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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 ~~neutron sources~~ 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 ~~data that is~~ available data and relevant for the environment being ~~investigated. For example, the data available from power reactor and research reactor tests are expected to be different, and the most effective spectrum adjustment methodology may also differ for each case.~~ investigated.

1.3 This guide is to be used in conjunction with Guide E 720 to characterize neutron spectra.

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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:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[3]
E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra by Radioactivation Techniques[3]
E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques[3]
E 263 Test Method for Measuring Fast–Neutron Reaction Rates by Radioactivation of Iron[3]
E 264 Test Method for Determining Fast-Neutron Reaction Rates by Radioactivation of Nickel[3]
E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32[3]
E 266 Test Method for Determining Fast-Neutron Reaction Rates by Radioactivation of Aluminum[3]
E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters[3]
E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238[3]
E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237[3]
E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics[3]
E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics[3]
E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E706 (IIC)[3]
E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)[3]
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[3]
E 1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacements Damage Monitors[3]

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. ~~For activation reactions this would be the decay corrected activity.~~ The response is an integral parameter. Mathematically, the response, $R = \Sigma_i R_i$, 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 $f_i = R_i/\Phi(E_i)\Delta E_i$. ~~For example, if R_i is the induced activity within ΔE_i, then f_i is proportionate to the differential reaction cross section, $\sigma(E_i)$.~~ .

3.1.4 *sensor*—an object or material (sensitive to neutrons) whose response 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 ~~(such as calculated activities)~~ agree more closely ~~to~~ 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:* ~~*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 ~~Shielding~~ Safety Information Computation Center (at Oak Ridge National Laboratory).

[2] The boldface numbers in parentheses refer to the list of references at the end of this guide.
[3] *Annual Book of ASTM Standards*, Vol 12.02.

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, in the most general way,~~ relate radiation effects with device performance degradation.

~~4.2 Since it is necessary to ensure that a satisfactory knowledge of the neutron spectrum is available for each test environment, this~~

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 which will provide the most accurate spectrum is obtained. Th~~i~~ese data ~~may~~ include ~~portions of~~ the following ~~categories:~~ : (*1*) measured responses such as the activities of ~~the~~ foils exposed in the environment ~~to be characterized,~~ and their uncertainties, (*2*) response functions such as reaction cross sections along with appropriate correlations and uncertainties, (*3*) ~~knowledge of~~ 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. It is the accuracy, availability, quality, and cost of the data which determines the most efficient methodology to be used in determining the spectrum.~~ 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) whose responses adequately define (as a set) the ~~spectrum~~ fluence values ~~where~~ at energies to which the device that will 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. ~~It is important that as many response functions as are feasible be used, in order to minimize the uncertainties in the resulting spectrum as much as possible. This~~ The foil set ~~should~~ may include ~~even~~ the use of responses with thresholds outside ~~of~~ 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 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. In this case two options are available. First, seek other sensors to fill the gap (such as silicon devices sensitive to displacement effects (see ~~No~~ Test Method E 1855)), ^{93}Nb(n,n')^{93m}Nb (see Test Method E 1297) or ^{103}Rh(n,n')^{103m}Rh. ~~See, for example, Method E 1297.~~ 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 ~~forward and adjoint~~ transport calculations to generate a ~~trial function~~ 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.

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 the counting sensitivity above background?

5.1.4 Once the experimental opportunities and constraints are understood and dealt with to optimize the experimental design and 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 ~~has~~ 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 ~~reasonable smoothness and~~ positive ~~definite~~ values. 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.

This equation is also discussed in Guide E 720. The 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.

5.2.2 Neutron spectra generated from sensor response data ~~are presently~~ may be obtained with either of two types of spectrum adjustment code. One type is the iterative method; an example of which is the SAND II approach **(2)**. The second is the method of least squares used by codes such as LSL-M2 **(3)**. ~~Both approaches have complementary strengths and weaknesses, and it is recommended that researchers acquire the ability to use both techniques to ensure that the most reliable results are obtained.~~ If used properly and with sufficient, high-quality data, the two methods will usually yield nearly the same values for the primary integral parameters (±10 to 15 %).

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. If a choice must be made, then the analyst must understand how the character of the experiment being conducted and the required results influence the choice the analyst should make.~~ LSL-M2.

5.3 *Iterative Code Characteristics*:

5.3.1 The so-called "iterative" code~~s~~ uses a trial function supplied by the analyst and integrates 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. ~~A 640 energy group (in~~ See Guide E 1018 for ~~the SAND II format)~~ **(2)** cross-section library **(4)** based on ENDF/B-V data has been ~~recommended in the community standard. Now new cross-section response functions, from ENDF/B-VI~~ **(5)**, ~~have replaced~~ selection of dosimetry-quality cross sections. Available dosimetry-quality cross section libraries ~~the ENDF/B-V evaluation. The IRDF-90 dosimetry~~ International Reactor Dosimetry File (IRDF-90 release 2) cross section library ~~incorporates many~~ (6), release 6 of the ~~early release~~ ENDF/B-VI ~~materials~~ (4, 5) cross section library and ~~supplants this data with~~ the ~~best~~ SNLRML package (20) which is available ~~cross sections for reactions with specific importance to neutron dosimetry.~~ through RSICC.

5.3.2 The code ~~then~~ compares the measured and calculated responses for each effect and invokes an algorithm designed to alter the trial function so as to reduce the ~~standard deviation of~~ 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. The SAND II-type code will alter the trial with each iteration most rapidly where the foil set has the highest response. If the trial is incompatible with the measurements, the spectrum can become ~~severely~~ 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. ~~It is unlikely that a real, thin foil will actually modify the spectrum by that amount, but SAND II cannot discern whether this is real or not.~~ The ~~power of the iterative process comes in the next crucial step. 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. ~~In fact, he will want to use a~~ A new trial drawn smoothly near the spectrum values where the sensor set has high response may improve the solution. ~~H~~ This direct modification becomes ~~a part of~~ 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.

5.3.4 ~~T~~Good data are the key to success for the iterative ~~process is the phrase "good data."~~ process. Good data ~~in this section~~ comprises ~~only~~ three elements: (*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 3—The reference to not using data with large uncertainties in the "final" stages of the spectrum determinations is intended to indicate that uncertain data can be very useful in the early stages in the 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 spectrum these "bad" reactions should not be used with an iterative method that does not incorporate uncertainty data.

5.4 *Suitability of the Iterative Adjustment Codes*:

~~5.4.1 The characteristics of the iterative codes described in 5.3 indicate that they are most useful in transient radiation effects on electronics, TREE, testing environments. These can exhibit very diverse characteristics. These environments tend to exhibit relatively short radiation periods that permit use of many reactions (15 to 25) some of which have relatively short half-lives. Furthermore, the possibility that the experimenter may have to contend with many and complicated environments, each of which must be characterized, may mean that extensive transport calculations cannot be made, either because of the expense or because the details of all the relevant materials or dimensions in the environment are not known. In this case it can be very advantageous to be able to start with a convenient and available trial function. It should be pointed out that one cannot extrapolate a measured spectrum to that of another location without a transport calculation.~~

~~5.4.2 The characteristic of iterative codes that only response and standardized response-function data are required may be of advantage for interlaboratory comparisons because no detailed information about the environments need be exchanged.~~

~~5.4.3 SAND~~

5.4.1 SAND II in its usual form does not have a capability to weight the responses according to uncertainties, it does not provide error or uncertainty analysis, and it does not use variance or covariance ~~information as discussed in the last paragraph.~~ information. However, it is possible to assign errors in the spectrum in appropriate energy regions by making use of 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 ~~the uncertainties as discussed in 4.1.2 makes~~ physical arguments based on the energy-dependence of cross se~~,~~ctions but it is difficult to justify mathematically. This situation further supports the arguments for maximizing response coverage. In addition, it is ~~generally~~ usually the uncertainties of integral parameters that are of primary importance, not the uncertainty of $\Phi(E)$ at individual energy values.

5.4.~~4~~2 Covers are used over many of the foils to restrict the response ranges, as is explained in Guide E 720. The SAND II code ~~in particular~~ 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 ~~sufficient~~ accurate because of scattering. See Guide E 720.

5.5 *Least-Squares Code Characteristics*:

5.5.1 The least-squares-~~type~~ codes, represented by LSL-M2 **(3)** ~~uses four data sets besides the activity and cross-section sets required by SAND II. These are the trial function and the~~ use variance and covariance data for the ~~first three sets mentioned already. Although far more information is required, much more information may be returned provided all of these data sets are properly represented.~~ measured responses, response functions, and prior spectrum. The LSL-M2 code finds a unique solution spectrum which is the most likely solution in the least-squares sense using all the available information. The code, therefore, allows not only the ~~trial~~ prior spectrum but also the ~~activities~~ responses and the ~~c~~ respons~~s se~~ functions to ~~vary~~ be adjusted in a manner constrained by their individual uncertainties and correlations in order to find that most likely solution. In principle this approach ~~is certainly~~ provides the ~~proper way to determine~~ best estimate of a spectrum and its uncertainties, but ~~as with the iterative approach~~ some practical difficulties remain. The least-squares method is described more fully in Guide E 944 and in Appendix X2.

~~5.5.2 Not all the~~

5.5.2 The variance and covariance matrix quantities are not always well determined and some may have to be estimated. The analyst must then deal with the fact that his estimates of these quantities can affect ~~his~~ the results.

5.5.3 No least-squares code in the form distributed by code libraries ~~presently~~ conveniently handles the effects of covers over the foils even though the use of covers is strongly recommended. See X2.5.1.

5.5.4 The code automatically weights the data according to uncertainties. Therefore, data with large uncertainties can be used in the analysis, but will have a weak influence on the results.

5.5.5 The trial spectrum shape must correspond fairly well to the final spectrum (within 1 or 2 standard deviations) if the results are to be reliable **(9)**. Experience with this method has shown that the trial spectrum can drive the spectrum determination when its uncertainties are small. See Ref **3**.

~~5.5.6 The fact that~~

5.5.6 If a transport code prediction of the spectrum is ~~usually required implies that~~ used, then this methodology is useful for finding spectra at a different location than that in which the foils were exposed. If the LSL-M2 run verifies the trial (by altering it only a minor amount), then the spectrum might be satisfactorily calculated in a nearby or related environment.

5.5.7 The analyst must be careful that the input variances and covariances, including those associated with the ~~trial function~~ 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).

5.6 *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 reasonable trial spectrum can be generated and in which the activity is limited to a few foils (<10). All available information must then be used. The ~~LSL-M2~~ use of transport code ~~was~~ generated prior spectra in ~~fact designed for~~ least-squares codes has the ~~reactor pressure vessel surveillance program~~ problem of obtaining a mathematically defensible covariance matrix for the prior spectrum which ~~long exposures at low-irradiation levels often exclude~~ is not correlated (in an unknown way) with the input responses. In principle, a sensitivity analysis based of~~n~~ the ~~many reactions available~~ radiation transport code methodology could be used to ~~pulsed or high-fluence reactors. (The use of transport-code-generated-trial functions may~~ provide the prior spectrum uncertainty and energy-dependent correlation, but this is not ~~be justified if a multitude of configurations must be considered.)~~ an easy analysis and is seldom attempted.

6. Discussion and Comparison of Methology Characteristics

6.1 As mentioned in 5.5.1, in principle the least-squares method is superior because it should be able to directly incorporate all that is known about the test environment and about the response functions to arrive at the most likely solution. The iterative codes do not propagate uncertainties nor make use of variance or covariance information.

6.2 Considerable experience with both approaches has demonstrated that they yield approximately the same integral parameter values provided that adequate and accurate primary experimental information is available. Specifically this means the analyst must have access to a set of carefully measured responses covering a broad range of energies with effects whose response functions are well established over these energy ranges.

~~6.3 In comparing the two techniques as they are presently developed, the analyst must keep in mind that the~~

6.3 Transient radiation ~~environments encountered and the experimental information required may be the determining elements in the experiment design and in the methodologies to be used in the data reduction and analysis. If one is interested in the long-term radiation response of materials, as is the case in the field of pressure vessel surveillance, then the primary objective may be to characterize only a few configurations. The exposure times for sensors may also be so long that only a limited number of long half-half activation foils can be used. In this situation it may be best to accept fewer response functions in exchange for an accurate calculated trial function and the use of the full variance and covariance information that can presumably be acquired for use with the least-square codes. On short time scales, however, many more appropriate reactions are available to cover the full range of interest. An iterative code can efficiently provide satisfactory spectra without biasing by a potentially erroneous trial function and without requiring the detailed knowledge needed for a transport code calculation.~~

~~6.4 Transient radiation~~ effects on electronics 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 timeconsuming and expensive. In fact, the user may not even know just what the total assemblage of material structure that affects the radiation environment is.

6.~~5~~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 final standard deviation 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, ~~poor data requires~~ a very good trial function~~, a~~ 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. In these cases then,~~ trial because less use ~~is~~ should be made of the measured data.

6.~~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.~~7~~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. ~~At~~ Available versions of the ~~present time the iterative technique requires much less expertise in or knowledge about the environment than the least-squares methodology. However,~~ SAND II code provides less subsidiary information than least-squares codes can ~~now~~ supply, particularly with regards to uncertainties. More detailed discussions of the SAND II and LSL-M2 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 SAND II CODE

X1.1 Summary of the Iterative Method, SAND II

X1.1.1 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 **10,11**. This code employs a mild perturbation method that reduces the formation of spurious structure in the output energy spectrum. ~~In the traditional procedure the~~ 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 ~~from the code~~ that are consistent with the trial spectrum. The code adjusts the trial spectrum to ~~minimize~~ 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 ~~response data~~ responses and ~~that~~ those calculated from the solution energy spectrum. A course of action to take in cases when the solution is unsatisfactory is suggested in X1.2.2 and X1.2.5.

X1.2 Operational Characteristics of the Code

X1.2.1 The measured responses determined for a set of sensors are related to the incident neutron energy-fluence spectrum, $\Phi(E)$, by Eq 1.

X1.2.2 The unknown incident spectrum $\Phi(E)$ is approximated by a trial spectrum. The ~~$\Phi_t(E)$ in Eq 1 and the SAND II~~ code ~~is run for the set of measured responses, R_j. The code~~ calculates the various resultant trial responses, ~~R~~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 satisfactory library is provided in Ref* ~~(5)~~**()**. *See Note 1. 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 E 720. 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.*

X1.2.3 The fractional differences between the measured activities and the trial activities are calculated by the code. They are given as follows:

$$\Delta_{j0} = \frac{R_j - r_{jt}}{r_{jt}} \tag{X1.1}$$

The standard deviation, S_0 of the set of $\Delta_{\chi 0}$ values, also is determined. Here the subscript zero indicates the first run of the code and r_{jt} is the ~~measured~~ calculated value.

X1.2.4 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 ~~above the threshold energies E_{jt} for~~ in which the corresponding ~~Δ~~ values of $^\circ_{j0}$s are ~~large.~~ 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 $[\Phi_1(E),\{\Delta_{11}, \ldots \Delta_{n1}\}, S_1] \ldots [\Phi_k, \{\Delta_{1k}, \ldots \Delta_{nk}\}, S_k]$ where $S_k \leq 5$ % (or whatever value is chosen).

X1.2.5 The procedure of adjusting the trial often leads to a very 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 references **(1), (8), (12)**, and **(13)**.

X1.2.6 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 ~~type~~ 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 effect 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 E 722 about integral parameters.

X1.2.7 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.

X1.2.8 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.

X1.3 Constraints on Use of the Code

X1.3.1 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 X1.2.5.

X1.3.2 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 is spurious. The operator should examine the set of disparities, Δ_j, $(1 \leq j \leq n)$, 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 ~~such as transcription or incorrect input information supplied to the gamma-ray spectrum analysis code used in the counting laboratory~~ 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 X1.1—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.

X1.3.3 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.

X1.4 Operating Procedures for the Code

X1.4.1 *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 or is obviously incompatible because SAND II does not weight data according to its expected accuracy.~~ 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.

X1.4.2 *Choice of a Trial Spectrum $\Phi_t(E)$*:

X1.4.2.1 Although not absolutely necessary, it is preferable for the trial spectrum to be close to the real spectrum. ~~When the code does not have to alter the trial very much, time taken to modify the trial and interpret what the solution indicates is a better trial is significantly reduced, and the efficiency of choosing a better trial is also improved.~~ On the other ~~hand a state of unnecessarily diminishing economic returns~~ hand, unnecessary cost can be ~~reached~~ incurred by attempting very detailed calculations to predict the spectrum as closely as possible. The most reliable trial will ~~most~~ 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:

X1.4.2.2 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.

X1.4.2.3 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, ~~fit~~ 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 X1.2—The slowing down of neutrons in water gives a $1/E$ fluence from about 1 eV to 100 keV. Because the moderator produces this $\sim 1/E$ behavior, this weighting function is ~~traditionally~~ used for calculating integrals for the resonance reaction region.

X1.4.2.4 In another example, ~~fit~~ 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.

X1.4.2.5 The experimenter should be aware that if the measurements are made behind a boron shield, the ~~1/E~~ 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.

X1.4.2.6 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 ~~adjust~~ 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.

X1.4.3 *Criteria for an Acceptable Spectrum Solution*:

X1.4.3.1 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 ~~(approximately~~ (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 $E\Phi(E)$ and versus energy. In this way, ~~the~~ a $1/E$ low-energy tail appears as a flat line, the steep slope of $\Phi(E)$ above a few million electronvolts is reduced, and differences between ~~the~~ spectra become ~~more~~ apparent.

X1.4.3.2 If $\Phi(E)$ has a shape very different from any ~~reasonable~~ expected trial function, the operator should examine the Δ_j values (given by the SAND II printout) for spurious values of ~~Δ~~ the $^\circ_j$ ~~and corresponding values of~~corresponding R_j. Any ~~spurious~~ 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.

X1.5 Limitations of the Code

~~X1.5.1 Because SAND II~~

X1.5.1 It is ~~a mild perturbation technique and because the response data below 1 MeV is often limited, it is necessary~~ necessary to have a ~~final~~ good estimate of the actual source spectrum for use as the ~~trial-input~~ 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. ~~Again, the limitation is the need for good response over all energies. Specifically, sensors~~ 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 **(14)**.

X1.5.2 If the measured sensor responses have a wide range of uncertainties, then ~~an adjustment code should be used that accounts for the uncertainty of each response used as input to the code (see Practice E 944). An alternative is to~~ do not use SAND-III. 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 E 720. 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 ~~predict~~ estimate the fluences at an energy value where measurements ~~cannot be made.~~

~~X1.5.3 Since SAND II does~~ are not ~~propagate errors from the trial, cross sections or response measurements to provide error bands in the spectrum values, the only recourse is to use sensitivity~~ sensitive.

X1.5.3 Sensitivity analysis may be used to test ~~for~~ how ~~much reasonable~~ variations in the ~~primary~~ input data influences the final spectrum. With adequate data, the ~~parameter~~ solution values seldom ~~differ~~ vary by more than a few percent when derived from perturbed trial ~~r~~ functions.

X1.6 Precision and Bias

NOTE X1.3—Note 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[**18, 19**]. 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.

X1.6.1 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.

X1.6.2 Comparisons of SAND II calculated spectra have been made to proton-recoil spectrometer data and to neutron transport calculations **(14)**. These studies indicate that the uncertainty in the SAND II ~~desired~~ output spectra is in the range from ±5 to 25 % (one standard deviation) depending on the energy. ~~Adequate responses can almost always be obtained in fluences >10^{13} neutrons/cm^2 which can be accumulated in less than one hour.~~

X2. APPLICATION OF THE LSL-M2 CODE

X2.1 The Least-Squares Method, LSL-M2

~~X2.1.1 It is the purpose of this~~

X2.1.1 This appendix ~~to~~ provides guidance for the application of the LSL-M2 adjustment code to hardness testing of electronic devices. The code is described in Refs and **16**. 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.

X2.2 Introduction

X2.2.1 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 E 720 for guidance on foil selection), (2) energy-response functions, and (3) an approximation to the solution.

X2.2.2 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 (Guide E 944). ~~Thus, these codes require significantly more data than the older codes. This~~ These additional data ~~is~~ are used to establish uncertainty estimates on the output ~~data. The inability to quantify the uncertainties in the output~~ data.

X2.2.3 The LSL-M2 code **[27]**is one example of ~~codes such as SAND II is a serious deficiency of them.~~

~~X2.2.3 Not until the release of the LSL-M2~~ least square code package ~~has~~ which is distributed with a suitable set of auxiliary data (cross sections and covariance files) to permit its application ~~b~~ for the adjustment of reactor pressure vessel neutron spectra. As part of the REAL exercises **[21, 22, 23]**the International Atomic Energy Agency (IAEA) compiled and distributed ~~with a least-squares code. The LSL-M2 code package is~~ Neutron Metrology File NMF-90 **[24]**which includes versions of the ~~first to contain a dosimetry~~ MIEKE **[25]**and STAY'SL **[26]**least square adjustment codes along with compatible cross ~~section (ENDF/B-V)~~ 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 ~~a covariance matrix for each reaction~~ suitable cross section ~~in the set.~~

~~X2.2.4 Historically, an~~ libraries.

X2.2.4 An adequate ~~trial~~ prior or theoretical prediction ~~for~~ of the ~~exposure conditions~~ fluence spectrum (with its covariance matrix) ~~has been~~ is often the most difficult information set to ~~obtain for determining the neutron spectrum from response data.~~ obtain. If a transport calculation is ~~available at all,~~ available, it ~~is likely to~~ may be a generic type of run such as a leakage spectrum from the reactor or a criticality calculation that ~~happens to provide output which gives a" typical"~~ provides typical spectrum ~~at~~ for some ~~location. The person testing the electronics device has neither the expertise nor the funds available from the project to obtain a calculation suitable for the application of the LSL-M2 code as described in its accompanying documentation.~~ location.

X2.2.5 An error estimate of the group-wise fluences, with correlations, is essential to LSL-M2, but is not always readily available to the analyst. ~~While the~~ 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 X2.4.

X2.3 Constraints on the Use of the Code

X2.3.1 The LSL-M2 code is distinguished ~~from the other least-squares types of codes~~ by its use of lognormal distributhmsions 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 E 944 are all logarithmic. As stated in the manual, care should be taken to input uncertainties as *ln* (observed/actual) (see Note 3). In the same fashion, the output uncertainties are actually logarithmic ratios. ~~Unlike SAND II, the~~ The primary output of LSL-M2 is not the adjusted spectrum, but rather ~~LSL-M2 has been optimized to provide~~ the damage-related integral parameters with their errors. This feature is ideally suited to the calculation of silicon damage as defined in Practice E 722.

NOTE X2.1—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 nonlogarithmic ~~ratio in an ever-increasing manner.~~

~~X2.3.1.1 The dosimetry~~ ratio.

X2.3.1.1 Dosimetry cross-section set and ~~their~~ associated covariance matrices are available with the LSL-M2 code package. ~~If a different set is used, the user should make certain that these data are~~ The cross sections distributed by RSICC with this code have been derived from ENDF/B-V ~~or later~~ evaluations ~~**4-6**.~~ [27].

X2.3.1.2 The response data is obtained through the application of Guides E 720 and E 844, Practice E 261 and Test Methods E 262, E 263, E 264, E 265, E 393, E 704, and E 705. The uncertainty estimate for each response ~~function~~ should not be simply an estimate of the counting uncertainty, but rather should be an estimate of the total uncertainty for that reaction. Correlations between reactions ~~are normally considered to~~ may be ~~z~~ important, particularly when the radioactive product is measured.

X2.3.1.3 The code requires a prior fluence or fluence-rate spectrum ~~from a transport code~~ and an estimate of ~~the~~ its uncertainties with correlations. The better the quality of the ~~calculation,~~ prior, the better the quality of the results from LSL-M2. There is no ideal substitute for ~~the~~ 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 may be followed).

X2.4 Operation of the Code

X2.4.1 The ~~general~~ 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.

X2.4.2 If a covariance analysis, such as described by Maerker **(16)** ~~and used as the test case distributed with the LSL-M2 code,~~ 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.

X2.4.3 Section 5.3 of Guide E 944 describes the general principles for constructing usable covariance matrices for fluence spectra when a full sensitivity analysis is not available. Experience has shown that this type of procedure produces acceptable results **(9, 10)**. For the purposes of hardness testing, the following formula is suggested:

$$c_{ik} = \exp\left(- \frac{\text{abs}[ln(E_i) - ln(E_k)]}{A} \right) \quad \text{(X2.1)}$$

X2.4.4 If Eq X2.1 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 X2.1, *A* is a measure of how closely correlated are spectrum values at energies E_i and E_k. It is not 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.

X2.4.4.1 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 **9**.

X2.4.5 The uncertainties assigned to each group ~~are perhaps the hardest to determine in an absolute fashion, yet these uncertainties will~~ 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.

~~X2.4.6 In general, very~~

X2.4.6 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 and should be avoided.~~ case. This solution spectrum ~~will also~~ should produce a very low value for the χ^2 per degree of freedom ~~since the overall error estimates are severely overestimated.~~ . 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.

X2.4.7 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 ~~will~~ may be unrealistically low. This is the other limiting case.

X2.4.8 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, unless it can be shown in a particular case that these uncertainties are insensitive to the uncertainties of the ~~group~~ prior fluences.

~~X2.4.9 Because the~~

X2.4.9 The LSL-M2 code ~~presumes that a transport calculation will be performed for the irradiation conditions, the LSL-M2 code was designed for and the~~ documentation recommends that the prior fluence values be normalized in an absolute fashion. ~~In the documentation, the use of one of the reactions to normalize the spectrum is discouraged.~~ However, if a ~~generic-type~~ 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 ~~specifically~~ for the specific

irradiation conditions is absolute normalization of the fluence spectrum justified.

X2.4.10 As in all adjustment codes, bad response data will invalidate the results. Since bad response data ~~is~~ 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 obtained. Further, if there is a known systematic uncertainty in the response data, suspect responses should not be included in the analysis. ~~Assigning an appropriately higher uncertainty to that response will not produce acceptable results since one of the underlying assumptions in the mathematical development is that all the errors in the data are random.~~ If there is a known but unquantified 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.

X2.4.11 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. The value obtained for χ^2 should be reported in all cases.

X2.5 Deficiencies of the Code

X2.5.1 *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. Since there are compelling reasons for the use of covers for certain sensors as described in Guide E 720, this shortcoming of the code should be addressed in a future release of the code. Until then, it is the responsibility of the person performing the LSL-M2 analysis to properly adjust the sensor response function for attenuation of the fluence spectrum by the cover. This can conveniently be performed after the response function has been collapsed with the FLXPRO subroutine to the group structure to be used in the analysis. An effective response function can be estimated in accordance with the following equation:

$$\sigma'_j(E_i) = \sigma_j(E_i) \times \exp[-N\sigma_c(E_i)X] \tag{X2.2}$$

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 X2.2—As described in Guide E 720, 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.

~~X2.5.2 As is often the case, this will lead to~~

X2.5.2 Each reaction may require several response ~~functions for the same reaction,~~ functions, each differing from the others by the cover assumed in the calculation, and by the cover thickness assumed. ~~While this is not the best of circumstances in that keeping track of which cross section corresponds to what cover thickness, it does produce usable results.~~ This method ~~ignores, however,~~ ignores the ~~issue of the~~ effect of the cover adjustment on the covariance ~~matrix and~~ for the ~~resulting reaction cross section.~~ response function.

X2.6 Precision and Bias

X2.6.1 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.

X2.6.2 In the more common case where Eq X2.1 was used to generate the covariance matrix and the group-wise fluence, uncertainties were not established by methods similar to those employed in Ref **(16)**, 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.

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