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Standard Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics[1]

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

1. Scope

1.1 This guide covers procedures for determining the energy-differential fluence spectra of neutrons used in radiation-hardness testing of electronic semiconductor devices. The types of neutron sources specifically covered by this guide are fission or degraded energy fission sources used in either a steady-state or pulse mode.

1.2 This guide provides guidance and criteria that can be applied during the process of choosing the spectrum adjustment methodology that is best suited to the available data and relevant for the environment being investigated.

1.3 This guide is to be used in conjunction with Guide E 720 to characterize neutron spectra and is used in conjunction with Practice E 722 to characterize damage-related parameters normally associated with radiation-hardness testing of electronic-semiconductor devices.

NOTE 1—Although Guide E 720 only discusses activation foil sensors, any energy-dependent neutron-responding sensor for which a response function is known may be used (**1**).[2]

NOTE 2—For terminology used in this guide, see Terminology E 170.

1.4 The values stated in SI units are to be regarded as the standard.

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 170 Terminology Relating to Radiation Measurements and Dosimetry
E 261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques
E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron
E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel
E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum
E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters
E 523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper
E 526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium
E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238
E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237
E 720 Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics
E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics
E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706(IIC)
E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)
E 1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E 706 (IIB)
E 1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium
E 1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors

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[2] The boldface numbers in parentheses refer to the list of references at the end of this guide.

[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.

3. Terminology

3.1 *Definitions:* The following list defines some of the special terms used in this guide:

3.1.1 *effect*—the characteristic which changes in the sensor when it is subjected to the neutron irradiation. The effect may be the reactions in an activation foil.

3.1.2 *response*—the magnitude of the effect. It can be the measured value or that calculated by integrating the response function over the neutron fluence spectrum. The response is an integral parameter. Mathematically, the response, $R = \sum_i R_i$, where R_i is the response in each differential energy region at E_i of width ΔE_i.

3.1.3 *response function*—the set of values of R_i in each differential energy region divided by the neutron fluence in that differential energy region, that is, the set $f_i = R_i/(\Phi(E_i)\Delta E_i)$.

3.1.4 *sensor*—an object or material (sensitive to neutrons) the response of which is used to help define the neutron environment. A sensor may be an activation foil.

3.1.5 *spectrum adjustment*—the process of changing the shape and magnitude of the neutron energy spectrum so that quantities integrated over the spectrum agree more closely with their measured values. Other physical constraints on the spectrum may be applied.

3.1.6 *trial function*—a neutron spectrum which, when integrated over sensor response functions, yields calculated responses that can be compared to the corresponding measured responses.

3.1.7 *prior spectrum*—an estimate of the neutron spectrum obtained by transport calculation or otherwise and used as input to a least-squares adjustment.

3.2 *Abbreviations:*

3.2.1 *DUT*—device under test.

3.2.2 ENDF—evaluated nuclear data file.

3.2.3 *NNDC*—National Nuclear Data Center (at Brookhaven National Laboratory).

3.2.4 *RSICC*—Radiation Safety Information Computation Center (at Oak Ridge National Laboratory).

3.2.5 *TREE*—transient radiation effects on electronics.

4. Significance and Use

4.1 It is important to know the energy spectrum of the particular neutron source employed in radiation-hardness testing of electronic devices in order to relate radiation effects with device performance degradation.

4.2 This guide describes the factors which must be considered when the spectrum adjustment methodology is chosen and implemented. Although the selection of sensors (foils) and the determination of responses (activities) is discussed in Guide E 720, the experiment should not be divorced from the analysis. In fact, it is advantageous for the analyst conducting the spectrum determination to be closely involved with the design of the experiment to ensure that the data obtained will provide the most accurate spectrum possible. These data include the following : (*1*) measured responses such as the activities of foils exposed in the environment and their uncertainties, (*2*) response functions such as reaction cross sections along with appropriate correlations and uncertainties, (*3*) the geometry and materials in the test environment, and (*4*) a trial function or prior spectrum and its uncertainties obtained from a transport calculation or from previous experience.

5. Spectrum Determination With Neutron Sensors

5.1 *Experiment Design*:

5.1.1 The primary objective of the spectrum characterization experiment should be the acquisition of a set of response values (activities) from effects (reactions) with well-characterized response functions (cross sections) with responses which adequately define (as a set) the fluence values at energies to which the device to be tested is sensitive. For silicon devices in fission-driven environments the significant neutron energy range is usually from 10 keV to 15 MeV. Lists of suitable reactions along with approximate sensitivity ranges are included in Guide E 720. Sensor set design is also discussed in Guide E 844. The foil set may include the use of responses with sensitivities outside the energy ranges needed for the DUT to aid in interpolation to other regions of the spectrum. For example, knowledge of the spectrum below 10 keV helps in the determination of the spectrum above that energy.

5.1.2 An example of the difficulty encountered in ensuring response coverage (over the energy range of interest) is the following: If fission foils cannot be used in an experiment because of licensing problems, cost, or radiological handling difficulties (especially with ^{235}U, ^{237}Np or ^{239}Pu), a large gap may be left in the foil set response between 100 keV and 2 MeV—a region important for silicon and gallium arsenide damage (see Figs. A1.1 and A2.3 of Practice E 722). In this case two options are available. First, seek other sensors to fill the gap (such as silicon devices sensitive to displacement effects (see Test Method E 1855)),^{93}Nb(n,n')^{93m}Nb (see Test Method E 1297) or ^{103}Rh(n,n')^{103m}Rh. Second, devote the necessary resources to determine a trial function that is close to the real spectrum. In the latter case it may be necessary to carry out transport calculations to generate a prior spectrum which incorporates the use of uncertainty and covariance information.

5.1.3 Other considerations that affect the process of planning an experiment are the following:

5.1.3.1 Are the fluence levels low and of long duration so that only long half-life reactions are useful? This circumstance can severely reduce the response coverage of the foil set.

5.1.3.2 Are high gamma-ray backgrounds present which can affect the sensors (or affect the devices to be tested)?

5.1.3.3 Can the sensors be placed so as to ensure equal exposure? This may require mounting the sensors on a rotating fixture in steady-state irradiations or performing multiple irradiations with monitor foils to normalize the fluence between runs.

5.1.3.4 Does the DUT perturb the neutron spectrum?

5.1.3.5 Can the fluence and spectrum seen in the DUT test later be directly scaled to that determined in the spectrum characterization experiment (by monitors placed with the tested device)?

5.1.3.6 Can the spectrum shape and intensity be characterized by integral parameters that permit simple intercomparison of device responses in different environments? Silicon is a semiconductor material whose displacement damage function

is well established. This makes spectrum parameterization for damage predictions feasible for silicon.

5.1.3.7 What region of the spectrum contributes to the response of the DUT? In other words, is the spectrum well determined in all energy regions that affect device performance?

5.1.3.8 How is the counting system set up for the determination of the activities? For example, are there enough counters available to handle up to 25 reactions from a single exposure? (This may require as many as six counters.) Or can the available system only handle a few reactions before the activities have decayed below detectable limits?

5.1.4 Once the experimental opportunities and constraints have been addressed and the experiment designed to gather the most useful data, a spectrum adjustment methodology must be chosen.

5.2 *Spectrum Adjustment Methodology*:

5.2.1 After the basic measured responses, response functions, and trial spectrum information have been assembled, apply a suitable spectrum adjustment procedure to reach a "solution" that is as compatible as possible with that information. It must also meet other constraints such as, the fluence spectrum must be positive and defined for all energies. The solution is the energy-dependent spectrum function, $\Phi(E)$, which approximately satisfies the series of Fredholm equations of the first kind represented by Eq 1 as follows:

$$R_j = \int_0^\infty \sigma_j(E)\Phi(E)\,dE \quad 1 \le j \le n \tag{1}$$

where:

R_j = measured response of sensor j,
$\sigma_j(E)$ = neutron response function at energy E for sensor j,
$\Phi(E)$ = incident neutron fluence versus energy, and
n = number of sensors which yield n equations.

One important characteristic of this set of equations is that with a finite number of sensors, j, which yield n equations, there is no unique solution. With certain restrictions, however, the range of physically reasonable solutions can be limited to an acceptable degree.

NOTE 3—Guides E 720 and E 844 provide general guidance on obtaining a suitable set of responses (activities) when foil monitors are used. Practice E 261 and Test Method E 262 provide more information on the data analysis that generally is part of an experiment with activation monitors. Specific instructions for some individual monitors can be found in Test Methods E 263 (iron), E 264 (nickel), E 265 (sulfur-32), E 266 (aluminum), E 393 (barium-140 from fission foils), E 523 (copper), E 526 (titanium), E 704 (uranium-238), E 705 (neptunium-237), E 1297 (niobium).

5.2.2 Neutron spectra generated from sensor response data may be obtained with either of two types of spectrum adjustment codes. One type is the iterative method, an example of which is SAND II (**2**). The second is least squares minimization used by codes such as LSL-M2 (**3**). If used properly and with sufficient, high-quality data, the two methods will usually yield nearly the same values (±10 to 15 %) for the primary integral parameters discussed in E 722.

NOTE 4—Another class of codes often referred to as Maximum Entropy may also prove useful for this type of analysis. These have historically not been used to estimate spectra for radiation-damage purposes.

5.2.3 Appendix X1 and Appendix X2 discuss in some detail the implementation and the advantages and disadvantages of the two approaches as represented by SAND II and LSL-M2.

5.3 *Iterative Code Characteristics*:

5.3.1 The "iterative" codes use a trial function supplied by the analyst and integrate it over the response functions of the sensors exposed in the unknown environment to predict a set of calculated responses for comparison with the measured values. The calculated responses are obtained from Eq 1. The code obtains the response functions from a library. See Guide E 1018 for the recommendations in the selection of dosimetry-quality cross sections. Available dosimetry-quality cross section libraries include: the International Reactor Dosimetry File (IRDF-2002) cross section library (4), release 6 of the ENDF/B-VI (5, 6) cross section library and the SNLRML package (7) which is available through RSICC.

5.3.2 The code compares the measured and calculated responses for each effect and invokes an algorithm designed to alter the trial function so as to reduce the deviations between the measured and calculated responses. The process is repeated with code-altered spectra until the standard deviation drops below a specified value—at which time the code declares that a solution has been obtained and prepares a table of the last spectrum. This should not be the end of the process unless the initial trial was very close to the final result. In each iteration, the SAND II-type code will alter the trial most rapidly where the foil set has the highest response. If the trial is incompatible with the measurements, the spectrum can become distorted in a very unphysical manner.

5.3.3 For example, if a trial function predicts an incorrect gold activity, it may alter the spectrum by orders of magnitude at the gold high-response resonance at 5 eV while leaving the trial spectrum alone in the immediate vicinity. The analyst must recognize that the trial must be changed in a manner suggested by the previous result. For example, if a peak develops at the gold resonance, this suggests that the trial spectrum values are too low in that whole energy region. A new trial drawn smoothly near the spectrum values where the sensor set has high response may improve the solution. This direct modification becomes an outer iteration on the spectrum adjustment process, as described in Refs (**8**,**9**). The outer iteration methodology coupled with good activity data is usually so successful that the form of the initial trial does not overly influence the integral results.

5.3.4 For any of the iterative type codes to succeed at producing a spectrum that is both representative of the measured data and likely to be close to the true spectrum of neutrons that caused the activation data, experience has shown that the following are important: (*1*) the use of sensors with well-established response functions (≤8 % for spectrum-averaged cross sections), (*2*) a sensor set that has good response over all the important regions of the spectrum, and (*3*) sufficiently accurate measured responses (on the order of ±5 %). No direct use is made of uncertainty data (variance and covariance information) that exists for each cross section, of uncertainty in the trial spectrum, or in the uncertainties in the