Designation: E 1855 – 04

Standard Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors[1]

This standard is issued under the fixed designation E 1855; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the use of 2N2222A silicon bipolar transistors as dosimetry sensors in the determination of neutron energy spectra, and as silicon 1-MeV equivalent displacement damage fluence monitors.

1.2 The neutron displacement damage is especially valuable as a spectrum sensor in the range 0.1 to 2.0 MeV when fission foils are not available. It has been applied in the fluence range between 2 × 10 12 n/cm^2 and 1×10^{14} n/cm^2 and should be useful up to 1015 n/cm^2. This test method details the steps for the acquisition and use of silicon 1-MeV equivalent fluence information (in a manner similar to the use of activation foil data) for the determination of neutron spectra.

1.3 In addition, this sensor can provide important confirmation of neutron spectra determined with other sensors, and yields a direct measurement of the silicon 1-MeV fluence by the transfer technique.

1.4 *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 requirements prior to use.*

2. Referenced Documents

2.1 The ASTM standards listed in 2.2 from Terminology E 170 through Test Method E 265 provide a background for understanding how sensors are used in radiation measurements and general dosimetry. The rest of the standards referenced in the list discuss the choice of sensors, spectrum determinations with sensor data, and the prediction of neutron displacement damage in some semiconductor devices, particularly silicon.

2.2 *ASTM Standards:* [2]

E 170 Terminology Relating to Radiation Measurements and Dosimetry

E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra Radioactivation Techniques

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32

E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics

E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics

E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E706 (IIC)

E 854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance, E706 (IIIB)

E 944 Practice for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)

E 1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts

E 2005 Guide for the Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields

3. Terminology

3.1 *Symbols:*

Φ_1 = the silicon 1-MeV equivalent fluence (see Practice E 722).

$h_{FE} = i_c/i_b$ where i_c is the collector current and i_b is base current, in a common emitter circuit.

4. Summary of Test Method

4.1 Gain degradation of 2N2222A silicon bipolar transistors measured in the test (simulation) environment is compared with that measured in a reference neutron environment. The Φ_{1r} in the reference environment is derived from the known

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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

reference spectrum and is used to determine a measured Φ_{1t} in the test environment (**1**,**2**)[3] by the transfer technique. The *r* and *t* refer to the reference and test environments respectively.

4.2 The measured Φ_{1t} may be used as a sensor response in a spectrum adjustment code in a manner similar to the use of reaction foil activities to determine the spectrum (**3**,**4**).

4.3 Spectra compatible with the responses of many sensors may be used to calculate a more reliable measure of the displacement damage.

5. Significance and Use

5.1 The neutron spectrum in a test (simulation) environment must be known in order to use a measured device response in the test environment to predict the device performance in an operational environment (see Practice E 1854). Typically, spectra are determined by use of a set of sensors that have response functions that are sensitive over the neutron energy region to which the device under test (DUT) responds (see Guide E 721). In particular, for silicon devices exposed in reactor neutron spectra, this effective energy range is between 0.01 and 10 MeV. A typical set of activation reactions which lack fission reactions from nuclides such as ^{235}U, ^{237}Np, or ^{239}Pu, will have very poor sensitivity to the spectrum between 0.01 and 2 MeV. For a pool-type reactor spectrum, 70 % of the DUT electronic damage response may lie in this range. Often, fission foils are not included in the sensor set for spectrum determinations because their use must be licensed, and they require special handling for health physics considerations. The silicon transistors provide the needed response to define the spectrum in this critical range.

5.2 If fission foils are a part of the sensor set, the silicon sensor provides an important confirmation of the spectrum shape.

5.3 Bipolar transistors, such as type 2N2222A, are inexpensive, are smaller than fission foils contained in a boron ball, and are easy and quick to read provided the proper steps are taken. They also can be used directly in arrays to map 1-MeV equivalent fluence. The proper set of steps to take in reading the transistor-gain degradation is the primary subject of this test method.

5.4 Fig. 1 shows the displacement damage function for silicon. As can be seen from the figure, the major portion of the response for the silicon transistors will generally be above 100 keV. The currently recommended silicon damage function is listed in Practice E 722.

6. Apparatus

6.1 A transistor with demonstrated response in agreement with calculated Φ_1 values in widely varied environments is the silicon bipolar transistor 2N2222A. It is recommended that three or more of these transistors be calibrated together and used at each location to be characterized. At least three others should be used as temperature correction devices (control devices) during readout. The control transistors should be exposed one time to a calibration exposure of about 1.0×10^{13} n/cm^2 1-MeV equivalent fluence and then annealed (baked out) at 180°C for 24 h followed by ambient air cooling before being used as controls. These control transistors are not exposed either during the calibration or test step, but are read with the exposed transistors to provide temperature correction.

6.2 A dry oven for annealing is needed to stabilize the gain after both the calibration-exposure and gain readout are completed for the reference environment. The oven shall be able to maintain the set temperature to within ±3.0°C at 80°C and at 180°C. It would be prudent to have a timer for automatic shutdown and an emergency power system (UPS). Shutdown with a timer will require a door-opening mechanism for ambient air cooling.

6.3 An electronic system is required to maintain appropriate transistor bias and currents and to read the currents for the gain

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[3] The boldface numbers in parentheses refer to a list of references at the end of this test method.

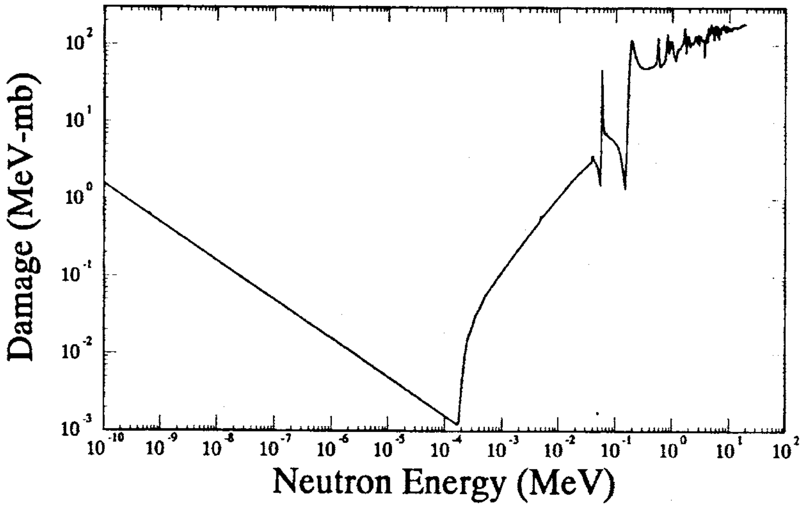

FIG. 1 Silicon Displacement Damage Response Function

measurements. It is recommended that a programmable semiconductor parameter tester (such as a Hewlett Packard 4145A) be used. A programmable tester can operate in pulsed mode to control heating effects and provide gain values quickly. The parameter tester determines the common emitter current gain by injecting a pulse of current into the base region, measuring the collector current, and determining the current ratio i_c/i_b at a fixed bias of 10 V, where i_c is the collector current and i_b is the base current. The bias voltage is measured between the collector and the base (see Ref (**5**)).

6.4 A reference neutron source (see Guide E 2005) for calibration of the transistors is required. The neutron fluence and neutron fluence spectrum of the reference source must be known. National Institute for Standards and Technology (NIST) benchmark fields (**6**) are recommended for use as primary standards, and the Fast Burst Reactors (FBRs) at Sandia National Laboratories, White Sands Missile Range, and Aberdeen Proving Ground also are recommended as reference benchmark fields.

6.5 If the transistors are exposed on a different run than the one used to expose foils for spectrum determination, a suitable monitor such as a nickel foil must be exposed along with the transistors during calibration to relate the magnitude of the neutron fluence during the spectrum determination exposure to that during the transistor calibration exposure (see Section 7). A photon-sensitive (and neutron insensitive) detector such as a CaF_2 thermoluminescent detector (TLD) shall be included in each test package to monitor the gamma-ray dose in case a correction must be made for the transistor damage from gamma-rays.

7. Description of the Test Method

7.1 2N2222A transistors exhibit a range of initial gain values and responses, but each responds linearly with 1-MeV equivalent fluence,Φ_1, at fixed collector current according to the Messenger-Spratt equation (**7**), if gamma rays do not contribute to the change of gain.

$$\frac{1}{h_{FE\Phi}} - \frac{1}{h_{FEO}} = K_\tau \Phi(1\text{ MeV}) \tag{1}$$

The term h_{FEO} is the common emitter current gain at some fixed collector current before irradiation in the test environment, and $h_{FE\Phi}$ is the same quantity measured at the same collector current after irradiation. K_τ is the damage constant. If gamma-ray dose contributes to the change in the reciprocal of the gain, then that contribution must be subtracted from the left side of Eq 1 before the right side is valid for neutrons (see 8.3).

7.2 A semiconductor parameter analyzer may be used to determine h_{FE}. A basic schematic circuit used by semiconductor analyzers for measuring $h_{FE} = i_c/i_b$ is shown in Fig. 2. Any equivalent method for making the electrical measurement is acceptable as long as the currents do not exceed the limits detailed in 8.1.2 and 8.1.3.

7.3 Since K_τ differs for each transistor, each must be calibrated. When the technology of manufacture is such that the K_τ's within a batch are the same to within a few percentage points, a calibration by batch may be satisfactory. A typical value for K_τ is about 1.5×10^{-15} cm^2/neutron for a collector current of 1 mA.

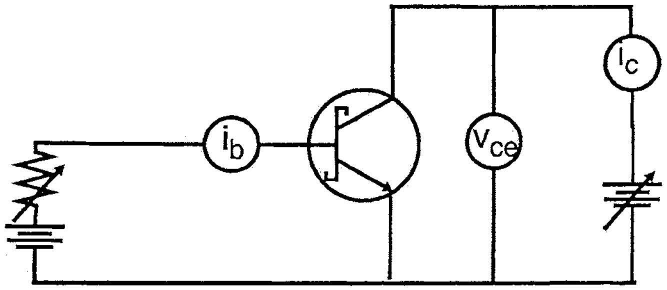

FIG. 2 Schematic for Transistor Read-Out

7.4 The linearity of response of a given batch of transistors shall be verified by exposure of samples of the batch to at least three levels of neutron fluence covering the range in which the devices will be used.

7.5 The calibration is accomplished by exposing the transistors in a reference field for which the absolute values of the neutron fluence spectrum are known over the neutron energy range in which significant damage is caused. The 1-MeV equivalent fluence of the reference environment, Φ_{1r}, is obtained by folding the spectrum with the silicon displacement damage response as is described in Practice E 722. The gain values, h_{FEO} before irradiation, and $h_{FE\Phi}$ after irradiation are measured, and the left side of Eq 1 is calculated. The following quantity can be defined.

$$\Delta\left(\frac{1}{h}\right) = \frac{1}{h_{FE\Phi}} - \frac{1}{h_{FEO}} \tag{2}$$

This is the change in reciprocal gain. A subscript of r is used to denote the reciprocal gain change in the reference calibration environment. A subscript of t is used to denote the reciprocal gain change in the test or unknown environment. This measurement and the known value of Φ_{1r} in the reference environment provide the calibration for the transistor, K_τ.

NOTE 1—As mentioned in 6.5, if the transistors are exposed on a different run than the run for measuring the spectrum, a monitor foil must be included with the transistors. This monitor foil should be the same as one of the sensor set so that a simple ratio of the monitor responses multiplied by the transistor response will provide the proper scaling between the runs. This procedure of using the ratio of activities to scale the fluences is valid because the same spectrum is used for both runs.

7.6 When the $\Delta(1/h)$ is measured in the unknown test environment, the Φ_{1t} can be found in the following manner. Take the ratio of equations (Eq 1) for the reference and test environments and rearrange the terms to yield Eq 3 (see Ref (**3**)).

$$\Phi_{1t} = \frac{\Delta\left(\frac{1}{h}\right)_t}{\Delta\left(\frac{1}{h}\right)_r} \Phi_{1r} = \frac{1}{K_\tau}\Delta\left(\frac{1}{h}\right)_t \tag{3}$$

7.7 The Φ_{1t} is the quantity needed as a sensor value in the spectrum determination procedure. The $\Delta(1/h)_t$ is the change in the reciprocal gain induced by the test environment. For neutron damage on 2N2222A transistors, K_τ is a constant for neutron fluences up to about 10^{15} n/cm^2. The method described here provides a direct determination of Φ_{1t}. Strictly speaking, if Φ_{1t} is the only quantity desired from the test when the transistor is irradiated, then a monitor is not needed. However, it is recommended that a monitor be included for possible scaling and for ensuring that the ratio of responses between the transistors and the monitor remain the same at characterized positions in the neutron field.

8. Experimental Procedure

8.1 To ensure proper calibration of the sensor, follow the steps described in 8.1.1-8.1.9.

8.1.1 *Step 1*—The 2N2222A transistors are inexpensive and can be purchased in large lots from electronic supply houses. Those purchased from readily available commercial sources have been found to be fairly uniform in electrical properties and come with initial gains between about 50 and 200. The first step is to measure, at 1 mA collector current, the initial gain values of all the transistors in the batch. Throw out all those with gain less than 100, and then remove the top and bottom 5 % fractions of the remaining set. Thus, if one begins with 100 transistors there may be two with gains below 100, and after removing 10 % of the remaining distribution, one might end up with about 88 transistors that can be calibrated. If the calibration environment is large enough to provide a uniform fluence to all the transistors on the same run, it is best to calibrate the whole batch together. The minimum number of transistors should be three.

8.1.2 The gain measurements may conveniently be made with a programmable semiconductor parameter analyzer, or with a specially designed circuit tester. The measurement details provided in 8.1.2.1-8.1.2.6 correspond to the steps on an HP 4145A programmable semiconductor parameter analyzer with an HP16058A Test Fixture. Any equivalent method for making the electrical measurement is acceptable as long as the currents do not exceed the limits detailed in 8.1.2 and 8.1.3. The manuals for other parameter analyzers can be used to see how this procedure should be adopted to other equipment.

8.1.2.1 *Setup*—Place the transistor in the test fixture. Note the assignment of leads to the transistor collector, base, and emitter.

8.1.2.2 *Channel Definition*—Use the channel definition screen to assign the variables, V_E/I_E, V_B/I_B, and V_C/I_C, to the nomenclature for the proper lead. The V stands for voltage, I for current, B for base, C for collector, and E for emitter.

8.1.2.3 *Source Setup*—Use the source setup screen to initialize the variable ranges for the measurements and the constraints or compliance rules for the measurements. I_B should be variable with 71 logarithmic steps from 100 pA to 1 mA. The V_B compliance voltage is 10 volts. V_{CE} is set as a fixed parameter of 10 V with a compliance current of 18 mA. I_C is assigned a compliance current of 18 mA.

NOTE 2—The upper bound placed on the base current range will never be reached given a nominal device gain of 100 and a maximum collector current of 1 mA. The nominal maximum base current seen during a measurement is ~0.01 mA. The base current range is set so that it does not prove to be a limiting factor for a properly operating 2N2222A transistor.

8.1.2.4 *Plot*—Set the display variables and ranges. Set the *x*-axis variable to I_C with a logarithmically spaced range from 1 µA to 12 mA. Set the first *y*-axis variable to I_B with a logarithmic range from 100 pA to 15 mA. Set the second *y*-axis variable to h_{FE} with a linear range from 0 to 250. The second *y*-axis appears on the right-hand side of the plot.

8.1.2.5 *Measurement*—Have the analyzer make the measurements initialized in the setup and display the resulting plot. The transistor measurements are automatically made with a 3 ms pulse at each of the defined base current settings. The plot will be displayed with collector current along the bottom axis, base current along the left-hand side, and gain along the right-hand side. A marker (highlighted spot) will appear on the plot. The *x* and *y* values for this highlighted point will appear in a text screen above the plot. No measurements are made for settings that are outside the compliance conditions. Thus for collector currents above 18 mA, both curves drop to zero. The gain curve should be fairly flat except for very low base currents.

8.1.2.6 *Data Extraction*—Use the marker dial to move the pointer along the *x*-axis until the I_C value is 1 mA. A value for I_B and h_{FE} will be displayed on the top of the plot. These values can be verified by looking at the *y*-axis values for the two curves drawn on the plot. Record the h_{FE} gain value.

8.1.3 The measurement procedure detailed in 8.1.2.5 was designed to avoid large currents that would saturate the device or result in current-injection annealing of the radiation-induced damage to the test 2N2222A transistor. Collector currents larger than 1 mA should not be permitted except in a pulsed mode of operation. In pulsed mode, collector currents of up to 20 mA are permitted with pulse widths less than ~4 ms. Collector current measurements of 1 mA may be made in a steady state mode. The measurement procedure detailed in 8.1.2 had 71 logarithmically spaced steps with a maximum collector current of 18 mA. If a different pulsed readout method is used, the amount of time (number of steps multiplied by the pulse time) spent at collector currents greater than 1 mA should not significantly exceed that which results from the described procedure. At collector currents lower than 1 mA the gains are less reproducible and are more sensitive to temperature and gamma-ray background contributions. There are also surface and emitter losses. At higher collector currents, there can be emitter crowding, nonlinearities and heating effects. A standardized sequence and duration of measurement is necessary because of variations of the charge state of traps within the devices, particularly after exposure to ionizing radiation (from sources such as the gamma-ray background).

NOTE 3—Avoid handling the transistors with fingers just before reading, because the warmed transistors will exhibit a higher gain. When reading the gains, intersperse the control transistors with the test transistors and try to maintain uniform temperature throughout the readout process. It is good practice to have all transistors in the same temperature environment for approximately 5 minutes before the device readout begins.

8.1.4 *Step 2*—Separate out at least three transistors to be used as controls for correcting the gain measurements to account for differences in the temperature of the transistors when they are read after each exposure and anneal step of the transistors. The temperature dependence of the gain is expected to be different for unirradiated and irradiated transistors. Therefore the transistors that are to be used to correct the measured gains for the temperature at readout (the control transistors) shall be exposed to a neutron fluence of $\sim 10^{13}$

n/cm^2 and then annealed at 180°C for 24 h followed by ambient air cooling before they are used as controls. From then on the controls should not be exposed or annealed. For example, after the calibration run, the control transistors are read for gain along with the exposed transistors. The temperature correction factor R_c, is computed using:

$$R_c = \frac{1}{n}\sum_{i=1}^{n}\frac{R_i}{C_i} \tag{4}$$

where:

n = number of control transistors,

R_i = transistor gain of the present readout for the ith control transistor, and

C_i = transistor gain of the ith control transistor determined in 8.1.1.

8.1.5 *Step 3*—Expose the sensor transistors uniformly in the reference neutron environment, unbiased and with the leads shorted. It is important that the irradiation be sufficient to degrade the gain by about 30 % or more. For a fast neutron spectrum this means 5×10^{12} n/cm^2 $\leq \Phi_1 \leq 1 \times 10^{14}$ n/cm^2. See Appendix X1 for an explanation of the choice of the lower limit. Include monitor foils such as nickel or sulfur, or both, and TLDs in the irradiation package.

8.1.6 *Step 4*—In order to remove the variations associated with ambient temperature annealing during and after the irradiation, an annealing step at 80°C for two hours shall be performed before readout. This will only be effective in ensuring reproducible results if the environmental conditions during irradiation and subsequent handling do not include exposure at temperatures above 60°C. An additional precaution is to standardize the delay time between irradiation and readout. Annealing at 80°C for two hours removes no more than 20 % of the displacement damage. Under this condition, fading (further annealing) has not been observed. Do not anneal the control transistors once they have been prepared as described in 8.1.4.

8.1.7 *Step 5*—Measure the gains of the controls and sensors under standardized conditions. The environmental temperature during this measurement shall be within 10°C of the pre-irradiation measurement temperature.

8.1.8 *Step 6*—Apply a correction to the post-irradiation gain values for the effect of the difference in temperature between the initial characterization and the present reading. This may be done either by means of a measured temperature coefficient of irradiated transistors that have been annealed (see 8.1.4), or by multiplying the observed gain values by the ratio of the average of the values of the controls, as measured when the sensors were first being read, to their average gain values measured at the same time as the post-irradiation measurement of the sensors as described in 8.1.4.

8.1.9 *Step 7*—Use the monitor foil activity as a normalizing factor and the reference environment spectrum to determine Φ_{1r}, which was experienced during the sensor calibration. The normalization is accomplished by multiplying Φ_1, determined when the spectrum was measured by the ratio of the monitor foil activities in the respective spectrum and calibration exposure. Then calculate K_τ from Eq 1 for each transistor.

8.2 *Determination of the Measured Φ_{1t} in the Test Environment:*

8.2.1 *Step 8*—After the calibration readout and before exposure in the test environment, the transistors shall be given a "hard anneal" to further stabilize and reset the gains before the next exposure. The recommended annealing is 180°C for 24 h. This annealing will heal about 70 % of the damage caused by the latest irradiation so that the sensor can be used in more than one test environment.

8.2.2 *Step 9*—The initial gain, h_{FEO}, to be used in this second application of Messenger's Eq 1 is the gain after the "hard anneal" described in 8.2.1, because it is the new gain change induced by the test environment that we want to determine. Measure the gain of each transistor after the above hard anneal. Make certain that the transistors have had the opportunity to cool down to ambient temperature before reading these gains. Apply the temperature correction described in 8.1.4 by using the control transistor gain ratios obtained in Step 1 and Step 9 (the latter obtained by reading the controls again with the test transistors).

8.2.3 *Step 10*—Expose the calibrated transistor sensors in the test environment along with monitor foils. Steps 3 through 5 delineated in 8.1.5-8.1.7 must be repeated.

NOTE 4—If the same transistor is exposed three times or more with hard anneals between each irradiation, and no light anneal is carried out for some reason for both calibration and test, a correction for the gain recovery during hard anneals for earlier groups must be made (see Appendix X2 and Ref (**4**)).

8.2.4 *Step 11*—Apply the temperature correction to the exposed transistors in accordance with 8.1.4.

8.2.5 *Step 12*—Use the gain values obtained in 8.2.2 (the new values of h_{FEO}) and those obtained in 8.2.4 to calculate the change in the reciprocal of the gains, $\Delta\,(1/h)$, in Eq 3. Multiply $\Delta\,(1/h)_\tau$ by $1/K_\tau$ to determine Φ_{1t} for each transistor. Average the Φ_{1t} values for transistors in the same location to determine the most likely value of Φ_{1t}.

8.2.6 *Step 13*—Check the ratio of the monitor foil and TLD readings to see whether a correction for gamma ray damage is necessary. If so, apply corrections as discussed in 8.3-8.3.3.

8.3 *Potential Gamma Ray Effects*:

8.3.1 Gamma rays will always be present in reactor-produced neutron environments. Under normal circumstances the atomic displacements and surface effects generated by Compton-scattered electrons will contribute a negligibly small percent of the damage generated by neutrons. However, in some environments, the gamma ray-to-neutron fluence ratio can be so large or the photon energy is so large that corrections need to be made to the gain measurement. One is interested in obtaining the $\Delta(1/h)$ from neutron displacements alone when the sensors are being used to measure neutron spectra.

NOTE 5—Activation foils may also be affected by gamma rays if the flux and photon energy are high enough to generate (γ,γ') (γ,n), (γ,np) and (γ,p) reactions that lead to the daughter isotopes being counted as neutron reactions. The thresholds for (γ,p) and (γ,np) reactions tend to be above 7 MeV for typical activation foil materials.

8.3.2 To monitor for gamma ray contributions, TLDs shall be included with all sensor sets. For this discussion, define the symbol γ, when not used in an expression such as (n,γ), to mean the gamma ray ionizing dose to silicon. Use the 1 MeV fluence from the reference spectrum and that derived from Eq

3 for the test spectrum to calculate Φ_1/γ ratios for the two environments. The γ values are obtained from the TLD readings for the two cases. If either of these ratios is less than 10^{11} neutrons/(cm^2 × Gy) then a correction may have to be applied to the $\Delta(1/h)$ for gamma ray damage. This means that the $\Delta(1/h)_\gamma$ from the gamma ray induced damage must be subtracted from the total measured $\Delta(1/h)_T$ to yield $\Delta(1/h)$ from the neutrons to be used in Eq 1. An approximate value of $\Delta(1/h)_\gamma$ can be determined by exposing the transistors to a ^{60}Co source along with TLD monitors. In the γ sensitivity calibration, the transistors shall also be annealed at 80°C for 2 h before they are read. The measured $\Delta(1/h)_\gamma$ is then scaled by the ratio of the TLD doses measured in the test and ^{60}Co environments to yield the $\Delta(1/h)_\gamma$ in the test environment. This should be done for each transistor. For the purpose of making estimates, the gamma ray sensitivity for some 2N2222A transistors has been measured to be approximately:

$$K_\gamma = \frac{\Delta\left(\frac{1}{h}\right)_\gamma}{D_\gamma\,(TLD)} \approx 1.5 \times 10^{-15}\, Gy^{-1} \tag{5}$$

This value of K_γ may not be valid if the test gamma-ray ray spectrum is very different from that of the ^{60}Co gamma ray source. It is best to choose a reference environment for which the gamma ray correction would be negligible.

8.3.3 *^{60}Co Tests*—If necessary, expose transistors to ^{60}Co irradiation to a level comparable to that measured by the TLDs in the test environment and establish the effect on $\Delta(1/h)$. Subtract this contribution from the $\Delta(1/h)$ measured in the test environment. This correction may not be sufficiently accurate if it constitutes more than 20 % of the total $\Delta(1/h)$. It has been observed that the gamma-ray induced damage anneals more rapidly than neutron damage, so the 80°C anneal for 2 h reduces the relative gamma ray contribution to $\Delta(1/h)$.

8.4 *Recommended Comparison with Fission Foils*:

8.4.1 The fission foils (^{235}U, ^{237}Np, and ^{239}Pu) with boron covers have responses that overlap the same important 0.1 to 2 MeV energy range as does the silicon displacement damage. If in the test environment fission foils can be included in the sensor set, the compatibility of all the sensors can be tested where their responses overlap. Although the need to make a correction for gamma ray effects on silicon devices should be made on the basis of the TLD data, an indication of gamma sensitivity is given when the transistor-measured Φ_{1t} appears to be too large compared to that calculated from a spectrum derived only from the activation foils, as discussed in 8.3.3. If the transistors are responding to the gamma rays in the test environment, similar transistors should be calibrated at a ^{60}Co source (to the same dose as is measured by the TLDs in the test environment or from a calibration curve). Then the $\Delta(1/h)_\tau$ should be subtracted from the total $\Delta(1/h) = 1/h_{FE\Phi} - 1/h_{FEO}$ in Eq 1. The correction is not likely to be reliable if it is larger than 20 % of the total reciprocal gain change. Otherwise, it is best to alter the test environment by adding lead shielding. In the absence of gamma ray effects, the damage, as measured by 2N2222A's, has been shown to be consistent to within 10 % with spectra determined with the aid of fission foil for many different spectra (see, for example, Appendix X3).

8.4.2 General discussions of the determination of spectra and silicon damage are provided in Guides E 720, E 721, and E 844, and Practices E 722 and E 944.

9. Use of Φ_{1t} as a Spectrum Sensor Response

9.1 As stated in previous sections of this test method, the measured value of Φ_{1t} can be used as a sensor response in the determination of the spectrum in the test environment in the same way that appropriate foil reaction activities can be used. To use Φ_{1t} with foil activities in a spectrum adjustment code, it is necessary to add a properly scaled version of the damage response function to the applicable cross section library used by the code. Φ_{1t} is then treated in exactly the same fashion by the code as any other sensor (foil activity). An example of how to interface Φ_{1t} with a spectrum determination code is given in Ref (**3**). Depending upon the spectrum adjustment code and its treatment of uncertainty information, Φ_{1t} may be given a weight relative to other sensors.

9.2 The advantage of adding silicon to the useful inventory of sensors for spectrum determination is that, in the absence of fission foils, it provides a response in the critical 0.1 to 2 MeV range. This means that not only the neutron integral parameters associated with silicon alone will be established with improved fidelity, but also the parameters for other materials with known response functions can be established with more accuracy (**8**). In the absence of silicon or fission foils, relatively small errors or changes in the sensor activities can lead to large changes in the shape of the spectrum and to very large errors in the silicon-equivalent fluence determination.

10. Precision and Bias

10.1 The uncertainty in the measured value of Φ_{1t} depends on the random and systematic errors in the three terms of Eq 3. Because there is a ratio of $\Delta(1/h)_t/\Delta(1/h)_r$ in the equation, most of the systematic error associated with the measurement of the gains will cancel. The cancellation of the systematic error depends directly on the care taken to conduct all measurements in a carefully controlled and consistent manner. The same transistors (sensors and controls) must be used in the calibration and test environments, the temperature corrections must be applied, the same readout device should be used in all the gain measurements, the same collector current, i_c, the same collector voltage, V_c, and the same handling procedures followed. It is recommended that the systematic errors in the gain measurements be ignored and the random errors be added in quadrature.

NOTE 6—Measurement uncertainty is described by a precision and bias statement in this test method. Another acceptable approach is to use Type A and B uncertainty components (**9,10**). 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.

10.2 Other factors that indirectly affect the gain measurement accuracy are the placement of the monitor and sensors in the environments if there are fluence gradients, reproducibility of gain measurements, possible temperature history differences of the sensors during the two stages of the measurement, and differences in gamma ray effects in the two environments. The various independent uncertainties should be combined in