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Designation: E722 – 09$^{\epsilon 1}$

StandardPractice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics[1]

This standard is issued under the fixed designation E722; 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 Department of Defense.

ε^1 NOTE—Editorial changes were made throughout in October 2009.

1. Scope

1.1 This practice covers procedures for characterizing neutron fluence from a source in terms of an equivalent monoenergetic neutron fluence. It is applicable to neutron effects testing, to the development of test specifications, and to the characterization of neutron test environments. The sources may have a broad neutron-energy range, or may be mono-energetic neutron sources with energies up to 20 MeV. This practice is not applicable in cases where the predominant source of displacement damage is from neutrons of energy less than 10 keV. The relevant equivalence is in terms of a specified effect on certain physical properties of materials upon which the source spectrum is incident. In order to achieve this, knowledge of the effects of neutrons as a function of energy on the specific property of the material of interest is required. Sharp variations in the effects with neutron energy may limit the usefulness of this practice in the case of mono-energetic sources.

1.2 This practice is presented in a manner to be of general application to a variety of materials and sources. Correlation between displacements (**1-3**)[2] caused by different particles (electrons, neutrons, protons, and heavy ions) is beyond the scope of this practice. In radiation-hardness testing of electronic semiconductor devices, specific materials of interest include silicon and gallium arsenide, and the neutron sources generally are test and research reactors and californium-252 irradiators.

1.3 The technique involved relies on the following factors: *(1)* a detailed determination of the fluence spectrum of the neutron source, and *(2)* a knowledge of the degradation (damage) effects of neutrons as a function of energy on specific material properties.

1.4 The detailed determination of the neutron fluence spectrum referred to in 1.3 need not be performed afresh for each test exposure, provided the exposure conditions are repeatable. When the spectrum determination is not repeated, a neutron fluence monitor shall be used for each test exposure.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, 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.*

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2. Referenced Documents

2.1 *ASTM Standards:*[3]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32

E693 Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E 706(ID)

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

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[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applicationsand 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 a list of references at the end of this practice.

[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.

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E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)

2.2 *International Commission on Radiation Units and Measurements (ICRU) Reports:*
ICRU Report 13—Neutron Fluence, Neutron Spectra, and Kerma[4]
ICRU Report 26—Neutron Dosimetry for Biology and Medicine[4]
ICRU Report 33—Radiation Quantities and Units[4]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *displacement damage function*—($F_{\mathrm{D,mat}}$) an energy-dependent parameter proportional to the quotient of the observable displacement damage per target atom and the neutron fluence. Different displacement-related damage functions may exist, so the damage mode of interest and the observation procedure shall be identified when the specific damage function is defined. See, for example, Annexes A1.2.2 and A2.2.2.

3.1.1.1 *Discussion*—Observable changes in a material's properties attributable to the atomic displacement process are useful indices of displacement damage in that material. In cases where the observed displacement damage is not in linear proportion to the applied fluence, the displacement damage function represents the quotient $F_{\mathrm{D,mat}}(\mathrm{E})/d\Phi$ in the limiting case of zero fluence. Examples of suitable representations of displacement damage functions are given in the annexes. In the case of silicon, damage mode of interest is the change in minority-carrier recombination lifetime in the bulk semiconductor material. While several procedures exist to directly measure the minority carrier lifetime in bulk material, since this lifetime is related to the gain of a bipolar junction transistor (BJT), one observable damage metric is the BJT gain degradation. For this damage mode, it has been shown that the displacement damage function may be successfully equated with the microscopic displacement kerma factor. This question is discussed further in the annexes.

3.1.2 *microscopic displacement kerma factor*—($\kappa_{\mathrm{D,mat}}(\mathrm{E})$) the energy-dependent quotient of the displacement kerma per target atom and the neutron fluence. $\kappa_{\mathrm{D,mat}}(\mathrm{E})$ is proportional to $K_{\mathrm{D,mat}}\bar{\mathrm{A}}/\Phi$, where $K_{\mathrm{D,mat}}$ is the displacement kerma, $\bar{\mathrm{A}}$ is the mean atomic mass of the material and Φ is the neutron fluence from a monoenergetic source of energy E.

3.1.2.1 *Discussion*—This quantity may be calculated from the microscopic neutron interaction cross sections, the kinematic relations for each reaction and from a suitable partition function which divides the total kerma into ionization and displacement kerma. The use of the term *microscopic* kerma factor in this standard is to indicate that energy times area per atom is used, instead of per unit mass, as in the term kerma factor defined in E170.

3.1.3 *fluence spectrum hardness parameter*—($H_{\mathrm{mat}} = \Phi_{\mathrm{eq,Eref,mat}}/\Phi$) this parameter is defined as the ratio of the equivalent monoenergetic neutron fluence to the total fluence, $\Phi_{\mathrm{eq,Eref,mat}}/\Phi$. The numerical value of the hardness parameter is also equal to the fluence of monoenergetic neutrons at the specific energy, Eref, required to produce the same displacement damage in the specified material, mat, per unit fluence of neutrons of neutron spectrum $\Phi(\mathrm{E})$.

3.1.3.1 *Discussion*—For damage correlation, a convenient method of characterizing the shape of an incident neutron fluence spectrum $\Phi(\mathrm{E})$, is in terms of a fluence spectrum hardness parameter. The hardness parameter in a particular neutron field depends on the displacement damage function used to compute the damage (see annexes) and is therefore different for different semiconductor materials.

3.1.4 *equivalent monoenergetic neutron fluence*— ($\Phi_{\mathrm{eq,Eref,mat}}$) an equivalent monoenergetic neutron fluence, $\Phi_{\mathrm{eq,Eref,mat}}$, characterizes an incident fluence spectrum, $\Phi(\mathrm{E})$, in terms of the fluence of monoenergetic neutrons at a specific energy Eref required to produce the same displacement damage in a specified irradiated material, mat, as $\Phi(\mathrm{E})$.

3.1.4.1 *Discussion*—Note that $\Phi_{\mathrm{eq,Eref,mat}}$ is equivalent to $\Phi(\mathrm{E})$ if, and only if, the specific device effect (for example, current gain degradation in silicon) being correlated is described by the displacement damage function used in the calculation.

3.1.5 *fluence* and *fluence spectrum*—see *neutron fluence* and *neutron fluence spectrum*.

3.1.6 *kerma factor*—($\kappa_{\mathrm{mat}}(\mathrm{E})$) the **kerma** per unit fluence of particles of energy E present in a specified material, mat. See Terminology E170 for the definition of **kerma**, and a formula for calculating the kerma factor.

3.1.6.1 *Discussion*—When a material is irradiated by a neutron field, the energy imparted to charged particles in the material may be described by the kerma. The kerma may be divided into two parts, ionization kerma and displacement kerma. See 3.1.2.1 for the distinction between kerma factor and microscopic kerma factor. Calculations of ionization and microscopic displacement kerma in silicon and gallium arsenide as a result of irradiation by neutrons with energies up to 20 MeV are described in Refs **5-8** and in the annexes.

3.1.7 *neutron fluence* and *neutron fluence spectrum* are used in this standard, and are special cases of **particle fluence** and **particle fluence spectrum** as defined in E170.

3.1.7.1 *Discussion*—In cases where the context makes clear that neutrons are referred to, the terms *fluence* and *fluence spectrum* are sometimes used.

4. Summary of Practice

4.1 The equivalent monoenergetic neutron fluence, $\Phi_{\mathrm{eq,Eref,mat}}$, is given as follows:

$$\Phi_{\mathrm{eq,Eref,mat}} = \frac{\int_0^\infty \Phi(\mathrm{E}) F_{\mathrm{D,mat}}(\mathrm{E})\,d\mathrm{E}}{F_{\mathrm{D,Eref,mat}}} \quad (1)$$

where:

$\Phi(\mathrm{E})$ = incident neutron fluence spectrum,

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[4] Available from International Commission on Radiation Units and Measurements, 7910 Woodmont Avenue Suite 400 Bethesda, MD 20841-3095, http://www.icru.org/

$F_{\mathrm{D,mat}}$ = neutron displacement damage function for the irradiated material (displacement damage per unit fluence) as a function of energy, and

$F_{\mathrm{D,Eref,mat}}$ = displacement damage reference value designated for the irradiated material and for the specified equivalent energy, Eref, as given in the annexes.

The energy limits on the integral are determined in practice by the incident neutron fluence spectrum and by the material being irradiated.

4.2 The neutron spectrum hardness parameter, H_{mat}, is given as follows:

$$H_{\mathrm{mat}} = \frac{\int_0^\infty \Phi(\mathrm{E}) F_{\mathrm{D,mat}}(\mathrm{E}) \mathrm{dE}}{F_{\mathrm{D,Eref,mat}} \int_0^\infty \Phi(E) dE} \tag{2}$$

4.3 Once the neutron fluence spectrum has been determined (for example, in accordance with Test Method E721) and the equivalent monoenergetic fluence calculated, then a monitor (such as an activation foil) can be used in subsequent irradiations at the same location to determine the fluence; that is, the neutron fluence is then described in terms of the equivalent monoenergetic neutron fluence per unit monitor response, $\Phi_{\mathrm{eq,Eref,mat}}/M_r$. Use of a monitor foil to predict $\Phi_{\mathrm{eq,Eref,mat}}$ is valid only if the neutron spectrum remains constant.

5. Significance and Use

5.1 This practice is important in characterizing the radiation hardness of electronic devices irradiated by neutrons. This characterization makes it feasible to predict some changes in operational properties of irradiated semiconductor devices or electronic systems. To facilitate uniformity of the interpretation and evaluation of results of irradiations by sources of different fluence spectra, it is convenient to reduce the incident neutron fluence from a source to a single parameter—an equivalent monoenergetic neutron fluence—applicable to a particular semiconductor material.

5.2 In order to determine an equivalent monoenergetic neutron fluence, it is necessary to evaluate the displacement damage of the particular semiconductor material. Ideally, this quantity is correlated to the degradation of a specific functional performance parameter (such as current gain) of the semiconductor device or system being tested. However, this correlation has not been established unequivocally for all device types and performance parameters since, in many instances, other effects also can be important. Ionization effects produced by the incident neutron fluence or by gamma rays in a mixed neutron fluence, short-term and long-term annealing, and other factors can contribute to observed performance degradation (damage). Thus, caution should be exercised in making a correlation between calculated displacement damage and performance degradation of a given electronic device. The types of devices for which this correlation is applicable, and numerical evaluation of displacement damage are discussed in the annexes.

5.3 The concept of 1-MeV equivalent fluence is widely used in the radiation-hardness testing community. It has merits and disadvantages that have been debated widely **(9-12)**. For these reasons, specifics of a standard application of the 1-MeV equivalent fluence are presented in the annexes.

6. Procedure for Calculating $\Phi_{\mathrm{eq,Eref,mat}}$

6.1 To evaluate Eq 1 and 2, determine the energy limits E_{min} and E_{max} to be used in place of zero and infinity in the integrals of (Eq 1) and (Eq 2) and the values of the displacement damage function $F_{\mathrm{D,mat}}(\mathrm{E})$ for the irradiated material and perform the indicated integrations.

6.1.1 Choose the upper limit E_{max} to be at an energy above which the integral damage falls to an insignificant level. For Godiva- or TRIGA-type spectra, this limit is about 12 MeV.

6.1.2 Choose the lower-energy limit E_{min} to be at an energy below which the integral damage falls to an insignificant level. For silicon irradiated by Godiva-type spectra, this energy has been historically chosen to be about 0.01 MeV. More highly moderated spectra may require lower thresholds or specialized filtering requirements such as a boron shield, or both.

6.1.3 The values of the neutron displacement damage function used in Eq 1 and 2 obviously depend on the material and the equivalent energy chosen. For silicon, resonance effects cause large variations (by a factor of 20 or more) in the displacement damage function as a function of energy over the range from about 0.1 to 8 MeV (**4**, **5**). Therefore, monoenergetic neutron sources with these energies may not be useful for effects testing. Also, for a selected equivalent energy, the value of $F_{\mathrm{D,Eref,mat}}$ at that specific energy may not be representative of the displacement damage function at nearby energies. In such cases, a method of averaging the damage function over a range of energies around the chosen equivalent energy can be used. Such averaging is discussed in the annexes. Because the $F_{\mathrm{D,mat}}(\mathrm{E})$ term is normalized by dividing by $F_{\mathrm{D,Eref,mat}}$ in Eq 1 and 2, only the shape of the $F_{\mathrm{D,mat}}(\mathrm{E})$ function versus energy is of primary importance. In such a case, precise knowledge of the absolute values of $F_{\mathrm{D,mat}}(\mathrm{E})$ is not required in evaluating $\Phi_{\mathrm{eq,Eref,mat}}$ and H_{mat}.

7. Determining $\Phi_{\mathrm{eq,Eref,mat}}$ with a Monitor Foil

7.1 At the same time that the fluence spectrum, Φ(E), of the source is determined (for example, with an activation foil set in accordance with Guides E720 or E844, or both, and Test Method E721 or Practice E944, or both, place a fast-neutron monitor foil in the neutron field at an appropriate location. After $\Phi_{\mathrm{eq,Eref,mat}}$ is determined and the monitor foil counted, calculate the ratio of the equivalent monoenergetic fluence to the unit monitor response, $\Phi_{\mathrm{eq,Eref,mat}}/\mathrm{M_r}$.

7.2 Use the response of the fast-neutron monitor foil, M_r, to predict $\Phi_{\mathrm{eq,Eref,mat}}$ in subsequent routine device test irradiations. For this method to be valid, it is important to keep the source-foil geometry essentially identical to that used for calibrating the monitor foil. Moderate changes in source-to-foil distance are allowable. In addition, make sure the source location (of a Godiva-type reactor) with respect to scattering materials (walls, floor, etc.) is the same. Do not change or move nearby scattering materials or moderators.

7.3 Precautions in maintaining original calibration conditions are necessary to avoid altering the neutron fluence

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spectrum significantly in subsequent irradiations. An appreciable change in the spectrum will invalidate the calibration of the monitor foil and, therefore, would necessitate a new measurement of Φ(E) and recalibration of the monitor foil. Whenever the neutron source configuration is changed, as for example, if the core fuel elements are replaced or rearranged in a nuclear reactor, the activation foil spectrum measurements and all quantities derived from them may need to be remeasured.

7.4 The choice of a monitor foil material depends on several factors:

7.4.1 The activation threshold should be high enough so as to make it insensitive to neutrons below the E_{min} value used in Eq 1 and 2. However, the threshold energy should be low enough to sample a significant fraction of the total fluence.

7.4.2 The monitor foil should have a high neutron sensitivity and a convenient half-life.

7.4.3 The detector system available for counting the monitor foil may dictate the choice of foil material. A germanium gamma-ray detector system can be used, and ^{54}Fe or ^{58}Ni foils utilized as monitors. However, if a beta particle detector system is available, then ^{32}S foils are suitable. Details of the use of sulfur foils are given in Test Method E265.

8. Report

8.1 In the report of the results of radiation-hardness tests in which an equivalent monoenergetic neutron fluence is calculated, the report should include at least the following information:

8.1.1 Semiconductor material and device performance parameter (for example, current gain in silicon bipolar transistors) degradation being correlated to displacement damage should be specified.

8.1.2 Neutron source as to type and mode of operation during tests (fast-pulse or steady state).

8.1.3 Neutron fluence spectrum and how it was determined.

8.1.4 Monitor foil employed and the detector system used for counting the foil. If an effective fission cross section for the monitor foil is used, its value should be stated.

8.1.5 The neutron displacement damage function should be given, or referenced. The specific material (for example, silicon) whose applicable damage function was used must be specified. The values cited in Annex A1 and Annex A2 shall be used for silicon and GaAs, respectively.

8.1.6 Methods used for determining the average value of $F_{D,Eref,mat}$ and the value of Eref selected. The values cited in Annex A1 and Annex A2 shall be used for silicon and GaAs, respectively.

8.1.7 Method used for evaluating the integrals of Eq 1 and 2 (for example, the energy bin width and number of bins in a numerical integration).

8.1.8 Values of $\Phi_{eq,Eref,mat}$, H_{mat}, and $\Phi_{eq,Eref,mat}/M_r$.

9. Precision and Bias

9.1 The precision in calculating $\Phi_{eq,Eref,mat}$ and H_{mat} will depend on the method of evaluation of the integrals in Eq 1 and 2 (for example, the width of the energy bins used in a numerical integration).

9.2 The uncertainty of the calculated results depends on *(1)* knowledge of the neutron fluence spectrum, *(2)* knowledge of the displacement damage functions over that energy spectrum, and *(3)* knowledge of the value of the average displacement damage function at the specified equivalent energy.

9.3 A specific example of the uncertainty associated with the calculation of a 1-MeV equivalent fluence for silicon is given in Annex A1.

10. Keywords

10.1 displacement damage; electronic hardness; gallium arsenide; hardness parameter; silicon; silicon damage; silicon equivalent damage (SED); 1–MeV equivalent fluence

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ANNEXES

(Mandatory Information)

A1. CALCULATION OF 1-MeV EQUIVALENT NEUTRON FLUENCE FOR SILICON

A1.1 Background

A1.1.1 The observable damage metric of interest in this annex is the change in gain of a silicon bipolar junction transistor (BJT) due to bulk displacement damage effects. The damage mechanism is the change in minority-carrier recombination lifetime in the bulk semiconductor material. While a BJT gain may also be degraded by oxide traps and interface states introduced by the ionizing dose to the oxide, this is a surface effect and is not within the scope of this standard. In interpreting measurements of this 1-MeV(Si) damage, efforts must be made to eliminate any interference from ionization-related surface effects.

A1.1.2 The choice of the specific energy for determining an equivalent fluence has been the subject of some controversy within the electronics hardness-testing community (**9**). Some workers (**10**) have proposed that 1 MeV be used while others (**11, 12**) have suggested 14 MeV to be more appropriate. The concept of 1-MeV equivalent fluence has gained broad acceptance in practice, and procedures for applying it to silicon are described in this annex in some detail.

A1.1.3 An important basis of the practice is the correlation of radiation damage effects in a semiconductor device with the displacement kerma produced in bulk silicon by neutron irradiation. This correlation assumes that volume (versus surface) effects are the dominant radiation damage mechanism. Experimental evidence indicates that displacement kerma is a valid measure of device performance degradation (for example, reduction in current gain) in bipolar transistors whose operation basically depends on volume mechanisms (**13**, **14**). However, for device types governed by surface phenomena (such as MOSFET devices), it is clear that this correlation is not valid. Surface-effect devices are more sensitive than are volume-effect devices to ionization radiation effects produced either by a neutron field or a mixed neutron-gamma field. Therefore, the basic mechanism associated with device performance and the effect being correlated (for example, gain degradation) should be kept in mind before applying this practice at any equivalent energy.

A1.2 Calculation of $\Phi_{eq,1MeV,Si}$

A1.2.1 The displacement damage function, $F_{D,mat}(E)$, defined for silicon in this annex is the silicon microscopic displacement kerma factor, as tabulated in Table A1.1.

A1.2.2 A 1-MeV equivalent fluence in silicon is defined for an irradiation by neutrons of any neutron spectrum for which the predominant source of displacement damage is from neutrons of energy between 10 keV and 20 MeV. The neutron fluence spectrum, $\Phi(E)$, may be that determined from a neutron transport calculation, that determined from measurements, or that given in an environment specification document.

A1.2.3 The neutron fluence spectrum, $\Phi(E)$, may be determined experimentally by measuring a set of activation foils and then by application of a spectral adjustment computer code (see Guide E720 and Test Method E721 for details).

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A1.2.4 Results of calculations of silicon microscopic displacement kerma factors (displacement kerma per target atom per unit neutron fluence), $\kappa_{D,Si}(E)$, are given in Table A1.1 as a function of neutron energy over the range from 10^{-10} to 20 MeV (**11**, **15**). The unit of the microscopic kerma factor is megaelectron volt times millibarns (MeV·mbarn). Each factor can be multiplied by 3.435×10^{-13} to convert to rad(Si)·cm^2, or by 3.435×10^{-19} to convert to J·m^2/kg or Gy(Si)·m^2. The silicon microscopic displacement kerma factor as given in Table A1.1 is the accepted silicon damage function to be used in the application of this standard: $F_{D,Si}(E) = \kappa_{D,Si}(E)$. This microscopic displacement kerma was computed by using the ENDF/B-VI^{28}Si cross section evaluation (**18**), a displacement threshold energy of 25 eV, the Robinson fit to the Lindhard energy partition function (**19**), and the NJOY97 processing code (**20**). Fig. A1.1 shows the energy dependence of the silicon 1-MeV damage function.

A1.2.5 An average value of neutron microscopic displacement kerma factor near 1 MeV is difficult to determine because of sharp neutron cross-section resonances in that energy region. To avoid these difficulties, Namenson, Wolicki, and Messenger (**13**) fitted the function $AE(1 - \exp(- B/E))$ to various tabulations of $\kappa_D(E)$ versus energy. The values of A and B obtained by a least squares fit yielded an average value at 1 MeV of 95 ± 4 MeV·mbarn. A similar procedure applied to the data given in Table A1.1 also gives a value close to 95 MeV·mbarn. Accordingly, the designated value of $F_{D,1MeV,Si}$ to be used in Eq 1 and 2 to calculate a 1-MeV equivalent fluence is 95 MeV·mbarn.

A1.2.6 For purposes of intercomparison of hardness testing results from various laboratories, the value of $F_{D,1MeV,Si}$ used in obtaining such results is very important; therefore, reporting of results should include confirmation that the value of $F_{D,1MeV,Si}$ designated in A1.2.5 was used in any calculation.

A1.2.7 Once the neutron fluence spectrum $\Phi(E)$ has been determined for the energy range of interest, then use numerical integration to evaluate Eq 1 and 2, using values for $F_D(E)$ from Table A1.1 and $F_{D,1MeV,Si} = 95$ MeV·mbarn.

NOTE A1.1—The damage function provided here differs from that in versions of this practice earlier than E722 – 93, and will result in a different value for $\Phi_{eq,1MeV,Si}$. For fast-burst and TRIGA reactors, the value calculated for $\Phi_{eq,1MeV,Si}$ will typically be 5 to 10 % lower than that calculated using E722 – 85.

A1.3 Precision and Bias

A1.3.1 The values for $\kappa_{D,Si}(E)$ given in Table A1.1 are determined by calculating the total kerma and then partitioning it into ionization and displacement fractions. Because of the lack of adequate theory to partition the kerma and uncertainties in cross sections, the estimated uncertainty in the microscopic displacement kerma factor is about 10 % up to 3 MeV. Correlation of displacement kerma with measured damage in many neutron fields has been confirmed with uncertainties no larger than 10 % (**14**).

A1.3.2 Uncertainties in the neutron fluence spectrum, $\Phi(E)$, will vary based on the method used to obtain it. If neutron sensors such as activation foils were used, see Standard Guide E721.

A1.3.3 Since this mandatory annex requires the use of Table A1.1 and $F_{D,1MeV,Si} = 95$ MeV·mbarn, no uncertainty in the calculation of 1-MeV equivalent fluence is attributable to the consistent use of these data. Therefore only the uncertainty in the determination of $\Phi(E)$ need be considered in assigning an uncertainty to the 1-MeV equivalent fluence. An uncertainty in the spectrum in the range ±20 %, would most often lead to uncertainties no more than ±10 % in the integral quantity $\Phi_{eq,1MeV,Si}$. While no specific group structure for representing the neutron fluence spectrum is recommended, the choice of energy bin boundaries will affect the uncertainty in the 1-MeV equivalent fluence. The energy bin boundaries should be chosen with due consideration for the shape of both the neutron spectrum and the 1-MeV equivalent damage function. A poor choice of the energy group structure used to evaluate the integral in Eq 2 could increase this uncertainty (see 8.1.7).

TABLE A1.1 Silicon Microscopic Displacement Kerma Factor

Bin	Mid-Point Energy	Displacement Damage Function
#	(MeV)	(MeV·mbarn)
1	19.9500	182.8700
2	19.8500	183.0000
3	19.7500	183.1200
4	19.6500	183.2500
5	19.5500	183.3800
6	19.4500	183.5100
7	19.3500	183.6300
8	19.2500	183.7500
9	19.1500	183.8800
10	19.0500	184.0000
11	18.9500	184.1100
12	18.8500	184.2000
13	18.7500	184.2800
14	18.6500	184.3700
15	18.5500	184.4500
16	18.4500	184.3100
17	18.3500	183.9700
18	18.2500	183.6200
19	18.1500	183.2800
20	18.0500	182.9400
21	17.9500	182.5900
22	17.8500	182.2400
23	17.7500	181.9100
24	17.6500	181.5800
25	17.5500	181.2400
26	17.4500	180.6700
27	17.3500	179.8800
28	17.2500	179.0800
29	17.1500	178.2800
30	17.0500	177.4900
31	16.9500	177.2400
32	16.8500	177.5000
33	16.7500	177.7600
34	16.6500	178.0100
35	16.5500	178.2700
36	16.4500	178.3200
37	16.3500	178.1800
38	16.2500	178.0300
39	16.1500	177.8900
40	16.0500	177.7400
41	15.9500	176.3000
42	15.8500	173.6300
43	15.7500	171.3200
44	15.6500	170.8600
45	15.5500	170.7200
46	15.4500	170.5600
47	15.3500	170.4000
48	15.2500	170.2500
49	15.1500	170.0900
50	15.0500	169.9300
51	14.9500	169.7900
52	14.8500	169.6600
53	14.7500	169.5200
54	14.6500	169.3700
55	14.5500	169.2100
56	14.4500	168.7300
57	14.3500	167.9400
58	14.2500	167.1400
59	14.1500	166.3400
60	14.0500	165.5400
61	13.9500	165.4000
62	13.8500	165.8600
63	13.7500	166.2900
64	13.6500	166.7300
65	13.5500	167.1600
66	13.4500	167.5300
67	13.3500	167.8300
68	13.2500	168.1100
69	13.1500	168.3900
70	13.0500	168.6600
71	12.9500	168.6200
72	12.8500	168.2800
73	12.7500	167.9400

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https://standards.iteh.ai/catalog/standards/sist/1b 9c-cd0e-4bb2-9 020075a251a/astm-e722-09e1

TABLE A1.1 *Continued*

Bin	Mid-Point Energy	Displacement Damage Function
#	(MeV)	(MeV·mbarn)
74	12.6500	167.6000
75	12.5500	167.2700
76	12.4500	167.2200
77	12.3500	167.4700
78	12.2500	167.7100
79	12.1500	167.9500
80	12.0500	168.1700
81	11.9500	165.6600
82	11.8500	165.4600
83	11.7500	166.6200
84	11.6500	165.7900
85	11.5500	168.6200
86	11.4500	165.3800
87	11.3500	166.0300
88	11.2500	159.5200
89	11.1500	155.6100
90	11.0500	158.7500
91	10.9500	160.0500
92	10.8500	162.9100
93	10.7500	159.0000
94	10.6500	155.5100
95	10.5500	154.6000
96	10.4500	154.7600
97	10.3500	164.6700
98	10.2500	163.3600
99	10.1500	168.6300
100	10.0500	166.2100
101	9.9500	164.4900
102	9.8500	164.0600
103	9.7500	161.9600
104	9.6500	156.1000
105	9.5500	164.4100
106	9.4500	169.8200
107	9.3500	166.2100
108	9.2500	150.6900
109	9.1500	153.8800
110	9.0500	174.5800
111	8.9500	177.5700
112	8.8500	160.2200
113	8.7500	146.7500
114	8.6500	163.8600
115	8.5500	165.8300
116	8.4500	166.6100
117	8.3500	162.0200
118	8.2500	158.4200
119	8.1500	154.4300
120	8.0500	165.0000
121	7.9500	186.4000
122	7.8500	175.3400
123	7.7500	174.8000
124	7.6500	170.3100
125	7.5500	162.9100
126	7.4500	167.0500
127	7.3500	168.4300
128	7.2500	169.2700
129	7.1500	139.1600
130	7.0500	161.1000
131	6.9500	141.7700
132	6.8500	146.8900
133	6.7500	162.2500
134	6.6500	150.9200
135	6.5500	119.2700
136	6.4500	139.2700
137	6.3500	150.0900
138	6.2500	175.3800
139	6.1500	127.7100
140	6.0500	153.0000
141	5.9500	137.1000
142	5.8500	164.7000
143	5.7500	180.0500
144	5.6500	152.0700
145	5.5500	145.6000
146	5.4500	116.9800

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ASTM E722-09e1
https://standards.iteh.ai/catalog/standards/sist/1b9[illegible]d9c-cd0e-4bb2-9[illegible]020075a251a/astm-e722-09e1

TABLE A1.1 *Continued*

Bin	Mid-Point Energy	Displacement Damage Function
#	(MeV)	(MeV·mbarn)
147	5.3500	120.1500
148	5.2500	145.7000
149	5.1500	170.3100
150	5.0500	149.1600
151	4.9500	145.5000
152	4.8500	160.6700
153	4.7500	185.6100
154	4.6500	158.6400
155	4.5500	138.3800
156	4.4500	140.9200
157	4.3500	134.8600
158	4.2500	164.4100
159	4.1500	108.7100
160	4.0500	131.6400
161	3.9500	134.3400
162	3.8500	108.8400
163	3.7500	115.1300
164	3.6500	69.52400
165	3.5500	111.2700
166	3.4500	119.0600
167	3.3500	113.8700
168	3.2500	118.0200
169	3.1500	131.5000
170	3.0500	120.2000
171	2.9500	98.84500
172	2.8500	135.0400
173	2.7500	106.9100
174	2.6500	115.6700
175	2.5500	131.1900
176	2.4500	118.9200
177	2.3500	102.8200
178	2.2500	105.4900
179	2.1500	106.9200
180	2.0500	95.21800
181	1.9500	129.4000
182	1.8500	129.2100
183	1.7500	78.34200
184	1.6500	163.0200
185	1.5500	105.9800
186	1.4500	98.97900
187	1.3500	88.76000
188	1.2500	88.99400
189	1.1500	62.67300
190	1.0500	75.69200
191	0.98000	111.7900
192	0.94000	111.4900
193	0.90000	87.78100
194	0.86000	78.33600
195	0.82000	136.8000
196	0.78000	87.94400
197	0.74000	64.57500
198	0.70500	59.30200
199	0.67500	56.76700
200	0.64500	55.29000
201	0.61500	52.61800
202	0.58750	58.33400
203	0.56250	124.5500
204	0.53750	77.95800
205	0.51250	57.41600
206	0.48750	55.40500
207	0.46250	53.50800
208	0.43750	52.65400
209	0.41250	51.89700
210	0.39000	52.10700
211	0.37000	49.72200
212	0.35000	50.09500
213	0.33000	49.28000
214	0.31000	50.23700
215	0.29000	51.32600
216	0.27500	52.55800
217	0.26250	54.95900
218	0.24750	58.46000
219	0.23500	64.07300

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ASTM E722-09e1
https://standards.iteh.ai/catalog/standards/sist/1b9 9c-cd0e-4bb2-9 020075a251a/astm-e722-09e1

TABLE A1.1 *Continued*

Bin	Mid-Point Energy	Displacement Damage Function
#	(MeV)	(MeV·mbarn)
220	0.22500	69.75000
221	0.21500	78.66700
222	0.20500	91.83600
223	0.19500	111.2800
224	0.18500	114.1000
225	0.17500	64.49300
226	0.16500	19.04800
227	0.15500	4.323200
228	0.14625	1.350900
229	0.13875	1.870700
230	0.13125	2.552600
231	0.12375	3.352800
232	0.11750	3.982800
233	0.11250	4.431900
234	0.10750	4.876000
235	0.10250	5.197800
236	0.98000E-01	5.417300
237	0.94000E-01	5.611900
238	0.90000E-01	5.844300
239	0.86000E-01	6.040100
240	0.82000E-01	6.185300
241	0.78000E-01	6.310600
242	0.74000E-01	6.595600
243	0.70500E-01	6.831900
244	0.67500E-01	7.178200
245	0.64500E-01	6.972900
246	0.61500E-01	7.992000
247	0.58750E-01	11.45300
248	0.56250E-01	47.95000
249	0.53750E-01	1.498700
250	0.51250E-01	1.847000
251	0.48750E-01	2.470200
252	0.46250E-01	2.820300
253	0.43750E-01	3.026800
254	0.41250E-01	3.234200
255	0.39000E-01	3.697700
256	0.37000E-01	2.995800
257	0.35000E-01	2.949100
258	0.33000E-01	2.823100
259	0.31000E-01	2.689600
260	0.29000E-01	2.556800
261	0.27500E-01	2.452700
262	0.26250E-01	2.363100
263	0.24750E-01	2.261300
264	0.23500E-01	2.180800
265	0.22500E-01	2.116100
266	0.21500E-01	2.050100
267	0.20500E-01	1.979200
268	0.19500E-01	1.900700
269	0.18500E-01	1.820900
270	0.17500E-01	1.738500
271	0.16500E-01	1.655100
272	0.15500E-01	1.565500
273	0.14625E-01	1.485300
274	0.13875E-01	1.414100
275	0.13125E-01	1.342200
276	0.12375E-01	1.270100
277	0.11750E-01	1.210800
278	0.11250E-01	1.165800
279	0.10750E-01	1.121000
280	0.10250E-01	1.076200
281	0.98000E-02	1.036000
282	0.94000E-02	0.9989800
283	0.90000E-02	0.9611300
284	0.86000E-02	0.9232700
285	0.82000E-02	0.8854100
286	0.78000E-02	0.8475500
287	0.74000E-02	0.8096600
288	0.70500E-02	0.7753600
289	0.67500E-02	0.7451400
290	0.64500E-02	0.7149200
291	0.61500E-02	0.6847000
292	0.58750E-02	0.6570400

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ASTM E722-09e1
https://standards.iteh.ai/catalog/standards/sist/

TABLE A1.1 *Continued*

Bin	Mid-Point Energy	Displacement Damage Function
#	(MeV)	(MeV·mbarn)
293	0.56250E-02	0.6318600
294	0.53700E-02	0.6066800
295	0.51250E-02	0.5821900
296	0.48750E-02	0.6085100
297	0.46250E-02	0.5211400
298	0.43750E-02	0.4872300
299	0.41250E-02	0.4598900
300	0.39000E-02	0.4361800
301	0.37000E-02	0.4151300
302	0.35000E-02	0.3939900
303	0.33000E-02	0.3727900
304	0.31000E-02	0.3514300
305	0.29000E-02	0.3298500
306	0.27500E-02	0.3137700
307	0.26250E-02	0.3002000
308	0.24750E-02	0.2834300
309	0.23500E-02	0.2693700
310	0.22500E-02	0.2580800
311	0.21500E-02	0.2467900
312	0.20500E-02	0.2355000
313	0.19500E-02	0.2243300
314	0.18500E-02	0.2132400
315	0.17500E-02	0.2021500
316	0.16500E-02	0.1910600
317	0.15500E-02	0.1799600
318	0.14625E-02	0.1697200
319	0.13875E-02	0.1606400
320	0.13125E-02	0.1515600
321	0.12375E-02	0.1424900
322	0.11750E-02	0.1349500
323	0.11250E-02	0.1289000
324	0.10750E-02	0.1228500
325	0.10250E-02	0.1168000
326	0.98000E-03	0.1115900
327	0.94000E-03	0.1071900
328	0.90000E-03	0.1028000
329	0.86000E-03	0.98406E-01
330	0.82000E-03	0.94013E-01
331	0.78000E-03	0.89045E-01
332	0.74000E-03	0.83513E-01
333	0.70500E-03	0.78736E-01
334	0.67500E-03	0.75315E-01
335	0.64500E-03	0.72097E-01
336	0.61500E-03	0.68880E-01
337	0.58750E-03	0.65583E-01
338	0.56250E-03	0.62205E-01
339	0.53750E-03	0.58827E-01
340	0.51250E-03	0.55449E-01
341	0.48750E-03	0.51682E-01
342	0.46250E-03	0.47534E-01
343	0.43750E-03	0.43386E-01
344	0.41250E-03	0.39238E-01
345	0.39000E-03	0.36301E-01
346	0.37000E-03	0.34546E-01
347	0.35000E-03	0.32464E-01
348	0.33000E-03	0.28456E-01
349	0.31000E-03	0.24134E-01
350	0.29000E-03	0.20712E-01
351	0.27500E-03	0.18816E-01
352	0.26250E-03	0.17222E-01
353	0.24750E-03	0.14956E-01
354	0.23500E-03	0.12137E-01
355	0.22500E-03	0.98052E-02
356	0.21500E-03	0.74733E-02
357	0.20500E-03	0.51414E-02
358	0.19500E-03	0.34199E-02
359	0.18500E-03	0.22979E-02
360	0.17500E-03	0.13235E-02
361	0.16500E-03	0.12182E-02
362	0.15500E-03	0.12548E-02
363	0.14625E-03	0.12918E-02
364	0.13875E-03	0.13292E-02
365	0.13125E-03	0.13666E-02

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Document Preview
ASTM E722-09e1
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