Designation: E722 − 14

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

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, except for MeV, keV, eV, MeV·mbarn, rad(Si)·cm^2, rad(GaAs)·cm^2.

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.*

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

---

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:*[4]

ICRU Report 13 Neutron Fluence, Neutron Spectra, and Kerma

ICRU Report 60 Fundamental Quantities and Units for Ionizing Radiation

ICRU Report 85 Fundamental Quantities and Units for Ionizing Radiation (Revised)

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *displacement damage function*—($F_{D,mat}(E)$) 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 d(observed damage)/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, 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*—($\kappa_{D,mat}(E)$) the energy-dependent quotient of the displacement kerma per target atom and the neutron fluence. $\kappa_{D,mat}(E)$ is proportional to $K_{D,mat}\bar{A}/\Phi$, where $K_{D,mat}$ is the displacement kerma, $\bar{A}$ 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*—($H_{Eref,mat} = \Phi_{eq,Eref,mat}/\Phi$) this parameter is defined as the ratio of the equivalent monoenergetic neutron fluence to the 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, as unit fluence of neutrons of neutron spectrum $\Phi(E)$.

3.1.3.1 *Discussion*—For damage correlation, a convenient method of characterizing the shape of an incident neutron fluence spectrum $\Phi(E)$, is in terms of a fluence 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 fluence spectrum, $\Phi(E)$, 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 $\Phi(E)$.

3.1.4.1 *Discussion*—Note that $\Phi_{eq,Eref,mat}$ is equivalent to $\Phi(E)$ 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*—($K_{mat}(E)$) 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 **fluence** and **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, $\Phi_{eq,Eref,mat}$, is given as follows:

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

---

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

2

where:

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

$F_{D,mat}(E)$ = 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 neutron fluence spectrum and by the material being irradiated.

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

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

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, $\Phi_{eq,Eref,mat}/M_r$. Use of a monitor foil to predict $\Phi_{eq,Eref,mat}$ 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 $\Phi_{eq,Eref,mat}$

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, 5). Therefore, monoenergetic neutron sources with these energies may not be useful for effects testing. Also, for a selected equivalent energy, the value of $F_{D,Eref,mat}$ 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 $H_{Eref,mat}$.

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

7.1 At the same time that the fluence spectrum, $\Phi(E)$, 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 $\Phi_{eq,Eref,mat}$ 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 fluence

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, and the limits of integration).

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

9. Precision and Bias

9.1 The precision in calculating $\Phi_{eq,Eref,mat}$ and $H_{Eref,mat}$ 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

---

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).

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 (**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-VII cross sections (**16**) for ^{28}Si, ^{29}Si and ^{30}Si in their natural abundance composition, a displacement threshold energy of 20.5 eV, the Robinson fit to the Lindhard energy partition function (**17**), and the NJOY-2012 processing code (**18**). 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.

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 natSilicon Damage Function

Bin Number	Upper Energy Bound (MeV)	Energy Mid-point (MeV)	Displacement Damage Function (MeV·mbarn)
1	2.000000E+01	1.995000E+01	1.974223E+02
2	1.990000E+01	1.985000E+01	1.967937E+02
3	1.980000E+01	1.975000E+01	1.961647E+02
4	1.970000E+01	1.965000E+01	1.955857E+02
5	1.960000E+01	1.955000E+01	1.952768E+02
6	1.950000E+01	1.945000E+01	1.950267E+02
7	1.940000E+01	1.935000E+01	1.949968E+02
8	1.930000E+01	1.925000E+01	1.951260E+02
9	1.920000E+01	1.915000E+01	1.955842E+02
10	1.910000E+01	1.905000E+01	1.969098E+02
11	1.900000E+01	1.895000E+01	1.982156E+02
12	1.890000E+01	1.885000E+01	1.991628E+02
13	1.880000E+01	1.875000E+01	1.999799E+02
14	1.870000E+01	1.865000E+01	1.978047E+02
15	1.860000E+01	1.855000E+01	1.938940E+02
16	1.850000E+01	1.845000E+01	1.920378E+02
17	1.840000E+01	1.835000E+01	1.930547E+02
18	1.830000E+01	1.825000E+01	1.941904E+02
19	1.820000E+01	1.815000E+01	1.956167E+02
20	1.810000E+01	1.805000E+01	1.964416E+02
21	1.800000E+01	1.795000E+01	1.941766E+02
22	1.790000E+01	1.785000E+01	1.917115E+02
23	1.780000E+01	1.775000E+01	1.905113E+02
24	1.770000E+01	1.765000E+01	1.897319E+02
25	1.760000E+01	1.755000E+01	1.907675E+02
26	1.750000E+01	1.745000E+01	1.921653E+02
27	1.740000E+01	1.735000E+01	1.923810E+02
28	1.730000E+01	1.725000E+01	1.922374E+02
29	1.720000E+01	1.715000E+01	1.924440E+02
30	1.710000E+01	1.705000E+01	1.926999E+02
31	1.700000E+01	1.695000E+01	1.921279E+02
32	1.690000E+01	1.685000E+01	1.915772E+02
33	1.680000E+01	1.675000E+01	1.937092E+02
34	1.670000E+01	1.665000E+01	1.953922E+02
35	1.660000E+01	1.655000E+01	1.903341E+02
36	1.650000E+01	1.645000E+01	1.856649E+02
37	1.640000E+01	1.635000E+01	1.865918E+02
38	1.630000E+01	1.625000E+01	1.877974E+02
39	1.620000E+01	1.615000E+01	1.883864E+02
40	1.610000E+01	1.605000E+01	1.883452E+02
41	1.600000E+01	1.595000E+01	1.875458E+02
42	1.590000E+01	1.585000E+01	1.843038E+02
43	1.580000E+01	1.575000E+01	1.803025E+02
44	1.570000E+01	1.565000E+01	1.792159E+02
45	1.560000E+01	1.555000E+01	1.793850E+02
46	1.550000E+01	1.545000E+01	1.812501E+02
47	1.540000E+01	1.535000E+01	1.824167E+02
48	1.530000E+01	1.525000E+01	1.825359E+02
49	1.520000E+01	1.515000E+01	1.785266E+02
50	1.510000E+01	1.505000E+01	1.758240E+02
51	1.500000E+01	1.495000E+01	1.795943E+02
52	1.490000E+01	1.485000E+01	1.789953E+02
53	1.480000E+01	1.475000E+01	1.757235E+02
54	1.470000E+01	1.465000E+01	1.748468E+02
55	1.460000E+01	1.455000E+01	1.772119E+02
56	1.450000E+01	1.445000E+01	1.823635E+02
57	1.440000E+01	1.435000E+01	1.822088E+02
58	1.430000E+01	1.425000E+01	1.809770E+02
59	1.420000E+01	1.415000E+01	1.797454E+02
60	1.410000E+01	1.405000E+01	1.768178E+02
61	1.400000E+01	1.395000E+01	1.788456E+02
62	1.390000E+01	1.385000E+01	1.847664E+02
63	1.380000E+01	1.375000E+01	1.784289E+02
64	1.370000E+01	1.365000E+01	1.760411E+02
65	1.360000E+01	1.355000E+01	1.782104E+02
66	1.350000E+01	1.345000E+01	1.816978E+02
67	1.340000E+01	1.335000E+01	1.785120E+02
68	1.330000E+01	1.325000E+01	1.772619E+02
69	1.320000E+01	1.315000E+01	1.805299E+02
70	1.310000E+01	1.305000E+01	1.837276E+02
71	1.300000E+01	1.295000E+01	1.828576E+02
72	1.290000E+01	1.285000E+01	1.825162E+02

TABLE A1.1 *Continued*

Bin Number	Upper Energy Bound (MeV)	Energy Mid-point (MeV)	Displacement Damage Function (MeV·mbarn)
73	1.280000E+01	1.275000E+01	1.831141E+02
74	1.270000E+01	1.265000E+01	1.812270E+02
75	1.260000E+01	1.255000E+01	1.735857E+02
76	1.250000E+01	1.245000E+01	1.767395E+02
77	1.240000E+01	1.235000E+01	1.797322E+02
78	1.230000E+01	1.225000E+01	1.790482E+02
79	1.220000E+01	1.215000E+01	1.787140E+02
80	1.210000E+01	1.205000E+01	1.759861E+02
81	1.200000E+01	1.195000E+01	1.743238E+02
82	1.190000E+01	1.185000E+01	1.730297E+02
83	1.180000E+01	1.175000E+01	1.727131E+02
84	1.170000E+01	1.165000E+01	1.742102E+02
85	1.160000E+01	1.155000E+01	1.752101E+02
86	1.150000E+01	1.145000E+01	1.739761E+02
87	1.140000E+01	1.135000E+01	1.710272E+02
88	1.130000E+01	1.125000E+01	1.668493E+02
89	1.120000E+01	1.115000E+01	1.656722E+02
90	1.110000E+01	1.105000E+01	1.709562E+02
91	1.100000E+01	1.095000E+01	1.736557E+02
92	1.090000E+01	1.085000E+01	1.737472E+02
93	1.080000E+01	1.075000E+01	1.699377E+02
94	1.070000E+01	1.065000E+01	1.650493E+02
95	1.060000E+01	1.055000E+01	1.671501E+02
96	1.050000E+01	1.045000E+01	1.683353E+02
97	1.040000E+01	1.035000E+01	1.743913E+02
98	1.030000E+01	1.025000E+01	1.736199E+02
99	1.020000E+01	1.015000E+01	1.752688E+02
100	1.010000E+01	1.005000E+01	1.731668E+02
101	1.000000E+01	9.950000E+00	1.749790E+02
102	9.900000E+00	9.850000E+00	1.725378E+02
103	9.800000E+00	9.750000E+00	1.680329E+02
104	9.700000E+00	9.650000E+00	1.643838E+02
105	9.600000E+00	9.550000E+00	1.737880E+02
106	9.500000E+00	9.450000E+00	1.790983E+02
107	9.400000E+00	9.350000E+00	1.719788E+02
108	9.300000E+00	9.250000E+00	1.585817E+02
109	9.200000E+00	9.150000E+00	1.642940E+02
110	9.100000E+00	9.050000E+00	1.840511E+02
111	9.000000E+00	8.950000E+00	1.844116E+02
112	8.900000E+00	8.850000E+00	1.649178E+02
113	8.800000E+00	8.750000E+00	1.543472E+02
114	8.700000E+00	8.650000E+00	1.719501E+02
115	8.600000E+00	8.550000E+00	1.726602E+02
116	8.500000E+00	8.450000E+00	1.737737E+02
117	8.400000E+00	8.350000E+00	1.725798E+02
118	8.300000E+00	8.250000E+00	1.702067E+02
119	8.200000E+00	8.150000E+00	1.629746E+02
120	8.100000E+00	8.050000E+00	1.776760E+02
121	8.000000E+00	7.950000E+00	1.951620E+02
122	7.900000E+00	7.850000E+00	1.818550E+02
123	7.800000E+00	7.750000E+00	1.819305E+02
124	7.700000E+00	7.650000E+00	1.750185E+02
125	7.600000E+00	7.550000E+00	1.721660E+02
126	7.500000E+00	7.450000E+00	1.750415E+02
127	7.400000E+00	7.350000E+00	1.771959E+02
128	7.300000E+00	7.250000E+00	1.762695E+02
129	7.200000E+00	7.150000E+00	1.436002E+02
130	7.100000E+00	7.050000E+00	1.734795E+02
131	7.000000E+00	6.950000E+00	1.482196E+02
132	6.900000E+00	6.850000E+00	1.534783E+02
133	6.800000E+00	6.750000E+00	1.735103E+02
134	6.700000E+00	6.650000E+00	1.573224E+02
135	6.600000E+00	6.550000E+00	1.287192E+02
136	6.500000E+00	6.450000E+00	1.476404E+02
137	6.400000E+00	6.350000E+00	1.597855E+02
138	6.300000E+00	6.250000E+00	1.843861E+02
139	6.200000E+00	6.150000E+00	1.327218E+02
140	6.100000E+00	6.050000E+00	1.618680E+02
141	6.000000E+00	5.950000E+00	1.427187E+02
142	5.900000E+00	5.850000E+00	1.741425E+02
143	5.800000E+00	5.750000E+00	1.877007E+02
144	5.700000E+00	5.650000E+00	1.566230E+02

TABLE A1.1 *Continued*

Bin Number	Upper Energy Bound (MeV)	Energy Mid-point (MeV)	Displacement Damage Function (MeV·mbarn)
145	5.600000E+00	5.550000E+00	1.521489E+02
146	5.500000E+00	5.450000E+00	1.239832E+02
147	5.400000E+00	5.350000E+00	1.296535E+02
148	5.300000E+00	5.250000E+00	1.558386E+02
149	5.200000E+00	5.150000E+00	1.773568E+02
150	5.100000E+00	5.050000E+00	1.558377E+02
151	5.000000E+00	4.950000E+00	1.523304E+02
152	4.900000E+00	4.850000E+00	1.659307E+02
153	4.800000E+00	4.750000E+00	1.936596E+02
154	4.700000E+00	4.650000E+00	1.615820E+02
155	4.600000E+00	4.550000E+00	1.446275E+02
156	4.500000E+00	4.450000E+00	1.454466E+02
157	4.400000E+00	4.350000E+00	1.391803E+02
158	4.300000E+00	4.250000E+00	1.718335E+02
159	4.200000E+00	4.150000E+00	1.106764E+02
160	4.100000E+00	4.050000E+00	1.377047E+02
161	4.000000E+00	3.950000E+00	1.398655E+02
162	3.900000E+00	3.850000E+00	1.143880E+02
163	3.800000E+00	3.750000E+00	1.189786E+02
164	3.700000E+00	3.650000E+00	7.205235E+01
165	3.600000E+00	3.550000E+00	1.166491E+02
166	3.500000E+00	3.450000E+00	1.209489E+02
167	3.400000E+00	3.350000E+00	1.171509E+02
168	3.300000E+00	3.250000E+00	1.233782E+02
169	3.200000E+00	3.150000E+00	1.371566E+02
170	3.100000E+00	3.050000E+00	1.225885E+02
171	3.000000E+00	2.950000E+00	1.017558E+02
172	2.900000E+00	2.850000E+00	1.380089E+02
173	2.800000E+00	2.750000E+00	1.104907E+02
174	2.700000E+00	2.650000E+00	1.185021E+02
175	2.600000E+00	2.550000E+00	1.324304E+02
176	2.500000E+00	2.450000E+00	1.213907E+02
177	2.400000E+00	2.350000E+00	1.059031E+02
178	2.300000E+00	2.250000E+00	1.077988E+02
179	2.200000E+00	2.150000E+00	1.108041E+02
180	2.100000E+00	2.050000E+00	9.770454E+01
181	2.000000E+00	1.950000E+00	1.330953E+02
182	1.900000E+00	1.850000E+00	1.348081E+02
183	1.800000E+00	1.750000E+00	8.041240E+01
184	1.700000E+00	1.650000E+00	1.700470E+02
185	1.600000E+00	1.550000E+00	1.090791E+02
186	1.500000E+00	1.450000E+00	1.035514E+02
187	1.400000E+00	1.350000E+00	9.048161E+01
188	1.300000E+00	1.250000E+00	9.292444E+01
189	1.200000E+00	1.150000E+00	6.372608E+01
190	1.100000E+00	1.050000E+00	7.763185E+01
191	1.000000E+00	9.800000E-01	1.131754E+02
192	9.600000E-01	9.400000E-01	1.131017E+02
193	9.200000E-01	9.000000E-01	9.118594E+01
194	8.800000E-01	8.600000E-01	8.053426E+01
195	8.400000E-01	8.200000E-01	1.406037E+02
196	8.000000E-01	7.800000E-01	8.943636E+01
197	7.600000E-01	7.400000E-01	6.524542E+01
198	7.200000E-01	7.050000E-01	5.860863E+01
199	6.900000E-01	6.750000E-01	5.631161E+01
200	6.600000E-01	6.450000E-01	5.497674E+01
201	6.300000E-01	6.150000E-01	5.337400E+01
202	6.000000E-01	5.875000E-01	5.845961E+01
203	5.750000E-01	5.625000E-01	1.238521E+02
204	5.500000E-01	5.375000E-01	7.387514E+01
205	5.250000E-01	5.125000E-01	5.861309E+01
206	5.000000E-01	4.875000E-01	5.610784E+01
207	4.750000E-01	4.625000E-01	5.453479E+01
208	4.500000E-01	4.375000E-01	5.326508E+01
209	4.250000E-01	4.125000E-01	5.275325E+01
210	4.000000E-01	3.900000E-01	5.195346E+01
211	3.800000E-01	3.700000E-01	4.929888E+01
212	3.600000E-01	3.500000E-01	4.988140E+01
213	3.400000E-01	3.300000E-01	5.080230E+01
214	3.200000E-01	3.100000E-01	5.115308E+01
215	3.000000E-01	2.900000E-01	5.263600E+01
216	2.800000E-01	2.750000E-01	5.408311E+01

TABLE A1.1 *Continued*

Bin Number	Upper Energy Bound (MeV)	Energy Mid-point (MeV)	Displacement Damage Function (MeV·mbarn)
217	2.700000E-01	2.625000E-01	5.621729E+01
218	2.550000E-01	2.475000E-01	6.002709E+01
219	2.400000E-01	2.350000E-01	6.508627E+01
220	2.300000E-01	2.250000E-01	7.103450E+01
221	2.200000E-01	2.150000E-01	8.003430E+01
222	2.100000E-01	2.050000E-01	9.342780E+01
223	2.000000E-01	1.950000E-01	1.112661E+02
224	1.900000E-01	1.850000E-01	1.143433E+02
225	1.800000E-01	1.750000E-01	6.670408E+01
226	1.700000E-01	1.650000E-01	2.042371E+01
227	1.600000E-01	1.550000E-01	4.389965E+00
228	1.500000E-01	1.462500E-01	1.001896E+00
229	1.425000E-01	1.387500E-01	1.144801E+00
230	1.350000E-01	1.312500E-01	1.886640E+00
231	1.275000E-01	1.237500E-01	2.722165E+00
232	1.200000E-01	1.175000E-01	3.374691E+00
233	1.150000E-01	1.125000E-01	3.836533E+00
234	1.100000E-01	1.075000E-01	4.231811E+00
235	1.050000E-01	1.025000E-01	4.577435E+00
236	1.000000E-01	9.800000E-02	4.858211E+00
237	9.600000E-02	9.400000E-02	5.061763E+00
238	9.200000E-02	9.000000E-02	5.239306E+00
239	8.800000E-02	8.600000E-02	5.416013E+00
240	8.400000E-02	8.200000E-02	5.530739E+00
241	8.000000E-02	7.800000E-02	5.667758E+00
242	7.600000E-02	7.400000E-02	5.824413E+00
243	7.200000E-02	7.050000E-02	6.004439E+00
244	6.900000E-02	6.750000E-02	6.452232E+00
245	6.600000E-02	6.450000E-02	6.704520E+00
246	6.300000E-02	6.150001E-02	7.759747E+00
247	6.000000E-02	5.875000E-02	1.131117E+01
248	5.750000E-02	5.625000E-02	4.881800E+01
249	5.500000E-02	5.375000E-02	1.394853E+00
250	5.250000E-02	5.125000E-02	1.665855E+00
251	5.000000E-02	4.875000E-02	2.324566E+00
252	4.750000E-02	4.625000E-02	2.627535E+00
253	4.500000E-02	4.375000E-02	2.766006E+00
254	4.250000E-02	4.125000E-02	2.815044E+00
255	4.000000E-02	3.900000E-02	3.236911E+00
256	3.800000E-02	3.700000E-02	2.761191E+00
257	3.600000E-02	3.500000E-02	2.694322E+00
258	3.400000E-02	3.300000E-02	2.615048E+00
259	3.200000E-02	3.100000E-02	2.523839E+00
260	3.000000E-02	2.900000E-02	2.416137E+00
261	2.800000E-02	2.750000E-02	2.327857E+00
262	2.700000E-02	2.625000E-02	2.251406E+00
263	2.550000E-02	2.475000E-02	2.159320E+00
264	2.400000E-02	2.350000E-02	2.075862E+00
265	2.300000E-02	2.250000E-02	2.006089E+00
266	2.200000E-02	2.150000E-02	1.936267E+00
267	2.100000E-02	2.050000E-02	1.866401E+00
268	2.000000E-02	1.950000E-02	1.793231E+00
269	1.900000E-02	1.850000E-02	1.716946E+00
270	1.800000E-02	1.750000E-02	1.640070E+00
271	1.700000E-02	1.650000E-02	1.560138E+00
272	1.600000E-02	1.550000E-02	1.556516E+00
273	1.500000E-02	1.462500E-02	1.408101E+00
274	1.425000E-02	1.387500E-02	1.344240E+00
275	1.350000E-02	1.312500E-02	1.280620E+00
276	1.275000E-02	1.237500E-02	1.216535E+00
277	1.200000E-02	1.175000E-02	1.161918E+00
278	1.150000E-02	1.125000E-02	1.117882E+00
279	1.100000E-02	1.075000E-02	1.073083E+00
280	1.050000E-02	1.025000E-02	1.028187E+00
281	1.000000E-02	9.800000E-03	9.874197E-01
282	9.600000E-03	9.400000E-03	9.506696E-01
283	9.200000E-03	9.000000E-03	9.139211E-01
284	8.800000E-03	8.600000E-03	8.768218E-01
285	8.400000E-03	8.200000E-03	8.391631E-01
286	8.000000E-03	7.800000E-03	8.014963E-01
287	7.600000E-03	7.400000E-03	7.636029E-01
288	7.200000E-03	7.050000E-03	7.300621E-01

9

TABLE A1.1 *Continued*

Bin Number	Upper Energy Bound (MeV)	Energy Mid-point (MeV)	Displacement Damage Function (MeV·mbarn)
289	6.900000E-03	6.750000E-03	7.012189E-01
290	6.600000E-03	6.450000E-03	6.723806E-01
291	6.300000E-03	6.150000E-03	6.433160E-01
292	6.000000E-03	5.875000E-03	6.163418E-01
293	5.750000E-03	5.625000E-03	5.917502E-01
294	5.500000E-03	5.375000E-03	5.670536E-01
295	5.250000E-03	5.125000E-03	5.426664E-01
296	5.000000E-03	4.875000E-03	5.478224E-01
297	4.750000E-03	4.625000E-03	4.921758E-01
298	4.500000E-03	4.375000E-03	4.669758E-01
299	4.250000E-03	4.125000E-03	4.417112E-01
300	4.000000E-03	3.900000E-03	4.189391E-01
301	3.800000E-03	3.700000E-03	3.985144E-01
302	3.600000E-03	3.500000E-03	3.780234E-01
303	3.400000E-03	3.300000E-03	3.573080E-01
304	3.200000E-03	3.100000E-03	3.365366E-01
305	3.000000E-03	2.900000E-03	3.157687E-01
306	2.800000E-03	2.750000E-03	3.002674E-01
307	2.700000E-03	2.625000E-03	2.870274E-01
308	2.550000E-03	2.475000E-03	2.711862E-01
309	2.400000E-03	2.350000E-03	2.582637E-01
310	2.300000E-03	2.250000E-03	4.285303E-01
311	2.200000E-03	2.150000E-03	2.373112E-01
312	2.100000E-03	2.050000E-03	2.260708E-01
313	2.000000E-03	1.950000E-03	2.153233E-01
314	1.900000E-03	1.850000E-03	2.045339E-01
315	1.800000E-03	1.750000E-03	1.937540E-01
316	1.700000E-03	1.650000E-03	1.829727E-01
317	1.600000E-03	1.550000E-03	1.720326E-01
318	1.500000E-03	1.462500E-03	1.624055E-01
319	1.425000E-03	1.387500E-03	1.541113E-01
320	1.350000E-03	1.312500E-03	1.459994E-01
321	1.275000E-03	1.237500E-03	1.378551E-01
322	1.200000E-03	1.175000E-03	1.309130E-01
323	1.150000E-03	1.125000E-03	1.253166E-01
324	1.100000E-03	1.075000E-03	1.197011E-01
325	1.050000E-03	1.025000E-03	1.140764E-01
326	1.000000E-03	9.800000E-04	1.089957E-01
327	9.600000E-04	9.400000E-04	1.044395E-01
328	9.200000E-04	9.000000E-04	9.987921E-02
329	8.800000E-04	8.600000E-04	9.530343E-02
330	8.400000E-04	8.200000E-04	9.069958E-02
331	8.000000E-04	7.800000E-04	8.607882E-02
332	7.600000E-04	7.400000E-04	8.144432E-02
333	7.200000E-04	7.050000E-04	7.738508E-02
334	6.900000E-04	6.750000E-04	7.388832E-02
335	6.600000E-04	6.450000E-04	7.038044E-02
336	6.300000E-04	6.150000E-04	6.686015E-02
337	6.000000E-04	5.875000E-04	6.361766E-02
338	5.750000E-04	5.625000E-04	6.065090E-02
339	5.500000E-04	5.375000E-04	5.760463E-02
340	5.250000E-04	5.125000E-04	5.454441E-02
341	5.000000E-04	4.875000E-04	5.136848E-02
342	4.750000E-04	4.625000E-04	4.811422E-02
343	4.500000E-04	4.375000E-04	4.506059E-02
344	4.250000E-04	4.125000E-04	4.182278E-02
345	4.000000E-04	3.900000E-04	3.875193E-02
346	3.800000E-04	3.700000E-04	3.631544E-02
347	3.600000E-04	3.500000E-04	3.391288E-02
348	3.400000E-04	3.300000E-04	3.126043E-02
349	3.200000E-04	3.100000E-04	2.849958E-02
350	3.000000E-04	2.900000E-04	2.549538E-02
351	2.800000E-04	2.750000E-04	2.322776E-02
352	2.700000E-04	2.625000E-04	2.124416E-02
353	2.550000E-04	2.475000E-04	1.885846E-02
354	2.400000E-04	2.350000E-04	1.683389E-02
355	2.300000E-04	2.250000E-04	1.509236E-02
356	2.200000E-04	2.150000E-04	1.325680E-02
357	2.100000E-04	2.050000E-04	1.128237E-02
358	2.000000E-04	1.950000E-04	8.452462E-03
359	1.900000E-04	1.850000E-04	4.783556E-03
360	1.800000E-04	1.750000E-04	1.586685E-03