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StandardPractice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources[1]

This standard is issued under the fixed designation E1249; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This practice covers recommended procedures for the use of dosimeters, such as thermoluminescent dosimeters (TLD's), to determine the absorbed dose in a region of interest within an electronic device irradiated using a Co-60 source. Co-60 sources are commonly used for the absorbed dose testing of silicon electronic devices.

NOTE 1—This absorbed-dose testing is sometimes called "total dose testing" to distinguish it from "dose rate testing."

NOTE 2—The effects of ionizing radiation on some types of electronic devices may depend on both the absorbed dose and the absorbed dose rate; that is, the effects may be different if the device is irradiated to the same absorbed-dose level at different absorbed-dose rates. Absorbed-dose rate effects are not covered in this practice but should be considered in radiation hardness testing.

1.2 The principal potential error for the measurement of absorbed dose in electronic devices arises from non-equilibrium energy deposition effects in the vicinity of material interfaces.

1.3 Information is given about absorbed-dose enhancement effects in the vicinity of material interfaces. The sensitivity of such effects to low energy components in the Co-60 photon energy spectrum is emphasized.

1.4 A brief description is given of typical Co-60 sources with special emphasis on the presence of low energy components in the photon energy spectrum output from such sources.

1.5 Procedures are given for minimizing the low energy components of the photon energy spectrum from Co-60 sources, using filtration. The use of a filter box to achieve such filtration is recommended.

1.6 Information is given on absorbed-dose enhancement effects that are dependent on the device orientation with respect to the Co-60 source.

1.7 The use of spectrum filtration and appropriate device orientation provides a radiation environment whereby the absorbed dose in the sensitive region of an electronic device can be calculated within defined error limits without detailed knowledge of either the device structure or of the photon energy spectrum of the source, and hence, without knowing the details of the absorbed-dose enhancement effects.

1.8 The recommendations of this practice are primarily applicable to piece-part testing of electronic devices. Electronic circuit board and electronic system testing may introduce problems that are not adequately treated by the methods recommended here.

1.9 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

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

E1250 Test Method for Application of Ionization Chambers to Assess the Low Energy Gamma Component of

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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.

Cobalt-60 Irradiators Used in Radiation-Hardness Testing of Silicon Electronic Devices

2.2 *International Commission on Radiation Units and Measurements Reports:*

ICRU Report 14 Radiation Dosimetry: X-Rays and Gamma Rays With Maximum Photon Energies Between 0.6 and 50 MeV[3]

ICRU Report 18 Specification of High Activity Gamma-Ray Sources[3]

3. Terminology

3.1 *absorber*—material that reduces the photon fluence rate from a Co-60 source by any interaction mechanism.

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 *absorbed-dose enhancement factor*— ratio of the absorbed dose at a point in a material of interest to the equilibrium absorbed dose in that same material.

3.4 *average absorbed dose*—mass weighted mean of the absorbed dose over a region of interest.

3.5 *average absorbed-dose enhancement factor*—ratio of the average absorbed dose in a region of interest to the equilibrium absorbed dose (**1**).[4]

NOTE 3—For a description of the necessary conditions for measuring equilibrium absorbed dose, see 6.3.1 and the term charged particle equilibrium in Terminology E170, which provides definitions and descriptions of other applicable terms of this practice.

3.6 *beam trap*—absorber that is designed to remove the beam that has been transmitted through the device under test. Its purpose is to eliminate the scattering of the transmitted beam back into the device under test.

3.7 *clean spectrum*—one that is relatively free of low energy components in the photon energy spectrum. For example, for a Co-60 source an ideally clean spectrum would contain only the primary 1.17 and 1.33 MeV photons of Co-60 decay.

3.8 *equilibrium absorbed dose*—absorbed dose at some incremental volume within the material in which the condition of charged particle equilibrium (the energies, number, and direction of charged particles induced by the radiation are constant throughout the volume) exists (see Terminology E170).

NOTE 4—For practical purposes 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 the range of the maximum energy secondary electrons generated by the incident photons.

3.9 *filter box*—container, made of one or more layers of different materials, surrounding a device under test or a dosimeter, or both, for the purpose of minimizing low energy components of the incident photon energy spectrum.

3.10 *spectrum filter*—material layer intercepting photons on their path between the Co-60 source and the device under test. The purpose of the filter is to reduce low energy components of the photon energy spectrum.

3.11 *spectrum hardening*—process by which the fraction of low energy components of the photon energy spectrum is reduced.

3.12 *spectrum softening*—process by which the fraction of low energy components of the photon energy spectrum is increased.

4. Significance and Use

4.1 *Division of the Co-60 Hardness Testing into Five Parts:*

4.1.1 The equilibrium absorbed dose shall be measured with a dosimeter, such as a TLD, located adjacent to the device under test. Alternatively, a dosimeter may be irradiated in the position of the device before or after irradiation of the device.

4.1.2 This absorbed dose measured by the dosimeter shall be converted to the equilibrium absorbed dose in the material of interest within the critical region within the device under test, for example the SiO_2 gate oxide of an MOS device.

4.1.3 A correction for absorbed-dose enhancement effects shall be considered. This correction is dependent upon the photon energy that strikes the device under test.

4.1.4 A correlation should be made between the absorbed dose in the critical region (for example, the gate oxide mentioned in 4.1.2) and some electrically important effect (such as charge trapped at the Si/SiO_2 interface as manifested by a shift in threshold voltage).

4.1.5 An extrapolation should then be made from the results of the test to the results that would be expected for the device under test under actual operating conditions.

NOTE 5—The parts of a test discussed in 4.1.2 and 4.1.3 are the subject of this practice. The subject of 4.1.1 is covered and referenced in other standards such as Practice E668 and ICRU Report 14. The parts of a test discussed in 4.1.4 and 4.1.5 are outside the scope of this practice.

4.2 *Low-Energy Components in the Spectrum*—Some of the primary Co-60 gamma rays (1.17 and 1.33 MeV) produce lower energy photons by Compton scattering within the Co-60 source structure, within materials that lie between the source and the device under test, and within materials that lie beyond the device but contribute to backscattering. As a result of the complexity of these effects, the photon energy spectrum striking the device usually is not well known. This point is further discussed in Section 5 and Appendix X1. The presence of low-energy photons in the incident spectrum can result in dosimetry errors. This practice defines test procedures that should minimize dosimetry errors without the need to know the spectrum. These recommended procedures are discussed in 4.5, 4.6, Section 7, and Appendix X5.

4.3 *Conversion to Equilibrium Absorbed Dose in the Device Material*—The conversion from the measured absorbed dose in the material of the dosimeter (such as the CaF_2 of a TLD) to the equivalent absorbed dose in the material of interest (such as the SiO_2 of the gate oxide of a device) is dependent on the incident

[3] Available from International Commission on Radiation Units, 7910 Woodmont Ave., Washington, DC 20014.

[4] The boldface numbers in parentheses refer to the list of references appended to this practice.

photon energy spectrum. However, if the simplifying assumption is made that all incident photons have the energies of the primary Co-60 gamma rays, then the conversion from absorbed dose in the dosimeter to that in the device under test can be made using tabulated values for the energy absorption coefficients for the dosimeter and device materials. Where this simplification is appropriate, the error incurred by its use to determine equilibrium absorbed dose is usually less than 5 % (see 6.3).

4.4 *Absorbed-Dose Enhancement Effects*— If a higher atomic number material lies adjacent to a lower atomic number material, the energy deposition in the region adjacent to the interface is a complex function of the incident photon energy spectrum, the material composition, and the spatial arrangement of the source and absorbers. The absorbed dose near such an interface cannot be adequately determined using the procedure outlined in 4.3. Errors incurred by failure to account for these effects may, in unusual cases, exceed a factor of five. Because microelectronic devices characteristically contain layers of dissimilar materials with thicknesses of tens of nanometres, absorbed-dose enhancement effects are a characteristic problem for irradiation of such devices (see 6.1 and Appendix X2).

4.5 *Minimizing Absorbed-Dose Enhancement Effects*— Under some circumstances, absorbed-dose enhancement effects can be minimized by hardening the spectrum. Hardening is accomplished by the use of high atomic number absorbers to remove low energy components of the spectrum, and by minimizing the amount and proximity of low atomic number material to reduce softening of the spectrum by Compton scattering (see Sections 6 and 7).

4.6 *Limits of the Dosimetry Errors*— To correct for absorbed-dose enhancement by calculational methods would require a knowledge of the incident photon energy spectrum and the detailed structure of the device under test. To measure absorbed-dose enhancement would require methods for simulating the irradiation conditions and device geometry. Such corrections are impractical for routine hardness testing. However, if the methods specified in Section 7 are used to minimize absorbed-dose enhancement effects, errors due to the absence of a correction for these effects can be kept within bounds that may be acceptable for many users. An estimate of these error bounds for representative cases is given in Section 7 and Appendix X5.

4.7 *Application to Non-Silicon Devices*— The material of this practice is primarily directed toward silicon based solid state electronic devices. The application of the material and recommendations presented here should be applied to gallium arsenide and other types of devices only with caution.

5. Description of Co-60 Sources

5.1 Cobalt-60 principally decays by emitting gamma rays of 1.17 and 1.33 MeV. In most sources, Co-60 is doubly encapsulated in stainless steel; the sources are supported on structures, usually of aluminum alloys or stainless steel. For some sources, the output is collimated using iron, lead, or other high-density metals or combinations of these absorbers. Finally, shielding materials of tungsten, lead, concrete, or water are often present. Therefore, a significant fraction of the photons incident on the device under test are the result of Compton scattering that produces low energy components in the source output photon energy spectrum (see ICRU Report 18 for additional discussion of gamma-ray sources).

NOTE 6—As an example, the energy spectrum from even a relatively clean Co-60 source has about 35 % of its total number of photons with energies of less than 1 MeV (see Ref **(2)** and Appendix X1).

5.2 Even for a given source, a considerable variability exists in the output energy spectrum depending on the geometry and position of irradiation. The spectrum at any position is affected by scattering from walls, floor, and ceiling and by scattering from material located nearby.

NOTE 7—A qualitative estimate of the spectrum hardness for a given source can be obtained using Method E1250.

5.3 The following Co-60 source types are described briefly and listed in the order of decreasing relative spectrum hardness under the most favorable conditions of irradiation.

NOTE 8—Diagrams of typical sources, a nominal photon energy spectrum for each, and references are given in Appendix X1.

5.3.1 A *teletherapy source* is a completely shielded source from which the photon output is confined to a beam that is usually collimated. The source output is typically directed into a shielded room, but a shielded container, or box, is used in some cases.

5.3.2 A *room source* is a source contained in a shielded well from which it is moved into a shielded room by remote control. Its position in the room relative to walls, floor, and ceiling and other scattering material determines the relative hardness of its effective photon energy spectrum. As a result, the photon energy spectrum obtained in a room source can be relatively hard or relatively soft as compared with other Co-60 sources.

5.3.3 A *water well source* is a completely shielded source at a certain depth in a pool of water to which access for irradiations is by means of a water-tight container, or can. A cylindrical array of sealed stainless-steel pencils containing Co-60 pellets is the normal source geometry. The photon energy spectrum depends on whether irradiations are made inside or outside the array, with the former arrangement having the hardest spectrum.

5.3.4 A *shielded-cavity irradiator* is a self-contained shielded source that is usually contained in steel and lead surrounding a cavity in which irradiations can be carried out. Self-absorption and scattering affect the photon energy spectrum.

6. Factors Affecting Absorbed Dose Measurement

6.1 *Absorbed-dose Enhancement Near Material Interfaces:*

6.1.1 For illustration, most semiconductor devices can be represented as one-dimensional planar layers of active and structural materials. The energy deposition by secondary electrons produced by photons near the interface between layers depends, in a complex way, on (*a*) the effective atomic number of the layers, (*b*) the photon energy, (*c*) the photon direction, and (*d*) the layer thickness.

6.1.2 An illustration of the effect of photon energy and direction is shown in Fig. 1 **(3)**. It shows the absorbed dose as a function of distance from an interface between high- and low-atomic-number materials.

6.1.2.1 The effect at the interface at low-photon energies (about 10–200 keV) is strongly dependent on energy and material atomic number and not very dependent on the direction of incident photons. The effect extends over a region of the order of hundreds of nanometers from the interface.

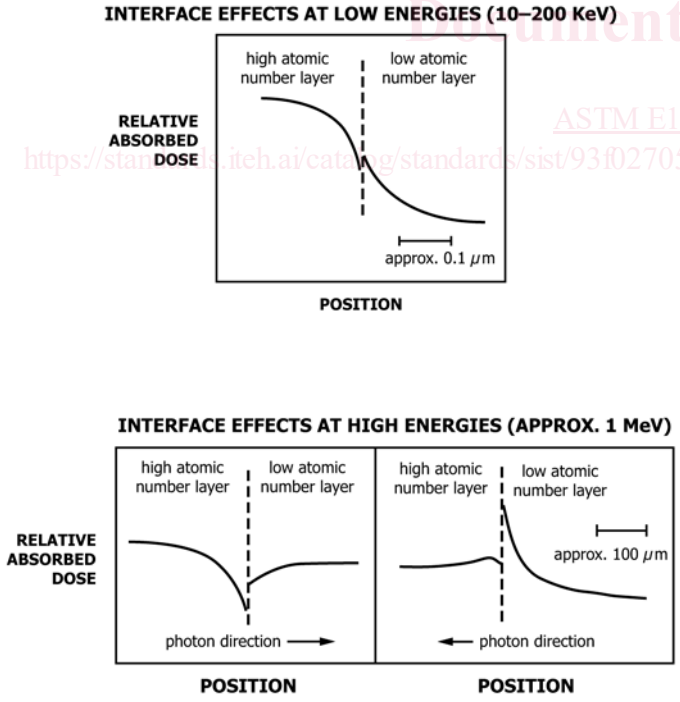
6.1.2.2 The effect at higher photon energies (about 1 MeV) is not strongly dependent on photon energy or the atomic numbers of the materials; however, it is strongly dependent on the direction of the incident photons. At such energies, the effect extends over a region of hundreds of micrometers from the interface.

6.1.3 Absorbed-dose enhancement effects are caused mainly by nonequilibrium electron transport (see Appendix X2).

6.2 *Co-60 Photon Energy Spectrum Hardening and Softening:*

6.2.1 The Co-60 photons will pass through, or be scattered from, other materials on their path from the source location to the region of interest within the device under test.

6.2.2 Such intervening materials will add low energy photons to the Co-60 spectrum through Compton scattering and will remove low energy photons from the spectrum through photoelectric absorption.



NOTE 1—(*a*) Schematic illustration of absorbed-dose enhancement effects at low photon energies. The actual magnitude of these effects depends on the energies and materials used.
(*b*) Schematic illustration of absorbed-dose enhancement effects at high photon energies **(3)**. Note that the vertical scales of Figs. 1(*a*) and 1(*b*) are not necessarily the same.

FIG. 1 Absorbed-Dose Enhancement Effects

6.2.3 High atomic number materials (such as Pb) tend to harden the spectrum. Low atomic number materials (such as Al or H_2O) tend to soften the spectrum.

6.2.4 For more details of the interaction of the test setup with the Co-60 photon beam, see Appendix X3.

6.3 *Conversion of Dosimeter Absorbed Dose to Device Absorbed Dose:*

6.3.1 Conversion from the measured absorbed dose in the dosimeter (such as a TLD) to the equilibrium absorbed dose in the device material of interest can be performed using the following equation:

$$D_a = D_b \frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_b} \quad (1)$$

where:

D_a = equilibrium absorbed dose in the device material,
D_b = equilibrium absorbed dose in the dosimeter,
$(\mu_{en}/\rho)_a$ = mass energy absorption coefficient for the device material, and
$(\mu_{en}/\rho)_b$ = mass energy absorption coefficient for the dosimeter.

6.3.2 Since the mass energy absorption coefficients appear in the equation as a ratio, the values of those coefficients shall be, therefore, in the same units. Values of mass energy absorption coefficients for typical materials encountered are given in Appendix X4. The unit of the absorbed dose in the device material will be consistent with the unit of absorbed dose measured by the dosimeter. (For a discussion of units, see Terminology E170).

6.3.3 An example of a dosimeter would be a CaF_2 TLD. An example of a device material of interest would be the SiO_2 of the gate oxide of a device. For further discussion and other examples of the application of this calculation, see Practices E666 and E668.

6.3.4 The use of Eq 1 is strictly applicable only if the following assumptions and restrictions are met:

6.3.4.1 Both the dosimeter and device are sufficiently thin that the incident photons are not significantly attenuated.

6.3.4.2 Charged particle equilibrium is established in the sensitive volume of the device and in the dosimeter.

6.3.4.3 The ratio of mass energy absorption coefficients is constant over the photon energy range.

6.3.4.4 The incident photon energy spectrum is the same for the dosimeter and the device material of interest.

6.3.4.5 Absorbed-dose enhancement effects are negligible.

6.3.5 The use of Eq 1, without a correction for absorbed-dose enhancement effects, gives good accuracy when the volume of interest is sufficiently far from interfaces, or where interface regions form a negligible fraction of the volume of interest. The thickness of the region where absorbed-dose enhancement effects are important is dependent on the range of Compton electrons and photoelectrons produced in the energy deposition processes. Additional detail on the processes can be found in 6.1 and Appendix X2. The thickness of the absorbed-dose enhancement region for Co-60 irradiation is of the order of hundreds of micrometres. Therefore, for example, in MOS

devices where the critical gate oxide is 10–200 nm thick, the volume of interest will generally lie within the enhancement region.

6.3.6 Since mass energy absorption coefficients are a function of photon energy, the use of Eq 1 requires knowledge of the incident photon spectrum. However, for photon energies greater than 250 keV, ratios of mass energy absorption coefficients are slowly varying functions of photon energy (see Fig. X4.1). As a result it is often adequate to use the values of $(\mu_{en}/\rho)_{dosimeter}$ and $(\mu_{en}/\rho)_{device}$ tabulated for 1 MeV (see Appendix X4). For photon energies greater than 250 keV the errors introduced by this approximation are usually less than about 5 %. The advantage of this approximation is that it requires no knowledge of the Co-60 source photon energy spectrum. Such spectrum information frequently is unavailable.

NOTE 9—Another consideration in absorbed-dose conversion is that the photons will generally have passed through somewhat different layers of material in going from the source to the dosimeter as compared to going from the source to the device under test. Therefore, the photon energy spectrum incident on the dosimeter will be different from that incident on the device. For Co-60 irradiations of electronic devices, these differences can be neglected if care is taken to make the irradiation geometry of the dosimeters and devices essentially the same. The resulting dosimetry errors are generally less than 10 %.

6.4 *Examples of Conditions That May Lead to Large Absorbed-Dose Enhancement Effects:*

6.4.1 A *soft spectrum* is typically caused by Compton scattering from low atomic number materials. It is particularly important in water well sources, if long water paths are used, and in room sources, if there is significant photon backscattering from walls and floors.

6.4.2 *High Atomic Number Materials* in devices or device packaging can lead to large effects. A common example of such a structure is the device packaged with a gold layer on the inside of a Kovar lid.

7. Procedures for Minimizing Dosimetry Errors Due to Absorbed-Dose Enhancement

7.1 The principal errors in dosimetry in Co-60 irradiation hardness testing of electronic devices are caused by absorbed-dose enhancement effects resulting from non-equilibrium electron transport. Such errors can be reduced by using appropriate procedures assuming that the dosimetry measurements are made correctly (See Practice E668 for the use of TLDs). The dosimeter shall be irradiated under the same conditions as the device under test (see 4.1.1).

7.2 *Minimizing Errors Due to Low Energy Photons:*

7.2.1 Low energy absorbed-dose enhancement effects are due to low energy components of the Co-60 photon spectrum (see Section 5 and 6.1). This form of absorbed-dose enhancement can be reduced by spectrum hardening.

7.2.2 A filter box shall be used for spectrum hardening of all types of Co-60 sources described in Section 5. Such a box can be constructed with an outer layer of between 1.5 and 2.0 mm (approximately 0.063 in.) of Pb and an inner layer of between 0.7 and 1.0 mm (approximately 0.030 in.) of Al.

NOTE 10—The purpose of the indicated thickness of aluminum is to eliminate dose enhancement effects that could be caused by the lead layer. This aluminum layer should be thick enough to produce an approximate charged particle equilibrium with the largely low atomic number materials usually present in devices. It can be seen from Fig. X5.1 that the absorbed-dose enhancement effects of a high atomic number material are largely eliminated after about 0.8 mm (about 0.03 in.) of aluminum.

7.2.3 For the teletherapy and room type sources, other procedures should be used in addition to the use of a filter box. Potential scatterers within the vicinity of the irradiation position or near the direct path of the radiation beam should be removed. Those potential scatterers that cannot be removed, including the walls, floor, and ceiling, should be covered with Pb, when practical (see X3.2.2).

7.2.4 In the case of room type sources, when the Co-60 is contained within an individual capsule, the effect of scattering from the walls, floor and ceiling can be estimated by exposing an appropriate dosimeter at different radial distances, r, from the source. If the dosimeter response shows no significant deviation from an inverse square law ($1/r^2$), corrected if necessary for the calculated effects of infinite source and detector size, it may be concluded that, at the positions tested, no effects are present from scatterers, other than those associated with the support structures of the source and detector. An appropriate dosimeter in this context must be one capable of responding to low energy photons.

7.2.5 For a teletherapy source, proper collimators should be used and a beam trap can often be used effectively to reduce backscattering.

7.3 *Minimizing Errors Due to High Energy Photons:*

7.3.1 A form of absorbed-dose enhancement is present even for relatively high energy Co-60 photons. This form of absorbed-dose enhancement cannot be reduced by the use of spectrum hardening, but can be minimized by proper device orientation (see X2.3).

7.3.2 The orientation of the plane of the semiconductor chip in the device under test shall be perpendicular to the incident radiation to the extent possible. The device shall be oriented with higher atomic number layers toward the incident radiation in order to minimize absorbed-dose enhancement effects. These requirements do not apply for irradiations in source geometries in which the photons are incident nearly isotropically on the device under test; for example, in a self-shielded cavity source or in the center of a cylindrical array of a water well or room source.

NOTE 11—An orientation to be avoided is that of a unidirectional beam directed so that it passes from a low-atomic-number material to a high-atomic-number material. For example, for a 1.25 MeV beam passing through aluminum to gold, an absorbed-dose enhancement factor as large as 1.5 has been reported (see X2.3).

7.4 If the procedures of 7.2 and 7.3 are used, the absorbed-dose enhancement factor is expected to be between 0.9 and 1.2 and, therefore, contributes no more than 20 % to the dosimetry error (see Appendix X5).

NOTE 12—Dosimetry errors of less than 20 % may be acceptable in many cases of radiation hardness testing of electronics. Appendix X5 indicates that without using these procedures, the absorbed-dose enhancement factor can be as large as five.

8. Minimum Information for Test Reports

8.1 *Source*—Type, source strength, and any information on a measured or calculated energy spectrum.

8.2 *Dosimeter System*—Type, calibration data, and relevant environmental conditions during the irradiation.

8.3 *Device*—Type, manufacturer, lot or batch number, and any available information on its specific construction.

8.4 *Irradiation Geometry*—Position and orientation of source and device under test as well as position and description of materials or objects in the vicinity that could lead to either spectrum softening or spectrum hardening.

8.5 *Filter Box (or Can)*—Materials used, thicknesses, and dimensions.

9. Keywords

9.1 absorbed dose; Co-60 irradiation; dose enhancement; radiation hardness testing

APPENDIXES

(Nonmandatory Information)

X1. TYPICAL ^{60}CO FACILITIES

X1.1 This appendix provides simplified schematic diagrams of various types of available ^{60}Co irradiation facilities, along with tabular and graphical information on typical energy spectra for each source. Caution should be employed in using the spectral information for calculation or interpretation of absorbed dose or absorbed dose enhancement for any specific application. A given source spectrum may be altered significantly by the presence of scattering material, by a change in location relative to the source, and by other effects.

X1.2 Source and energy spectral information are provided in the following figures:

X1.2.1 Teletherapy source in Fig. X1.1 and Fig. X1.2,

X1.2.2 Room source in Fig. X1.3 and Fig. X1.4,

X1.2.3 Water well sources in Fig. X1.5 and Fig. X1.6, and

X1.2.4 Shielded-cavity irradiator in Fig. X1.7 and Fig. X1.8.

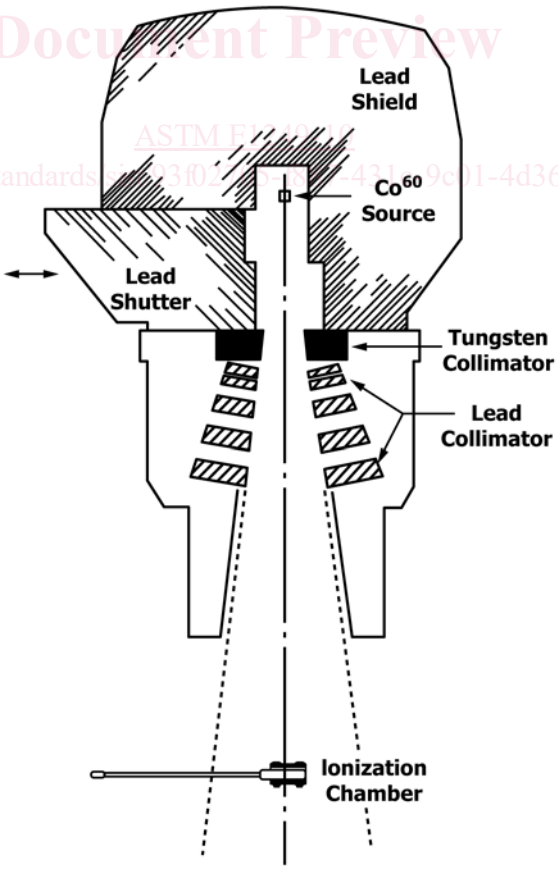


FIG. X1.1 Diagram of a Teletherapy Source (4)