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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-fluence spectra of neutron sources used in radiation-hardness testing of electronic semiconductor devices. The types of 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 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.

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 1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium[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

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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.

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 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.

3.2 *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 *RSIC*—Radiation Shielding Information 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, in the most general way, 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 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. This 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, (*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 spectrum and its uncertainties obtained from a transport calculation or 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.

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 values where the device that will be tested is sensitive. For silicon devices in fission-driven environments the significant 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 set should include even the use of responses with thresholds outside of the 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 Note 1)), $^{93}Nb(n,n')^{93m}Nb$ 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 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 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 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.

5.3 *Iterative Code Characteristics*:

5.3.1 The so-called "iterative" code 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 the SAND II format) **(2)** cross-section library **(4)** based on ENDF/B-V data has been the community standard. Now new cross-section response functions, from ENDF/B-VI **(5)**, have replaced the ENDF/B-V evaluation. The IRDF-90 dosimetry library incorporates many of the early release ENDF/B-VI materials and supplants this data with the best available cross sections for reactions with specific importance to neutron dosimetry.

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 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 new trial drawn smoothly near the spectrum values where the sensor set has high response. His 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 The key to success for the iterative process is the phrase "good data." 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 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. 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 with the uncertainties as discussed in 4.1.2 makes physical sense, but it is difficult to justify mathematically. This situation further supports the arguments for maximizing response coverage. In addition it is generally the uncertainties of integral parameters that are of primary importance, not the uncertainty of $\Phi(E)$ at individual energy values.

5.4.4 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 because of scattering. See Guide E 720.

5.5 *Least-Squares Code Characteristics*:

5.5.1 The least-squares-type code, 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 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. 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 but also the activities and the cross sections to vary in a manner constrained by their individual uncertainties and correlations in order to find that most likely solution. In principle this approach is certainly the proper way to determine 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 variance and covariance matrix quantities are well determined and some have to be estimated. The analyst must then deal with the fact that his estimates of these quantities affect his results.

5.5.3 No least-squares code in the form distributed by code libraries presently 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.

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. See Ref **3**.

5.5.6 The fact that a transport code prediction of the spectrum is usually required implies that 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 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 code was in fact designed for the reactor pressure vessel surveillance program for which long exposures at low-irradiation levels often exclude the use of the many reactions available to pulsed or

high-fluence reactors. (The use of transport-code-generated-trial functions may not be justified if a multitude of configurations must be considered.)

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 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 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, and the solution cannot be allowed to deviate very much from the trial. In these cases then, less use is made of the measured data.

6.6 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 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 the present time the iterative technique requires much less expertise in or knowledge about the environment than the least-squares methodology. However, SAND II 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 measured responses of the sensor set, along with 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 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 and that calculated from the

solution energy spectrum. A course of action to take in cases when the solution is unsatisfactory is suggested inX1.2.2 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_{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 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 which the corresponding Δ_{j0}s are large. 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 $[\Phi_1(E), \{\Delta_{11}, ... \Delta_{n1}\}, S_1]$ ... $[\Phi_k, \{\Delta_{1k}, ... \Delta_{nk}\}, S_k]$ 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