If there is a non-negligible fast-neutron or thermal-neutron response, a fast-neutron monitor (for example, nickel) or thermal-neutron monitor (for example, gold) must also be exposed with the device under test.

5.3 The neutron spectrum must be known (see Guides E 720 and E 721). This may be determined in a separate exposure. The device under test must not significantly perturb the neutron spectrum.

5.4 Practices E 668 and E 1854 provide information on the calibration and use of $\text{CaF}_2(\text{Mn})$ dosimeters.

6. Neutron Sensitivity of $\text{CaF}_2(\text{Mn})$

6.1 Thermal Neutrons:

6.1.1 Thermal neutron responses of $\text{CaF}_2(\text{Mn})$ ranging from 0.06 to 0.89 Gy($\text{CaF}_2(\text{Mn})$) (6 to 89 rad ($\text{CaF}_2(\text{Mn})$)) per 10^{12}n/cm^2 are reported (2). The sensitivity may depend on the manganese doping of the TLD. The sensitivity may also be a function of dosimeter size, since the dosimeter surface-to-volume ratio affects the portion of the charged particles born within the TLD that deposit their dose outside the TLD. Horowitz (3) calculates a thermal neutron response of 0.34 Gy(CaF_2) (34 rad (CaF_2)) per 10^{12}n/cm^2 for $\text{CaF}_2(\text{Mn}$ (2 % by weight)) for TLD of dimensions 0.165 by 0.165 by 0.083 cm.

NOTE 1—Thermal neutron response is typically reported in terms of TLD response relative to a Co-60 equivalent Roentgen (R)/ n/cm^2 . For Co-60 decay gamma rays, the conversion from Roentgen to Gy(air) is 0.00869 Gy(air)/R. The conversion from Gy(air) to Gy(CaF_2) is 0.975. Thus Gy(CaF_2) is 0.0085 times the exposure in Roentgen.

6.1.2 A value of 0.45 ± 0.45 Gy (45 ± 45 rad) (1σ) ($\text{CaF}_2(\text{Mn})$) per 10^{12} thermal n/cm^2 shall be used for $\text{CaF}_2(\text{Mn})$ TLDs.

NOTE 2—The variation in measured thermal neutron sensitivities for $\text{CaF}_2(\text{Mn})$ is as large as the average sensitivity.

6.2 *Fast Neutrons*—A recommended fast-neutron response is displayed in Fig. 1 and listed in Table 1. For the purpose of this practice, the fast-neutron response is the response due to all neutrons above 0.4 eV. Table 1 is the Rinard (4) response function multiplied by 1.2. The factor of 1.2 was used to scale the response function to give an optimal fit to a variety of measured data. See Fig. 2 for the quality of this coverage. Use this response to calculate the fast neutron response in Gy(CaF_2).

$$\text{Response} = \int R(E) \cdot \Phi(E) dE \quad (2)$$

where $R(E)$ is taken from Table 1 and $\Phi(E)$ is the neutron spectrum in $\text{n}\cdot\text{cm}^{-2}\cdot\text{MeV}^{-1}$. Take the 1σ uncertainty in this response as 50 % of the calculated value.

6.3 Subtract the thermal and fast neutron responses from the measured responses to obtain the gamma-ray response:

$$D_G = D_{\text{Meas}} - D_{\text{Thermal}} - D_{\text{Fast}} \quad (3)$$

6.3.1 The uncertainties are added in quadrature:

$$\sigma_{D_G} = \sqrt{\sigma_{D_{\text{Meas}}}^2 + \sigma_{D_{\text{Thermal}}}^2 + \sigma_{D_{\text{Fast}}}^2} \quad (4)$$

7. Reporting

7.1 The gamma-ray dose is reported after the neutron corrections are made. Sometimes an additional correction is made to convert from dose $\text{CaF}_2(\text{Mn})$ to dose in the material of the device under test (see Practice E 666). The corrections for neutron response shall be retained by the measuring laboratory and be made available upon request.

7.2 If the correction is negligible (<5 %), a correction need not be made. The lack of correction, and the reasons, shall be stated.

7.3 The uncertainty in the dose reported from the TLD measurement shall include any uncertainty due to neutron effects.

Fast Neutron Sensitivity

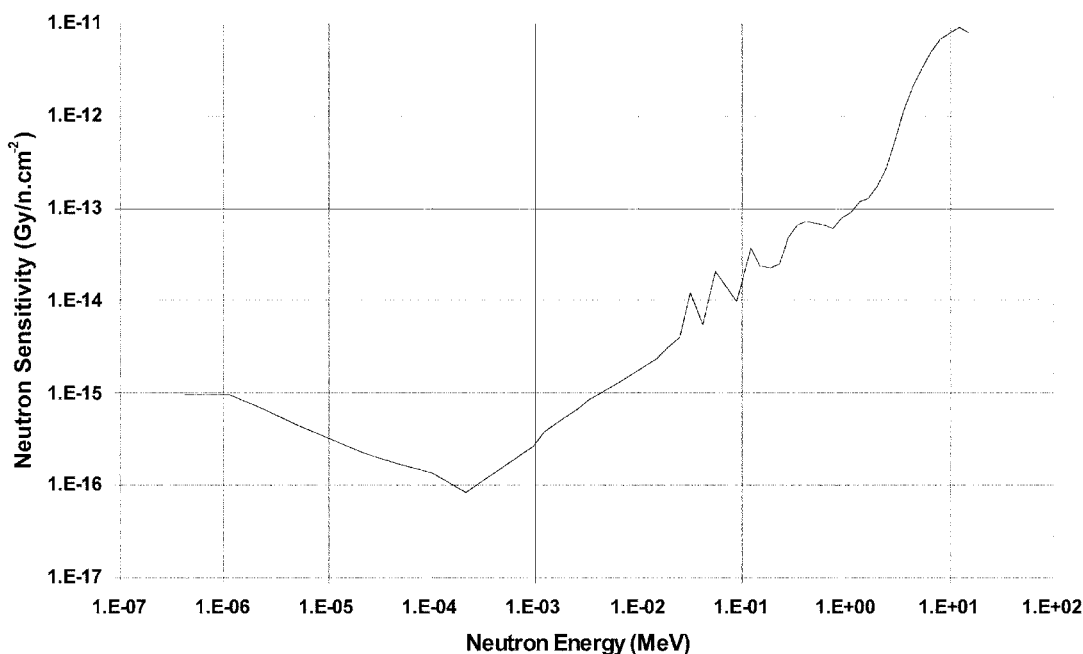


FIG. 1 Fast-Neutron Sensitivity of $\text{CaF}_2(\text{Mn})$ TLDs

TABLE 1 Fast Neutron Sensitivity of $\text{CaF}_2(\text{Mn})$ TLDs

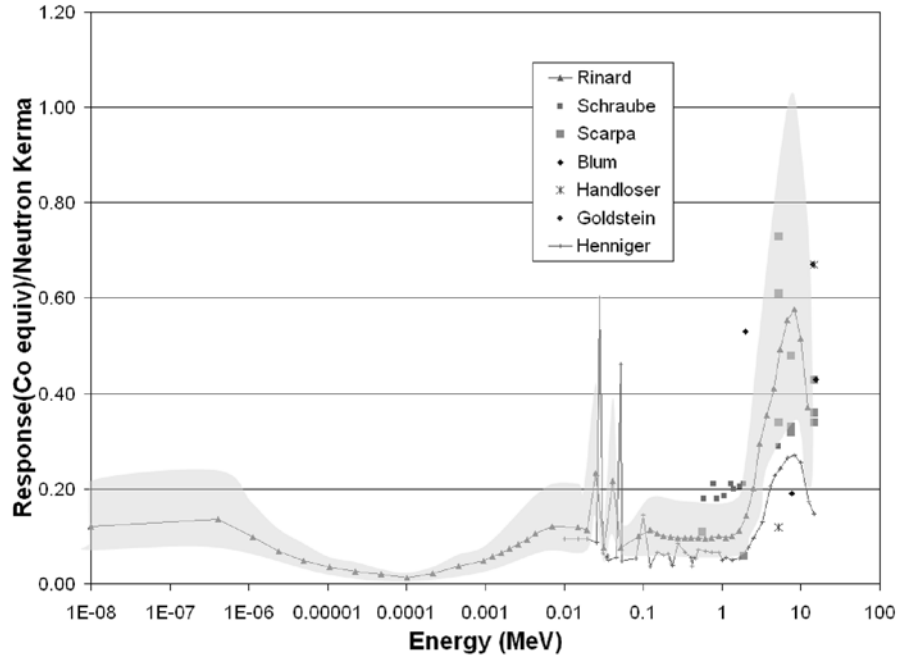
Energy (MeV)	Response $\text{Gy}(\text{CaF}_2)/\text{n}\cdot\text{cm}^{-2}$	Energy (MeV)	Response $\text{Gy}(\text{CaF}_2)/\text{n}\cdot\text{cm}^{-2}$	Energy (MeV)	Response $\text{Gy}(\text{CaF}_2)/\text{n}\cdot\text{cm}^{-2}$
4.14E-07	9.78E-16	1.50E-02	2.33E-15	1.11E+00	9.18E-14
1.13E-06	9.78E-16	1.93E-02	3.17E-15	1.35E+00	1.15E-13
2.38E-06	6.72E-16	2.48E-02	4.02E-15	1.65E+00	1.31E-13
5.04E-06	4.63E-16	3.19E-02	1.22E-14	2.02E+00	1.75E-13
1.07E-05	3.22E-16	4.09E-02	5.56E-15	2.47E+00	2.69E-13
2.26E-05	2.28E-16	5.25E-02	2.05E-14	3.01E+00	5.64E-13
4.78E-05	1.69E-16	8.65E-02	9.67E-15	3.68E+00	1.17E-12
1.01E-04	1.36E-16	1.23E-01	3.74E-14	4.49E+00	2.08E-12
2.14E-04	8.42E-17	1.50E-01	2.41E-14	5.49E+00	3.32E-12
4.54E-04	1.51E-16	1.83E-01	2.24E-14	6.70E+00	4.99E-12
9.61E-04	2.68E-16	2.24E-01	2.46E-14	8.19E+00	6.59E-12
1.23E-03	3.83E-16	2.73E-01	4.87E-14	1.00E+01	8.10E-12
1.59E-03	4.67E-16	3.34E-01	6.47E-14	1.22E+01	9.18E-12
2.04E-03	5.66E-16	4.08E-01	7.24E-14	1.49E+01	8.05E-12
2.61E-03	6.84E-16	4.98E-01	6.77E-14		
3.36E-03	8.42E-16	6.08E-01	6.49E-14		
4.31E-03	1.03E-15	7.43E-01	6.11E-14		
7.10E-03	1.40E-15	9.07E-01	8.04E-14		

8. Precision and Bias

8.1 None of the uncertainty attributable to this practice is derived by statistical techniques. Therefore, all the uncertainty is Type B. The level of uncertainty is quite large, since it encompasses the range of response of $\text{CaF}_2(\text{Mn})$ independent of manufacturer or batch. The uncertainty in the reported gamma-ray dose will depend on the relative amounts of neutrons and gamma rays in the exposure field.

8.2 See Practice E 668 for a description of the statistical (Type A) uncertainties involved with TLD use.

8.3 Fig. 2 shows the relative neutron sensitivity of $\text{CaF}_2(\text{Mn})$ as determined by various authors. The relative neutron response is given as the light output from one neutron $\text{Gy}(\text{CaF}_2)$ divided by the light output of the TLD to one $\text{Gy}(\text{CaF}_2)$ in a Co-60 gamma ray field. There is a large range of response. The shaded area represents the 1σ range of values



As measured and calculated by various authors, including Rinard (4), Schraube (5), Scarpa (6), Blum (7), Handloser (8), Goldstein (9), and Henniger (10).
FIG. 2 Relative Neutron Sensitivity of CaF₂(Mn)

specified by this practice. Reference (11) suggests an average value of 0.29 ± 0.18 for neutrons below 10 MeV. For reactor fields based on ²³⁵U fission, a lower value would be more appropriate, such as 0.12 ± 0.1 . Thus, the light output of the CaF₂(Mn) is approximated by:

$$light = K[D_G(CaF_2(Mn)) + 0.12 \cdot D_N(CaF_2(Mn))] \quad (5)$$

where the total light output is proportional to the gamma-ray dose D_G plus 12 % of the neutron dose D_N .

9. Keywords

9.1 dosimetry; gamma; LET; mixed-field; neutron; TLD

APPENDIX

(Nonmandatory Information)

X1. LET DEPENDENCE OF LIGHT OUTPUT OF TLDs

X1.1 Both neutrons and gamma rays produce dose in CaF₂(Mn). Only a few percent of the absorbed energy is released in the form of light when the TLD is heated. The efficiency of the conversion of absorbed dose into light is different for gamma rays and for neutrons. Gamma rays produce electrons, which have a low LET. The heavy ions resulting from neutron interactions have high LET. This tends to suppress the neutron response. Fig. X1.1 (12) shows the relative efficiency for conversion of absorbed dose into TLD light (η) as a function of LET/density (L/ρ). Fig. X1.1 is normalized to a Co-60 efficiency of 1.0. The figure shows that the heavy charged particles produced by neutron interactions in TLD material have a greatly reduced efficiency.

X1.2 Calculations (4, 10) of the neutron response of TLDs

to neutrons have taken this LET dependence into account. Fig. X1.1 shows substantial variation (even for a given LET) in the efficiency for producing a measurable response. This gives rise to a large uncertainty in the sensitivity of TLDs to neutrons. Additionally, other aspects of the recoil ions also affect the neutron sensitivity. See Ref (13) for a description of these considerations.

X1.3 The neutron sensitivity of TLDs may be dependent on the structure of the material. Small variations in manufacturing process, the introduction of ppm contaminants, the annealing procedure used, and irradiation with large neutron fluences may change the neutron sensitivity. These effects are ignored in this practice except to the extent that they are bounded by the corrections in Section 6.

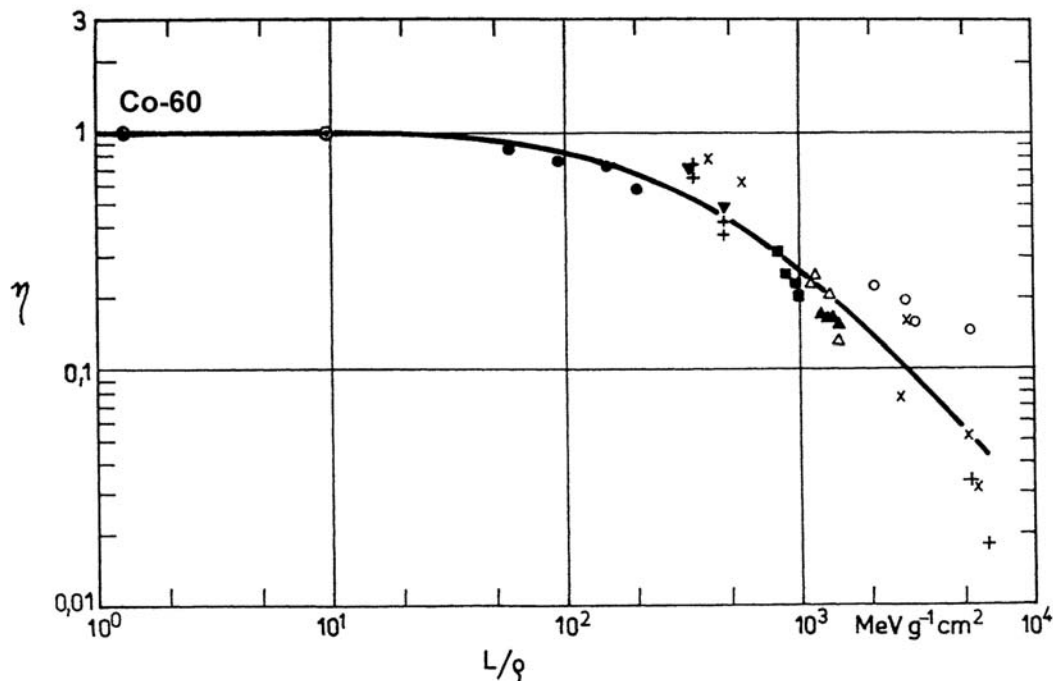


FIG. X1.1 Efficiency Relative to Co-60 for Conversion of Charged-Particle Energy into Light as a Function of LET

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