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Standard Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics¹

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.

^{ε1} NOTE—Table A1.1 and A2.1 were corrected editorially in February 2005.

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^{ε2} NOTE—An = sign was added in Eq 1 in April 2007.

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 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 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:³

E 265 [Test Method for Measuring Reaction Rates for and Fast-Neutron Fluences by Radioactivation of Sulfur-32](#)

E 693 [Practice for Characterizing Neutron Exposures in Ferritic Steels in Terms of Displacement per Atom \(DPA\)—Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom \(DPA\), E 706\(ID\)](#)

E 720 [Guide for Selection and Use of Neutron-Activation Foils/Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics](#)

E 721 [Test Method for Determining Neutron Energy Spectra with Neutron Activation Foils for Radiation-Hardness Testing of Electronics—Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics](#)

¹ This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.07 on Radiation Dosimetry for Radiation Effects on Materials and Devices.

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² The boldface numbers in parentheses refer to a list of references at the end of this practice.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E 844 [Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706\(IIC\)](#)

E 944 [Practice Guide for Applications of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 \(IIA\)](#)

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

ICRU Report 13—Neutron Fluence, Neutron Spectra, and Kerma⁴

ICRU Report 26—Neutron Dosimetry for Biology and Medicine⁴

ICRU Report 33—Radiation Quantities and Units⁴

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 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 $F_{D,mat}(E)/d\Phi$, in the limiting case of zero fluence. Examples of suitable representations of displacement damage functions are given in the annexes. In the case of silicon, 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, E_{ref} , required to produce the same displacement damage in the specified material, mat unit fluence of neutrons of spectral distribution $\Phi(E)$.

3.1.3.1 *Discussion*—For damage correlation, a convenient method of characterizing the shape of an incident neutron energy-fluence spectrum $\Phi(E)$, 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, $\Phi(E)$, in terms of the fluence of monoenergetic neutrons at a specific energy E_{ref} 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 *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:

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

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

where:

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

- $\Phi(E)$ = 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, E_{ref} , 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: [/standards/sist/4625dc8d-659e-4a4a-878c-e201facb19fb/astm-e722-04e2](https://standards.sist/4625dc8d-659e-4a4a-878c-e201facb19fb/astm-e722-04e2)

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, $\Phi(E)$, 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, $\Phi_{\text{eq,Eref,mat}}/M_r$.

7.2 Use the response of the fast-neutron monitor foil, M_r , to predict $\Phi_{\text{eq,Eref,mat}}$ 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 $\Phi(E)$ 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 $F_{\text{D,Eref,mat}}$ and the value of E_{ref} 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 $\Phi_{\text{eq,Eref,mat}}$, H_{mat} , and $\Phi_{\text{eq,Eref,mat}}/M_r$.

9. Precision and Bias

9.1 The precision in calculating $\Phi_{\text{eq,Eref,mat}}$ 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, $\Phi(E)$, may be that determined from a neutron transport calculation, that determined from measurements, or that given in an environment specification document.

A1.2.2 The neutron energy-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 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)-cm², or by 3.435×10^{-19} to convert to J-m²/kg or Gy(Si)-m². 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 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 $\Phi(E)$ 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-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 uncertainties in cross

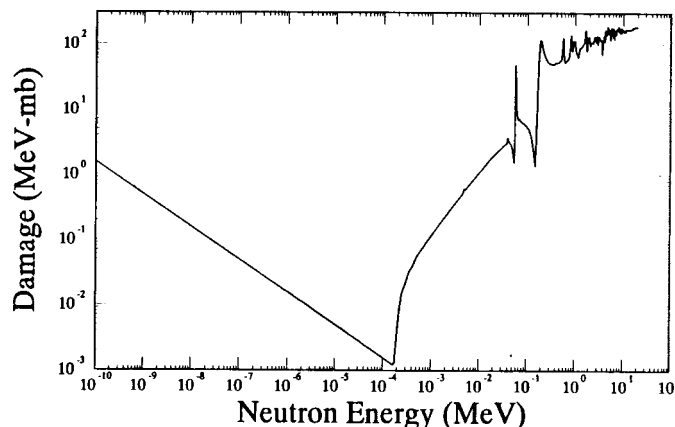


FIG. A1.1 Silicon Damage Function

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 $\Phi(E)$ 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 $F_{D,1\text{MeV,Si}} = 95 \text{ MeV}\cdot\text{mbarn}$, 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 $\pm 20 \%$, would most often lead to uncertainties no more than $\pm 10 \%$ in the integral quantity $\Phi_{\text{eq},1\text{MeV,Si}}$. 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 # | Mid-Point 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 |

TABLE A1.1 *Continued*

| Bin | Mid-Point Energy | Damage |
|-----|------------------|----------|
| # | (MeV) | (MeV-mb) |
| 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 |
| 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 |

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TABLE A.1.1 *Continued*

| Bin | Mid-Point Energy | Damage |
|-----|------------------|----------|
| # | (MeV) | (MeV-mb) |
| 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 |
| 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 |

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TABLE A1.1 *Continued*

| Bin | Mid-Point Energy | Damage |
|-----|------------------|----------|
| # | (MeV) | (MeV-mb) |
| 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 |
| 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 |

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TABLE A1.1 *Continued*

| Bin | Mid-Point Energy | Damage |
|-----|------------------|-------------|
| # | (MeV) | (MeV-mb) |
| 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 |
| 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 |