Designation: E1855 – 20

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 E1855; 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 1-MeV(Si) equivalent displacement damage fluence monitors.

1.2 The neutron displacement in silicon can serve as a neutron spectrum sensor in the range 0.1 to 2.0 MeV and can serve as a substitute when fission foils are not available. It has been applied in the fluence range between 2×10^{12} n/cm^2 to 1×10^{14} n/cm^2 and should be useful up to 1×10^{15} n/cm^2. This test method details the acquisition and use of 1-MeV(Si) equivalent fluence information for the partial determination of the neutron spectra by using 2N2222A transistors.

1.3 This sensor yields a direct measurement of the silicon 1-MeV equivalent fluence by the transfer technique.

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

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 The ASTM standards E170, E261, and E265 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 relevant terminology, 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]

E170 Terminology Relating to Radiation Measurements and Dosimetry
E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E720 Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics
E721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics
E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics
E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance
E1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts
E2005 Guide for Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields
E2450 Practice for Application of $CaF_2(Mn)$ Thermoluminescence Dosimeters in Mixed Neutron-Photon Environments

3. Terminology

3.1 *Symbols:*

Φ_1 = the silicon 1-MeV equivalent fluence (see Practice E722).
$h_{FE} = i_c/i_b$ where i_c is the collector current and i_b is the base current, in a common-emitter circuit.

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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.

4. Summary of Test Method

4.1 Gain degradation resulting from neutron displacement damage in 2N2222A silicon bipolar transistors that is produced by a test environment is compared with gain degradation produced by a reference neutron environment. The Φ_{1r} in the reference environment is derived from the known reference spectrum and serves to calibrate the device response for future determination of a measured Φ_{1t} in the test environment (**1, 2**)[3]. The subscripts *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. The results given by this sensor can be combined with 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 test spectrum must be known in order to use a measured device response to predict the device performance in an operational environment (Practice E1854). Typically, neutron spectra are determined using a set of sensors with response functions sensitive over the neutron energy region to which the device under test (DUT) responds (Guide E721). For silicon bipolar devices exposed in reactor neutron spectra, this effective energy range is between 0.01 and 10 MeV. A typical set of activation reactions that 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 making its determination of critical importance.

5.2 When dosimeters with a significant response in the 0.01 to 2 MeV energy region, such as fission foils, are unavailable, silicon transistors can provide a dosimeter with the needed response to define the spectrum in this critical energy range. When fission foils are part of the sensor set, the silicon sensor provides confirmation of the spectral shape in this energy region.

5.3 Silicon bipolar transistors, such as type 2N2222A, are inexpensive, smaller than fission foils contained in a boron ball, and sensitive to a part of the neutron spectrum important to the damage of modern silicon electronics. They also can be used directly in arrays to spatially map 1-MeV(Si) equivalent displacement damage fluence. The proper set of steps to take in reading the transistor-gain degradation is described in this test method.

5.4 The energy-dependence of the displacement damage function for silicon is found in Practice E722. The major portion of the response for the silicon transistors will generally be above 100 keV.

6. Apparatus

6.1 The 2N2222A silicon bipolar transistor has a demonstrated response in agreement with calculated Φ_1 values in widely varied environments (**5**). It is recommended that a minimum of three transistors be calibrated together and used at each location to be characterized. In addition, at least three transistors should be used as control devices that will not be irradiated during the test exposure. The control transistors should be exposed one time to a calibration exposure of about 1.0×10^{13} n/cm^2 1-MeV(Si) equivalent fluence and then annealed (baked out) at 180°C for 24 h followed by ambient air cooling to room temperature before being used as controls. These control transistors are not exposed again to radiation during the testing steps, 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 to initiate 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 measurements. A programmable tester or parameter analyzer can operate in pulsed mode to mitigate 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 on the collector terminal. The bias voltage is measured between the collector and the base (see Ref (**6**)).

6.4 A reference neutron source (Guide E2005) 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 (**7**) are recommended for use as primary standards, and a well characterized fast burst reactor, such as the one at White Sands Missile Range, is recommended as a reference benchmark field.

6.5 A suitable fluence monitor, such as a nickel foil, shall be exposed along with the transistors during exposures. A photon-sensitive detector such as a CaF_2 thermolumenescence detector (TLD) shall be included in each test package to monitor the gamma ray dose. Care must be taken in the determination of the gamma environment to correct for any neutron response from the photon-sensitive detector that is used. Practice E2450 provides guidance on how to correct a CaF_2:Mn TLD for the neutron response.

NOTE 1—Ionizing dose is produced by photon irradiation in bulk silicon and SiO_2. The ionizing dose can induce trapped holes and interface states in the oxide of the silicon devices. This resulting trapped charge can induce electric fields and create interface traps that change the gain in a bipolar device.

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

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(Si) equivalent displacement damage fluence, Φ_1, at fixed collector current according to the Messenger-Spratt equation (**8**), 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 measured gain value taken 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 (see 8.3).

7.2 A basic schematic circuit used by semiconductor analyzers for measuring $h_{FE} = i_c/i_b$ is shown in Fig. 1. A semiconductor parameter analyzer may be used to determine h_{FE}. Any equivalent method for making the electrical measurement is acceptable as long as the measurement is taken at a consistent collector current. The experimenter must ensure that 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; see paragraph 8.1.1. A typical value for K_τ is about 1.5×10^{-15} cm^2/neutron for a collector current of 1 mA.

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. This step is important because manufacturing processes may change over time and can impact device response.

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 across the 0.01 to 10 MeV neutron energy range in which significant damage is caused. The 1-MeV(Si) equivalent displacement damage fluence of the reference environment, Φ_{1r}, is obtained by folding the spectrum with the silicon displacement damage response as is described in Practice E722. 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.

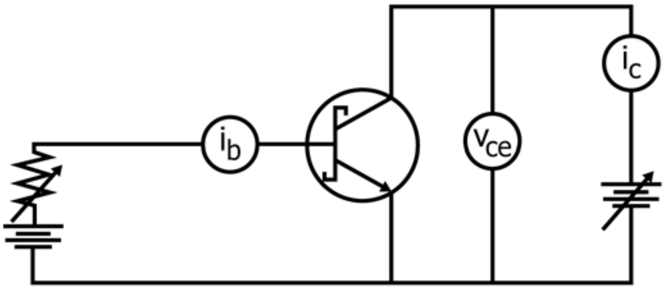

FIG. 1 Schematic for Transistor Read-Out

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

This is the change in reciprocal gain and should have a positive value (for example, the gain should decrease after irradiation). 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} provide the calibration for the transistor, K_τ.

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 (**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 reciprocal gain induced by the test environment. For neutron damage on 2N2222A transistors, K_τ is a constant for neutron fluences up to about 1×10^{15} n/cm^2. The method described here provides a direct determination of Φ_{1t}.

7.8 The 2N2222A may be used as a 1-MeV(Si) displacement monitor. In this use, Eq 3 gives the desired quantity directly, independent of the neutron spectrum. This may be useful, for example, to measure the 1-MeV(Si) displacement damage at several locations inside a massive test item without a full spectral measurement at each point. The gamma-ray corrections especially must be made if the DUT receives significant ionizing dose during the irradiation.

8. Experimental Procedure

8.1 To ensure proper calibration of the sensor, follow steps 8.1.1 – 8.1.9.

8.1.1 *Step 1*—Measure the initial gain values at I_c = 1 mA of all the 2N2222A transistors in the batch. Throw out all those with gain less than 100 and then remove the top and bottom 5 % of the remaining set. 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. Three is the minimum number of transistors needed for test measurement.

8.1.2 The gain measurements may conveniently be made with a programmable semiconductor parameter analyzer, or with a specially designed circuit tester.

8.1.2.1 *Setup*—I_B should be variable from 100 pA to 1 mA. The V_B compliance voltage is 10 V. V_{CE} is 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 pre-irradiation 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.

8.1.2.2 *Measurement*—Vary resistance high to low till I_c is 1 mA. Measure I_B, $h_{FE} = I_c/I_B$. For pulsed measurements the transistor measurements are made with a 3 ms pulse at each of the defined base current settings.

8.1.2.3 *Data Recording*—Record all I_C and I_B measurements. Use the I_C value at 1 mA to calculate I_C/I_B.

8.1.3 The measurement procedure 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. The measurement procedure detailed in 8.1.2 had a maximum collector current of 18 mA. If a different pulsed readout method is used, the amount of time spent at collector currents greater than 1 mA should not significantly exceed that which results from the described procedure. 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). Collector current measurements of 1 mA and down to 0.1 mA may be made in a steady-state mode. At collector currents lower than 1 mA the gains are less reproducible and are more sensitive to temperature and gamma ray background contributions. There can also be surface and emitter losses.

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 min before the device readout begins.

8.1.4 *Step 2*—Isolate 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 un-irradiated and irradiated transistor. Therefore, the control transistors shall be exposed to a neutron fluence of ~10^{13} n/cm^2 and then annealed at 180°C for 24 h followed by ambient air cooling before use. Controls shall not be further 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 *i*th control transistor, and
C_i = transistor gain of the *i*th 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. Appendix X1 shows how the nonlinear propagation of gain measurement error into the implied 1–MeV(Si) fluence can result in significantly larger fluence uncertainties. For smaller exposed fluences, the multiplication factor in the gain-to-fluence uncertainty is much larger. For a nominal irradiation where the gain is degraded by 30 %, a 1 % uncertainty in the gain measurements can, in a worst-case anti-correlated scenario addressed in Appendix X1, result in a 5 % uncertainty in the implied neutron fluence. Since use of the silicon gain degradation as a dosimeter requires that the uncertainty in the implied neutron fluence be small, the irradiation should be sufficient to degrade the gain by ≃30 % or more. An upper limit on the neutron fluence is motivated by the larger fractional measurement uncertainty when the transistor gain is degraded to levels less than ~5. For a fast neutron spectrum and using a representative damage constant of $K_\tau = 1.5 \times 10^{-15}$ cm^2/neutron and an initial gain of 90, this desired 30 % change in gain and consideration of the maximum gain degradation means that ~5×10^{12} 1–MeV(Si)-eqv.-n/cm^2 $\leq \Phi_1 \leq \simeq 1 \times 10^{14}$ 1-MeV(Si)-eqv.-n/cm^2. Include monitor foils nickel or sulfur and include 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, a "stabilization" anneal step at 80°C for two hours shall be performed before every readout, even before the initial irradiation. 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 2 h removes no more than 20 % of the displacement damage (**9**). Under this condition, fading (further annealing) has not been observed. Do not anneal the control transistors.

NOTE 4—The importance of limiting the exposure of the device to high currents was discussed in 8.1.3. In addition to the annealing by high current charge injection, there are other high current-related effects that can reverse the annealing of some types of silicon defects. There is a bi-stable silicon defect (**10, 11**) that, under high current charge injection, can reverse the effects of the stabilizing anneal step discussed in 8.1.6. This results in a decrease in the gain. After a high current exposure, the transistor may again be subjected to a time-dependent annealing under ambient temperature/time conditions.

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. If available, mount the device in a temperature-controlled block.

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 control values as measured when the sensors were first being read, to their average gain values measured at the same time as the post-irradiation measurement.

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 "recovery anneal" to further stabilize and reset the gains before the next exposure. The recommended annealing is 180°C for 24 h. This annealing will recover about 70 % of the damage caused by the latest irradiation (see Ref (**9**)) 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 "recovery 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 recovery anneal. Make certain the transistors have cooled 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 must be repeated.

NOTE 5—If the same transistor is exposed three times or more with recovery anneals between each irradiation, a correction for the gain recovery during recovery anneals for earlier groups must be made.

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 new gain values obtained in 8.2.2 with those obtained in 8.2.4 to calculate the change in the reciprocal of the gains, Δ (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 determine 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 produced by neutron bombardment and the displacements generated by Compton-scattered electrons will contribute a negligibly small percent of the damage generated by neutrons. However, ionizing dose to the oxides in the transistor can trap charge that affects the electric fields in the transistor and change the device gain. In some environments, the gamma ray-to-neutron fluence ratio can be so large that corrections need to be made to the gain measurement.

NOTE 6—Some 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 or an ionizing dose sensor 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(Si) equivalent displacement damage 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(Si) then a correction may have to be applied to the Δ (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 Δ (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:

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

This value of K_γ may not be valid if the test gamma-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 Δ (1/*h*). Subtract this contribution from the Δ (1/*h*) measured in the test environment. This correction may not be sufficiently accurate if it constitutes more than 20 % of the total Δ (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 Δ (1/*h*).

8.4 *Recommended Comparison with Fission Foils:*

8.4.1 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 X2).

8.4.2 General discussions of the determination of spectra and silicon damage are provided in Guides E720, E721, and E844, and Practices E722 and E944.

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

9.1 The measured value of Φ_{1t} can be used as a sensor response in the determination of the spectrum in the test environment. 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 (for example, 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 (**12**), 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 (**13**). 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 1-MeV(Si) equivalent displacement damage 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 under the assumption they are uncorrelated.

NOTE 7—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 (**14**, **15**). 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. DUTs receiving ionizing dose outside of this procedure (for example, from storage in a radiation area) will introduce uncertainty and skew measurement results. Careful attention should be paid to intermediate storage conditions and corrective measures should be applied as proscribed in 8.3. The various independent uncertainties should be combined in quadrature. The question as to whether and how much a silicon device's response differs from that caused by neutron displacement damage is beyond the scope of this test method, and no uncertainty in the determination of Φ_{1t} has been added here to the overall uncertainty of the measurement.

10.3 If the procedures are carried out properly, the ratio of the change in gains can be established with a precision or reproducibility of 2 to 3 %. The bias in the 1-MeV equivalent fluence depends primarily on two factors, the accuracy with which Φ_{1r} is known in the reference calibration environment and the accuracy of the normalization of the monitor foil activities used to establish the transfer calibration. The determination of Φ_{1r} is discussed in Guides E720 and E721, and Practice E722. Φ_{1r} can be established to uncertainties of 5 to 10 %. The monitor activity ratio uncertainties can be as low as 3 % if the monitor foil activity is counted with sufficient statistical accuracy on the same counting system in both the calibration and test environment. Assuming uncertainties of 3 % for the measured device gain changes, 7 % for Φ_{1r} determination, and 3 % for the monitor transfer activity ratio, the overall uncertainties should be in the range of ±8 %.

10.4 Correlation of actual silicon device degradation with the accepted Φ_1 neutron displacement function, the silicon displacement kerma function, is discussed in the Annex Precision and Bias Section of Practice E722. This correlation is important if Φ_{1r} in the reference field is determined by calculation (from a good spectrum determination and the accepted damage function) and Φ_{1f} in the test environment is determined by measured damage ratios. The Φ_{1r} uncertainty in 10.3 includes systematic terms that arise from comparing measured damage ratios and calculated damage ratios in research and test reactors and ^{252}Cf irradiators. Thus the Φ_{1r} uncertainty includes this consideration if both the reference and test environment are standard research or test reactors or ^{252}Cf irradiators. For monoenergetic sources with $E > 3$ MeV and for thermal neutron sources, the Φ_{1r} uncertainty may be larger than 10 %. Thus it is recommended that the reference source used for calibration purposes be a fast burst reactor environment or a ^{252}Cf irradiator. Energy-dependent uncertainties on the silicon damage function are not yet available. The closer the similarity of the test environment spectrum to the reference calibration environment, the better will be the comparison between measured damage ratios and calculated damage ratios in the reference and test environment.