Designation: E721 – 16

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

This standard is issued under the fixed designation E721; 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 U.S. 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 E720 to characterize neutron spectra and is used in conjunction with Practice E722 to characterize damage-related parameters normally associated with radiation-hardness testing of electronic-semiconductor devices.

NOTE 1—Although Guide E720 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 E170.

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

E170 Terminology Relating to Radiation Measurements and Dosimetry

E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques

E262 Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques

E263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron

E264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel

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

E266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum

E393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters

E523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper

E526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium

E704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238

E705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237

E720 Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics

E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

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

Current edition approved Dec. 1, 2016. Published December 2016. Originally approved in 1980. Last previous edition approved in 2011 as E721 – 11. DOI: 10.1520/E0721-16.

[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.

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)
E1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E706 (IIB)
E1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium
E1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors

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 E720, 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 E720. Sensor set design is also discussed in Guide E844. 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 E722). 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 E1855)), ^{93}Nb(n,n') ^{93m}Nb (see Test Method E1297) 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 Do the DUT or the spectrum sensors perturb the neutron spectrum?

5.1.3.5 Are response functions available that account for self-shielding for all sensors using (n,γ) or non-threshold (n,f) reactions, unless the material is available in a dilute form of certified composition?

5.1.3.6 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)?

5.1.3.7 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.

5.1.3.8 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?

5.1.3.9 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 or prior spectrum information have been assembled, apply a suitable spectrum adjustment procedure to reach a solution that satisfies the criteria of the chosen procedure. 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.

NOTE 3—Guides E720 and E844 provide general guidance on obtaining a suitable set of responses (activities) when foil monitors are used. Practice E261 and Test Method E262 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 E263 (iron), E264 (nickel), E265 (sulfur-32), E266 (aluminum), E393 (barium-140 from fission foils), E523 (copper), E526 (titanium), E704 (uranium-238), E705 (neptunium-237), E1297 (niobium).

5.2.2 One important characteristic of the set of equations (Eq 1) is that with a finite number of sensors, n, which yield n equations, there is no unique solution. Exact solutions to equations (Eq 1) may be readily found, but are not generally considered useful. When the least squares adjustment method is used, equations (Eq 1) are supplemented by the constraint that the solution spectrum must be approximately equal to the prior spectrum. This additional constraint guarantees that the set of equation is overdetermined and that a unique least squares solution does exist. The tolerances of the approximations are dependent on the specified variances and covariances of the prior spectrum, the response functions, and the measured responses. When other adjustment methods are used it must be assumed that the range of physically reasonable solutions can be limited to an acceptable degree.

5.2.3 Neutron spectra generated from sensor response data may be obtained with several types of spectrum adjustment codes. One type is linear least squares minimization used by codes such as STAY'SL **(2)** or the logarithmic least squares minimization as used by LSL-M2 **(3)**. When the spectrum adjustments are small, these methods yield almost identical results. Another type is the iterative method, an example of which is SAND II **(4)**. If used properly and with sufficient, high-quality data, this method will usually yield nearly the same values as the least squares methods (±10 to 15 %) for the primary integral parameters discussed in E722.

NOTE 4—Another class of codes often referred to as Maximum Entropy **(5)** has also been used for this type of analysis.

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

5.3 *Least-Squares Code Characteristics:*

5.3.1 The least-squares codes, represented by STAY'SL **(2)** and LSL-M2 **(3)**, use variance and covariance data for the measured responses, response functions, and prior spectrum. The STAY'SL code finds the unique maximum likelihood solution spectrum when the uncertainties ar assumed to be distributed according to a normal distribution. The LSL-M2 code finds the unique maximum likelihood solution spectrum when the uncertainties are assumed to be distributed according to a multivariate lognormal distribution. The codes allow not only the prior spectrum but also the responses and the response functions to be adjusted in a manner constrained by their individual uncertainties and correlations in order to find the most likely solution. In principle this approach provides the best estimate of a spectrum and its uncertainties. The least-squares method is described more fully in Guide E944 and in Appendix X2.

5.3.2 The solution to the linear least squares spectrum adjustment problem is given in matrix form by:

$$\Phi' - \Phi_0 = C_{\Phi_0} S_{\Phi_0}^T \left(S_{\Phi_0} C_{\Phi_0} S_{\Phi_0}^T + S_{\Sigma_0} C_{\Sigma_0} S_{\Sigma_0}^T + C_{R_m}\right)^{-1} (R_m - R_0) \tag{2}$$

where:

Φ' = a column vector of the adjusted groupwise fluences,

Φ_0 = a column vector of the prior spectrum fluences,
C_{Φ_0} = the covariance matix of the prior spectrum,
S_{Φ_0} = the matrix of sensitivities of the calculated responses to the prior fluences,
S_{Σ_0} = the matrix of sensitivities of the calculated responses to the response functions,
C_{Σ_0} = the covariance matrix of the response functions,
C_{R_m} = the covariance matrix of the measured responses,
R_m = a column vector of the measured responses,
R_0 = a column vector of the responses calculated using the prior spectrum and response functions,

superscript T indicates the transpose of a matrix, and

superscript –1 indicates the inverse of a matrix.

5.3.3 Further details, including the sensitivity matrix entries, may be found in (**2**)). In the case of logarithmic least squares, the fluences and the responses are replaced by their natural logarithms, and the covariance matrices are replaced by the fractional covariance matrices, see (**3**)).

5.3.4 The input variance and covariance matrix quantities are not always well known and some may have to be estimated. The analyst must understand that his estimates of these quantities can affect the results.

5.3.5 No least-squares code in the form distributed by code libraries conveniently handles the effects of covers over the foils even though the use of covers is strongly recommended. See Section 7.2 of Guide E720 and X1.5.1 of this standard for more information.

5.3.6 The code automatically weights the data according to uncertainties. Therefore, data with large uncertainties can be used in the analysis, and will have the appropriately small influence on the results.

5.3.7 The solution spectrum shape must correspond fairly well to the prior spectrum (within 1 or 2 standard deviations) if the results are to be reliable (**6**). The prior spectrum determines the solution spectrum when its uncertainties are so small that the uncertainties of the prior calculated responses are small compared to those of the measured responses. Conversely, the prior spectrum does not strongly constrain the solution spectrum when the prior calculated responses are large compared to the measured responses. See Ref (**3**).

5.3.8 If a transport code calculation of the spectrum is used as the starting point for the analysis, then this methodology can be useful for adjusting spectra at a different location from that in which the foils were exposed. If the transport calculation includes a location where an experiment can be conducted and a similar one where such an experiment would be difficult or impossible (such as inside a test fixture or other structure), then this type of code can be used to adjust both spectra simultaneously. In accepting the results for the unmonitored location, it is important that the transport calculation be adjusted minimally.

5.3.9 The analyst must be careful the input variances and covariances, including those associated with the prior spectrum, are realistic. It is not sufficient to take statistical scoring errors from a Monte Carlo transport calculation and use these as a measure of the uncertainty in the trial spectrum. All uncertainties, and in particular, uncertainties in the reactor modeling, material densities, and response functions should be represented in the input uncertainty. The value of the chi-squared (χ^2) parameter may be used as a good indication of the consistency of the input data (including the uncertainty data).

5.4 *Suitability of the Least-Squares Adjustment Codes*—The least-squares codes are particularly well suited to situations in which the environment is fairly well characterized physically so that a prior spectrum can be calculated. They work best when detailed transport calculated spectra are available for use as the prior spectra for the analysis. However, it is often difficult to obtain a mathematically defensible covariance matrix for these spectra. In such cases, the specified uncertainties in the prior spectrum should be large enough to ensure that the measured response uncertainties are larger than their calculated prior uncertainties. In principle, a sensitivity analysis based on the radiation transport code methodology could be used to provide the prior spectrum uncertainty and energy-dependent correlation, but this is not an easy analysis and is seldom attempted.

5.5 *Iterative Code Characteristics:*

5.5.1 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 E1018 for the recommendations in the selection of dosimetry-quality cross sections.

5.5.2 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 coded 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.

5.5.3 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 (**7**, **8**). 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.

5.5.4 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 measured responses. These uncertainties can vary greatly among sensors or environments. It follows that data with large uncertainties should not be used in the final stages of this methodology because it can cripple the final results.

NOTE 5—Response data that exhibits a strong disagreement with other data in the data ensemble can be very useful in the early stages of an analysis. For example, if the activity of a particular reaction is incompatible with the other foils in the spectrum adjustment process, it can indicate one of two important possibilities. First, if it is a reaction whose energy-dependent cross section is well known and has repeatedly demonstrated compatibility in the past, an experimental or transcription error is suggested. Second, if the activity measurement was accurately carried out, and this reaction has repeatedly demonstrated incompatibility in the same direction in other spectra determinations in different environments, an incorrect cross section or energy-specific counting calibration error is indicated (**8**)). A number of specific cross section problems have been uncovered by analysis of incompatibility data. But in the construction of the neutron spectrum, these "bad" reactions should not be used with a method that does not incorporate uncertainty data.

5.6 *Suitability of the Iterative Adjustment Codes:*

5.6.1 Iterative codes usually do not have a capability to weight the responses according to uncertainties, do not provide error or uncertainty analysis, do not use variance or covariance information, and provide no direct quantification of the output uncertainties for any calculated quantities. However, it is possible to assign errors in the spectrum in appropriate energy regions using perturbation analysis. (Also computerized perturbation and random draw from response error may be utilized.) The analyst perturbs the trial spectrum upwards and downwards in each energy region and observes to what degree the code brings the two trials into agreement. This is, however, a laborious process and has to be interpreted carefully. In the resonance region where foil responses are spiked, the code will only yield agreement at resonances where there exists high response. The analyst must not only interpolate the spectrum values between high response regions but also the spectrum uncertainties. This step can be rationalized with physical arguments based on the energy-dependence of cross sections but it is difficult to justify mathematically. This situation further supports the arguments for maximizing response coverage. In addition, it is usually the uncertainties of integral parameters that are of primary importance, not the uncertainty of $\Phi(E)$ at individual energy values

5.6.2 Covers are used over many of the foils to restrict the response ranges, as is explained in Guide E720. The SAND II code handles the attenuations in the covers in a simple manner by assuming exponential attenuation through the cover material. There is considerable evidence that for some spectra the calculated exponential attenuation is not accurate because of scattering.

6. Discussion and Comparison of Methodology Characteristics

6.1 The least-squares codes are superior because it should be possible to directly incorporate all that is known about the test environment and about the response functions to arrive at the most likely solution in a least-squares sense. The codes provide mathematically defensible output with uncertainties when covariance data is available for all the input quantities. The iterative codes do not propagate uncertainties nor make use of any variance or covariance information which may exist.

6.2 Considerable experience with both approaches has demonstrated that they yield approximately the same integral parameter values when applied to the methodology in E722, provided that adequate and accurate primary experimental information is available. This means the analyst must have access to a set of carefully measured responses, usually activation data. The associated set of responses functions, usually activation cross sections, must cover a broad range of energies. And, the response functions for the measured data must be well established over these energy ranges.

6.3 Transient radiation effects testing of electronics (TREE testing) is carried out in a wide variety of different environments that are often customized with complicated filters and shields. For these cases, detailed transport calculations can be time-consuming and expensive. The user may not be aware of the total assemblage of material structure that affects the radiation environment.

6.4 The iterative type code performs at its best with accurate response data and well-known response functions because the range of acceptable solutions is then severely restricted, and the acceptance criterion of measured-to-calculated activity values can be set to a low value. Also, incompatible responses, perhaps caused by experimental errors, stand out clearly in the results. The least-squares type code seems much more forgiving because wide variances are assigned to less well-known cross sections and activities, so marginal data can be more easily tolerated. For both methods, a very good trial function or prior spectrum is required when limited or imprecise measured responses are available. In these cases, the solution cannot be allowed to deviate very much from the trial because less use should be made of the measured data.

6.5 SAND II should not be used to generate trial functions for LSL-M2, because the SAND II solution spectrum is correlated to the activities, but the LSL method assumes there is no such correlation.

6.6 Neither methodology can be used indiscriminately and without careful monitoring by a knowledgeable analyst. The analyst must not only apply physical reasoning but must examine the data to determine if it is of adequate quality. At the very least the analyst must evaluate what is seen in a plot of the solution spectrum. Available versions of the SAND II code provides less subsidiary information than least-squares codes can supply, particularly with regards to uncertainties. More detailed discussions of the LSL-M2 and SAND II methodologies are provided in the appendixes.

7. Precision and Bias

7.1 Precision and bias statements are included in each of the appendixes.

8. Keywords

8.1 neutron sensors; neutron spectra; radiation-hardness testing; spectrum adjustment

APPENDIXES

(Nonmandatory Information)

X1. APPLICATION OF THE LSL-M2 CODE

X1.1 The Least-Squares Method, LSL-M2

X1.1.1 This appendix provides guidance for the application of the LSL-M2 adjustment code to hardness testing of electronic devices. The code is described in Refs (**9**) and (**10**). However, it is designed for commercial power reactor pressure vessel surveillance applications and the documentation was developed accordingly. This appendix provides guidance for those circumstances where the documentation is inadequate or inappropriate for hardness-testing applications.

X1.2 Introduction

X1.2.1 As Eq 1 implies, three basic data sets are required in the determination of the neutron energy-fluence spectrum: *(1)* a set of measured responses (see Guide E720 for guidance on foil selection), *(2)* energy-response functions, and *(3)* an approximation to the solution.

X1.2.2 Several codes have been developed which implement a least-squares approach to the determination of the neutron spectrum from sensor data. The least-squares codes require a minimum of three additional data sets in the form of uncertainty estimates for all the above data, complete with the correlations between all the data. These additional data are used to establish uncertainty estimates on the output data. See Section 3.2 of Guide E944 for more information.

X1.2.3 The LSL-M2 code (**10**) is one example of a least square code package which is distributed with a suitable set of auxiliary data (cross sections and covariance files) to permit its application for the adjustment of reactor pressure vessel neutron spectra. As part of the REAL exercises (**11**, **12**, **13**) the International Atomic Energy Agency (IAEA) compiled and distributed a Neutron Metrology File NMF-90 (**14**) which includes versions of the MIEKE (**15**) and STAY'SL (**2**) least square adjustment codes along with compatible cross sections and sample input decks. These three codes are examples of least square adjustment codes which are available to the general community and include interfaces with suitable cross section libraries.

X1.2.4 An adequate prior or theoretical prediction of the fluence spectrum (with its covariance matrix) is often the most difficult information set to obtain. If a transport calculation is available, it may be a generic type of run such as a leakage spectrum from the reactor or a criticality calculation that provides a typical spectrum for some location.

X1.2.5 An error estimate of the group-wise fluences, with correlations, is essential to LSL-M2, but is not always readily available to the analyst. The error analysis distributed with the code may be applied, with caution, to pool-type reactors if nothing else is available, but it is not applicable to fast-burst reactors or ^{252}Cf sources and should not be used. However, the LSL-M2 code can be applied to most reactors used for testing of electronic devices whether an error estimate of the spectrum is available or not. The practical aspects of this will be described in X1.4.

X1.3 Constraints on the Use of the Code

X1.3.1 The LSL-M2 code is distinguished by its use of lognormal distributions for all the parameters of interest. This imposes the physically realistic constraint that all quantities are positive and real. The formulation of the equations described in Section 3 of Guide E944 were all converted to logarithmic counterparts by the writers of LSL-M2. As stated in the manual, care should be taken to input covariances as fractional covariances: the expected values of $\frac{\delta x_i}{x_i}\frac{\delta x_j}{x_j}$. In the same fashion, the output uncertainties are actually logarithmic ratios of the standard deviation to the expected value. The primary output of LSL-M2 is not the adjusted spectrum, but rather the damage-related integral parameters with their errors. This feature is ideally suited to the calculation of silicon damage as defined in Practice E722.

NOTE X1.1—There is little difference between these logarithmic ratios and the more normal values if the percentages quoted are less than 10 %. But, as the ratio of (observed/actual) increases, the LSL ratio diverges from the non-logarithmic ratio.

X1.3.1.1 Dosimetry cross-section sets and associated covariance matrices are available with the LSL-M2 code package. The cross sections distributed by RSICC with this code have been derived from ENDF/B-V evaluations (**10**). The newer IRDF-2002 distribution (**16**) is recommended as a replacement for the code's build-in data sets. In most cases, it contains newer evaluations for the actual cross sections and much more refined evaluations of the associated covariance data for each reaction.

X1.3.1.2 The response data is obtained through the application of Guides E720 and E844, Practice E261 and Test Methods E262, E263, E264, E265, E393, E704, and E705. The uncertainty estimate for each response should not be simply an estimate of the counting statistics, but rather should include all contributors of uncertainty to the measured value, such as uncertainties in counting efficiency, branching ratio, foil composition, mass, experimental positioning, etc. Correlations between reactions may be important, particularly when the same radioactive product is measured on the same detector.

X1.3.1.3 The code requires a prior fluence or fluence-rate spectrum and an estimate of its uncertainties with correlations. Experience has shown that the better the quality of the input spectrum, the better the quality of the results from LSL-M2. There is no ideal substitute for a transport calculation combined with a sensitivity analysis for error propagation. However, for a bare fast reactor a leakage spectrum with extrapolated fission shape for the high energies and a $1/E$ shape for the resonance/thermal region can give acceptable results if the uncertainties assigned to the calculation are appropriately chosen. (The guidance in X1.4.3 may be followed).

X1.4 Operation of the Code

X1.4.1 The application of the code is adequately described in the documentation. The six data sets required by LSL-M2 along with the damage functions are stored in individual files and the code's output is designed to go into individual files. An adequate method of assigning file names and keeping track of input and output files is required.

X1.4.2 If a covariance analysis, such as described by Maerker (**9**), of a transport calculation for a similar reactor type and location is available, it can be used. The Maerker analysis will be generally applicable to water-moderated reactors such as some positions of pool-type reactors. It is not applicable to GODIVA or similar fast-fission types of reactor spectra. Similarly, the covariance data with the reference spectra provided as part of IRDF-2002 (**16**) may or may not be appropriate depending upon the type of test configuration and neutron source used.

X1.4.3 Section 5.3 of Guide E944 describes the general principles for constructing usable covariance matrices for fluence spectra when a full sensitivity analysis is not available. Equation 14 of Guide E944 is a general representation of a distance formula. Several functions that satisfy the requirements of Eq. 14 follow in the standard. Experience has shown that this type of procedure produces acceptable results. For the purposes of hardness testing, the following distance formula is suggested:

$$c_{ik} = \exp\left(- \frac{\text{abs}\left[ln(E_i) - ln(E_k) \right]}{A} \right) \qquad \text{(X1.1)}$$

X1.4.4 If Eq X1.1 is used, it then only remains to provide guidance on the proper selection of a value for the parameter "A." As seen from the structure of Eq X1.1, A is a measure of how closely correlated are spectrum values at energies E_i and E_k. It is neither possible nor desirable to specify a value for A in this guide since the best value is somewhat dependent upon the nature of the exposure environment. Instead, a discussion of the effects of varying the value of A will allow the tester to make an appropriate selection of A for the exposure environment.

X1.4.4.1 The parameter A can be viewed as a measure of the group-to-group stiffness of the calculation. In a well-moderated spectrum, the lower energy groups are all populated by down-scattering events, the group-to-group correlations are therefore strong and a large value for A "near 1.0" is justified. Such would be appropriate for a TRIGA-type reactor, or the epithermal groups of a GODIVA-like reactor. But, the high-energy part of all reactor spectra are dominated by the fission-neutron production process, and therefore the uncertainties are dominated by those in the fission-spectrum representation used. In these spectra a small value of A "near 0.0" is appropriate. See Ref (**6**).

X1.4.5 The uncertainties assigned to each group (the diagonal of the matrix) may have a marked effect on the results. If there is no knowledge as to what these uncertainties may be, then the only alternative is to carry out a series of runs to determine the sensitivity of the results to the selection of uncertainties. The value of χ^2 per degree of freedom should be monitored for unrealistically high and low values. Those runs with such unrealistic values of χ^2 per degree of freedom should be discarded or serve as boundaries.

X1.4.6 Very large assigned uncertainties for all groups (100 to 1000 %) in the input spectrum will produce output only dependent upon the responses and response functions so long as the entire energy range is covered by the reaction cross sections. The temptation to use these results will be great for this reason. However, this should be considered as a limiting case. This solution spectrum should produce a very low value for the χ^2 per degree of freedom. If it does not, then there is a very large error in one or more of the responses. Large assigned uncertainties may be appropriately used for limited neutron energy ranges, for example, the thermal or epithermal part of a fast-reactor spectrum.

X1.4.7 Very small assigned uncertainties in the input spectrum will produce adjusted spectra which are essentially the same as the calculated spectrum (regardless of what is in the covariance matrix). While this will normally produce abnormally high chi-squared per degree of freedom values, it may not if there are only a few sensor responses available. However, the uncertainty assignments to the results may be unrealistically low. This is the other limiting case.

X1.4.8 When a good estimate of the input uncertainties on the group fluences is not available, the uncertainties on the resulting damage parameters are not well defined regardless of the value of χ^2 per degree of freedom. This is true, unless it can be shown in a particular case that these uncertainties are insensitive to the uncertainties of the prior fluences.

X1.4.9 The LSL-M2 code documentation recommends that the prior fluence values be normalized in an absolute fashion. However, if a generic calculation is used, absolute normalization of the fluences is not justified. Therefore, for most hardness-testing applications, the use of a scaling reaction is recommended. Only in those cases where core modeling was performed for the specific irradiation conditions is absolute normalization of the fluence spectrum justified.

X1.4.10 As in all adjustment codes, bad response data will invalidate the results. Since bad response data are sometimes hard to spot from the output of LSL-M2, it is imperative that the response data be checked prior to accepting the results. Further, if there is a known systematic uncertainty in the response data, suspect responses should not be included in the analysis. If there is a known but un-quantified systematic error in a response, that response should not be used until a suitable

correction factor can be obtained. Its inclusion will adversely affect the resulting spectrum and damage parameters. (There is a temptation to include bad data by ascribing large uncertainties because the algorithm can tolerate it. However, it will hurt the output and usually will invalidate the results.)

X1.4.11 The consistency of the data ensemble input to LSL-M2 is tested by the code using a χ^2 test. The output value of the χ^2 should approximate the number of degrees of freedom. Deviations from this value, if significant, should always result in rejection of the results and a re-examination of the input. The value obtained for χ^2 should be reported in all cases.

X1.5 Deficiencies of the Code

X1.5.1 *Sensor Foil Covers*—Unlike the SAND II code, which has a built-in method of handling covers, LSL-M2 does not directly handle this aspect of the measurement. LSL-M2 allows the use of sensor covers by allowing the testing of the sensor data for a cover identifier. It makes the assumption that if a cover was present, the response function for that sensor has been adjusted in some prior processing step to the execution of LSL-M2. It is the responsibility of the person performing the LSL-M2 analysis to supply the sensor response function that is applicable to the sensor and cover used. This is best calculated in a Monte Carlo calculation of the responses to neutrons per unit incident fluence for each individual energy group. This can be performed before or after the response function has been collapsed with the FLXPRO subroutine to the group structure to be used in the analysis.

X1.5.1.1 An effective approximate response function for a sensor inside a cover can be estimated in accordance with the following equation:

$$\sigma'_j(E_i) = \sigma_j(E_i) \times \exp[-N\sigma_c(E_i)X] \qquad (X1.2)$$

where:

$\sigma_j(E_i)$ = jth response function at energy E_i,
$\sigma_c(E_i)$ = cover absorption cross section at energy E_i, and
NX = number density per unit area of the cover.

NOTE X1.2—As described in Guide E720, this treatment may not be adequate in that it ignores the scattering effects of the cover. It almost certainly leads to appreciable error in the attenuation (on the order of 10 % or more) for threshold foils when Boron-10 encapsulation is used.

X1.5.2 Each reaction may require several response functions, each differing from the others by the cover assumed in the calculation, and by the cover thickness assumed. This method ignores the effect of the cover adjustment on the covariance for the response function.

X1.5.2.1 When a sensor is used with and without a cover which absorbs strongly in some energy region, it is preferable to use the measured response with the cover and the difference between the two measured responses. The response function for the difference is simply the difference of the two response functions. The reason for this is that the response with the cover and the difference response are nearly uncorrelated with each other.

X1.6 Precision and Bias

X1.6.1 In the rare case where all the input uncertainties data are reliable, the LSL-M2 code provides the required output uncertainty information for both the neutron-energy spectrum and damage-related parameters.

X1.6.2 In the more common case where Eq X1.1 was used to generate the covariance matrix and the group-wise fluence uncertainties were not established by methods similar to those employed in Ref (**9**), an input uncertainty perturbation study should be performed to determine the range of output uncertainties. This range should be reported. Alternatively, a similar procedure can be used to demonstrate that the output uncertainties are insensitive to the group-wise input uncertainties (which should be true when the sensor set used has good energy coverage). In this case the output of the code is sufficient.

X2. APPLICATION OF THE SAND II CODE

X2.1 Summary of the Iterative Method, SAND II

X2.1.1 SAND II is discussed here as an example of an iterative adjustment code. Its use in radiation-hardness testing of electronics is discussed in detail in Refs (**17, 18**). This code employs a mild perturbation method that reduces the formation of spurious structure in the output energy spectrum. The measured responses of the sensor set, along with the response functions and a trial spectrum, are inputs to the code. The output of the code gives the fractional differences between the measured responses and calculated responses that are consistent with the trial spectrum. The code adjusts the trial spectrum to reduce these fractional differences and to obtain better agreement between the measured responses and those calculated from the solution spectrum. Iteration of this process continues until satisfactory agreement is obtained between measured responses and those calculated from the solution energy spectrum. A course of action to take in cases when the solution is unsatisfactory is suggested in X2.2.2 and X2.2.5.

X2.2 Operational Characteristics of the Code

X2.2.1 The measured responses determined for a set of sensors are related to the incident neutron energy-fluence spectrum, $\Phi(E)$, by Eq 1.

X2.2.2 The unknown incident spectrum $\Phi(E)$ is approximated by a trial spectrum. The code calculates the various resultant trial responses, r_{jt}, that are consistent with $\Phi_t(E)$. If the response functions are cross sections, they are obtained from an up-to-date evaluated cross-section library, such as ENDF/B-VI adapted to the SAND II cross-section format for 640 energy groups. A recommended library is provided in Ref (**16**). It is appropriate here to remind the reader once again of the importance of choosing a set of reactions with well-known

and experimentally substantiated cross-section values for use in the spectrum adjustment procedure, because the solution spectrum cannot be well established unless the reaction rates are compatible with a physically reasonable spectrum. See Guide E720. Furthermore, it is very important that the relative responses be accurately established by making certain all sensors are subjected to the same fluence and read with high-statistical and calibration accuracy. The code, when used properly, is quite sensitive to incompatible responses, but when incompatible data are included in the set to be adjusted, the spectrum solution may become severely distorted. While it represents a mathematical solution, it may not be physically meaningful.

X2.2.3 The fractional differences between the measured activities and the trial activities are calculated by the code. They are given as follows:

$$\Delta_{j0} = \frac{R_j - r_{jt}}{r_{jt}} \quad \text{(X2.1)}$$

The standard deviation, S_0 of the set of Δ_{j0} values, also is determined. Here the subscript zero indicates the first run of the code and r_{jt} is the calculated value.

X2.2.4 The code operator must choose an input value for the standard deviation S (for example, 5 %). If S_0 is less than that value, then $\Phi_t(E)$ is the solution. If S_0 is larger than the chosen input value, then the code adjusts the trial spectrum in the energy regions in which the corresponding values of $\Delta°_{j0}$s are sensitive. On the next iteration, the adjusted trial spectrum, $\Phi_1(E)$, reduces the Δ_{j1} values and consequently, reduces S_1. This iterative process is repeated to generate the sequence of sets of data:

$$\Phi_1(E), \{\Delta_{11}, \ldots \Delta_{n1}\}, S_1$$

.

.

$$\Phi_k(E), \{\Delta_{1k}, \ldots \Delta_{nk}\}, S_k$$

This continues until S_k, achieves the preset goal of 5 % (or whatever the operator chose for the standard deviation).

X2.2.5 The procedure of adjusting the trial often leads to a distorted spectrum if the trial is very different from one that is really compatible with the response set. The most direct way to discern any distortion is to examine a plot of the output spectrum. SAND II alters the trial spectrum most strongly where Δ_j is large and cannot change the trial significantly where the foil set response is low. Thus the analyst should alter the trial by smoothly connecting the points where the sensor set is responsive. This mode of using SAND II makes it more useful and more powerful. The improvement gained by this "outer iteration" is generally quite obvious. The method is more thoroughly discussed in Refs **(1), (8), (19)**, and **(20)**.

X2.2.6 There are some circumstances in which real spectra may exhibit resonance-like structure, and if this structure occurs at a high enough energy to overlap a similar structure in the response function of the electronic part (>100 keV for silicon) the smoothing procedure that this methodology requires will be invalidated. (It takes a large amount of most materials around the field point to cause this type of structure to be superimposed on the spectrum.) For example, a thick layer of iron will strongly attenuate the neutrons except at the anti-resonance dip at about 25 keV. The energy window there will allow a sharp peak to develop in the spectrum. The foil set used with a smoothed trial spectrum may not exhibit this structure with any resolution even though the integral of the spectrum will be properly represented. This structure should not affect the integral parameters for silicon since its threshold is above 100 keV. Since SAND II does not alter the trial where it has no sensitivity, one could add a calculated peak in the trial spectrum and not smooth it. There will be very little alteration in the integral parameters (such as the 1-MeV equivalent fluence) in any case. See Practice E722 about integral parameters.

X2.2.7 A second example of problems with smoothing is perhaps more realistic. It is possible that through large thicknesses of air, oxygen, and nitrogen resonance structure could be superimposed on the spectrum. These resonances will be at higher energies and might overlap the silicon response region. Each case will have to be investigated individually. However, it is important to point out that if sharp spectrum structure overlaps a slowly changing region of the response function of the DUT, the integral parameters will still be relatively unaffected.

X2.2.8 Three important points emerge from the above discussion. First, for a broad coverage sensor set, erroneous sensor responses usually stand out clearly for identification because they are not compatible with the rest of the set. Second, considerable experience **(7)** has shown that the final spectrum is insensitive to the form of the initial trial, and therefore, third, an accurate trial spectrum to start the adjustment process may not be required. This means that the detailed knowledge required for a careful transport code calculation of the trial may not be needed in order to obtain a solution spectrum that approximates the real spectrum satisfactorily.

X2.3 Constraints on Use of the Code

X2.3.1 Because of the limited data available from a set of responses, a physically meaningful trial spectrum, (that is, somewhat representative of the real spectrum) must be input to the code during the last outer iteration in order for SAND II to give reliable results. The trial spectrum may be obtained in one of three ways: (*1*) from a neutron transport calculation, (*2*) from an appropriate trial spectrum from the SAND II spectrum library, or (*3*) from the trial adjustment procedure in accordance with X2.2.5.

X2.3.2 The operator must interact with the code in order to achieve acceptable results with a reasonable number of iterations. SAND II may require an unreasonably large number of iterations if one or more responses are spurious. The operator should examine the set of disparities, Δ_{ji}s, printed out after the first run. If a single value is appreciably different from the rest of the set, it is (potentially) a spurious activity value. If at all possible, a careful reexamination of the data should be made, because very often a simple error is easily discovered and corrected. If no such error can be identified, the spurious R_j value should be eliminated from the set and the code rerun.

NOTE X2.1—The elimination is necessary because the code very often cannot provide a well-defined (or satisfactory) solution if incompatible data prevents the attainment of a suitably small standard deviation (≤5 %). Often with SAND II the solution standard deviations will drop rapidly between iterations at first and then converge much more slowly. This is often an indication that at the elbow the solution has been reached within the self-consistency of the data set.

X2.3.3 However, if two or more values of Δ_j corresponding to adjacent threshold energies E_{jt} are large, of the same sign, and approximately the same magnitude, then the trial spectrum $\Phi_t(E)$ should be adjusted in the energy region corresponding to such large Δ_j values. Additional guidance in adjusting the input spectrum may be obtained by examining the energy "band" where 95 % of the activation of each foil has occurred. This is printed out by the code for each spectrum calculated.

X2.4 Operating Procedures for the Code

X2.4.1 *Input Data*—In order to obtain results applicable to either fast-pulse or steady-state irradiations, operate the SAND II code in the "time integrated" (that is, time-independent) mode. The code inputs required are a trial spectrum, $\Phi_t(E)$, the measured responses, R_j, and data on the foil covers (if any). Exclude data that is known to be poor. If, for example, the spectrum shape is such that the response of a particular foil is shifted to an energy region where its cross section is poorly defined, its activity may become incompatible with the rest of the foil set. In all cases deleted data must be explained and documented.

X2.4.2 *Choice of a Trial Spectrum $\Phi_t(E)$:*

X2.4.2.1 Although not absolutely necessary, it is preferable for the trial spectrum to be close to the real spectrum. On the other hand, unnecessary cost can be incurred by attempting very detailed calculations to predict the spectrum as closely as possible. The most reliable trial will often be the result of a previous spectrum measurement made in the same facility in a closely related environment. If that is not available, follow a course similar to the following suggestions:

X2.4.2.2 The SAND II code has available a library of trial spectra that may be appropriate for use for specific applications. One of these is called GODIVA (obtained by a neutron transport calculation) and is similar to a fission spectrum. Use it as the trial spectrum to begin the adjustment process for the spectrum in the cavity of a fast-burst reactor.

X2.4.2.3 For locations outside a fast-burst reactor, the trial spectrum usually has to be altered to account for neutron moderation. For example, for a location 5 m from the reactor with the reactor 2 m above a concrete floor, join the GODIVA trial spectrum with a $1/E$ component below 0.01 MeV. This will help avoid distortion of the output spectrum above 0.01 MeV.

NOTE X2.2—The slowing down of neutrons in water gives a $1/E$ fluence from about 1 eV to 100 keV. Because the moderator produces this $1/E$ behavior, this spectral shape should be used for calculating integrals for the resonance reaction region.

X2.4.2.4 In another example, join the $1/E$ component on the GODIVA trial spectrum at 0.15 MeV to obtain a $\Phi_t(E)$ for a TRIGA-type reactor.

X2.4.2.5 The experimenter should be aware that if the measurements are made behind a boron shield, the low-energy tail will be depressed. In this case, the gold and other resonance reactions will indicate the drooping shape of the spectrum in the low-energy region.

X2.4.2.6 If the Δ_j values are large and of the same sign in the energy region above a few million electron volts, it is generally not necessary to change $\Phi_t(E)$. Usually enough foil threshold data exist in this region for SAND II to achieve a good solution in a few iterations. On the other hand, modest adjustment of the trial here can improve the fit and sometimes reveal real structure in the shape of the spectrum.

X2.4.3 *Criteria for an Acceptable Spectrum Solution:*

X2.4.3.1 When the R_j values and the responses calculated with the trial spectrum are consistent, the SAND II code will yield a solution in a few iterations (typically 10 or less). The solution should have a shape similar to the final trial function. Comparisons of the spectra are best done by making log-log plots of $E\Phi(E)$ versus energy. In this way, a $1/E$ low-energy tail appears as a flat line, the steep slope of $\Phi(E)$ above a few million electron-volts is reduced, and differences between spectra become apparent.

X2.4.3.2 If $\Phi(E)$ has a shape very different from any expected trial function, the operator should examine the Δ_j values (given by the SAND II printout) for spurious values of the $\Delta°_j$ corresponding R_j. Any suspect values of R_j are omitted and the code is run again. At a later stage when the trial function is improved, deleted reactions can sometimes be reinstated.

X2.5 Limitations of the Code

X2.5.1 It is necessary to have a good estimate of the actual source spectrum for use as the final trial spectrum in order for the code to yield good results. However, the manner in which the final trial function is arrived at is not important, and if a satisfactory library trial or calculated trial is not available, then the trial adjustment procedure can yield a very good solution. Sensors sensitive in the thermal, epithermal, and intermediate ranges (^{197}Au, ^{55}Mn, ^{235}U, ^{239}Pu, and ^{237}Np) are needed to define the spectrum normalization and shape at low energy even if the analyst's primary interest is only in the range above 10 keV. Versions of SAND II are available that allow some weighting of response data according to their uncertainties (**21**).

X2.5.2 If the measured sensor responses have a wide range of uncertainties, do not use SAND-II. Use only those reactions that have been demonstrated to yield consistent sets of activities over many spectra and whose cross sections are well established. See Guide E720. There are enough well-established cross sections (together with cadmium-filtered cross sections) to yield satisfactory results. Without a transport calculation neither of the spectrum adjustment methods can estimate the fluences at an energy value where measurements are not sensitive.

X2.5.3 Sensitivity analysis may be used to test how variations in the input data influences the final spectrum. With adequate data, the solution values seldom vary by more than a few percent when derived from perturbed trial functions.

X2.6 Precision and Bias

NOTE X2.3—Measurement uncertainty is described by a precision and bias statement in this standard. Another acceptable approach is to use Type A and B uncertainty components (**22**, **23**). This Type A/B uncertainty specification is now used in International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

X2.6.1 The uncertainties in the solution spectrum calculated with the SAND II code can be attributed to uncertainties in the three basic inputs to the code: the measured foil activities, the activation cross sections, and the trial-input spectrum.

X2.6.2 Comparisons of SAND II calculated spectra have been made to proton-recoil spectrometer data and to neutron transport calculations (**21**). These studies indicate that the uncertainty in the SAND II output spectra is in the range from ±5 to 25 % (one standard deviation) depending on the energy and the quality of response coverage.

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