Standard Practice for Characterizing Neutron Energy 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 E 722; 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.

1. Scope

1.1 This practice covers procedures for characterizing a 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 spectrum, or may be monoenergetic neutron sources with energies up to 20 MeV. 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 energy 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 energy 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 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 265 Test Method for Measuring Reaction Rates for Fast-Neutron Fluences by Radioactivation of Sulfur-32[3]

E 693 Practice for Characterizing Neutron Exposures in Ferritic Steels in Terms of Displacement per Atom (DPA)[3]

E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics[3]

E 721 Test Method for Determining Neutron Energy Spectra with Neutron Activation Foils for Radiation-Hardness Testing of Electronics[3]

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E706 (IIC)[3]

E 944 Practice for Applications of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)[3]

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*—($F_{D,mat}$) an energydependent parameter proportional to the quotient of the observable displacement damage per target atom and the neutron fluence.

3.1.1.1 *Discussion*—Observable changes in a material's

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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 E10.07on 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] *Annual Book of ASTM Standards*, Vol 12.02.

[4] Available from International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Bethesda, MD 20814.

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 $F_{D,mat}$ (E)/dΦ, 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, it has been shown that the displacement damage function may be successfully equated with the displacement kerma factor. This question is discussed further in the annexes.

3.1.2 *displacement kerma factor*—($K_{D,mat}$(E)) the energy dependent quotient of the displacement kerma per target atom and the neutron fluence.

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.

3.1.3 *energy-spectrum hardness parameter*—($H_{mat} = \Phi_{eq,Eref,mat}/\Phi$) this parameter is defined as the ratio of the equivalent monoenergetic neutron fluence to the true total fluence, $\Phi_{eq,Eref,mat}/\Phi$. 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 unit fluence of neutrons of spectral distribution Φ(E).

3.1.3.1 *Discussion*—For damage correlation, a convenient method of characterizing the shape of an incident neutron energy-fluence spectrum Φ(E), is in terms of an energy spectrum hardness parameter **(4)**. 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*— ($\Phi_{eq,Eref,mat}$) an equivalent monoenergetic neutron fluence, $\Phi_{eq,Eref,mat}$, characterizes an incident energy-fluence spectrum, Φ(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 Φ(E).

3.1.4.1 *Discussion*—Note that $\Phi_{eq,Eref,mat}$ is equivalent to Φ(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 *kerma*—(K_{mat} (E)) the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles (for example, neutrons) in a volume element containing a unit mass of the specified material (see ICRU reports 13 and 33).

3.1.5.1 *Discussion*—When a material is irradiated by a neutron field, the energy imparted to the material may be described by the quantity kerma. The total kerma may be divided into two parts, ionization kerma and displacement kerma. Calculations of ionization and 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.

4. Summary of Practice

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

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

where:

Φ(E)	=	incident neutron energy-fluence spectral distribution,
$F_{D,mat}$	=	neutron displacement damage function for the irradiated material (displacement damage per unit fluence) as a function of energy, and
$F_{D,Eref,mat}$	=	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-energy spectrum and by the material being irradiated.

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

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

4.3 Once the neutron energy-fluence spectrum has been determined (for example, in accordance with Test Method E 721) 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, $\Phi_{eq,Eref,mat}/M_r$. Use of a monitor foil to predict $\Phi_{eq,Eref,mat}$ is valid only if the energy 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 energy 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 $\Phi_{eq,Eref,mat}$

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 $F_{D,mat}$ (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)**. Therefore, monoenergetic neutron sources with these energies may not be useful for effects testing. Also, for a selected equivalent energy, the value of $F_{D,Eref,mat}$ 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 $F_{D,mat}$ (E) term is normalized by dividing by $F_{D,Eref,mat}$ in Eq 1 and 2, only the shape of the $F_{D,mat}$ (E) function versus energy is of primary importance. In such a case, precise knowledge of the absolute values of $F_{D,mat}$ (E) is not required in evaluating $\Phi_{eq,Eref,mat}$ and H_{mat}.

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

7.1 At the same time that the energy spectrum, Φ(E), of the source is determined (for example, with an activation foil set in accordance with Guides E 720 or E 844, or both, and Test Method E 721 or Practice E 944, or both, place a fast-neutron monitor foil in the neutron field at an appropriate location. After $\Phi_{eq,Eref,mat}$ is determined and the monitor foil counted, calculate the ratio of the equivalent monoenergetic fluence to the unit monitor response, $\Phi_{eq,Eref,mat}/M_r$.

7.2 Use the response of the fast-neutron monitor foil, M_r, to predict $\Phi_{eq,Eref,mat}$ 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 energy 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 E 265.

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 energy-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 source energy-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

ANNEXES

(Mandatory Information)

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

A1.1 Background

A1.1.1 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.

A1.1.2 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 A 1-MeV equivalent fluence in a given material can be defined for an irradiation by neutrons of any neutron spectrum. The neutron energy fluence, Φ(E), may be that determined from a neutron transport calculation, that determined from measurements, or that given in an environment specification document.

A1.2.2 The neutron energy-fluence spectrum, Φ(E), may be determined experimentally by measuring a set of activation foils and then by application of a spectral adjustment computer code (see Guide E 720 and Test Method E 721 for details).

A1.2.3 Results of calculations of silicon displacement kerma factors (displacement kerma per unit neutron fluence), $K_{D,Si}$ (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 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 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) = $K_{D,Si}$ (E). Fig. A1.1 shows the energy dependence of the silicon 1-MeV damage function.

A1.2.4 An average value of neutron 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 K_D (E) versus energy. The values of A and B obtained by a least squares fit yielded an average value at 1 MeV of $K_{D,1MeV,Si} = 95 \pm 4$ MeV-mbarn. A similar procedure applied to the data given in Table A1.1 also gives a value close to 95

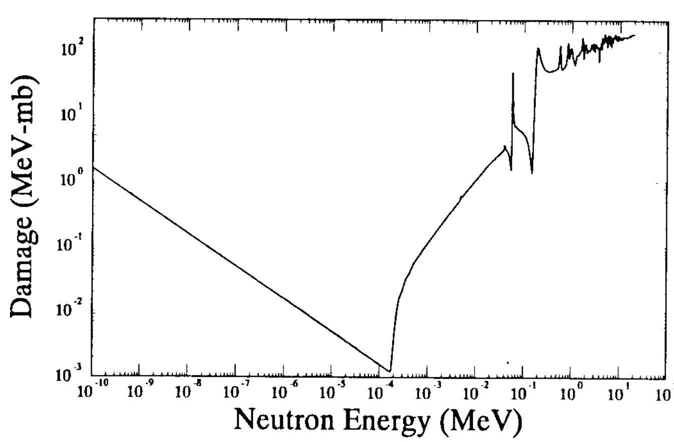

FIG. A1.1 Silicon Damage Function

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.

A1.2.5 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 A1.2.4 was used in any calculation.

A1.2.6 Once the neutron energy-fluence spectrum Φ(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-mb.

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 $K_{D,Si}$ (E) given in Table A1.1 are determined by calculating the total kerma and then partitioning it into ionization and displacement fractions **(5)**. Because of the lack of adequate theory to partition the kerma and uncertainities in cross sections, the estimated uncertainty in the 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 Comparisons between the calculations with the SAND II unfolding code (using activation-foil input data), neutron transport codes, and experimental spectrometry data give an estimated uncertainty in the determination of Φ(E) of about 20 % over the energy region of interest **(15)** (see Test Method E 721).

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 Φ(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 energy-fluence 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 Displacement Kerma Function

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
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
74	12.6500	167.6000
75	12.5500	167.2700

TABLE A1.1 *Continued*

Bin	Lower Energy	Damage
#	(MeV)	(MeV-mb)
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
147	5.3500	120.1500
148	5.2500	145.7000

TABLE A1.1 *Continued*

Bin	Lower Energy	Damage
#	(MeV)	(MeV-mb)
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
220	0.22500	69.75000
221	0.21500	78.66700

TABLE A1.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
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
293	0.56250E-02	0.6318600
294	0.53700E-02	0.6066800

TABLE A1.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
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
366	0.12375E-03	0.14070E-02
367	0.11750E-03	0.14484E-02

TABLE A1.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
368	0.11250E-03	0.14822E-02
369	0.10750E-03	0.15161E-02
370	0.10250E-03	0.15499E-02
371	0.98000E-04	0.15839E-02
372	0.94000E-04	0.16182E-02
373	0.90000E-04	0.16525E-02
374	0.86000E-04	0.16895E-02
375	0.82000E-04	0.17301E-02
376	0.78000E-04	0.17750E-02
377	0.74000E-04	0.18242E-02
378	0.70500E-04	0.18676E-02
379	0.67500E-04	0.19115E-02
380	0.64500E-04	0.19572E-02
381	0.61500E-04	0.20030E-02
382	0.58750E-04	0.20493E-02
383	0.56250E-04	0.20963E-02
384	0.53750E-04	0.21432E-02
385	0.51250E-04	0.21902E-02
386	0.48750E-04	0.22454E-02
387	0.46250E-04	0.23088E-02
388	0.43750E-04	0.23721E-02
389	0.41250E-04	0.24355E-02
390	0.39000E-04	0.25026E-02
391	0.37000E-04	0.25734E-02
392	0.35000E-04	0.26464E-02
393	0.33000E-04	0.27325E-02
394	0.31000E-04	0.28207E-02
395	0.29000E-04	0.29183E-02
396	0.27500E-04	0.29980E-02
397	0.26250E-04	0.30649E-02
398	0.24750E-04	0.31573E-02
399	0.23500E-04	0.32438E-02
400	0.22500E-04	0.33133E-02
401	0.21500E-04	0.33827E-02
402	0.20500E-04	0.34596E-02
403	0.19500E-04	0.35523E-02
404	0.18500E-04	0.36539E-02
405	0.17500E-04	0.37586E-02
406	0.16500E-04	0.38817E-02
407	0.15500E-04	0.40078E-02
408	0.14625E-04	0.41264E-02
409	0.13875E-04	0.42379E-02
410	0.13125E-04	0.43494E-02
411	0.12375E-04	0.44697E-02
412	0.11750E-04	0.45924E-02
413	0.11250E-04	0.46927E-02
414	0.10750E-04	0.47929E-02
415	0.10250E-04	0.48931E-02
416	0.98000E-05	0.50030E-02
417	0.94000E-05	0.51225E-02
418	0.90000E-05	0.52420E-02
419	0.86000E-05	0.53615E-02
420	0.82000E-05	0.54810E-02
421	0.78000E-05	0.56148E-02
422	0.74000E-05	0.57627E-02
423	0.70500E-05	0.58933E-02
424	0.67500E-05	0.60251E-02
425	0.64500E-05	0.61627E-02
426	0.61500E-05	0.63003E-02
427	0.58750E-05	0.64441E-02
428	0.56250E-05	0.65942E-02
429	0.53750E-05	0.67442E-02
430	0.51250E-05	0.68942E-02
431	0.48750E-05	0.70711E-02
432	0.46250E-05	0.72741E-02
433	0.43750E-05	0.74772E-02
434	0.41250E-05	0.76803E-02
435	0.39000E-05	0.78956E-02
436	0.37000E-05	0.81233E-02
437	0.35000E-05	0.83582E-02
438	0.33000E-05	0.86361E-02
439	0.31000E-05	0.89211E-02
440	0.29000E-05	0.92370E-02
441	0.27500E-05	0.94950E-02
442	0.26250E-05	0.97120E-02
443	0.24750E-05	0.99916E-02
444	0.23500E-05	0.10276E-01
445	0.22500E-05	0.10508E-01
446	0.21500E-05	0.10740E-01
447	0.20500E-05	0.10972E-01
448	0.19500E-05	0.1123500E-01
449	0.18500E-05	0.1153100E-01
450	0.17500E-05	0.1183500E-01
451	0.16500E-05	0.12196E-01
452	0.15500E-05	0.12566E-01
453	0.14625E-05	0.12938E-01
454	0.13875E-05	0.13313E-01
455	0.13125E-05	0.13688E-01
456	0.12375E-05	0.14093E-01
457	0.11750E-05	0.14508E-01
458	0.11250E-05	0.14847E-01
459	0.10750E-05	0.15187E-01
460	0.10250E-05	0.15526E-01
461	0.98000E-06	0.15879E-01
462	0.94000E-06	0.16247E-01
463	0.90000E-06	0.16615E-01
464	0.86000E-06	0.16982E-01
465	0.82000E-06	0.17350E-01
466	0.78000E-06	0.17778E-01
467	0.74000E-06	0.18266E-01
468	0.70500E-06	0.18696E-01
469	0.67500E-06	0.19134E-01
470	0.64500E-06	0.19591E-01
471	0.61500E-06	0.20049E-01
472	0.58750E-06	0.20501E-01
473	0.56250E-06	0.20949E-01
474	0.53750E-06	0.21425E-01
475	0.51250E-06	0.21927E-01
476	0.48750E-06	0.22476E-01
477	0.46250E-06	0.23071E-01
478	0.43750E-06	0.23710E-01
479	0.41250E-06	0.24392E-01
480	0.39000E-06	0.25056E-01
481	0.37000E-06	0.25732E-01
482	0.35000E-06	0.26488E-01
483	0.33000E-06	0.27350E-01
484	0.31000E-06	0.28229E-01
485	0.29000E-06	0.29186E-01
486	0.27500E-06	0.29964E-01
487	0.26250E-06	0.30690E-01
488	0.24750E-06	0.31600E-01
489	0.23500E-06	0.32440E-01
490	0.22500E-06	0.33135E-01
491	0.21500E-06	0.33919E-01
492	0.20500E-06	0.34716E-01
493	0.19500E-06	0.35582E-01
494	0.18500E-06	0.36547E-01
495	0.17500E-06	0.37608E-01
496	0.16500E-06	0.38770E-01
497	0.15500E-06	0.40035E-01
498	0.14625E-06	0.41221E-01
499	0.13875E-06	0.42307E-01
500	0.13125E-06	0.43491E-01
501	0.12375E-06	0.44747E-01
502	0.11750E-06	0.45901E-01
503	0.11250E-06	0.46859E-01
504	0.10750E-06	0.47951E-01
505	0.10250E-06	0.49064E-01
506	0.98000E-07	0.50159E-01
507	0.94000E-07	0.51222E-01
508	0.90000E-07	0.52310E-01
509	0.86000E-07	0.53540E-01
510	0.82000E-07	0.54793E-01
511	0.78000E-07	0.56171E-01
512	0.74000E-07	0.57669E-01
513	0.70500E-07	0.58984E-01

TABLE A1.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
514	0.67500E-07	0.60254E-01
515	0.64500E-07	0.61602E-01
516	0.61500E-07	0.63067E-01
517	0.58750E-07	0.64502E-01
518	0.56250E-07	0.65900E-01
519	0.53750E-07	0.67406E-01
520	0.51250E-07	0.69017E-01
521	0.48750E-07	0.70766E-01
522	0.46250E-07	0.72651E-01
523	0.43750E-07	0.74716E-01
524	0.41250E-07	0.76959E-01
525	0.39000E-07	0.79168E-01
526	0.37000E-07	0.81347E-01
527	0.35000E-07	0.83572E-01
528	0.33000E-07	0.86084E-01
529	0.31000E-07	0.88853E-01
530	0.29000E-07	0.91889E-01
531	0.27500E-07	0.94345E-01
532	0.26250E-07	0.96611E-01
533	0.24750E-07	0.99509E-01
534	0.23500E-07	0.1021500
535	0.22500E-07	0.1043500
536	0.21500E-07	0.1068400
537	0.20500E-07	0.1093600
538	0.19500E-07	0.1121500
539	0.18500E-07	0.1152200
540	0.17500E-07	0.1183400
541	0.16500E-07	0.1218700
542	0.15500E-07	0.1257700
543	0.14625E-07	0.1295000
544	0.13875E-07	0.1329500
545	0.13125E-07	0.1367700
546	0.12375E-07	0.1408400
547	0.11750E-07	0.1446100
548	0.11250E-07	0.1477300
549	0.10750E-07	0.1512500
550	0.10250E-07	0.1548500
551	0.98000E-08	0.1583700
552	0.94000E-08	0.1618000
553	0.90000E-08	0.1652500
554	0.86000E-08	0.1691700
555	0.82000E-08	0.1733200
556	0.78000E-08	0.1775300
557	0.74000E-08	0.1822500
558	0.70500E-08	0.1867200
559	0.67500E-08	0.1908200
560	0.64500E-08	0.1952500
561	0.61500E-08	0.1999200
562	0.58750E-08	0.2046100
563	0.56250E-08	0.2090800
564	0.53750E-08	0.2139100
565	0.51250E-08	0.2191100
566	0.48750E-08	0.2245800
567	0.46250E-08	0.2307200
568	0.43750E-08	0.2370600
569	0.41250E-08	0.2443800
570	0.39000E-08	0.2511300
571	0.37000E-08	0.2577000
572	0.35000E-08	0.2649200
573	0.33000E-08	0.2728300
574	0.31000E-08	0.2815400
575	0.29000E-08	0.2910500
576	0.27500E-08	0.2988700
577	0.26250E-08	0.3059100

TABLE A1.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
578	0.24750E-08	0.3150400
579	0.23500E-08	0.3233300
580	0.22500E-08	0.3306000
581	0.21500E-08	0.3379100
582	0.20500E-08	0.3463200
583	0.19500E-08	0.3551900
584	0.18500E-08	0.3642200
585	0.17500E-08	0.3744400
586	0.16500E-08	0.3856500
587	0.15500E-08	0.3978400
588	0.14625E-08	0.4096400
589	0.13875E-08	0.4205700
590	0.13125E-08	0.4324100
591	0.12375E-08	0.4454600
592	0.11750E-08	0.4571300
593	0.11250E-08	0.4670500
594	0.10750E-08	0.4782200
595	0.10250E-08	0.4894200
596	0.98000E-09	0.5004400
597	0.94000E-09	0.5112600
598	0.90000E-09	0.5221200
599	0.86000E-09	0.5344500
600	0.82000E-09	0.5475400
601	0.78000E-09	0.5607900
602	0.74000E-09	0.5756900
603	0.70500E-09	0.5897900
604	0.67500E-09	0.6027400
605	0.64500E-09	0.6166900
606	0.61500E-09	0.6314400
607	0.58750E-09	0.6462600
608	0.56250E-09	0.6603400
609	0.53750E-09	0.6755900
610	0.51250E-09	0.6920100
611	0.48750E-09	0.7092900
612	0.46250E-09	0.7286900
613	0.43750E-09	0.7487000
614	0.41250E-09	0.7718300
615	0.39000E-09	0.7931900
616	0.37000E-09	0.8139600
617	0.35000E-09	0.8368100
618	0.33000E-09	0.8618200
619	0.31000E-09	0.8893800
620	0.29000E-09	0.9194700
621	0.27500E-09	0.9442600
622	0.26250E-09	0.9665400
623	0.24750E-09	0.9954500
624	0.23500E-09	1.021700
625	0.22500E-09	1.044700
626	0.21500E-09	1.067800
627	0.20500E-09	1.094500
628	0.19500E-09	1.122500
629	0.18500E-09	1.151100
630	0.17500E-09	1.183400
631	0.16500E-09	1.218900
632	0.15500E-09	1.257500
633	0.14625E-09	1.294800
634	0.13875E-09	1.329400
635	0.13125E-09	1.366800
636	0.12375E-09	1.408100
637	0.11750E-09	1.445000
638	0.11250E-09	1.476400
639	0.10750E-09	1.511700
640	0.10250E-09	1.547100

A2. CALCULATION OF 1-MeV EQUIVALENT NEUTRON FLUENCE FOR GALLIUM ARSENIDE

A2.1 Background

A2.1.1 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)**. The concept of 1-MeV equivalent fluence has gained broad acceptance in practice, and procedures for applying it to gallium arsenide are described in this annex in some detail.

A2.1.2 An important part of the practice is the correlation of radiation damage effects in a semiconductor device with the displacement kerma produced in bulk gallium arsenide by neutron irradiation. This correlation assumes that displacement effects are the dominant radiation damage mechanism and that equal numbers of initially displaced atoms produce equal changes in device performance. Experimental evidence **(8, 16)** indicates that displacement kerma is not a valid measure of changes in the fundamental properties (carrier concentration, mobility, and carrier lifetime) thatdetermine device performance.

A2.1.3 The reason that displacement kerma does not correlate with property changes in gallium arsenide over the entire range of neutron energies of interest is attributed to variations in the defect production efficiency in displacement cascades of different sizes. This effect is also known to occur in other materials, including structural metals **(17)**.

A2.1.4 Despite the deficiencies mentioned above, displacement kerma may still be useful as an exposure parameter, analogous to the use of displacements per atom (dpa) for exposures of ferritic steel (see Practice E 693). When displacement kerma is used to compare property changes in gallium arsenide exposed to reactor neutrons in thermal and fast spectrum reactors, the discrepancies do not exceed ±10 % in reactors where careful comparisons have been made. When these reactor irradiations have been compared with accelerator irradiations with neutron energies of 3 and 14 MeV, however, much larger discrepancies have been observed **(8, 16)**.

A2.1.5 Empirical efficiency factors that depend on the energies of the primary knock-on atoms (pka) have been proposed **(8)** in order to remove the discrepancies described in A2.1.4. Fig. A2.1 shows the shape of the empirical damage efficiency factor for GaAs. This damage efficiency function can be fit with the following equation:

$$\zeta(r) = \begin{cases} 1.0 & r < 0.1\text{ keV} \\ a_0 + a_1\times\log(r) + a_2\times r^2\times\log(r) + a_3\times[\log(r)]^2 & 0.1\text{ keV} < r < 500.0\text{ keV} \\ 0.01 & r > 500.0\text{ keV} \end{cases}$$

where:

r = PKA recoil energy, keV,
$\zeta(r)$ = damage efficiency function,
a_0 = 0.872670,
a_1 = −0.187469,
a_2 = 1.237178E-7, and
a_3 = −0.060753.

As in Ref **(14)**, this PKA-energy damage efficiency factor is used in conjunction with a normalization factor of 2.2 in order to preserve the equivalence of the GaAs damage function and the displacement kerma for 1-MeV neutrons.

A2.2 Calculation of $\Phi_{eq,1MeV,GaAs}$

A2.2.1 A 1-MeV equivalent fluence in a given material can be defined for an irradiation by neutrons of any neutron spectrum. The neutron energy fluence, Φ(E), may be that determined from a neutron transport calculation, that determined from measurements, or that given in an environment specification document.

A2.2.2 The neutron energy-fluence spectrum, Φ(E), may be determined experimentally by measuring a set of activation foils and then by application of a spectral adjustment computer code (see Guide E 720 and Test Method E 721 for details).

A2.2.3 Results of calculations of gallium arsenide displacement kerma factors (displacement kerma per unit neutron fluence), $K_{D,GaAs}(E)$, are shown in Fig. A2.2 as a function of neutron energy **(7, 8)**. The unit of the kerma factor is megaelectron volt times millibarns (MeV-mbarn). Each factor can be multiplied by 1.334×10^{-13} to convert to rad-(GaAs)–cm^2 or by 1.334×10^{-19} to convert to J-m^2/kg or Gy(GaAs)–m^2.

A2.2.4 An average value of neutron displacement kerma factor near 1 MeV is 70 MeV-mbarn. As is the case for silicon

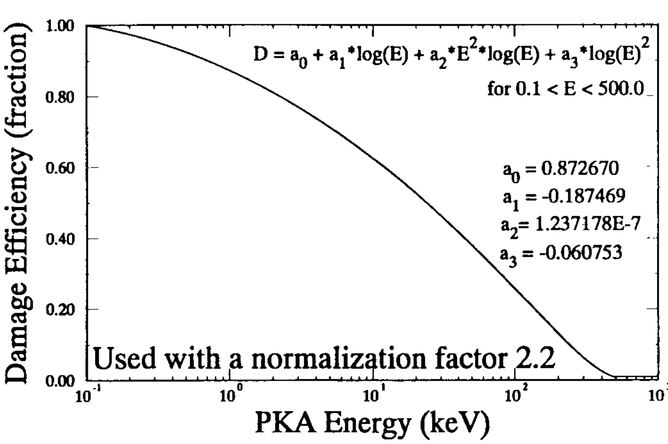

FIG. A2.1 GaAs Damage Efficiency Curve

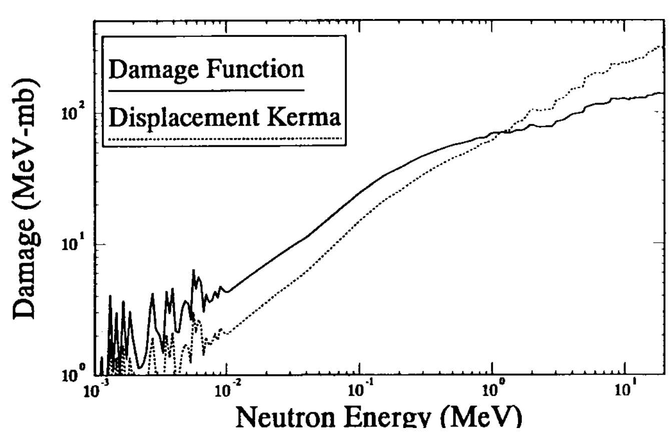

FIG. A2.2 Comparison of GaAs Displacement Kerma and Damage Function

(9), the actual value chosen for the designated 1-MeV reference damage is arbitrary. What is important is that the whole radiation hardness community use the same value in setting hardness specification and in testing electronic parts. The damage function for gallium arsenide is normalized to the same value as the displacement kerma factor at 1 MeV: $F_{D,1MeV,GaAs} = K_{D,1MeV,GaAs}$. Accordingly, the designated value to be used in Eq 1 and 2 to calculate a 1-MeV equivalent fluence in gallium arsenide is 70 MeV-mbarn.

A2.2.5 For purposes of intercomparison of hardness testing results from various laboratories, the value of $F_{D,1MeV,GaAs}$ used in obtaining such results is very important; therefore, reporting of results should include confirmation that the value of $F_{D,1MeV,GaAs}$ designated in A2.2.4 was used in any calculation.

A2.2.6 The empirical damage function derived from the efficiency factors, described in A2.1.5, are printed in Table A2.1 in the same energy structure as that used for the silicon damage factors of Table A1.1. The values are arbitrarily normalized to 70 MeV-mbarn at a neutron energy of 1 MeV. The values are also shown in Fig. A2.2, where they may be compared with the displacement kerma factors, and in Fig. A2.3.

A2.2.7 Once the neutron energy-fluence spectrum Φ(E) has been determined for the energy range of interest, then use numerical integration to evaluate Eq 1 and 2, using values for the displacement damage function, F_D (E), from Table A2.1 and $F_{D,1MeV,GaAs}$ = 70 MeV-mbarn.

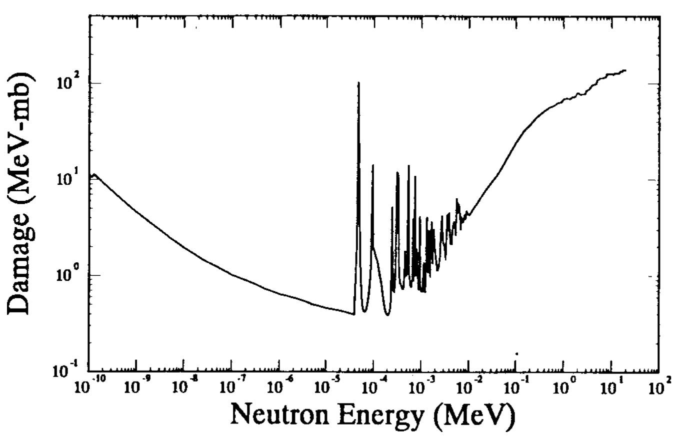

FIG. A2.3 GaAs Damage Function

TABLE A2.1 GaAs Damage Function

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
1	19.9500	137.1559
2	19.8500	137.2673
3	19.7500	137.3787
4	19.6500	137.4901
5	19.5500	137.6015
6	19.4500	137.7044
7	19.3500	137.7994
8	19.2500	137.8944
9	19.1500	137.9892
10	19.0500	138.0842
11	18.9500	138.1766
12	18.8500	138.2667
13	18.7500	138.3568
14	18.6500	138.4468
15	18.5500	138.5368
16	18.4500	138.6395
17	18.3500	138.7767
18	18.2500	138.9149
19	18.1500	139.0533
20	18.0500	139.1914
21	17.9500	139.0089
22	17.8500	138.5269
23	17.7500	138.0448
24	17.6500	137.5628
25	17.5500	137.0808
26	17.4500	136.9054
27	17.3500	137.0164
28	17.2500	137.1274
29	17.1500	137.2384
30	17.0500	137.3494
31	16.9500	137.1862
32	16.8500	136.7669
33	16.7500	136.3476
34	16.6500	135.9283
35	16.5500	135.5089
36	16.4500	135.0748
37	16.3500	134.6265
38	16.2500	134.1783
39	16.1500	133.7302
40	16.0500	133.2820
41	15.9500	133.1028
42	15.8500	133.1749
43	15.7500	133.2471
44	15.6500	133.3188
45	15.5500	133.3914
46	15.4500	133.4389
47	15.3500	133.4642
48	15.2500	133.4894
49	15.1500	133.5145
50	15.0500	133.5394
51	14.9500	132.9427
52	14.8500	131.9140
53	14.7500	130.8872
54	14.6500	129.8613
55	14.5500	128.8357
56	14.4500	128.3123
57	14.3500	128.2097
58	14.2500	128.1022
59	14.1500	127.9740
60	14.0500	127.8423
61	13.9500	127.7934
62	13.8500	127.8288

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
63	13.7500	127.8575
64	13.6500	127.8315
65	13.5500	127.7969
66	13.4500	127.7491
67	13.3500	127.8355
68	13.2500	128.1104
69	13.1500	128.3626
70	13.0500	128.6119
71	12.9500	128.4289
72	12.8500	127.7656
73	12.7500	127.2168
74	12.6500	127.3228
75	12.5500	127.5358
76	12.4500	127.7244
77	12.3500	127.8873
78	12.2500	128.0443
79	12.1500	128.1685
80	12.0500	128.2874
81	11.9500	127.5901
82	11.8500	126.5814
83	11.7500	126.5332
84	11.6500	126.4858
85	11.5500	126.4938
86	11.4500	126.4642
87	11.3500	126.4172
88	11.2500	126.4454
89	11.1500	126.4621
90	11.0500	126.5463
91	10.9500	125.2593
92	10.8500	123.5850
93	10.7500	123.8293
94	10.6500	124.1421
95	10.5500	124.4976
96	10.4500	124.8671
97	10.3500	125.2962
98	10.2500	125.8336
99	10.1500	126.3516
100	10.0500	126.8910
101	9.9500	127.0425
102	9.8500	126.9273
103	9.7500	126.8053
104	9.6500	126.6806
105	9.5500	126.6502
106	9.4500	126.5765
107	9.3500	126.2807
108	9.2500	125.9356
109	9.1500	125.5770
110	9.0500	125.2156
111	8.9500	125.1276
112	8.8500	125.2990
113	8.7500	125.4694
114	8.6500	125.6367
115	8.5500	125.8031
116	8.4500	125.9580
117	8.3500	126.1020
118	8.2500	126.2446
119	8.1500	126.3802
120	8.0500	126.5145
121	7.9500	124.9300
122	7.8500	121.7009
123	7.7500	118.8325
124	7.6500	118.0150
125	7.5500	117.5293
126	7.4500	117.0409
127	7.3500	116.5500
128	7.2500	116.0586
129	7.1500	115.5648
130	7.0500	115.0705
131	6.9500	114.8306
132	6.8500	114.8358
133	6.7500	114.8405
134	6.6500	114.8422
135	6.5500	114.8434

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
136	6.4500	114.8266
137	6.3500	114.7922
138	6.2500	114.7541
139	6.1500	114.6941
140	6.0500	114.6306
141	5.9500	114.2725
142	5.8500	113.6293
143	5.7500	112.9814
144	5.6500	112.3063
145	5.5500	111.6268
146	5.4500	110.9336
147	5.3500	110.2271
148	5.2500	109.5158
149	5.1500	108.7766
150	5.0500	108.0330
151	4.9500	102.0466
152	4.8500	99.23304
153	4.7500	98.96036
154	4.6500	98.66589
155	4.5500	98.35501
156	4.4500	98.02359
157	4.3500	97.65742
158	4.2500	97.25739
159	4.1500	96.83241
160	4.0500	96.38392
161	3.9500	95.29969
162	3.8500	93.60240
163	3.7500	91.90091
164	3.6500	90.19057
165	3.5500	88.46346
166	3.4500	87.28768
167	3.3500	86.65953
168	3.2500	86.02619
169	3.1500	85.38896
170	3.0500	84.75256
171	2.9500	81.21822
172	2.8500	78.03618
173	2.7500	77.94052
174	2.6500	77.78613
175	2.5500	77.61927
176	2.4500	77.45314
177	2.3500	77.17774
178	2.2500	77.12630
179	2.1500	78.23370
180	2.0500	79.77974
181	1.9500	79.77537
182	1.8500	76.39725
183	1.7500	73.49136
184	1.6500	72.47713
185	1.5500	73.01718
186	1.4500	71.02059
187	1.3500	69.15923
188	1.2500	69.89005
189	1.1500	70.16261
190	1.0500	69.97166
191	0.98000	68.69471
192	0.94000	66.38594
193	0.90000	64.33213
194	0.86000	63.91096
195	0.82000	63.72685
196	0.78000	63.43225
197	0.74000	62.66481
198	0.70500	61.24394
199	0.67500	60.41233
200	0.64500	59.68695
201	0.61500	58.89531
202	0.58750	58.23692
203	0.56250	57.71369
204	0.53750	57.12998
205	0.51250	56.48677
206	0.48750	55.66633
207	0.46250	54.67182
208	0.43750	53.63813

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
209	0.41250	52.56604
210	0.39000	51.54028
211	0.37000	50.55792
212	0.35000	49.54984
213	0.33000	48.33731
214	0.31000	47.06708
215	0.29000	45.63056
216	0.27500	44.43863
217	0.26250	43.43638
218	0.24750	42.16251
219	0.23500	40.91005
220	0.22500	39.89028
221	0.21500	38.87049
222	0.20500	37.85061
223	0.19500	36.89561
224	0.18500	36.00745
225	0.17500	35.09917
226	0.16500	34.05930
227	0.15500	32.99495
228	0.14625	31.87364
229	0.13875	30.69371
230	0.13125	29.51374
231	0.12375	28.31557
232	0.11750	27.26391
233	0.11250	26.41328
234	0.10750	25.56072
235	0.10250	24.70057
236	0.98000E-01	23.85536
237	0.94000E-01	23.02436
238	0.90000E-01	22.19209
239	0.86000E-01	21.35164
240	0.82000E-01	20.50865
241	0.78000E-01	19.65873
242	0 74000E-01	18.79961
243	0.70500E-01	18.04391
244	0.67500E-01	17.38495
245	0.64500E-01	16.72312
246	0.61500E-01	16.06063
247	0.58750E-01	15.44457
248	0.56250E-01	14.87455
249	0.53750E-01	14.30452
250	0.51250E-01	13.73448
251	0.48750E-01	13.16471
252	0.46250E-01	12.59518
253	0.43750E-01	12.02353
254	0.41250E-01	11.44880
255	0.39000E-01	10.98796
256	0.37000E-01	10.63791
257	0.35000E-01	10.28706
258	0.33000E-01	9.930538
259	0.31000E-01	9.543841
260	0.29000E-01	9.139377
261	0.27500E-01	8.821269
262	0.26250E-01	8.546266
263	0.24750E-01	8.212161
264	0.23500E-01	7.919796
265	0.22500E-01	7.683573
266	0.21500E-01	7.446482
267	0.20500E-01	7.197344
268	0.19500E-01	6.939925
269	0.18500E-01	6.681116
270	0.17500E-01	6.421101
271	0.16500E-01	6.149005
272	0.15500E-01	5.871399
273	0.14625E-01	5.620331
274	0.13875E-01	5.399389
275	0.13125E-01	5.173678
276	0.12375E-01	4.943371
277	0.11750E-01	4.750016
278	0.11250E-01	4.589880
279	0.17050E-01	4.426621
280	0.10250E-01	4.263193
281	0.98000E-02	4.303217

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
282	0.94000E-02	4.466909
283	0.90000E-02	4.747111
284	0.86000E-02	3.853745
285	0.82000E-02	4.347416
286	0.78000E-02	3.681936
287	0.74000E-02	3.570645
288	0.70500E-02	4.099506
289	0.67500E-02	3.008282
290	0.64500E-02	5.091309
291	0.61500E-02	5.613547
292	0.58750E-02	4.520483
293	0.56250E-02	6.368707
294	0.53700E-02	2.619797
295	0.51250E-02	3.498544
296	0.48750E-02	3.661220
297	0.46250E-02	3.187647
298	0.43750E-02	2.123645
299	0.41250E-02	2.143989
300	0.39000E-02	4.579587
301	0.37000E-02	2.916783
302	0.35000E-02	4.351841
303	0.33000E-02	1.471401
304	0.31000E-02	2.006934
305	0.29000E-02	2.245155
306	0.27500E-02	4.212828
307	0.26250E-02	3.107141
308	0.24750E-02	1.521695
309	0.23500E-02	1.237342
310	0.22500E-02	1.152334
311	0.21500E-02	1.124852
312	0.20500E-02	1.463002
313	0.19500E-02	1.909435
314	0.18500E-02	3.035858
315	0.17500E-02	1.313788
316	0.16500E-02	3.652810
317	0.15500E-02	0.9715682
318	0.14625E-02	2.976944
319	0.13875E-02	1.058469
320	0.13125E-02	4.039089
321	0.12375E-02	0.6729786
322	0.11750E-02	0.6776407
323	0.11250E-02	1.379635
324	0.10750E-02	0.6787618
325	0.10250E-02	0.6751838
326	0.98000E-03	0.7052754
327	0.94000E-03	4.117430
328	0.90000E-03	0.7085687
329	0.86000E-03	0.7433070
330	0.82000E-03	1.908450
331	0.78000E-03	0.9723304
332	0.74000E-03	10.85853
333	0.70500E-03	0.8728912
334	0.67500E-03	3.919608
335	0.64500E-03	0.7984169
336	0.61500E-03	0.7578828
337	0.58750E-03	0.7991196
338	0.56250E-03	1.021199
339	0.53750E-03	14.05596
340	0.51250E-03	1.050040
341	0.48750E-03	0.9816861
342	0.46250E-03	1.814618
343	0.43750E-03	0.7590081
344	0.41250E-03	0.7195444
345	0.39000E-03	0.7715850
346	0.37000E-03	0.8270449
347	0.35000E-03	0.9752603
348	0.33000E-03	10.95681
349	0.31000E-03	11.93249
350	0.29000E-03	0.8039847
351	0.27500E-03	0.6671034
352	0.26250E-03	0.7201912
353	0.24750E-03	5.170911
354	0.23500E-03	0.5295004

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
355	0.22500E-03	0.4305282
356	0.21500E-03	0.4002900
357	0.20500E-03	0.3863766
358	0.19500E-03	0.3902313
359	0.18500E-03	0.4021000
360	0.17500E-03	0.4396242
361	0.16500E-03	0.5259843
362	0.15500E-03	0.6701467
363	0.14625E-03	0.8222943
364	0.13875E-03	0.9446481
365	0.13125E-03	1.104201
366	0.12375E-03	1.314697
367	0.11750E-03	1.464778
368	0.11250E-03	1.523553
369	0.10750E-03	1.662977
370	0.10250E-03	1.836706
371	0.98000E-04	1.958603
372	0.94000E-04	14.13184
373	0.90000E-04	3.572621
374	0.86000E-04	1.064388
375	0.82000E-04	0.7545328
376	0.78000E-04	0.5942491
377	0.74000E-04	0.4988076
378	0.70500E-04	0.4475922
379	0.67500E-04	0.4247919
380	0.64500E-04	0.4175343
381	0.61500E-04	0.4277524
382	0.58750E-04	0.4620370
383	0.56250E-04	0.5505592
384	0.53750E-04	0.8595088
385	0.51250E-04	1.599728
386	0.48750E-04	13.23834
387	0.46250E-04	101.9115
388	0.43750E-04	2.114861
389	0.41250E-04	0.8668850
390	0.39000E-04	0.3909836
391	0.37000E-04	0.3949136
392	0.35000E-04	0.3988437
393	0.33000E-04	0.4028142
394	0.31000E-04	0.4068260
395	0.29000E-04	0.4108446
396	0.27500E-04	0.4138921
397	0.26250E-04	0.4164736
398	0.24750E-04	0.4195617
399	0.23500E-04	0.4221645
400	0.22500E-04	0.4242919
401	0.21500E-04	0.4264191
402	0.20500E-04	0.4285465
403	0.19500E-04	0.4308486
404	0.18500E-04	0.4333223
405	0.17500E-04	0.4358479
406	0.16500E-04	0.4384445
407	0.15500E-04	0.4411159
408	0.14625E-04	0.4435087
409	0.13875E-04	0.4456379
410	0.13125E-04	0.4478301
411	0.12375E-04	0.4500898
412	0.11750E-04	0.4520449
413	0.11250E-04	0.4536326
414	0.10750E-04	0.4553187
415	0.10250E-04	0.4570198
416	0.98000E-05	0.4593957
417	0.94000E-05	0.4624639
418	0.90000E-05	0.4655328
419	0.86000E-05	0.4686785
420	0.82000E-05	0.4719080
421	0.78000E-05	0.4751475
422	0.74000E-05	0.4785279
423	0.70500E-05	0.4815185
424	0.67500E-05	0.4841248
425	0.64500E-05	0.4868641
426	0.61500E-05	0.4896156
427	0.58750E-05	0.4921912

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
428	0.56250E-05	0.4946683
429	0.53750E-05	0.4971502
430	0.51250E-05	0.4997018
431	0.48750E-05	0.5041212
432	0.46250E-05	0.5102257
433	0.43750E-05	0.5164981
434	0.41250E-05	0.5229010
435	0.39000E-05	0.5287051
436	0.37000E-05	0.5341017
437	0.35000E-05	0.5395223
438	0.33000E-05	0.5450680
439	0.31000E-05	0.5508251
440	0.29000E-05	0.5567760
441	0.27500E-05	0.5613497
442	0.26250E-05	0.5653187
443	0.24750E-05	0.5702257
444	0.23500E-05	0.5744995
445	0.22500E-05	0.5780208
446	0.21500E-05	0.5816858
447	0.20500E-05	0.5854434
448	0.19500E-05	0.5893638
449	0.18500E-05	0.5934480
450	0.17500E-05	0.5976869
451	0.16500E-05	0.6021605
452	0.15500E-05	0.6068507
453	0.14625E-05	0.6111978
454	0.13875E-05	0.6151050
455	0.13125E-05	0.6192380
456	0.12375E-05	0.6236259
457	0.11750E-05	0.6274282
458	0.11250E-05	0.6306947
459	0.10750E-05	0.6340853
460	0.10250E-05	0.6376522
461	0.98000E-06	0.6421335
462	0.94000E-06	0.6473066
463	0.90000E-06	0.6527138
464	0.86000E-06	0.6582779
465	0.82000E-06	0.6641567
466	0.78000E-06	0.6701603
467	0.74000E-06	0.6764001
468	0.70500E-06	0.6821381
469	0.67500E-06	0.6871272
470	0.64500E-06	0.6924125
471	0.61500E-06	0.6979194
472	0.58750E-06	0.7032928
473	0.56250E-06	0.7083228
474	0.53750E-06	0.7134417
475	0.51250E-06	0.7189181
476	0.48750E-06	0.7267829
477	0.46250E-06	0.7370012
478	0.43750E-06	0.7475832
479	0.41250E-06	0.7586753
480	0.39000E-06	0.7688796
481	0.37000E-06	0.7785481
482	0.35000E-06	0.7885520
483	0.33000E-06	0.7988138
484	0.31000E-06	0.8098748
485	0.29000E-06	0.8214272
486	0.27500E-06	0.8305146
487	0.26250E-06	0.8384903
488	0.24750E-06	0.8486955
489	0.23500E-06	0.8573889
490	0.22500E-06	0.8650002
491	0.21500E-06	0.8728340
492	0.20500E-06	0.8808779
493	0.19500E-06	0.8898087
494	0.18500E-06	0.8989656
495	0.17500E-06	0.9085490
496	0.16500E-06	0.9191540
497	0.15500E-06	0.9299974
498	0.14625E-06	0.9404176
499	0.13875E-06	0.9500903
500	0.13125E-06	0.9603268

TABLE A2.1 *Continued*

Bin #	Lower Energy (MeV)	Damage (MeV-mb)
501	0.12375E-06	0.9716213
502	0.11750E-06	0.9811401
503	0.11250E-06	0.9895244
504	0.10750E-06	0.9983672
505	0.10250E-06	1.007774
506	0.98000E-07	1.018910
507	0.94000E-07	1.031486
508	0.90000E-07	1.044724
509	0.86000E-07	1.058283
510	0.82000E-07	1.072606
511	0.78000E-07	1.087689
512	0.74000E-07	1.103361
513	0.70500E-07	1.117827
514	0.67500E-07	1.131091
515	0.64500E-07	1.144762
516	0.61500E-07	1.159280
517	0.58750E-07	1.173100
518	0.56250E-07	1.186418
519	0.53750E-07	1.200595
520	0.51250E-07	1.215826
521	0.48750E-07	1.231169
522	0.46250E-07	1.248158
523	0.43750E-07	1.266257
524	0.41250E-07	1.284803
525	0.39000E-07	1.303812
526	0.37000E-07	1.321313
527	0.35000E-07	1.340211
528	0.33000E-07	1.360443
529	0.31000E-07	1.382568
530	0.29000E-07	1.406710
531	0.27500E-07	1.426260
532	0.26250E-07	1.443849
533	0.24750E-07	1.468284
534	0.23500E-07	1.492531
535	0.22500E-07	1.513096
536	0.21500E-07	1.534934
537	0.20500E-07	1.558010
538	0.19500E-07	1.582237
539	0.18500E-07	1.608285
540	0.17500E-07	1.636128
541	0.16500E-07	1.666099
542	0.15500E-07	1.698255
543	0.14625E-07	1.728731
544	0.13875E-07	1.757004
545	0.13125E-07	1.787079
546	0.12375E-07	1.819693
547	0.11750E-07	1.849165
548	0.11250E-07	1.873784
549	0.10750E-07	1.900419
550	0.10250E-07	1.929170
551	0.98000E-08	1.957366
552	0.94000E-08	1.985813
553	0.90000E-08	2.015834
554	0.86000E-08	2.047956
555	0.82000E-08	2.081214
556	0.78000E-08	2.117132
557	0.74000E-08	2.155843
558	0.70500E-08	2.192089
559	0.67500E-08	2.224487
560	0.64500E-08	2.259289
561	0.61500E-08	2.296491
562	0.58750E-08	2.332987
563	0.56250E-08	2.367185
564	0.53750E-08	2.404750
565	0.51250E-08	2.444634
566	0.48750E-08	2.490470
567	0.46250E-08	2.542870
568	0.43750E-08	2.598317
569	0.41250E-08	2.658137
570	0.39000E-08	2.715810
571	0.37000E-08	2.771724
572	0.35000E-08	2.830851
573	0.33000E-08	2.894506
574	0.31000E-08	2.963683
575	0.29000E-08	3.039487
576	0.27500E-08	3.100623
577	0.26250E-08	3.157093
578	0.24750E-08	3.226965
579	0.23500E-08	3.290611
580	0.22500E-08	3.345073
581	0.21500E-08	3.404336
582	0.20500E-08	3.465674
583	0.19500E-08	3.531984
584	0.18500E-08	3.603455
585	0.17500E-08	3.681443
586	0.16500E-08	3.763800
587	0.15500E-08	3.855147
588	0.14625E-08	3.941984
589	0.13875E-08	4.022763
590	0.13125E-08	4.110997
591	0.12375E-08	4.206987
592	0.11750E-08	4.292010
593	0.11250E-08	4.368166
594	0.10750E-08	4.444819
595	0.10250E-08	4.528198
596	0.98000E-09	4.611351
597	0.94000E-09	4.693213
598	0.90000E-09	4.781856
599	0.86000E-09	4.871137
600	0.82000E-09	4.967869
601	0.78000E-09	5.072682
602	0.74000E-09	5.186074
603	0.70500E-09	5.291282
604	0.67500E-09	5.388422
605	0.64500E-09	5.494944
606	0.61500E-09	5.603578
607	0.58750E-09	5.712392
608	0.56250E-09	5.821317
609	0.53750E-09	5.930476
610	0.51250E-09	6.047915
611	0.48750E-09	6.182956
612	0.46250E-09	6.329957
613	0.43750E-09	6.492437
614	0.41250E-09	6.659180
615	0.39000E-09	6.831114
616	0.37000E-09	6.989074
617	0.35000E-09	7.163126
618	0.33000E-09	7.353035
619	0.31000E-09	7.553178
620	0.29000E-09	7.781979
621	0.27500E-09	7.962666
622	0.26250E-09	8.127457
623	0.24750E-09	8.341032
624	0.23500E-09	8.542303
625	0.22500E-09	8.710299
626	0.21500E-09	8.878578
627	0.20500E-09	9.068738
628	0.19500E-09	9.275459
629	0.18500E-09	9.486740
630	0.17500E-09	9.732625
631	0.16500E-09	9.986153
632	0.15500E-09	10.26194
633	0.14625E-09	10.53162
634	0.13875E-09	10.78174
635	0.13125E-09	11.05266
636	0.12375E-09	11.35017
637	0.11750E-09	11.61529
638	0.11250E-09	11.84453
639	0.10750E-09	12.09051
640	0.10250E-09	12.35521

A2.3 Precision and Bias

A2.3.1 The values for $F_{D,GaAs}$ (E) shown in Fig. A2.2 were determined by calculating the total kerma and then partitioning it into ionization and displacement fractions **(5)** and applying the PKA-energy-dependent damage efficiency factors **(8)**. The estimated uncertainties in the values for total kerma is 5 to 10 %. Because of the lack of adequate theory to partition the kerma and uncertainties in cross sections, the estimated uncertainty in the displacement kerma factor is about 10 to 15 %.

A2.3.2 The uncertainties in the displacement damage function in Table A2.1 are at present quite large, ±20 % being a conservative figure.

A2.3.3 Comparisons between the calculations with the SAND II unfolding code (using activation-foil input data), neutron transport codes, and experimental spectrometry data give an estimated uncertainty in the determination of Φ(E) of about 20 % over the energy region of interest **(15)** (see Test Method E 721).

A2.3.4 Since this mandatory annex requires the use of Table A2.1 and $F_{D,1MeV,GaAs}$ = 70 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 Φ(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 $\Phi_{eq,1MeV,GaAs}$. While no specific group structure for representing the neutron energy-fluence 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).

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