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

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

1. Scope

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

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

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

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.

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[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.

3.1.2 *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, $R = \Sigma_i R_i$, 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 $f_i = R_i/\Phi(E_i)\Delta E_i$.

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 agree more closely with their measured values. Other physical constraints on the spectrum may be applied.

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

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

3.2 *Abbreviations:*

3.2.1 *DUT*—device under test.

3.2.2 ENDF—evaluated nuclear data file.

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

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

3.2.5 *TREE*—transient radiation effects on electronics.

4. Significance and Use

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

4.2 This guide describes the factors which must be considered when the spectrum adjustment methodology is chosen and implemented. Although the selection of sensors (foils) and the determination of responses (activities) is discussed in Guide E 720, the experiment should not be divorced from the analysis. In fact, it is advantageous for the analyst conducting the spectrum determination to be closely involved with the design of the experiment to ensure that the data which will provide the most accurate spectrum is obtained. 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) whose responses adequately define (as a set) the fluence values 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. The foil set may include the use of responses with thresholds 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 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 Test Method E 1855)), ^{93}Nb$(n,n')^{93m}$Nb (see Test Method E 1297) or ^{103}Rh$(n,n')^{103m}$Rh. Second, devote the necessary resources to determine a trial function that is close to the real spectrum. In the latter case it may be necessary to carry out transport calculations to generate a prior spectrum which incorporates the use of uncertainty and covariance information.

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

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

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

5.1.3.3 Can the sensors be placed so as to ensure equal exposure? This may require mounting the sensors on a rotating fixture in steady-state irradiations.

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 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 positive 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 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)**. 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.

5.3 *Iterative Code Characteristics*:

5.3.1 The so-called "iterative" codes 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. See Guide E 1018 for the recommendations in the selection of dosimetry-quality cross sections. Available dosimetry-quality cross section libraries the International Reactor Dosimetry File (IRDF-90 release 2) cross section library (6), release 6 of the ENDF/B-VI (4, 5) cross section library and the SNLRML package (20) which is available through RSICC.

5.3.2 The code compares the measured and calculated responses for each effect and invokes an algorithm designed to alter the trial function so as to reduce the deviations between the measured and calculated responses. The process is repeated with code-altered spectra until the standard deviation drops below a specified value—at which time the code declares that a solution has been obtained and prepares a table of the last spectrum. This should not be the end of the process unless the initial trial was very close to the final result. 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 distorted in a very unphysical manner.

5.3.3 For example, if a trial function predicts an incorrect gold activity, it may alter the spectrum by orders of magnitude at the gold high-response resonance at 5 eV while leaving the trial spectrum alone in the immediate vicinity. The analyst must recognize that the trial must be changed in a manner suggested by the previous result. For example, if a peak develops at the gold resonance, this suggests that the trial spectrum values are too low in that whole energy region. A new trial drawn smoothly near the spectrum values where the sensor set has high response may improve the solution. This direct modification becomes an outer iteration on the spectrum adjustment process, as described in Refs **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 Good data are the key to success for the iterative process. Good data comprises 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 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. 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 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.

5.4.2 Covers are used over many of the foils to restrict the response ranges, as is explained in Guide E 720. The SAND II code 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. See Guide E 720.

5.5 *Least-Squares Code Characteristics*:

5.5.1 The least-squares- codes, represented by LSL-M2 **(3)** use variance and covariance data for the 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 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 that most likely solution. In principle this approach provides the best estimate of a spectrum and its uncertainties, but some practical difficulties remain. The least-squares method is described more fully in Guide E 944 and in Appendix X2.

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 the results.

5.5.3 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 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 If a transport code prediction of the spectrum is 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 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 use of transport code generated prior spectra in least-squares codes has the problem of obtaining a mathematically defensible covariance matrix for the prior spectrum which is not correlated (in an unknown way) with the input responses. 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.

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 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.

6.4 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, 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 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. 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 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 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 satisfactory library is provided in Ref (). 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 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 in which the corresponding values of $^\circ_{j0}$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 $[\Phi_1(E),\{\Delta_{11}, \ldots \Delta_{n1}\}, S_1] \ldots [\Phi_k, \{\Delta_{1k}, \ldots \Delta_{nk}\}, S_k]$ 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 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 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. 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. 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:

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, join the GODIVA