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Standard Guide for Selecting Dosimetry Systems for Application in Pulsed X-Ray Sources¹

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1. Scope

1.1 This guide provides assistance in selecting and using dosimetry systems in flash X-ray experiments. Both dose and dose-rate techniques are described.

1.2 Operating characteristics of flash X-ray sources are given, with emphasis on the spectrum of the photon output.

1.3 Assistance is provided to relate the measured dose to the response of a device under test (DUT). The device is assumed to be a semiconductor electronic part or system.

2. Referenced Documents

2.1 ASTM Standards:²

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

E1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources

ISO/ASTM 51261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing

ISO/ASTM 51275 Practice for Use of a Radiochromic Film Dosimetry system

ISO/ASTM 51310 Practice for Use of a Radiochromic Optical Waveguide Dosimetry system

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² 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.

2.2 *International Commission on Radiation Units (ICRU) and Measurements Reports:*³

ICRU Report 14 Radiation Dosimetry: X rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 50 MeV

ICRU Report 17 Radiation Dosimetry: X rays Generated at Potentials of 5 to 150 kV

ICRU Report 33 Radiation Quantities and Units

ICRU Report 34 The Dosimetry of Pulsed Radiation

3. Terminology

3.1 *absorbed dose*—quotient of $d\bar{e}/dm$, where $d\bar{e}$ is the mean energy imparted by ionizing radiation to matter of mass dm :

$$D = \frac{d\bar{e}}{dm} \quad (1)$$

See ICRU Report 33. The special name for the unit for absorbed dose is the gray (Gy).

$$1 \text{ Gy} = 1 \text{ J/kg} \quad (2)$$

Formerly, the special unit for absorbed dose was the rad, where 1 rad = 100 erg/g.

$$1 \text{ rad} = 0.01 \text{ Gy} \quad (3)$$

Since the absorbed dose due to a given radiation field is material dependent, it is important to include the material composition for which the dose is being reported, e.g., 15.3 Gy(LiF).

3.2 *absorbed dose enhancement*—increase (or decrease) in the absorbed dose (as compared to the equilibrium absorbed dose) at a point in a material of interest. This can be expected to occur near an interface with a material of higher or lower atomic number.

3.3 *converter*—a target for electron beams, generally of a high atomic number material, in which bremsstrahlung X-rays are produced by radiative energy losses of the incident electrons.

³ Available from the International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814, U.S.A.

3.4 *dosimeter*—a device that, when irradiated, exhibits a quantifiable change in some property of the device which can be related to absorbed dose in a given material using appropriate analytical instrumentation and techniques.

3.5 *dosimetry system*—a system used for determining absorbed dose, consisting of dosimeters, measurement instruments, and their associated reference standards, and procedures for the system's use.

3.6 *DUT*—device under test. This is the electronic component or system tested to determine its performance during or after irradiation.

3.7 *endpoint energy*—endpoint energy refers to the peak energy of the electron beam, usually in MeV, generated in a flash X-ray source and is numerically equal to the maximum voltage in MV. The word endpoint refers to the highest photon energy of the bremsstrahlung spectra, and this endpoint is equal to the maximum or peak in the electron energy. For example, if the most energetic electron that strikes the converter is 10 MeV, this electron produces a range of bremsstrahlung photon energies but the maximum energy of any photon is equal to 10 MeV, the endpoint energy. Most photons have energies one-tenth to one-third of the maximum electron energy for typical flash X-ray sources in the 10 MV to 1 MV endpoint voltage region, respectively.

3.8 *endpoint voltage*—Endpoint voltage refers to the peak voltage across a bremsstrahlung diode in a flash X-ray source. For example, a 10-MV flash X-ray source is designed to reach a peak voltage of 10-MV across the anode-cathode gap which generates the electron beam for striking a converter to produce bremsstrahlung.

3.9 *equilibrium absorbed dose*—absorbed dose at some incremental volume within the material in which the condition of electron equilibrium (the energies, number, and direction of charged particles induced by the radiation are constant throughout the volume) exists. For lower energies where bremsstrahlung production is negligible the equilibrium absorbed dose is equal to the kerma.

NOTE 1—For practical purposes, assuming the spatial gradient in the X-ray field is small over the range of the maximum energy secondary electrons generated by the incident photons, the equilibrium absorbed dose is the absorbed dose value that exists in a material at a distance from any interface with another material greater than this range.

4. Significance and Use

4.1 Flash X-ray facilities provide intense bremsstrahlung radiation environments, usually in a single sub-microsecond pulse, which often fluctuates in amplitude, shape, and spectrum from shot to shot. Therefore, appropriate dosimetry must be fielded on every exposure to characterize the environment, see ICRU Report 34. These intense bremsstrahlung sources have a variety of applications which include the following:

4.1.1 Generation of X-ray and gamma-ray environments similar to that from a nuclear weapon burst.

4.1.2 Studies of the effects of X-rays and gamma rays on materials.

4.1.3 Studies of the effects of radiation on electronic devices such as transistors, diodes, and capacitors.

4.1.4 Vulnerability and survivability testing of military systems and components.

4.1.5 Computer code validation studies.

4.2 This guide is written to assist the experimenter in selecting the needed dosimetry systems (not all radiation parameters must be measured in a given experiment) for use at pulsed X-ray facilities. This guide also provides a brief summary of the information on how to use each of the dosimetry systems. Other guides (see Section 2) provide more detailed information on selected dosimetry systems in radiation environments and should be consulted after an initial decision is made on the appropriate dosimetry system to use. There are many key parameters which describe a flash X-ray source, such as dose, dose rate, spectrum, pulse width, etc., such that typically no single dosimetry system can measure all the parameters simultaneously.

5. General Characteristics of Flash X-ray Sources

5.1 *Flash X-ray Facility Considerations*—Flash X-ray sources operate like a dental X-ray source but at much higher voltages and intensities and usually in a single, very short burst, see ICRU Report 17. A high voltage is developed across an anode-cathode gap (the diode) and field emission creates a pulsed electron beam traveling from the cathode to the anode. A high atomic-number element such as tantalum is placed on the anode to maximize the production of bremsstrahlung created when the electrons strike the anode. Graphite or aluminum is usually placed downstream of the converter to stop the electron beam completely but let the X-radiation pass through. Finally, a debris shield made of Kevlar or low-density polyethylene is sometimes necessary to stop exploding converter material from leaving the source. All of these components taken together form what is commonly called a bremsstrahlung diode.

5.2 *Relationship Between Flash X-ray Diode Voltage and X-ray Energy of Bremsstrahlung*—Flash X-ray sources produce bremsstrahlung by generating an intense electron beam which then strikes a high atomic number (Z) converter such as tantalum. The electron-solid interactions produce “braking” radiation or, in German, bremsstrahlung. Fig. 1 shows the typical range of photon energies produced by three different sources. If the average radiation produced is in the 20–100 keV region, the source is said to be a medium-hard X-ray simulator. If the average photon energy is in the 100–300-keV region, the term used is “hard X-ray simulator.” At the high end of the flash X-ray range are sources which produce an average photon energy of around 2 MeV. Because this photon energy is in the typical gamma-ray spectral range, the source is called a gamma-ray simulator.

5.2.1 The average energy of the bremsstrahlung spectrum, \bar{E}_{photon} , through an optimized converter (1)⁴ in the medium-hard X-ray region ($50 \text{ keV} < \bar{E}_{\text{photon}} < 500 \text{ keV}$) is given empirically by,

$$\bar{E}_{\text{photon}} \approx 5 \varepsilon^{1/2} \quad (4)$$

where \bar{E}_{photon} is the average energy of the bremsstrahlung

⁴ The boldface numbers in parentheses refer to the list of references at the end of this standard.

DIFFERENTIAL BREMSSTRAHLUNG SPECTRA

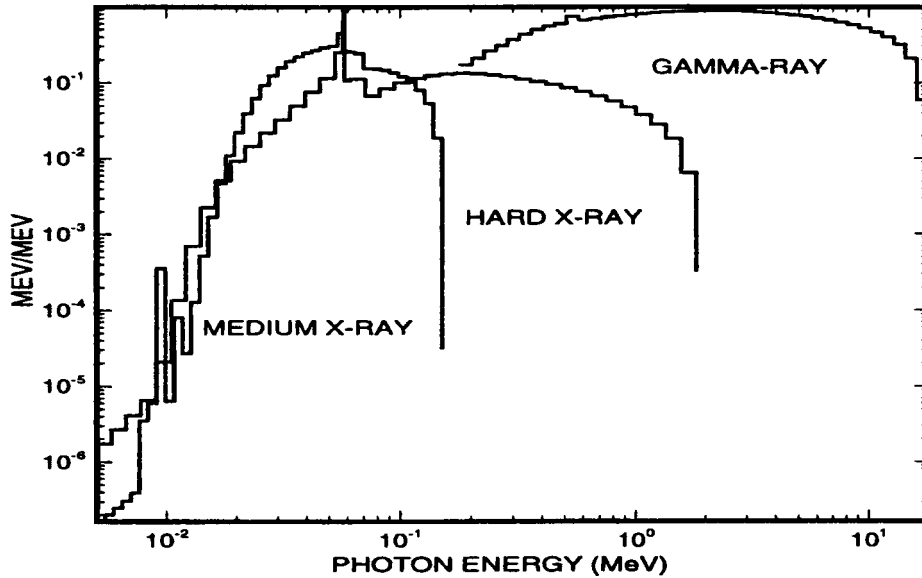


FIG. 1 Range of Available Bremsstrahlung Spectra from Flash X-ray Sources

photons in keV and ϵ is the average energy of the electrons in the electron beam incident on the converter in keV. This equation and Fig. 1 indicate that most of the photons have energies much less than the endpoint electron energy, or in voltage units, the flash X-ray voltage.

6. Measurement Principles

6.1 Typically in flash X-ray irradiations, one is interested in some physical change in a critical region of a device under test (DUT). The dosimetry associated with the study of such a physical change may be broken into three parts:

6.1.1 Determine the absorbed dose in a dosimeter.

6.1.2 Using the dosimeter measurement, estimate the absorbed dose in the region and material of interest in the DUT.

6.1.3 If required, relate the estimated absorbed dose in the DUT to the physical change of interest (holes trapped, interface states generated, photocurrent produced, etc.)

6.2 This section will be concerned with the first two of the above listed parts of dosimetry: (1) what is necessary to determine a meaningful absorbed dose for the dosimeter and (2) what is necessary to extrapolate this measured dose to the estimated dose in the region of interest. The final step in dosimetry, associating the absorbed dose with a physical change of interest, is outside the scope of this guide.

6.3 Energy Deposition:

6.3.1 *Secondary Electrons*—Both in the case of absorbed dose in the DUT and absorbed dose in the dosimeter, the energy is deposited largely by secondary electrons. That is, the incident photons interact with the material of, or surrounding, the DUT or the dosimeter and lose energy to Compton electrons, photoelectrons, and Auger electrons. The energy which is finally deposited in the material is deposited by these secondary particles.

6.3.2 *Transport of Photons*—In some cases, it is necessary to consider the transport and loss of photons as they move to the region whose absorbed dose is being determined. A correction for the attenuation of an incident photon beam is an example of such a consideration.

6.3.3 *Transport of Electrons*—Electron transport may cause energy originally imparted to electrons in one region to be carried to a second region depending on the range of the electrons. As a result, it is necessary to consider the transport and loss of electrons as they move into and out of the regions whose absorbed dose is being determined. In particular, it is necessary to distinguish between equilibrium and non-equilibrium conditions for electron transport.

6.3.3.1 *Charged Particle Equilibrium*—In some cases, the numbers, energies, and angles of particles transported into a region of interest are approximately balanced by those transported out of that region. Such cases form an important class of limiting cases which are particularly easy to interpret. (See “Equilibrium Absorbed Dose” in 3.9.)

6.3.3.2 *Dose Enhancement*—Because photoelectron production per atom is roughly proportional to the atomic number raised to the fourth power for energies less than 100 keV (2), one expects more photoelectrons to be produced in high atomic number layers than in low atomic number layers for the same photon fluence and spectrum. Thus, there may be a net flow of energetic electrons from the high atomic number layers into the low atomic number layers. This non-equilibrium flow of electrons may result in an enhancement of the dose in the low atomic number layer. Dose enhancement problems are often caused by high atomic number bonding layers (for example, gold), and metallization layers (for example, W-Si or Ta-Si).

6.4 Absorbed Dose in Dosimeter:

6.4.1 *Equilibrium Absorbed Dose in Dosimeter:*

6.4.1.1 It is frequently possible to use dosimeters under approximate equilibrium conditions. The interpretation of the output of the dosimeter is straightforward only when the energy deposition processes within the dosimeter are approximately in equilibrium. That is, when the absorbed dose within the dosimeter is an equilibrium absorbed dose.

6.4.1.2 It is possible to treat non-equilibrium energy deposition within a dosimeter, but such an analysis requires electron and photon transport calculations, often in the form of computer codes.

6.4.2 Limiting Cases:

6.4.2.1 There are two limiting cases for which the dosimeter data can be analyzed in a straightforward manner.

6.4.2.2 Limiting Case One: Short Electron Range:

(1) For this case, secondary electron ranges are small in comparison with the size of the dosimeter.

(2) Essentially all electrons which deposit energy within the dosimeter will be produced within the dosimeter.

(3) Non-equilibrium effects due to electron transport are negligible, but photon attenuation corrections may be necessary.

(4) An example of this limiting case would be 20 keV photons depositing energy in a typical (0.889 mm thick) thermoluminescence (TL) dosimeter (TLD). In this case, the secondary electrons have ranges which are small in comparison with the size of the TL dosimeter. As a result, it is not necessary to perform a correction for the effect of electron transport on absorbed dose. On the other hand, 20 keV photons may be significantly attenuated while traveling through a TL dosimeter depending on the material. Thus a correction due to this effect may be necessary.

6.4.2.3 Limiting Case Two: Large Electron Range:

(1) When the maximum secondary electron range is large compared with the size of the dosimeter, the dosimeter must be surrounded by an equilibrating layer. This layer must be chosen to be of an appropriate thickness, density and atomic number. Generally, the range of secondary electrons must be smaller than the thickness of the equilibrating layer. For further discussion of equilibrating layers, see Practice E668.

(2) Essentially all electrons which deposit energy within the dosimeter originate in the equilibrating layer.

(3) Bragg-Gray cavity theory applies. That is, the dose within the dosimeter is the equilibrium dose for the equilibrating layer (corrected by the differences in electron stopping power of the dosimeter and the equilibrating layer and any photon attenuation through the material).

(4) An example of this limiting case is 1-MeV photons incident on a typical TL dosimeter surrounded by an appropriate equilibrating layer. In this case, the range of the secondary electrons will be large in comparison to the size of the TLD. Thus the dose measured will be the equilibrium dose in the TLD (with a small correction for the differences in the stopping power for the electrons in the TLD material and the material of the equilibrating layer.)

6.4.2.4 Intermediate Cases

(1) The intermediate cases, where secondary electron ranges are neither small nor large in comparison to the dosimeter size, are cases where non-equilibrium energy deposition is to be expected.

(2) An example of an intermediate case is 100-keV photons incident on a typical thermoluminescence dosimeter.

(3) The careful treatment of dosimetry for intermediate cases requires the use of combined photon/electron radiation transport calculations of the energy deposition in the dosimeters in order to get satisfactory measurements.

6.5 Absorbed Dose in Device Under Test:

6.5.1 Absorbed Dose in Device Under Test—The conditions within a DUT during a flash X-ray irradiation are frequently far from equilibrium. In many cases, these are classic examples of experiments showing dose enhancement effects. As a result, it is frequently necessary to perform a dose-enhancement correction in order to estimate the absorbed dose within the region of interest. Unless the DUT meets the two limiting cases discussed in the previous section, which is rarely true, the dose should be obtained using combined photon/electron radiation transport calculations of the energy deposition in order to get satisfactory dose estimates. Within a system being tested, a

TABLE 1 Flash X-ray Dosimetry Characteristics for Three Energy Bands

Flash X-Ray Type	Absorbed Dose in Dosimeter	Absorbed Dose in DUT
Low energy (average photon energy, 20-100 keV)	Can get electron equilibrium. ^A May need photon transport correction. ^B	Depends on DUT: May need an electron transport calculation. ^C May need a photon transport calculation. ^B
Medium energy (average photon energy, 100-300 keV)	Often cannot get electron equilibrium and therefore need electron transport calculation. ^{C,D}	Depends on DUT: May need an electron transport calculation, especially without use of beam filtration. ^{C,E} May need a photon transport calculation. ^B
High energy (average photon energy, 300-3000 keV)	Can get electron equilibrium with proper equilibration layer. ^{F,D}	Depends on DUT: May need an electron transport calculation. ^C Usually no photon transport calculation needed. ^D

^AThe dosimeter or region of interest is large compared to the maximum secondary electron range. (6.4.2.2)

^BThe dosimeter or region of interest is large compared to the photon range. (6.4.2.2, Paragraph 4)

^CThe dosimeter or region of interest is of comparable size to the maximum secondary electron range. (6.4.2.4)

^DThe dosimeter or region of interest is small compared to the photon range. (6.4.2.3, Paragraph 4)

^EA filter may be used to essentially eliminate the lower energy portions of the flash X-ray spectrum. This makes the spectrum more nearly monochromatic and may simplify dosimetry.

^FThe dosimeter or region of interest is small compared to the electron range. (6.4.2.3)

calculation of the radiation transport through the system to the individual devices of interest must be performed.

6.6 Spectral Considerations:

6.6.1 Broad Energy Range—The set of available flash X-ray sources spans a very wide photon energy range. Useful intensities may be obtained for energies as low as 10 keV and as high as 10 MeV. Each individual flash X-ray source, of course, does not produce useful photons over such a wide range. Dosimetry for such flash X-ray sources is somewhat simplified if the different flash spectra are categorized into three types, low energy, medium energy, and high energy. This categorization refers to the average energy of the photon spectrum and not the higher endpoint energy (5.2).

6.6.2 Dosimetry for Three Energy Types—A summary of the dosimetry requirements for the three flash X-ray energy bands is provided in Table 1.

6.7 Absorbed Dose Interpretation:

6.7.1 In 6.1.2, it is pointed out that the second of three steps in the dosimetry process is the use of the measured absorbed dose in the dosimeter to estimate the absorbed dose in a region of interest within the device under test.

6.7.2 In the previous sections the dose in both the dosimeter (6.4) and the DUT (6.5) is estimated. Although the dose can easily be calculated from tables or a simple photon transport code for the dosimeter, which is often in equilibrium, the dose in the DUT, which is rarely in equilibrium, often requires a sophisticated combined photon/electron radiation transport code. Assuming this has been accomplished, one can use the ratio of the calculated doses at a given fluence and spectrum as the correction factor for the measured dose in the dosimeter to estimate the actual dose in the DUT.

$$D_{DUT} = \text{Calculated} \left(\frac{D_{DUT}}{D_{\text{Dosimeter}}} \right) \times D_{\text{Dosimeter}} \quad (5)$$

where D_{DUT} is the absorbed dose in the device material, and $D_{\text{Dosimeter}}$ is the equilibrium absorbed dose in the dosimeter.

7. Dosimetry Systems

7.1 Introduction—In this section a brief summary of eight different types of dosimetry systems is given. The intent of this guide is to provide enough information so that users can decide which system might be appropriate for their application. Users are expected to investigate in more detail the proper use and limitations of a system using references in this and other ASTM documents before undertaking any radiation measurements. The pros and cons of each system are quickly summarized in Table 2 and Table 3. The values cited in these Tables are indicative of what is typically obtained under normal testing conditions. Many of these parameters can be improved at the expenditure of considerable effort. Only the precision of each dosimeter is discussed here because the accuracy of the dosimeter will be determined by the quality of the calibration and specific usage and this is beyond the scope of this document.

7.2 Thermoluminescence Dosimeters:

7.2.1 Introduction—Thermoluminescence Dosimeters (TLDs), see Terminology E170, are popular dosimeters because they are small, passive, inexpensive, and can retain

TABLE 2 Dose Measurements

Dosimeter Type	TLD	Calorimeter	Optochromic	Radiochromic Film
Dose Range (Gy)	10 ⁻⁴ –5 × 10 ³	10–10 ⁵	0.4–2 × 10 ⁴	0.01–5 × 10 ⁴
Photon Energy Range (MeV)	>0.01	>0.01	>0.01	>0.01
Size	Small	Medium	Medium	Small to Large
Ease of calibration	Easy	Easy	Easy	Moderate
Precision	5-15 %	5 %	5 %	5 %
Active Material	CaF ₂ , LiF	Au, Si, Al	Organic	Organic
Availability	Buy	Make or Buy	Buy	Buy
System Cost	Medium	Low	Low	Low to High

TABLE 3 Dose-Rate Measurements

Dosimeter Type	PIN Diode	Compton Diode	Cerenkov/ Scintillator-Photodetector	PCD
Dose-Rate Range (Gy/s)	2 × 10 ¹ –10 ⁸	10 ⁷ –10 ¹⁰	10 ⁴ –10 ⁹	2 × 10 ⁵ –10 ¹⁰
Photon Energy Range (MeV)	>0.01	>0.5	>0.02	>0.01
Size	Small to Medium	Large	Very Large	Small to Medium
Ease of calibration	Moderate	Difficult	Moderate	Moderate
Precision	10 %	10 %	4 %	10 %
Active Material	Si, GaAs	Tungsten	Plastic	Diamond, GaAs
Availability	Buy	Buy or Make	Make	Buy or Make
System cost	Low	Medium	High	Medium

accurate dose information for long periods of time between irradiation and readout. The dose range of TLDs is typically > 10⁻⁴ to < 5 × 10³ Gy (> 10⁻² to < 5 × 10⁵ rad).

7.2.1.1 Many materials are available for thermoluminescence dosimetry; however, the favorites for radiation hardness testing are Lithium Fluoride (LiF), Manganese activated Calcium Fluoride (CaF₂:Mn), and Dysprosium activated Calcium Fluoride (CaF₂:Dy). Dosimeters are available as powder, chips made from polycrystalline material, and discs consisting of very fine powder uniformly dispersed throughout a polytetrafluoroethylene (PTFE, Teflon) matrix. A commonly used size of chip is 3.2 by 3.2 by 0.9 mm (0.125 by 0.125 by 0.035 in.) A commonly used size of Teflon dosimeter is a disc, 6 mm in diameter and 0.4 mm thick. In addition, these dosimeter materials can be made into arrays for dose mapping.

7.2.2 Principles—Thermoluminescent materials consist of a crystalline insulator with added dopants which introduce stable electron traps into the forbidden band gap. Ionizing radiation creates electrons and holes which are trapped by stable traps in the band gap. The density of filled traps is proportional to the dose absorbed by the material. Subsequent heating of the material empties the electron traps, allowing electrons from F-centers to recombine with free holes at luminescence centers, emitting light. The integrated light output is proportional to the density of filled traps, and therefore to the absorbed dose in the TLD material.

7.2.2.1 To make an equilibrium dose measurement, the TLD must be enclosed in an equilibrium capsule of the appropriate

material and thickness when it is exposed. Methods for determining equilibrium capsule thickness are given in Practice E666.

7.2.2.2 Readout of TLDs is accomplished by an instrument consisting of a heater, optical system and photomultiplier detector to measure the light emitted by the TLD during a predetermined heating cycle, and an integrating picoammeter which can measure the current or the charge from the photomultiplier. The total integrated charge from the photomultiplier during part or all of the heating cycle is usually related to the absorbed dose in the dosimeter. TLD readout instruments are available from a number of manufacturers.

7.2.3 *Applications*—The choice of the TLD and capsule material depend on the application. For high-energy photon sources (photon energy ≥ 200 keV) such as high voltage flash X-ray generators and Co^{60} and Cs^{137} sources, and where the quantity of interest is Si or SiO_2 equilibrium dose, a good combination of materials is a $\text{CaF}_2:\text{Mn}$ TLD in an Al equilibrium shield (See Practice E1249). For these materials and photon energies, all mass energy absorption coefficients and mass stopping powers are so close to those of silicon that the silicon equilibrium dose can be determined using Bragg-Gray cavity theory. The response of $\text{CaF}_2:\text{Mn}$ is nearly linear with absorbed dose and the dosimeters retain dose information for a long time with a small fading correction, whose form is well known (7.2.5).

7.2.3.1 For radiation sources which have significant photon energy below 200 keV, more detailed calculations are necessary regardless of which material is chosen for the TLD. In this case the choice of TLD and capsule material is flexible, and can be made on the basis of convenience or cost.

7.2.3.2 The choice of whether powder, chips, or PTFE discs are used is primarily one of convenience and cost. For specific instructions on the proper procedures for using TLD systems to determine absorbed dose in radiation hardness testing of electronic devices, see Practices E666 and E668.

7.2.4 *Advantages*—TLDs are small, inexpensive, and require no instrumentation during irradiation. They are thus ideally suited for measuring dose at many locations within a test object, or for measuring dose near the areas of interest in even very small (~ 3 mm) test objects. Their large sensitivity range makes it possible to measure Gy to kGy doses with one dosimetry system.

7.2.5 *Limitations*—Energy Range: TLDs are usable over the energy range from at least 10 keV to 10 MeV. (Indeed, their sensitivity extends down into the ultraviolet region; hence, TLDs must be protected from exposure to sunlight, etc., especially for low dose applications.) The dose response as a function of energy can be calculated for TLDs which consist of 100% TL phosphor by using standard equilibrium dose and Bragg-Gray cavity theories. (Practice E666) However, care must be exercised when using PTFE disc dosimeters at low energies. Since these dosimeters consist of fine grains of TL phosphor distributed throughout a PTFE matrix, these simple theories do not apply. At high energies (photon energy ≥ 2 MeV), the TLD can be treated using Bragg-Gray cavity theory, with all photon interactions assumed to take place in the equilibrium shield material, and the resultant secondary elec-

trons depositing energy in the phosphor grains. There is a smooth transition to more moderate energies (photon energy ≈ 200 keV) where the photon interactions must be considered to occur primarily in the PTFE matrix. Finally, at the lowest photon energies (photon energy ≤ 10 -20 keV), all photon interactions which eventually deposit energy in the phosphor grains must be assumed to originate in the individual phosphor grain itself. The dose response of PTFE TLDs as a function of photon energy is therefore a complex function of energy which is not easy to derive analytically. A modern electron/photon transport code such as ITS (3) can be helpful in calculating this relationship (4).

7.2.5.1 Most TLD phosphors exhibit fading of the TL response with time; that is, the observed TL response becomes progressively smaller as the time interval between irradiation and readout increases (5). For most of the common TL phosphors the fading behavior is well known. The fading of $\text{CaF}_2:\text{Mn}$ TLDs has been reported to obey the relationship (6)

$$(TL)/TL_o = (t/t_o)^{-0.017} \quad (6)$$

where t is in hours and the subscript o refers to the time of irradiation, and unsubscripted quantities refer to the time of readout. The value of the coefficient 0.017 is only typical and can vary from batch to batch and must be determined experimentally. Use the procedures in 8.7 of Practice E668 to test for fading effects in the type of TLD chosen.

7.2.6 *Sensitivity*—TLDs can be used to measure dose from 100 μGy to 5 kGy (10 mrad to 500 krad). Most TL materials saturate in the range of 3 to 10 kGy (300 krad to 1 Mrad). The dose response of calcium fluoride TLDs is independent of dose rate for dose rates less than 10^{10} Gy/s (10^{12} rad/s) (7). The dose response of lithium fluoride has been reported to be independent of dose rate only up to 10^9 Gy/s (10^{11} rad/s) (8).

7.2.7 *Calibration*—TLD systems (dosimeter plus reader) must be calibrated in a standard radiation field before use, see ICRU Report 14. The most convenient sources for this are calibrated Co^{60} or Cs^{137} sources. Care must be taken to expose the TLDs in an appropriate equilibrium shield. If the calibration source is calibrated in units of exposure rate, then the dose absorbed by the TLD can be found by:

$$D_{\text{TLD}} = \left(\frac{(\mu_{\text{en}}/\rho)_{\text{TLD}}}{(\mu_{\text{en}}/\rho)_{\text{air}}} \right) (D_{\text{air}}/X) X_o \exp[-(\mu_{\text{en}}/\rho)_{\text{eqmat}} \rho_{\text{eqmat}} x] \quad (7)$$

where:

- D_{TLD} = is the dose absorbed by the TLD,
- X_o = is the free-in-air exposure of the source,
- D_{air}/X = 33.68 Gy–kg/C (0.869 rad/R),
- μ_{en}/ρ = is the mass-energy absorption coefficient,
- ρ_{eqmat} = is the density of the equilibrator material, and
- x = is the thickness of the equilibrator material.

7.2.8 *Reproducibility*—The reproducibility of most TLD materials is about $\pm 8\%$ at 1σ . Better reproducibility can be achieved with TLD chips by irradiating a number of them to a low dose, reading them, and selecting those which fall into a tighter group. A reproducibility of $\pm 2\%$ is often achievable, and $\pm 1\%$ is possible by this means.

7.3 Calorimeters:

7.3.1 Introduction. Calorimetry comes closest of all the dosimetric techniques to providing a direct measure of dose or