Standard Practice for
Application of CaF_2(Mn) Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments[1]

This standard is issued under the fixed designation E2450; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes a procedure for correcting a CaF_2(Mn) thermoluminescence dosimeter (TLD) reading for its response to neutrons during the irradiation. The neutron response may be subtracted from the total TLD 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.

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

1.3 This practice does not discuss effects on the TLD reading from neutron interactions with the material surrounding the TLD and used to ensure a charged particle equilibrium. These effects will depend on the isotopic composition of the surrounding material and its thickness, and on the incident neutron spectrum (**1**).[2]

1.4 The values stated in SI units are to be regarded as standard.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E666 Practice for Calculating Absorbed Dose From Gamma or X Radiation

E668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices

E720 Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics

E721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics

E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts

F1190 Guide for Neutron Irradiation of Unbiased Electronic Components

3. Terminology

3.1 *Definitions:*

3.1.1 *absorbed dose*—see Terminology E170.

3.1.2 *exposure*—see Terminology E170.

3.1.3 *kerma*—see Terminology E170.

3.1.4 *linear energy transfer (LET)*—the energy loss per unit distance as a charged particle passes through a material.

3.1.4.1 *Discussion*—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,

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

where:

$\Phi(E)$ = the neutron fluence, and
$M(E)$ = the apparent dose (light output) in the TLD caused by neutrons of energy E.

4. Significance and Use

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

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[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.07 on Radiation Dosimetry for Radiation Effects on Materials and Devices.

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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.

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

4.2 CaF_2(Mn) TLDs are often used to monitor the gamma-ray dose in mixed neutron/gamma radiation fields. Since the dosimeters 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 interpretation of the TLD response grows. In fields with relatively few neutrons, the total TLD response may be used to make a correction for gamma response of the device under test. Under this condition, the relative uncertainty in the TLD neutron response is not likely to drive the overall uncertainty in the correction to the electronic device response.

4.3 This practice gives a means of estimating the response of CaF_2(Mn) TLDs to neutrons. This neutron response is then subtracted from the measured response to determine the TLD response due to gamma rays. The procedure has relatively high uncertainty because the neutron response of CaF_2(Mn) TLDs may vary depending on the source of the material, and this procedure is a generic calculation applicable to CaF_2(Mn) TLDs independent of their manufacturer/source. The neutron response given in this practice is a summary of CaF_2(Mn) TLD responses reported in the literature. The associated uncertainty envelops the range of results reported, and includes the variety of CaF_2(Mn) 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 CaF_2(Mn) 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(Si) equivalent fluence (E722). 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 maximum bound of the TLD response to the neutron environment. No further measurements are required for the purpose of documenting the neutron sensitivity of the TLDs.

5.2 Expose the TLD along with the device under test (see Practice E1854 and Guide F1190). 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 E720 and E721). This may be determined in a separate exposure. A neutron monitor should be used on the irradiation along with the device under test (see Practice E1854). The device under test must not significantly perturb the neutron spectrum.

5.4 Practice E668 provides information on the calibration and use of CaF_2(Mn) dosimeters for use in X-ray and gamma radiation fields as well as for electrons in a designated energy range. The guidance in this standard is to adopt, for use in mixed neutron-gamma radiation fields, these same calibration, handling, and read-out techniques for CaF_2(Mn) TLDs. In particular, the CaF_2(Mn) TLDs that are used in a mixed neutron photon field should only be calibrated in a well-characterized gamma-only radiation source. See Section 9 of E668.

6. Neutron Sensitivity of CaF_2(Mn)

6.1 *Thermal Neutrons:*

6.1.1 Thermal neutron responses of CaF_2(Mn) ranging from 0.06 to 0.89 Gy[CaF_2(Mn)] (6 to 89 rad[CaF_2(Mn)] per 10^{12} n/cm^2 are reported (**2**). The sensitivity may depend on several factors, one of the most important parameters being 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**) reported a thermal neutron response of 0.34 Gy(CaF_2) (34 rad[CaF_2]) per 10^{12} n/cm^2 for CaF_2(Mn), with 2 % Mn 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. For the Co-60 gamma energy, the conversion from Gy(air) to Gy(CaF_2) is 0.975. Thus, in a Co-60 source, 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) (1 σ) [CaF_2(Mn)] per 10^{12} thermal n/cm^2 shall be used for CaF_2(Mn) TLDs.

NOTE 2—The variation in measured thermal neutron sensitivities for CaF_2(Mn) is as large as the average sensitivity.

6.2 *Fast Neutrons*—A recommended energy-dependent 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 a neutron with an energy 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).

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

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

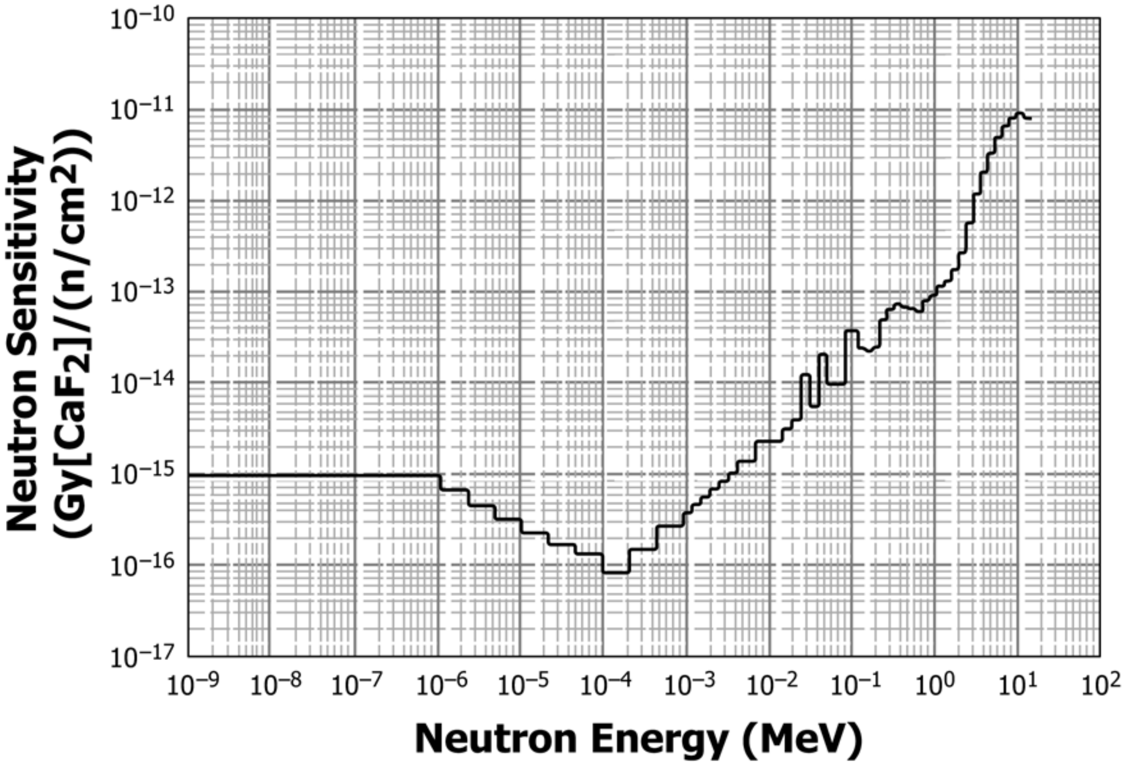

FIG. 1 Fast-Neutron Sensitivity of CaF_2(Mn) TLDs

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

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

6.3.1 The uncertainties are uncorrelated and should be added in quadrature:

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

7. Reporting

7.1 The gamma-ray dose is reported after the neutron corrections are made to the TLD response. Sometimes an additional correction is made to convert from units of dose in CaF_2(Mn) to dose in the material of the device under test (see Practice E666).

7.2 The corrections for neutron response shall be retained by the measuring laboratory and be made available upon request. The documentation for the correction should reference information used from fast or thermal neutron monitors and the neutron spectrum used to characterize the radiation field.

7.3 If the correction for neutron response to the TLD is negligible (<5 %), a correction need not be made. The lack of correction, and the reasons, shall be stated.

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

8. Precision and Bias

8.1 None of the uncertainty attributable to the neutron correction process addressed in 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 CaF_2(Mn) independent of a specific manufacturer or TLD 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 E668 for a description of the statistical (Type A) uncertainties involved with TLD use.

8.3 Fig. 2 shows the relative neutron sensitivity of CaF_2(Mn) as determined by various authors. The relative neutron response is given as the light output from one Gy(CaF_2) as delivered in the neutron field divided by the light output of the TLD from one Gy(CaF_2) as delivered in a Co-60 gamma ray field. There is a significant variation seen in the response. The shaded area represents the 1 σ range of values 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 ^{235}U fission, a lower value would be more appropriate, such as 0.12 ± 0.1. Thus, the light output of the CaF_2(Mn) in ^{235}U fission radiation fields is approximated by:

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

where K is the proportionality constant for the light output of the TLD reader as determined by the calibration in the gamma-only radiation field, thus making the total light output 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

TABLE 1 Fast Neutron Sensitivity of CaF$_2$(Mn) TLDs

Group Number	Lower Energy Bound (MeV)	Upper Energy Bound	Effective Response Gy[CaF^2]/(n/cm^2)
1	...	4.140E–07	9.78E–16
2	4.140E–07	1.125E–06	9.78E–16
3	1.125E–06	2.380E–06	6.72E–16
4	2.380E–06	5.040E–06	4.63E–16
5	5.040E–06	1.068E–05	3.22E–16
6	1.068E–05	2.260E–05	2.28E–16
7	2.260E–05	4.780E–05	1.69E–16
8	4.780E–05	1.010E–04	1.36E–16
9	1.010E–04	2.140E–04	8.42E–17
10	2.140E–0	4.540E–04	1.51E–16
11	4.540E–04	9.611E–04	2.68E–16
12	9.611E–04	1.234E–03	3.83E–16
13	1.234E–03	1.585E–03	4.67E–16
14	1.585E–03	2.035E–03	5.66E–16
15	2.035E–03	2.613E–03	6.84E–16
16	2.613E–03	3.355E–03	8.42E–16
17	3.355E–03	4.307Ev03	1.03E–15
18	4.307E–03	7.102E–03	1.40E–15
19	7.102E–03	1.503E–02	2.33E–15
20	1.503E–02	1.930E–02	3.17E–15
21	1.930E–02	2.479E–02	4.02E–15
22	2.479E–02	3.185E–02	1.22E–14
23	3.185E–02	4.087E–02	5.56E–15
24	4.087E–02	5.248E–02	2.05E–14
25	5.248E–02	8.652E–02	9.67E–15
26	8.652E–02	1.228E–01	3.74E–14
27	1.228E–01	1.500E–01	2.41E–14
28	1.500E–01	1.832E–01	2.24E–14
29	1.832E–01	2.237E–01	2.46E–14
30	2.237E–01	2.732E–01	4.87E–14
31	2.732E–01	3.337E–01	6.47E–14
32	3.337E–01	4.076E–01	7.24E–14
33	4.076E–01	4.979E–01	6.77E–14
34	4.979E–01	6.081E–01	6.49E–14
35	6.081E–01	7.427E–01	6.11E–14
36	7.427E–01	9.072E–01	8.04E–14
37	9.072E–01	1.108E+00	9.18E–14
38	1.108E+00	1.353E+00	1.15E–13
39	1.353E+00	1.653E+00	1.31E–13
40	1.653E+00	2.019E+00	1.75E–13
41	2.019E+00	2.466E+00	2.69E–13
42	2.466E+00	3.010E+00	5.64E–13
43	3.010E+00	3.680E+00	1.17E–12
44	3.680E+00	4.490E+00	2.08E–12
45	4.490E+00	5.490E+00	3.32E–12
46	5.490E+00	6.700E+00	4.99E–12
47	6.700E+00	8.190E+00	6.59E–12
48	8.190E+00	1.000E+01	8.10E–12
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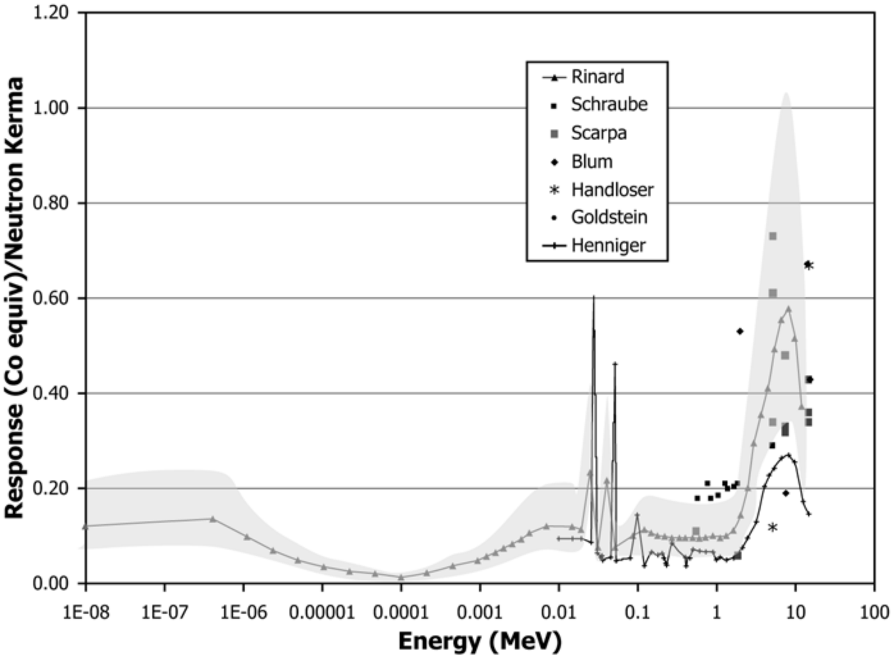
50	1.221E+01	1.492E+01	8.05E–12



The data in Fig 2 is reported 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 CaF_2(Mn)

APPENDIX

(Nonmandatory Information)

X1. LET DEPENDENCE OF LIGHT OUTPUT OF TLDS

X1.1 Both neutrons and gamma rays produce ionizing dose in CaF_2(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, i.e. a high density of the ionizing energy that may enhance recombination effects. The high LET of the dose results in increased charge recombination and tends to suppress the neutron response in the TLD. 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 to large neutron fluence levels 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.

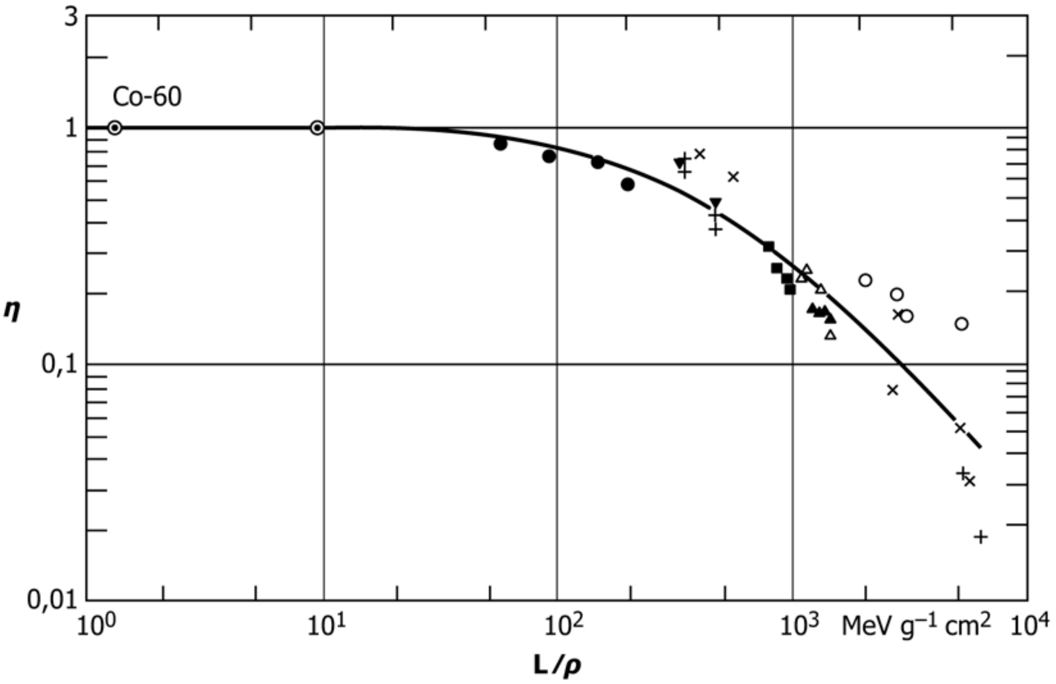


FIG. X1.1 Efficiency Relative to Co-60 for Conversion of Charged-Particle Energy into Light as a Function of LET

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