Designation: E 1854 – 03

Standard Practice for
Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts[1]

This standard is issued under the fixed designation E 1854; 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 practice sets forth requirements to ensure consistency in neutron-induced displacement damage testing of silicon and gallium arsenide electronic piece parts. This requires controls on facility, dosimetry, tester, and communications processes that affect the accuracy and reproducibility of these tests. It provides background information on the technical basis for the requirements and additional recommendations on neutron testing. In addition to neutrons, reactors are used to provide gamma-ray pulses of intensities and durations that are not achievable elsewhere. This practice also provides background information and recommendations on gamma-ray testing of electronics using nuclear reactors.

1.2 Methods are presented for ensuring and validating consistency in neutron displacement damage testing of electronic parts such as integrated circuits, transistors, and diodes. The issues identified and the controls set forth in this practice address the characterization and suitability of the radiation environments. They generally apply to reactor and 14-MeV neutron sources when used for displacement damage testing, and apply to ^{252}Cf testing when this source is used for this application. Facility and environment characteristics that introduce complications or problems are identified, and recommendations are offered as to how problems can be recognized and minimized or solved. This practice may be used by facility users, test personnel, facility operators, and independent process validators to determine the suitability of a specific environment within a facility and of the testing process as a whole, with the exception of the electrical measurements, which are addressed in other standards. Additional information on conducting irradiations can be found in Practices E 798 and F 1190. This practice also may be of use to test sponsors (that is, organizations that establish test specifications or otherwise have a vested interest in the performance of electronics in neutron environments).

1.3 Methods for evaluation and control of undesired contributors to damage are discussed in this practice, and references to relevant ASTM standards and technical reports are provided. Processes and methods used to arrive at the appropriate test environments and specification levels for electronics systems are beyond the scope of this practice; however, the process for determining the 1-MeV equivalent displacement specifications from operational environment neutron spectra should employ the methods and parameters described herein. Some important considerations are addressed in Appendix X1 through X1.3.1 (Nonmandatory information)..

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 limitations prior to use.*

2. Referenced Documents

2.1 The ASTM standards listed below present methods for ensuring proper determination of neutron spectra and fluences, gamma-ray doses, and damage in silicon and gallium arsenide devices. The proper use of these standards is the responsibility of the radiation metrology or dosimetry organization that is often closely affiliated with facility operations. The references listed in each standard are also relevant to all participants as background material for testing consistency.

2.2 *ASTM Standards:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[2]
E 181 Test Methods for Detector Calibration and Analysis of Radionuclides[2]
E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra by Radioactivation Techniques[2]
E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques[2]
E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron[2]
E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel[2]
E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32[2]
E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters[2]

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[1] This practice 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] *Annual Book of ASTM Standards*, Vol 12.02.

E 481 Test Method for Measuring Neutron Fluence Rate by Radioactivation of Cobalt and Silver[2]

E 482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E 706 (IID)[2]

E 523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper[2]

E 526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium[2]

E 665 Practice for Determining Absorbed Dose Versus Depth in Materials Exposed to the X-ray Output of Flash X-ray Machines[2]

E 666 Practice for Calculating Absorbed Dose From Gamma or X Radiation[2]

E 668 Practice for the Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices[2]

E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238[2]

E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237[2]

E 720 Guide for Selection and Use of Neutron-Activation Foils for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics[2]

E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics[2]

E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics[2]

E 798 Practice for Conducting Irradiations at Accelerator-Based Neutron Sources[2]

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[2]

E 944 Practice for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)[2]

E 1018 Guide for Application of ASTM Evaluated Cross Section Data File, E 706 (IIB)[2]

E 1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources[2]

E 1250 Test Method for Application of Ionization Chambers to Assess the Low Energy Gamma Component of Cobalt-60 Irradiators Used in Radiation-Hardness Testing of Silicon Electronic Devices[2]

E 1297 Test Method for Measuring Fast Neutron Reaction Rates by Radioactivation of Niobium[2]

E 1854 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Sensors and Displacement Damage Monitors[2]

E 2005 Guide for the Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron-Fields[2]

F 1190 Practice for Neutron Irradiation of Unbiased Electronic Components[3]

3. The Roles of the Participants

3.1 The following terms are used to identify key roles and responsibilities in the process of reactor testing of electronics. Some participants may perform more than one role, and the relationship among the participants may differ from test program to test program and from facility to facility.

3.2 *Sponsor*—Individual or organization requiring the test results and ultimately responsible for the test specifications and use of the results (for example, a system developer or procuring activity). Test sponsors should consider the objectives of the test and the issues raised in this practice. They shall clearly communicate to the user the test requirements, including specific test methods.

3.3 *User*—Generally the individual or team that contracts for the use of the facility, specifies the characteristics needed to accomplish the test objectives, and makes sure that the documentation of the test parameters is complete. If the test sponsor does not communicate clear requirements and sufficient information to fully interpret them, the user shall communicate to the sponsor, prior to the test, the assumptions made and any limitations of applicability of test data because of these assumptions. This may require consultation with a test specialist internal or external to the user organization. Facility users also should consider the objectives of their tests and the issues raised in this practice. The user may also conduct the tests. The user shall communicate the environmental, procedural (including specific test methods, if any) and reporting requirements to the other participants including the tester, the facility operators, and the test specialist.

3.4 *Facility Organization*—The group responsible for providing the radiation environment. The facility organization shall provide pre-test communication to the user on facility capabilities, cautions, and limitations, as well as dosimetry capabilities, characteristics of the test environment, and test consistency issues unique to the facility and/or test station within the facility. If there is no independent validator, the facility shall also be required to provide the user with documentation on the controls, calibrations, and validation tests, which verify its suitability for the proposed tests. Post-test, the facility shall report dosimetry results, relevant operational parameters, and any occurrences that might affect the test results. The radiation facility and test station used in the test shall meet the minimum quality assurance criteria specified in Section 5.

3.5 *Dosimetry Group*—Individual or team providing definitive data on dose, dose rate, neutron fluence, and spectra.

3.6 *Test Specialist*—Individual providing radiation test expertise. This individual may identify the appropriate damage function(s) and may fold them with neutron spectra to determine/predict damage and damage ratios. This individual may also provide information on experiment limitations, custom configurations that are advantageous, and interpretation of dosimetry results.

3.7 *Validator*—Independent person that may be responsible for verifying either the suitability of the radiation environment, the quality of the radiation test including the electrical measurements, or the radiation hardness of the electronic part production line.

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[3] *Annual Book of ASTM Standards*, Vol 10.04.

3.8 At the beginning of many of the paragraphs that discuss tasks to be carried out, a label is added in parentheses to designate the participant who usually has the primary responsibility for this task.

4. Significance and Use

4.1 This practice was written primarily to guide test participants in establishing, identifying, maintaining, and using suitable environments for conducting high quality neutron tests. Its development was motivated, in large measure, because inadequate controls in the neutron-effects-test process have in some past instances resulted in exposures that have differed by factors of three or more from irradiation specifications. A radiation test environment generally differs from the environment in which the electronics must operate; therefore, a high quality test requires not only the use of a suitable radiation environment, but also control and compensation for contributions to damage that differ from those in the operational environment. In general, the responsibility for identifying suitable test environments to accomplish test objectives lies with the sponsor/user/tester and test specialist part of the team, with the assistance of an independent validator, if available. The responsibility for the establishment and maintenance of suitable environments lies with the facility operator/dosimetrist and test specialist, again with the possible assistance of an independent validator. Additional guidance on the selection of an irradiation facility is provided in Practice F 1190.

4.2 This practice identifies the tasks that must be accomplished to ensure a successful high quality test. It is the overall responsibility of the sponsor or user to ensure that all of the required tasks are complete and conditions are met. Other participants provide appropriate documentation to enable the sponsor or user to make that determination.

4.3 The principal determinants of a properly conducted test are: (*1*) the radiation test environment shall be well characterized, controlled, and correlated with the specified irradiation levels; (*2*) damage produced in the electronic materials and devices is caused by the desired, specified component of the environment and can be reproduced at any other suitable facility; and (*3*) the damage corresponding to the specification level derived from radiation environments in which the electronics must operate can be predicted from the damage in the test environment. In order to ensure that these requirements are met, system developers, procurers, users, facility operators, and test personnel must collectively meet all of the essential requirements and effectively communicate to each other the tasks that must be accomplished and the conditions that must be met. Criteria for determining and maintaining the suitability of neutron radiation environments for 1-MeV equivalent displacement damage testing of electronics parts are presented in Section 5. Mandatory requirements for test consistency in neutron displacement damage testing of electronic parts are presented in Section 5. Additional background material on neutron testing and important considerations for use of a reactor facility for gamma dose and dose rate testing are presented in Appendixes Appendix X2 and Appendix X3, but compliance is not required.

4.4 Some neutron tests are performed with an end application of the electronics in mind. Others are performed merely to ensure that a 1-MeV-equivalent-displacement-damage-specification level is met. The issues and controls presented in this practice are necessary and sufficient to ensure consistency in the latter case. They are necessary but may not be sufficient when the objective is to determine device performance in an operational environment. In either case, a corollary consistency requirement is that test results obtained at a suitable facility can be replicated within suitable precision at any other suitable facility. If a facility user is not aware of the detailed characteristics of the operational radiation environment, it is prudent to select a test facility and test location in which contributors to damage by other than fast neutrons (E_n > 100 keV) are minimized.

4.4.1 An objective of radiation effects testing of electronic devices is often to predict device performance in operational environments from data obtained in test environments. If these environments differ materially from each other, then damage equivalence methodologies are required in order to make the required correspondences. The process is shown schematically in Fig. 1. The part of the process (A, in Fig. 1) that establishes the neutron environments required to select the appropriate 1-MeV-equivalent specification level, or levels, is beyond the scope of this practice. However, if a neutron spectrum is used to set a specification level (B, in Fig. 1), it is important that this process be consistent with this practice. Damage equivalence methodologies must address all of the important contributors to damage in the operational and test environments or the objectives of the reactor test are not ensured. In the mixed neutron-gamma radiation fields produced by nuclear reactors, most of the permanent damage in solid-state semiconductor devices results from displacement damage produced by fast neutrons through primary knock-on atoms and their associated damage cascades. The same damage functions must be used by all test participants to ensure damage equivalence. Damage functions for silicon and gallium arsenide are provided in the current edition of Practice E 722 (see Note 1). At present, no damage equivalence methodologies for neutron displacement damage have been developed and validated for semiconductors other than silicon and gallium arsenide.

NOTE 1—Pre-1993 editions of Practice E 722 reference outdated versions of the silicon damage function and do not include GaAs damage functions.

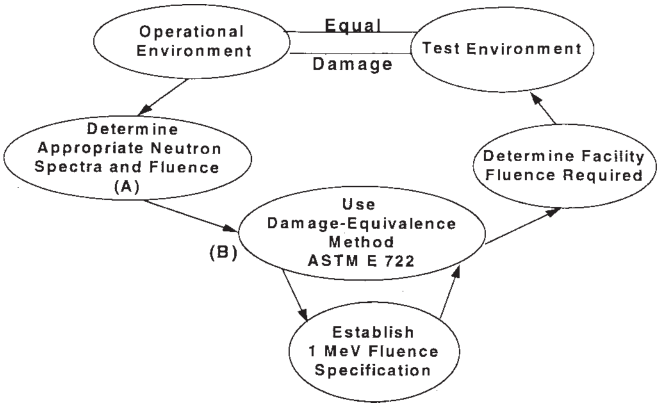

FIG. 1 Process for Damage Equivalence

4.4.2 If a 1-MeV equivalent neutron fluence specification, or a neutron spectrum, is provided, the damage equivalence methodology, shown schematically in Fig. 1, is used to ensure that the correct neutron fluence is provided and that the damage in devices placed in the exposure position correlates with the displacement energy from the neutrons at that location.

5. Requirements for Neutron Displacement Damage Testing

5.1 This section identifies the requirements that must be met to ensure consistency in neutron displacement damage testing of electronics. The following is not intended to dictate who will be responsible for individual tasks, as this may vary from program to program and is subject to negotiation. The user, supported by the other participants, shall ensure that all of the required tasks are accomplished.

5.2 *Test Specification* (Sponsor/User)—The sponsor or procuring group specifies the radiation test levels. Frequently, 1-MeV equivalent (Si) fluence levels are specified. The damage equivalence methodology and parameters used to determine the 1-MeV fluence shall be in accordance with Practice E 722.

5.2.1 (Optional) If desired by the sponsor/user/tester, together they determine if the test specifications are adequate to obtain the sponsor's test objectives. The first steps are to examine the characteristics of the operational environment where the devices are to perform, to choose the devices to be tested, and to determine the important damage parameters to be evaluated. Next, a radiation environment must be chosen that can meet the sponsor's test objectives and be effectively used to evaluate the responses of the required device parameters to the radiation environment. This step may require the support of a test specialist and facility operators.

5.3 *Sources*—The test station may be in or near a fast-burst reactor or a pool-type reactor (such as a TRIGA). A 14-MeV or ^{252}Cf neutron source also may be used. Operation may be in either pulse or steady state mode, as appropriate. The source shall be one that is acceptable to the sponsor. Preferred sources and test locations are those in which device damage contributions from anything other than fast neutrons are negligible (see Appendix X2).

5.4 *Environment Characterization* (Facility Operator and Test Specialist)—It is assumed in this section that the primary damage mechanism being investigated is the neutron displacement damage. If secondary effects (such as those caused be ionizing radiation) contribute to the response of the device, these processes must be taken into account in interpreting the test results. These issues are discussed in 5.10.1 and 5.10.2. The neutron environment is characterized by a neutron spectrum measurement.

5.4.1 (Dosimetry Group) At a minimum, the facility shall provide the experimenter with a neutron spectrum representing the free-field environment at the "Device Under Test" (DUT) location. This spectrum determination shall be derived with a methodology that gives appropriate weight to experimental measurements. These methodologies may include use of activation sensors within an iterative or least-squares spectrum adjustment code. (See Guides E 720 and E 721.) A free-field spectrum based solely upon neutron transport calculations is not acceptable. If the fixtures used by the experimenter significantly perturb the free-field environment, the appropriate spectrum in the proper relationship to those fixtures shall be determined.

NOTE 2—The determination of the spectrum at a location within or near an experimental fixture that perturbs the free-field spectrum is often best accomplished by calculations. Calculations alone may be sufficient in these cases as long as the calculational methodology and modeling have been validated by comparison with measurements for the free-field (unperturbed) case. Experimental validation of any calculations is always desirable, but is not always practical. The use of dosimetry sensors is discussed in Test Methods E 181, E 262, E 393, E 481, E 523, E 526, E 704, E 705, and E 1297, Practice E 261, and Guide E 844.

5.4.2 (Dosimetry Group) For the determination of the spectrum, the sensor set must be sensitive over the energy range within which the device under test is sensitive. In particular, the sensor set shall include a sensor with significant response in the 10-keV to 1-MeV energy region. Sensors with energy responses in this region include the fission foils, ^{235}U, ^{239}Pu, and ^{237}Np. In addition, niobium through the reaction ^{93}Nb(n,n′)^{93m}Nb can be useful, although its very long half-life of about 16 years usually results in a very low activity. In the absence of fission foils, silicon devices can be used effectively as spectrum sensors. It is suggested that both fission foils and silicon devices be used for mutual confirmation **(1,2)**.[4]

5.4.3 (Dosimetry Group) To provide information needed to account for possible gamma-ray effects on the DUT, the facility shall provide a measure of the gamma-ray dose to the silicon or gallium arsenide device. The selected gamma-ray sensor shall have been demonstrated to have a low neutron sensitivity. The gamma-ray detector response shall be traceable to NIST standards. One common gamma dose sensor with low neutron sensitivity is a CaF_2:Mn thermoluminescent detector (TLD). LiF TLDs (even LiF TLDs with a low enriched ^{7}Li component) are more sensitive to thermal neutrons than CaF_2 and should only be used with care in fast burst reactors and should be avoided in reactors with a significant thermal neutron flux. Both radiochromic films and alanine show a high neutron sensitivity due to proton recoil in the hydrogeneous dosimeter material, and are thus not recommended as gamma sensors for mixed neutron/gamma reactor environments.

5.5 *Damage Equivalence* (Facility operator, Validator)—The facility shall provide, at 15-month intervals or less, experimental confirmation that the equivalent fluence is equal to that predicted by the spectrum. This may be done by demonstrating that the damage measured in a standardized and calibrated silicon (or GaAs) device is equal to that calculated from the spectrum that is attributed to the test environment. The standardized device is denoted as the PHI1 monitor to distinguish it from the DUT. Two devices appropriate to this application, because of extensive investigations of their responses, are 2N2222A transistors (see Test Method E 1855) and DN-156 diodes **(3)**. The neutron-induced displacement damage changes the gain of the transistors in amounts inversely proportional to the 1-MeV equivalent fluence, Φ_1. In the diodes, the forward voltage increases with fluence in a

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[4] The boldface numbers in parentheses refer to a list of references at the end of this practice.

reproducible, but nonlinear, way (The shape of the calibration curve is the same for all of the diodes.) (see 5.8 and Practice E 722). Thus, 2N2222A transistors and DN-156 diodes are appropriate PHI1 monitors if they are calibrated in the environments whose spectra (and consequently Φ_1) are well established. The environment is considered to be satisfactorily characterized for electronic parts testing if the Φ_1, measured with the pHI1 monitors, is within 10 % of that predicted using the spectrum and fluence reported by the test facility for that location (see Note 3).

NOTE 3—It must be pointed out that the damage measurements discussed here are all ratio measurements in reference and test environments taken with the same PHI1 monitor. Therefore the damage constant that relates the change in reciprocal gain for 2N2222 transistors (or forward voltage for DN-156 diodes) to displacement damage cancels out.

5.6 *Delivery of the Characterization Information*—The user is responsible for ensuring that he receives the information about the test environment needed to evaluate the response of his DUT. The facility shall be prepared to supply a validated neutron spectrum and associated gamma-ray dose for each test environment. The user or facility operator may contract out this task to others, if desired. The identification and characterization of secondary effects and conditions that affect the DUT are also necessary. The facility should be prepared to provide uncertainty information about spectrum, fluence, and dose so that the user can evaluate the effect of these uncertainties on the response of the DUT. This information generally reduces to an evaluation of uncertainties in the integral parameters such as Φ_1, the neutron fluence-to-gamma-ray dose ratio, the fluence greater than 3 MeV, the silicon hardness parameter (defined in Practice E 722), the ratio of the fluence greater than 10 keV to the fluence greater than 3 MeV, and the ratio of the total fluence to the fluence greater than 3 MeV.

5.7 *Controls and Auditability* (Facility Operator)—The facility (including the reference source FBRs) must provide written assurance that an adequate environment characterization has been performed, that it meets the environment characterization requirements in 5.4 and 5.5, and that the environment has not changed (except for the possible alteration by the test object itself) between the time of the most recent characterization (which was used in the supporting documentation) and the test time. To guard against unaccounted for changes:

5.7.1 The facility shall have adequate in-house procedures for monitoring changes in the reactor configuration between the time at which the experiment takes place and the time the environment characterization took place.

5.7.2 The facility shall confirm in writing that the current environment delivered to the user/tester does not deviate significantly from the environment at which the damage verification and spectral determination were performed.

5.7.3 The facility shall employ a process to inform facility staff responsible for interfacing with users/testers, internal test specialists, and dosimetry specialists of changes that may impact test consistency.

5.7.4 Appropriate neutron and gamma ray monitors shall be included with the DUT on each exposure.

5.8 *Dosimetry Equipment* (Dosimetry Group)—The dosimetry group shall have at a minimum:

5.8.1 Appropriate activation foil counting and gamma dose readout equipment with calibrations traceable to NIST.

5.8.2 Fast neutron threshold activation reactions such as ^{32}S(n,p), ^{54}Fe(n,p), or ^{58}Ni(n,p) shall be used to monitor the neutron fluence. These reactions are recommended because of their relatively high cross sections and long half-lives.

5.8.3 Suitable gamma dose sensors shall be used to monitor the gamma-ray dose. If thermoluminescence dosimeters are selected as the gamma sensor, Practice E 668 provides useful information on the calibration and use of TLDs in gamma environments. In mixed neutron and gamma ray fields, the gamma sensor should have a demonstrated low neutron sensitivity. CaF_2:Mn TLDs are an appropriate sensor for most applications.

5.8.4 Calibrated silicon devices may be used as spectrum sensors and 1-MeV equivalent fluence monitors. If silicon devices are used as monitors, then an appropriate device parameter reader must be available along with an oven for annealing treatments.

NOTE 4—Although the dosimetry group is usually associated with the facility in order to ensure continuity of environment characterization, it is often advantageous for the user to add his own dosimetry so that he can more readily monitor consistency with the local dosimetry and the results obtained at other test facilities.

5.9 *Damage Correlations* (Facility Operator)—For neutron displacement damage equivalence, either the 1-MeV(Si) equivalent fluence or the 1-MeV(GaAs) equivalent fluence must be provided. Alternatively, a neutron spectrum may be provided and the corresponding 1-MeV equivalent fluence specification can be determined using Practice E 722. The damage equivalence methodology in this practice has been validated for both silicon and gallium arsenide by demonstrating that equal damage is achieved for the same 1-MeV equivalent fluence even in neutron environments having very different energy distributions **(4,5)**. The spectrum at the test facility exposure location must also be parameterized into a 1-MeV equivalent fluence, Φ_1, using the same practice. By providing the specified Φ_1 in the test environment, the desired damage is produced and test consistency is achieved if all other contributions to the damage are accounted for or are negligible. The damage equivalence methodology is fully described in Practice E 722, and a brief outline is provided in Appendix X1. It is essential that the proper damage function for the device be used, and accurate spectra for the environments be determined. Usually the responsibility for providing and measuring the spectrum falls to the facility operator, the test specialist, or the dosimetry group.

5.10 *Test Device Response Function* (User/Test Specialist)—Decisions must be made to determine the appropriate response mechanisms in the DUT. After the damage mechanisms have been determined, the correct response functions can be used to calculate the delivered damage level. If the primary device damage mode is neutron displacement damage in the silicon or gallium arsenide, then the latest functions from Practice E 722 should be used. Validated damage functions for other semiconductor materials are likely to become available later. If the DUT responds to other components of the environment, these responses must also be characterized for the delivered environment. Secondary effects are discussed in subsection 5.11.

5.10.1 It is recommended that the tester use a test environment that approximates the operational environment to avoid surprises, especially if a new semiconductor technology is being tested. Alternatively, a free-field or neutron-enhanced fast burst reactor environment may be used to minimize unwanted contributors to damage in a neutron displacement damage test. A neutron-enhanced environment is produced by shielding the DUT from gamma-rays with a high-Z shield. If environment-modifying materials are used, then separate gamma-ray tests may be called for so that the contributing damage factors can be determined. If filters such as lead or bismuth surround the test object, the neutron spectrum will be modified and must be determined for that configuration.

5.10.2 It is the user/tester's responsibility to make certain that the proper response functions are used for the DUT, but it is the responsibility of the facility or test specialist to make certain that the correct 1-MeV fluence is ascribed to the free-field environment.

5.11 *Device Testing*—This subsection deals primarily with the testing of the DUTs and with the considerations that must be made beyond the basic characterization and maintenance of the test environment.

5.11.1 *Secondary Gamma-Ray Effects* (Sponsor/User)—It is the primary responsibility of the user (with assistance of a test specialist, if desired) to account for the secondary effects that influence his device performance. The most important potential contributor to secondary-damage effects is the prompt gamma-ray flux associated with the fission neutron-generation process. The inclusion of gamma sensors in the dosimeter packages allows the potential gamma-ray effects to be evaluated, provided the response of the DUT to gamma rays is determined separately. The response of the DUT to gamma dose shall be determined separately using a pure gamma calibrated source such as ^{60}Co or ^{137}Cs. Frequently encountered gamma-ray effects are discussed further in Appendix X2. The contribution of gamma rays is usually not significant for fast burst reactor tests, unless something that enhances the gamma field is nearby. Guidance for the use of TLDs in gamma fields is found in Practice E 668. Details on gamma sources can be found in Practices E 665 and E 666.

5.11.2 *Other Secondary Effects*—Other potential contributors to measured DUT performance include displacement damage annealing (which can actually aid in device performance recovery), the temperature at which the device performance is tested, and displacements caused by thermal neutron capture in trace contaminants and dopants in the electronic parts. For example, boron is frequently used as a dopant in silicon parts and high energy recoil particles can result from thermal neutron interactions. Gamma dose enhancement effects can be induced in devices at interfaces between materials with dissimilar atomic number. Dose enhancement effects are discussed in Practice E 1249 and Test Method E 1250.

5.11.3 *Measurements for the DUT Environment* (Dosimetry Group)—The neutron fluence used for device irradiation shall be obtained by measuring the amount of radioactivity induced by a fast-neutron threshold activation reaction such as ^{32}S(n,p),^{54}Fe(n,p), or^{58}Ni(n,p) in a monitor foil which is irradiated at the same time and colocated with the device. A standard method for converting the measured radioactivity to fluence in the specific monitor foil employed in a neutron environment is given in Test Methods E 263, E 264, and E 265.

5.11.3.1 As discussed in 5.4, the conversion of the foil radioactivity into a neutron fluence requires a knowledge of the neutron spectrum incident on the foil. If the spectrum is not known, it shall be determined by use of Guide E 720 or E 721 or Practice E 722 or their equivalent.

5.11.4 The determination of (*1*) the spectrum shape from the environment characterization, and (*2*) the magnitude of the 1-MeV fluence (derived form the spectrum) with the fluence monitor, completes the characterization of the neutron environment for the test. The user is cautioned that if the neutron spectrum is perturbed, the fluence monitor may no longer provide an accurate measure of the 1-MeV fluence. Additional guidance on the determination of a neutron spectrum by the foil activation method can be found in Guides E 482 and E 1018, and Practice E 944.

NOTE 5—There are cases in which a spectrum cannot be obtained and yet a good estimate of the 1-MeV equivalent fluence is needed. In that case the fluence transfer method, discussed in Appendix X1, may be the only option available. In that case the derived equivalent fluence is not independently verified. This subject is discussed further in Appendix X2.

5.12 *Test Documentation*—The user, with the assistance of the other participants, is responsible for making certain that all the tasks listed above (in 5.1-5.10) are accomplished and documented. The additional user tasks that must be carried out and documented are DUT performance measurements. If necessary, the sponsor may require the prediction of the device responses in the operational environments based on the test results.

5.12.1 The user shall communicate fully to the facility and to the Test Specialist (TS) the purpose of the test, the test specifications, and the parameters to be determined. The user shall negotiate a schedule with these parties to accomplish these tasks.

5.12.2 In the usual mode of operation, as discussed in 5.6, the facility operator is responsible for providing, characterizing, and reporting on the test environment (the neutron spectrum, fluence, and gamma-ray dose during the test). Such characterizations are to be based on measurements traceable to NIST. The facility operator and test specialist evaluate the test specifications with respect to the capabilities of the facility and provide the documentation on the certified environments that are available to the user. Facility changes possibly affecting the test spectrum that have been made since the last spectrum characterization shall be documented, and the documentation made available to the user. More reliability is achieved if the characterization measurements and the test measurements are both made with the same dosimetry system and procedures, but this is not mandatory.

5.12.3 After the test environment characterization and certification has been carried out and documented, the characterization must be reconfirmed within 15 months to maintain the certification. This reconfirmation may be obtained by exposure of a more limited set of spectrum sensors that sample the range of spectrum energies to make sure that the ratios of sensor responses have not changed. This reconfirmation must be documented. Some suggested sensors for environment reconfirmation are given in Appendix X2.

5.13 Other required tasks include the monitoring of secondary effects and evaluation of the effects of the DUT on the environment. An extended set of recommendations for the best way to determine the displacement damage is provided in Appendix X2.

6. Keywords

6.1 electronics testing; neutron-induced damage; nuclear test reactor; test consistency

APPENDIXES

(Nonmandatory Information)

X1. 1-MeV NEUTRON DISPLACMENT DAMAGE EQUIVALENCE

X1.1 A general methodology for establishing damage equivalent fluence and neutron-displacement damage functions for silicon and gallium arsenide is provided in Practice E 722. Instead of directly relating the total displacement energy in two neutron environments, Practice E 722 introduces an intermediate step that is used to determine the equivalent neutron fluence that would deposit the same total displacement energy. Some of the definitions in Practice E 722 are repeated here to make it easier to follow the discussion of the transfer method for determining the 1-MeV equivalent fluence with silicon devices referred to in 5.4.2 and to use the methodology to predict the neutron response in an operational environment. In this section, brief descriptions of the damage equivalence method and of the steps needed to determine the parameters used for characterizing neutron environments in terms of damage in silicon devices are given.

X1.2 An assumption in Practice E 722 that has been widely validated is that neutron damage in silicon is proportional to the non-ionizing energy (or total displacement energy) deposited by the primary knock-on atom and its associated damage cascade. Therefore, the displacement kerma as a function of energy is used as the damage function. The neutron spectrum in the environment under consideration, Φ(E), and the damage function, F_D(E), are integrated over neutron energy to obtain the total displacement energy. The defining equation for the displacement damage is:

$$\frac{\int_0^\infty \Phi(E)F_D(E)dE}{\int_0^\infty \Phi(E)dE} = \bar{F}_D \tag{X1.1}$$

where:

$\bar{F}_D$ = average damage produced per neutron by the environment. It is a spectrum-averaged damage and is also called the damage constant for this spectrum.

Φ = $\int_0^\infty \Phi(E)dE$ is the total neutron fluence.

X1.3 Since $\bar{F}_D \times \Phi_1$ is the total displacement damage, a fluence of neutrons that would produce an equivalent amount of displacement damage is given by:

$$\Phi_{E_{ref}} \times F_{D,E_{ref}} = \bar{F}_D \times \Phi \tag{X1.2}$$

where:

E_{ref} = the specified reference energy, also called the equivalent energy.

When E_{ref} = 1 MeV, then $F_{D,1\ MeV}$ = average damage produced by a 1-MeV neutron. For silicon, $F_{D,1\ MeV}$ is defined to be a reference value of 95 MeV × mb so that there will be increased consistency in the determination of Φ_1 as the detailed energy-dependence of the silicon cross section is updated.

X1.3.1 From Eq X1.1 and Eq X1.2:

$$\Phi_1 = \frac{1}{F_{D,1}} \int_0^\infty \Phi(E)F_D(E)dE \tag{X1.3}$$

is the 1-MeV equivalent fluence.

X1.4 To determine the test environment fluence that will produce the same silicon displacement damage as a specified operational environment, the first step is to determine the 1-MeV equivalent fluence for the operational environment through Eq X1.3. This is often provided by the test sponsor as a test specification. Since $F_{D,1}$ is a constant, Eq X1.1 and Eq X1.2 may be used to determine the environment fluence that will provide the same 1-MeV equivalent fluence. Provided F_D(E) includes all the contributors to damage, a device subjected to a given Φ_1 will suffer the same damage in any other environment (or spectrum) that delivers the same Φ_1 to the device. Damage equivalence can be assured if the neutron spectrum, Φ(E), and the appropriate damage function, F_D(E), are known for each environment.

X1.5 In the case of silicon, it is advantageous to define some additional parameters, derived from the spectrum and the damage function, that aid in using neutron dosimetry results to calculate 1-MeV equivalent fluence. In Eq X1.4, $\Phi(E > 3\text{ MeV})$ equals the fluence of neutrons with energy greater than 3 MeV.

$$\Phi_1 = \Phi(E > 3\text{ MeV}) \times SP \times HP_{Si} \tag{X1.4}$$

$$SP = \Phi/\Phi(E > 3\text{ MeV}) \tag{X1.5}$$

is the spectral shape parameter that relates the total fluence to the 3-MeV fluence.

$$HP_{Si} = \int_0^\infty F_D(E)\Phi(E)dE/[\Phi(E > 3\ MeV) \times SP \times F_{D,1}] \tag{X1.6}$$

is called the silicon hardness parameter because it equals the average damage caused by neutrons of this spectrum compared to 1-MeV neutrons.

$$\bar{\sigma}_s = \frac{\int_0^\infty \sigma_s(E)\Phi(E)dE}{\int_0^\infty \Phi(E)dE} \tag{X1.7}$$

is the spectrum averaged cross section for the $^{32}S(n,p)\,^{32}P$ reaction.

X1.6 The 3-MeV reference fluence is useful because if the fluence is measured with sulfur or nickel monitor activation foils (which have an approximate reaction threshold at 3 MeV), then $\Phi = \Phi(E > 3\text{MeV}) \times SP$. By tabulating these parameters for a variety of neutron environments, the damage ratios for silicon devices subject to these environments may be predicted. All the experimenter needs to do is determine the activity of the monitor foil included with his devices during exposure to calculate Φ_1, if no other effects compromise the test.

X1.7 Although no specific method for determining spectra has been required here, the discussions and references reflect the fact that the foil activation technique has usually been the mode used by researchers in this field because of its flexibility and accuracy. Proton recoil spectroscopy and the flux-transfer technique have also been used successfully, and there are other methods. Knowledge of the spectrum is needed to derive the parameters and to confirm that measured damage ratios correlate with the neutron energy deposition.

X1.8 The steps to be taken to find Φ_1 are the following:

X1.8.1 Determine the neutron energy spectrum shape and magnitude in the test environment (for example, by the methods described in Guides E 720 and E 721).

X1.8.2 From this information, calculate SP, HP_{si}, and the expected response of the sensor to be used with the DUTs when they are tested. Use Eq X1.2-X1.7. (In most cases the spectrum adjustment code, such as SAND II **(13,14)** will provide the needed parameters during printout.) The damage function can readily be integrated over the spectrum to yield HP_{si}. Then determine the calculated response of the monitor sensor. If that monitor is a foil such as sulfur, calculate the activity, $A_s = \lambda_s \Phi \bar{\sigma}_s$, where λ_s is the decay constant for the product nucleus, ^{32}P in the case of the $^{32}S(n,p)^{32}P$ reaction. These are the quantities derived when the spectrum was determined.

X1.9 The response of the DUT is discussed in this section. The steps to be taken to determine the response of the device under test (DUT) to a given fluence in the test environment are the following:

X1.9.1 Expose the DUT in this test environment along with one or more monitor foils. Measure the response of the DUT and the monitor. For an activation foil monitor, measure the activity, A_{st} (The *t* index indicates the test run.).

X1.9.2 Calculate the 1-MeV equivalent fluence seen by the DUT during the test run by using Eq X1.4 and the monitor activities derived in the spectrum run and measured in the test run.

$$\Phi_{1t} = \frac{A_{st}}{A_s} \times \Phi(E > 3\text{MeV}) \times SP \times HP_{si} = \frac{A_{st}}{A_s}\Phi_1 \tag{X1.8}$$

This is the same procedure as is described in Practice E 722.

X1.9.3 The activity ratio in Eq X1.8 usually can be allowed to range far beyond 1.0 because activation reactions are rarely compromised by secondary effects (such as λ,n sensitivity) and because the two spectra used in Eq X1.8 have the same shape. One finds, however, that applying device displacement damage ratios in the same manner requires much more care because device damage is influenced more by secondary effects.

X1.10 *Tests of Bipolar Transistors:*

X1.10.1 The quantities given in the previous subsection may be used to predict the neutron response of a silicon device in the operational environment by the following steps. It is assumed here that the device response is proportional to the displacement damage function for silicon given in Practice E 722. For bipolar transistors in particular, this damage is manifested first by a reduction in minority carrier lifetime, which leads to a reduction in gain as governed by the Messenger-Spratt Eq X1.9.

$$\Delta\left(\frac{1}{h}\right) = \frac{1}{h_{FE\Phi}} - \frac{1}{h_{FEO}} = K_\tau\Phi_1 \tag{X1.9}$$

where:

$h_{FE\Phi}$ = common emitter current gain measured after exposure to fluence Φ_1,
h_{FEO} = common emitter current gain measured before exposure,
Φ_1 = defined in Eq X1.3, and
K_τ = the damage constant for the device (proportional to F_D).

X1.10.2 The purpose of this test example is to establish the value of K_τ for the device so that its performance can be predicted in any other environment for which the value of Φ_1 can be established. It is assumed at this point that the device is exposed under conditions in which whatever contributions gamma rays have to $\Delta(1/h)$ are either negligible or have been subtracted out. A subtraction might be made by exposing the same DUTs to a pure gamma-ray flux comparable to that encountered in the reactor test to measure the $\Delta(1/h)_\gamma$ response. This can then be subtracted from the total $\Delta(1/h)$ to yield the $\Delta(1/h)$ appropriate for use in Eq X1.9.

X1.10.3 It is also assumed, for this discussion, that K_τ is a constant ($K_\tau \neq f(\Phi)$), so that the radiation effect, the change in the reciprocal gain, $\Delta(1/h)$, is due only to a change in the minority carrier lifetime brought on by the neutron displacement damage. If the damage is so high that the base transit time is also affected, K_τ will be a function of the fluence. In this case, the base transit time after exposure will also have to be measured and a more complicated fluence-to-damage formula will be required. See Ref **(1)** for more details on the methodology. Nonlinear effects in bipolar devices should be considered when the fast neutron fluence approaches $\sim 10^{15}$n/cm^2.

NOTE X1.1—If carrier removal effects are important, and these depend on the resistivity of the critical device volume, then non-linear effects can become significant. If the critical device volume (for example, the base region in a transistor) is less than 1Ω-cm material, 10^{15}n/cm^2 will be below the onset of significant non-linear effects. For very high resistivity devices, non-linear effects can occur at very low fluences.

X1.10.4 If all of the assumptions just made are valid, and the spectrum in the test environment is known, then the performance in the operational environment can be predicted even if its spectrum is quite different. The spectrum in the operational environment must be known either by measurement or calculation, so that the 1-MeV equivalent fluence in the operational environment (Φ_{1O}) can be calculated by Eq X1.3. Since K_τ was determined from measurements in the test environment, damage in the operational environment can be calculated with Eq X1.9. Alternatively,

$$\Delta\left(\frac{1}{h}\right)_0 = K_\tau \times \Phi_{10}$$

$$\Delta\left(\frac{1}{h}\right)_0 = \Delta\left(\frac{1}{h}\right)_T \times \frac{\Phi_{10}}{\Phi_{1T}} \tag{X1.10}$$

The damage and hence the magnitude of the effect on device performance will be linearly dependent on the Φ_1.

X1.10.5 If, on the other hand, K_τ is a function of fluence, the tester has two choices to ensure test consistency. Either he conducts the test so that $\Phi_{1T} = \Phi_{10}$ or he must find out how K_τ for the device being tested varies as a function of the magnitude of Φ_1 and account for this change. That functional dependence will be very dependent on the device, and cannot be assumed to be the same as that of some other monitor device that he may be using (as discussed in X1.10.3).

X2. RECOMMENDATIONS FOR ENSURING TEST CONSISTENCY

X2.1 This appendix provides additional in-depth discussions and makes recommendations related to the required tasks in Section 5. This expansion of context leads to some repetition in order to preserve continuity. Ideally, all one needs to do is certify that the 1-MeV equivalent fluences in the two environments are the same. The problems in practice are: (*1*) the neutron environments may not be accurately characterized as to spectral shape or fluence; (*2*) there may be additional significant contributors to damage; and (*3*) there may be process faults. This appendix provides recommendations that may be used by test participants to facilitate implementation of the requirements and shed light on the bases for them.

X2.2 *Independent Validation* (Validator)—It would be very useful for all concerned to have in place a validation process that is independent of both the user and the facility that provides the test environment. It is not practical, at this time, to make independent validation mandatory. Nevertheless, a spectrum and 1 MeV-equivalent fluence validation methodology has been developed and validated **(2)** so that determination of suitability of test environments by an independent agency is possible. The process uses a limited set of long half-life foils, silicon transistor monitors, and TLD dosimeters that are exposed in the test environment and read at the validating agency's dosimetry laboratory.

X2.2.1 The user may wish to contract a validator to take on other tasks such as the following: verifying either the suitability of the radiation facility, the quality of the radiation test including the electrical measurements, or the radiation hardness of the electronic part production line. The responsibility includes confirmation that the requirements of this practice assigned to the facility organization (and external support groups, if used) are met and adequately documented. The documentation may include written procedures for calibration, operation, maintenance, hardware and software configuration control of dosimetry systems, procedures for ensuring the desired environments are obtained, and procedures for tracking parts from door to door within the facility. Upon request, the validator should provide documentation as to the suitability of the test environment(s) to users and to the facility organization.

X2.3 *The Neutron Spectra* (Dosimetrist):

X2.3.1 The spectrum should be determined with an accuracy sufficient to ensure that the derived 1-MeV equivalent fluence is known to ± 10 % relative to the reference environments discussed in using the damage function and 1-MeV normalization in Practice E 722. The uncertainty in the damage function is not included in this 10 % uncertainty, but it is assumed that all users use the function listed in Practice E 722. Although other means of determining spectra are available, as mentioned earlier, only the multiple-response-function-sensor-method (usually called the foil activation method) is discussed here. Other methods for determining equivalent fluences are mentioned in X2.6.3. Because the method is discussed thoroughly in Guides E 720 and E 721, the reader is referred to those standards for the full details. Considerations that arise in practical applications of the method are developed further in X2.3.1.1-X2.3.1.4.

X2.3.1.1 Use a large number (>15 if possible) of spectrum sensors, with, most importantly, good spectrum coverage, whose response functions are well established. Reactions with well established sensitivities have been evaluated for consistency with sets of reactions with overlapping sensitivities. See Guides E 720 and E 721 for reactions and references to recommended cross sections for use with activation foils. The set of sensors should have sensitivities that cover a neutron energy range that is broader than the energy range to which the DUTs are sensitive. Coverage beyond that range permits interpolation to interior points rather than extrapolation. In the case when a laboratory has no access to fission foils such as ^{235}U and ^{239}Pu, there tends to be a critical gap in sensor set response between 100 keV and 2 MeV. A silicon DUT may have on the order of 70 % of its response in this range in a pool-type reactor environment. In this case, sensitivity in that range can be obtained by using calibrated silicon bipolar transistors **(1)** or DN-156 diodes **(3)**. Activation foils whose response functions are reaction cross sections are the most commonly used sensors. However, any neutron-sensitive material or device having significant response in the energy and fluence ranges of interest could be qualified as a sensor if its response function is known within reasonable uncertainties. The spectrum adjustment codes can be adapted to use any sensor. The disadvantage of using the PHI1 monitors as spectrum sensors is that then they no longer provide an independent verification of the Φ_1 determined from the spectrum.

X2.3.1.2 The counting laboratory for the activation foils should be able to supply reaction product activities of 20 or more isotopes with a relative accuracy of 5 % or better. The laboratory must maintain calibration procedures that include routine comparisons with primary and secondary NIST-traceable sources.

X2.3.1.3 The sensors should be exposed uniformly in the same configuration as the DUTs. This requires careful attention to a number of factors: (*1*) Does the material of the experiment alter the spectrum at the DUT? (*2*) Can the immediate past operating history of the reactor before the test affect the reactor spectrum? In pool-type reactors, for example, the positions of control rods or even power level can affect the spectrum shape. (*3*) Are the radiation field gradients high enough to necessitate rotating the sensors (in steady state exposures) to ensure that they all see the same field? Corrections for fluence profiles are seldom satisfactory. (*4*) If the foils must be stacked, can there be shadowing? (*5*) Are self-shielding effects possible? Gold foils are particularly vulnerable and should be used in a dilute form (>0.2 % by weight); otherwise, one must anticipate making corrections for self shielding.

X2.3.1.4 Expertise and experience in using at least one of the currently accepted spectrum adjustment codes such as SAND II, LSL-M2, STAY'SL or FERRET are necessary for the proper interpretation of the data. (See Refs **(14–19)** through (22)). The use of SAND II and LSL-M2 is discussed in Guide E 721 for application in transient radiation effects on electronics (TREE) tests. Demonstrated success by the analyst in measuring spectra in well characterized environments is also important.

X2.3.2 Testing can be greatly simplified if the neutron spectrum shape in the test environment can be customized so that it is the same as that in the operational environment. Aside from the difficulty of proving that fact, the analyst can then use Eq X1.8 directly with the activities of a reliable activation monitor such as sulfur or nickel. It is always good practice to use a test environment that is as close as possible to the operational environment because the uncertainties introduced in relating them will then be minimized. Fast burst reactors are often the best choice for TREE testing because the spectrum shape approximates that of many specified operational environments. In addition, for free-field exposures the gamma-ray induced permanent damage is usually small compared to that induced by the neutrons. If possible, choose a test environment with a high neutron-to-gamma ratio, Φ_1/γ, so that corrections for gamma-ray effects either are not significant or can be applied easily. An additional discussion of methods for free-field FBR exposures is presented in X2.5.

NOTE X2.1—In a reactor environment, if the Φ_1/γ ratio is less than 10^{11} n/cm^2/Gy(Si), then the possibility of significant gamma-ray-induced permanent damage in silicon bipolar transistors should be investigated. Some devices such as interdigitated power transistors show significant ionizing dose damage (from gamma rays) even in FBRs.

X2.3.3 Neutron irradiation sources other than FBRs are used for effects testing for a number of reasons. First, the FBR environment may not be available or provide sufficient fluence. Second, for some operational environments, such as endoatmospheric conditions, another environment such as that provided by pool-type reactors may be a better match. These typically provide a spectrum with an enhanced low energy 1/E plus thermal tail, a longer pulse and smaller Φ_1/γ ratio. (The increased risk of gamma-ray contributions to damage is discussed in X2.5.7.) In any case, the spectrum should be determined experimentally for each test environment, or proof obtained that the differences introduced produce insignificant changes in the effects.

X2.3.4 Another complication with pool-type reactors is that the neutron spectrum and, hence, the neutron damage, may be affected by the reactor's operating history, fuel loading, and control rod positions. Verification must be obtained that the conditions were the same during the times of spectrum determination and of the test. Controls should be in place to ensure notification of the dosimetrist or test specialist of reactor changes that might affect the radiation environment at principal test locations. One way to verify that the spectrum has not changed is to compare the various ratios of the activities from the reactions ^{32}S(n,p) ^{32}P, ^{56}Fe(n,p) ^{56}Mn, ^{55}Mn(n,γ) ^{56}Mn, and ^{197}Au(n,γ) ^{198}Au with those obtained during the spectrum measurement. If significant changes in the ratios are observed (±5 %), then a new spectrum determination is required. (If the exposures are long compared to the half-lives of the foils suggested above, then the first three might be replaced by ^{54}Fe(n,p) ^{54}Mn, ^{48}Ti(n,p) ^{48}Sc, and ^{45}Sc(n,γ) ^{46}Sc). Calibrated silicon transistors can also be used to monitor environment changes **(1)**.

X2.3.5 Irradiation by ^{252}Cf may be suitable in instances when the typically low fluence available can be accommodated (such as with very sensitive devices). Although the undegraded spontaneous-fission neutron spectrum shape is well documented, materials around the source can severely modify the radiation field. An evaluation of the need to measure the spectrum must be made.

X2.4 *Neutron Fluence* (Dosimetrist):

X2.4.1 The monitor that is exposed with the DUT should usually be of the same kind as one of the sensors used in the spectrum determination. Its response in the test environment should be compared to the calculated response in the spectrum-measurement exposure to normalize the fluence. This minimizes random error. (It is assumed that during the spectrum-measurement process, the difference between the measured and calculated response is small, indicating small systematic error for that sensor compared to the others.) Sulfur or nickel foils are typical monitor foils because of their favorable sensitivity and half-lives. As with the other sensors, the dosimetry laboratories must maintain a regular calibration schedule with comparison against NIST standards and with other laboratories to ensure that shifts have not occurred in the time between the spectrum determination and the DUT tests.

X2.4.2 One advantage of foils as neutron monitors is that they are generally very insensitive to gamma rays. They also exhibit uniformity, known decay (fading), and lack of sensitivity to temperature and humidity. (If very hard gamma rays, $E > \sim 10$ MeV, are present, then γ,p and γ,n reactions may contribute to foil activation. Examples are ^{57}Fe(γ,p) ^{56}Mn and ^{25}Mg(γ,p) ^{24}Na. Both of these initial isotopes are present in the natural materials and will contribute daughter elements that will add activity not related to the reaction of interest for neutron fluence determination. The use of isotopically pure ^{56}Fe and ^{24}Mg foils eliminates this problem.) Also, the possibility of photofission reactions in fission foils must be considered. These considerations are usually not important for fission type or modified fission type spectra.

X2.5 *Contributors to Damage* (User/Tester)—The responsibility of identifying the major contributors to device damage is primarily the responsibility of the device user/tester.

X2.5.1 If the contributors to damage and the associated response functions for the DUT are not well defined, then the test environment should closely match the operational environment. Fortunately, the silicon response functions are well established, and a variety of environments, if properly characterized, can be used successfully for simulation tests.

X2.5.2 When the test and operational neutron spectra differ, the equivalent fluence methodology required in Section 5 should be applied to ensure displacement damage equivalence. This approach has been validated for silicon over a period of many years and in many environments.

X2.5.3 In 1979, Verbinski et al. **(20)** published the results of a study of the gain changes of bipolar 2N2222A transistors induced by neutrons having a variety of energy spectra. In that work, they provided extensive confirmation of "damage equivalence" for silicon. The damage function used was proportional to the energy available for atomic displacement processes from energetic recoils in bulk silicon. They verified two important concepts. First, the change in the reciprocal of the gain in a bipolar device is proportional to the 1-MeV equivalent fluence, Φ_1, incident on the device, as in Eq X1.9. The proportionality constant is K_τ. Second, that the relative damage induced in different neutron environments can be predicted, provided the neutron spectra and the silicon damage function are known. The spectra were measured by the foil activation method. Within their experimental uncertainty, they also verified the silicon damage function calculated by Rogers et al. **(21)**.

X2.5.4 Since that time, modifications of the silicon response function have been made by use of the improved NJOY Model **(22,23)** and improved cross sections. This updated kerma function is listed in Practice E 722. Also recently added is the damage function for GaAs. It has been demonstrated that the updated silicon cross section **(24)**, differs little from the previous version used in Practice E 722 below 7 MeV. The displacement kerma function for GaAs is multiplied by an empirically determined shape factor that depends on the initial energy of the knock-on nucleus. It has been speculated that this is a thermal-spike or cluster effect; it is not observed in silicon **(25)**.

X2.5.5 Paragraphs X2.3-X2.5.4 through discussed the acquisition of the spectrum and damage function information needed to calculate the neutron displacement damage in bulk silicon (or any other material for which the damage function is known). However, as suggested earlier, this is only part of the parts-testing task. The experimenter must next measure, with sufficient accuracy, the effect of the radiation field on his device (the response) and correlate it quantitatively with the relevant characteristics of that radiation field that affect the damage. Each device is different, so the connection between the effect (for example, change in gain) and the damage must be established by a measurement. In this way, the relationship between the radiation field and the effect is established.

X2.5.6 If the tester can arrange for the test and operational environments to be identical, he knows the device response will be the same barring process faults. At the next level, if he knows that the effect in both environments is a function of the 1-MeV equivalent neutron fluence only, and he can arrange it so that $\Phi_{1t} = \Phi_{1o}$, then consistency also is ensured even if the neutron spectrum shapes differ. This assumes that other phenomena do not contribute significantly to the response, or that the effects have been subtracted out.

X2.5.7 Secondary effects that must be accounted for are the following:

X2.5.7.1 In bipolar transistors, ionization caused both by gamma rays and indirectly by neutrons can lead to charge trapping and interface states that affect the gain. In metal-on-silicon transistors (MOS) and integrated circuits, the effects of interface states and trapped charge produced by both gamma-ray and neutron ionization are highly time-dependent. This leads to complex device response that is a function of ionizing dose, dose rate, and the time between irradiation and device characterization **(26)**. In addition, because of dose-enhancement effects at interfaces between high and low atomic number materials, the dose to a sensitive region of a device can be significantly different from that measured by standard dosimetry techniques **(27)**. This is especially true in the softer photon spectra present in pool reactors.

X2.5.7.2 High energy gamma-rays can indirectly produce displacements in semiconductor crystals. Therefore, if the flux of hard gamma-rays is high, the displacement damage from gamma rays can be comparable to that induced by neutrons. (For example, a 10-cm thick cadmium loaded polyethylene filter outside an FBR can reduce the Φ_1/γ ratio by a factor of 20). The gamma-ray-induced damage cannot be directly correlated with the neutron spectrum. If the device is tested in a pure gamma ray field so that a scaled version of its response can be subtracted, it is not certain that this response will be the same as that produced during the neutron test unless the photon spectra are the same. One should, nevertheless, always include thermoluminescent detectors along with the neutron monitors during tests.

X2.5.7.3 Displacement damage in gallium arsenide depends not only on the displacement kerma, but also on the energy of the primary recoil atoms **(25)**. At this time silicon and gallium arsenide are the only semiconductors with validated damage equivalence models.

X2.5.7.4 Thermal neutrons can produce damage through interactions with dopant materials such as boron that are not accounted for in standard damage-equivalence models. There have even been cases in which the natural abundance of fissile materials in the ceramic lids on memory devices is high enough for thermal neutrons to produce fission fragments that damage the devices.

X2.5.8 Semiconductor devices are more complicated than activation foils, and even the measurement of their response has to be carried out with an appreciation for the factors that affect their performance. The electrical characteristics, such as initial gain, and the response to radiation of individual devices may vary by unacceptable amounts, perhaps as high as a factor of two for the same type of device. The radiation sensitivity is reflected directly in K_τ. Therefore, to determine a damage constant that is representative of a batch, a large number may have to be exposed ($\geq$10), and the standard deviation of the K_τ for the calibration batch should be ~5 %.

X2.5.9 After exposure of bipolar transistors, annealing of defects (~20 % between 0.5 hours and 1 month) lead to a recovery of gain that necessitates annealing corrections, annealing treatments, or long waiting periods before measurements are carried out. Even a measurement on each transistor, at the same time interval after each exposure, must be handled carefully because after the second exposure, there are two populations of displaced atoms annealing at different rates. It has also been observed that the process of measurement (current injection) may alter the DUT performance. Thus, additional measurements may give different results. Furthermore, the response that is measured depends on the temperature of the device during the measurement **(1)**, and above a certain accumulated exposure the reduction of the base transit time makes the damage nonlinear with respect to fluence. Because of the effects cited in X2.5.8 or X2.5.9 that experimentally impose uncertainties onto the gain measurements, it is important to deliver enough radiation to induce gain changes much larger than the uncertainties. This is because the damage is proportional to the difference in the reciprocal of the gains before (h_{FEO}) and after ($h_{FE\Phi}$) exposure. If this difference, $1/h_{FE\Phi} - 1/h_{FEO}$, is small, the fractional error in the damage can be magnified by as much as $(h_{FEO} + h_{FE\Phi})/(h_{FEO} - h_{FE\Phi})$.

NOTE X2.2—In the testing of large systems, the neutron spectrum and neutron-to-gamma ratio may vary within the system. Therefore, either the environment at each location must be characterized or the uncertainties must be expanded.

X2.6 *The Device Transfer Method of Approximating* Φ_1:

X2.6.1 As mentioned in Note 5, the transfer method with transistors provides an estimate of the 1-MeV equivalent fluence, Φ_1, that can be used to predict silicon device performance in the operational environment. One would need to calibrate a well characterized transistor, such as a 2N2222A **(1)**, or a Harshaw DN-156 diode **(3)**, in a reference environment (whose spectrum is known) and then expose it in the test environment along with the DUT. The calibration determines the damage constant for the device so measurement of its response in the test environment determines the value of $\Phi^*_1 = \Delta(1/h)/K_\tau$. The transfer process is discussed at the end of Appendix X1. However, this process is inadequate in that it does not verify that the damage in the test environment correlates with neutron displacement damage because other factors such as gamma ray effects may contribute to the damage.)

X2.6.2 It is necessary to account for all the factors that affect the determination of Φ_1 that have been discussed in X2.5. This involves also the determination of the response for secondary effects for both the sensor and the DUT. A strong justification for the use of a silicon monitor as part of a spectrum sensor set is that its measured Φ_1 can be compared to the calculated fluence derived from about 20 other measurements from other sensors. Some risks and advantages of device-transfer method are listed in Appendix X3.

X2.6.3 Because fast burst reactors operated in a free air environment have already been so well characterized **(12, 28-30)** and their stability of output can be easily maintained over long periods of time, they are suitable for the application of the device-transfer technique, provided that the test and operational environments do not differ excessively from that "free air" character. In those cases 2N2222A bipolar transistors **(1)** and Harshaw DN-156 diodes **(3)** have been shown to be valid indicators of Φ_1 (silicon). Confirmation with additional measurements can be obtained with proton recoil, ionization chamber, and foil activation measurements along with calculated spectra. In fact, transport calculations offer significant additional information that cannot be obtained as yet from the multiple sensor measurements. Specifically, they can provide gamma-ray spectra and fine structure in the neutron spectra. (For damage in silicon, fine structure in the spectrum usually occurs at energies lower than is relevant to semiconductor damage.)

X2.6.4 The multiple sensor and device transfer methods of determining Φ_1 have contrasting advantages and disadvantages. The comparisons are discussed further in Appendix X3.

X3. DISCUSSION OF MULTIPLE SENSOR AND DEVICE TRANSFER METHODS

X3.1 There are some test conditions for which the device-transfer method for determining the 1-MeV equivalent fluence in the test environment may prove to be the only option available. This method yields the 1-MeV equivalent fluence without the use of a test environment spectrum. It is a better course than using the wrong spectrum, but provides no confirmation that the damage at the test location correlates directly with the neutron environment. Success in its use depends on the proper accounting for all factors that significantly affect the device performance, but any factors that depend on neutron spectrum cannot be properly treated. It is recommended, in this case, to apply the method only to silicon bipolar devices or diodes in situations in which the gamma-ray response of the monitors is small (because the DUT may differ from the PHI1 monitor) and in environments that can be shown to differ only moderately from the one for which a full spectrum determination has been obtained. Since confirmation of the measured 1-MeV equivalent fluence may be lacking, this method must be considered as a secondary level of characterization. Its use must be negotiated between the user and the facility operator.

X3.2 The multiple sensor and device transfer methods of characterizing radiation environments have contrasting advantages and disadvantages.

Foils Versus Devices for Reactor Environment Characterization

Multiple Sensor	Devices
Redundancy	One to two well characterized devices
Determine spectrum	No spectral knowledge
Source for transport code	No spectral knowledge
Works for all materials	Works for material of device (out)
No temperature problem	Temperature sensitive
Well known fading (decay)	Variable fading—compensated by oven annealing
Little gamma sensitivity	Gamma sensitive—gamma sensitivity of DN-156 Diodes is negligible for most environments
Expensive equipment	Less expensive
Multiple Sensor	Devices
Time consuming (experiment and unfolding)	Simple with defined controls
Non-portable	Portable
Some foils difficult to obtain (for example, Pu)	Commercially available, but n/γ response is variable

X3.2.1 Foils provide a spectrum and apply to all materials. Foils are not sensitive to environmental effects. Devices are straightforward to run, but are subject to additional test complications such as temperature effects, dose enhancement, and degradation. They are suitable for frequent checks and for interfacility comparisons.

X3.2.2 With devices alone, there is no confirmation from other sensors that the Φ_1 has been determined properly. When a full sensor set is used to characterize the test environment, the compatibility among all the sensors, including the silicon, confirms the characterization and the Φ_1. If only silicon or only ^{235}U or ^{239}Pu are used, the confirmation of the spectrum in the 10 keV to 600 keV is lost.

X3.2.3 It is more difficult to show that secondary effects are not contributing to the test device response. If a silicon monitor confirms the test spectrum, it implies that secondary effects, such as ionization response, are not contributing. Another example of a potential problem is the case where the device under test has gold as part of the package. This material may induce dose-enhancement effects or excessive activation. With a neutron spectrum and dose measurements available, one can evaluate these effects more reliably.

X3.2.4 Without a spectrum, the inclusion of the usual monitors, such as sulfur foils only, is no longer reliable if the operational and simulation environments differ. It is the spectrum shape that permits a connection to be made between the sulfur activity and the device damage. In principle, a PHI1 monitor could be used in place of a spectrum to determine Φ_1 if it has the same response as the DUT.

X3.2.5 With a known spectrum in hand, one can predict the response of any other object or material for which the response function is known.

X4. GAMMA RAY EFFECTS TESTING IN REACTOR ENVIRONMENTS

X4.1 An experimenter interested in observing the effects generated by photons may require nuclear reactors because they can provide some useful gamma-ray environments, such as modest dose rates (up to 10^9 rad(Si)/s with pulsewidths up to several milliseconds) that are not attainable from other sources. Reactors can provide high total dose without debiasing the electronic devices that are exposed. Given that a reactor source is needed, it is best to find configurations in which the relative neutron contributions are low. Many of the points discussed in this section are relevant in accounting for the secondary effects caused by gamma-rays when neutron damage is being investigated.

X4.2 When the experimenter is choosing an environment for his irradiations, he needs to compare the neutron fluence to gamma-ray dose ratios available. Presumably, when neutron fluence and spectra are determined, an ionizing dose will be measured simultaneously with a gamma sensor such as a thermoluminescent dosimeter. The gamma sensors should have electron equilibrating covers designed for the radiation environment being characterized. One can then calculate the Φ_1/γ ratio and choose the most suitable environment. To do this, one should evaluate the approximate contribution of the undesirable component of the radiation field to the device response, in order to make corrections. Clearly, for gamma-ray exposures, a low Φ_1/γ ratio is desirable. In spacious experimental regions, this might be obtained with cadmium and polyethylene filters.

NOTE X4.1—In most cases the neutron response of CaF_2 TLDs is quite small (typically recording a gamma-equivalent response of 1 to 2 % of the actual neutron-induced ionizing dose in silicon). Fortunately, when neutron damage dominates a test, the TLD dose is only used to make a small correction to the DUT response, and the error introduced by the TLD neutron response will have a negligible effect. On the other hand, if the test is designed to have a high gamma-to-neutron ratio so that gamma-ray effects dominate, a small TLD neutron response will still contribute only a small error to the gamma dose measurement.

X4.3 Both ionizing dose and dose rate determine the responses that are important in MOS devices because there are both oxide-trapped charge creation and interface-state generation occurring, and their effects on device performance have different time scales. Although the detailed mechanisms are not understood, dose rate dependency has also been observed in bipolar integrated circuits. The dose rate effects may be divided into three regimens.

X4.3.1 *Low Dose Rate*—In thin gate oxides, the oxide trapped charge is annealed during exposure. This causes the device response to be dominated by interface state charge. In thick gate oxides or field oxides, the buildup of oxide charge dominates despite the annealing and the creation of interface states.

X4.3.2 *High Dose Rate*—The prompt damage measured a short time after exposure may be dominated by oxide trapped charge. This may occur at rates between 10^1 and 10^7 Gy(Si)/s. At longer times after exposure, interface states may again dominate.

X4.3.3 *Intermediate Dose Rate*—These rates may be produced in gamma cells and other radioactive isotope environments. Since interface state and oxide trapped charge tend to compensate each other, the observed damage rate may actually be less than in either the high or low generation rate environments. Thus, the measured effects may be poor indicators of what the response will be in the operational environment.

NOTE X4.2—In some cases devices exposed at high dose rates can be annealed to determine their response in low dose-rate environment. However, it may not always be possible to simulate high dose-rate effects with lower dose-rate environments. Therefore, devices must sometimes be tested in the rate environment in which they will be used.

X4.4 In tests that require most of the dose to be delivered during a short pulse, the fraction of dose delivered during the pulse must be ascertained. In pool-type reactors, there may be large contributions from both the tail of the pulse and delayed gamma rays from the fission products in the reactor core. The tail contribution may be reduced by specifying a "short rod holdup" time. Then the package may have to be removed from the core very soon after the pulse to reduce the delayed gamma-ray contribution. This contribution can equal or exceed the gamma dose delivered during the pulse, especially if the reactor has recently been operated in a high energy mode (leaving many gamma-ray-emitting fission products in the vicinity of the test volume). Even the positions of material objects such as control rods can have significant effects on dose rates and gamma-ray spectra.

X4.5 It is important that the dose measured by the dosimeter be the same as was deposited in the sensitive regions of the test devices. Because many of these devices have electrodes and conductors incorporating high-Z materials, such as gold, the high photoelectric cross section can cause injection of more electrons into the sensitive regions of semiconductors than would be the case if electron equilibrium existed **(6,7)**. Thus, if the gamma-ray field contains a significant fraction of soft photons, the dose in the device can be much larger than the dose in the dosimeter. An ionization chamber has been designed **(8)** with gold or aluminum electrodes for measuring the relative contribution of soft photons in a gamma-ray field (see Test Method E 1250). A high ratio of current in the side with Au electrodes compared to that with Al electrodes, ($\sim$3), indicates soft components that must be eliminated if the dose measurement is to be meaningful (1.25-MeV average energy photons from ^{60}Co produce a ratio of 1.6). Some typical values for these chamber ratios are 1.8 for the Sandia Pulsed Reactor III (SPR III) at 43 cm, 1.8 for the SPR III cavity, and 3.2 for the Annular Core Research Reactor (ACRR) bare cavity. In configurations in which gamma-ray down scattering (Compton scattering) can take place without enough attenuation, the soft component can have a significant effect. The recommended procedure **(9)** is to line test boxes with 1.5 mm of lead followed by 1.0 mm of aluminum to reduce the soft component. Tests have shown that this lining procedure is very effective in reducing dose-enhancement effects **(10)** (see Practice E 1249).

X4.6 It is, in fact, rare that a measured gamma-ray spectrum is available to those testing parts in a reactor environment. It is usually necessary to assume that the simulation and operational environments have the same spectrum character and that it can be approximated by a fission-gamma shape **(11)**. At this time, it is not fruitful to develop an equivalent gamma-ray fluence testing methodology. The only recourse is to design the test environment to mimic the operational environment as closely as possible. That is one reason for using radiation filter systems to minimize the effects of undesirable components in the environment.

X5. CUSTOMIZED ENVIRONMENTS

X5.1 The advantages of finding simulation environments as close as possible to the operational environment provides an impetus for modifying or customizing the reactor environment. Furthermore, in reactors with large test volumes there is room for thick and massive filters for making the necessary modifications while still leaving room for the experiment. In particular, Cd-polyethylene and Pb-B filters (lead and boron) can be used to modify Φ_1/γ ratios by orders of magnitude. However, it may be necessary to consider how these environments differ from the operational environment in other ways.

X5.2 For example, two configurations, the SPR-III and the Pb-B lined external cavity at the ACRR, exhibit approximately the same Φ_1/γ ratio but differ by orders of magnitude at the epithermal end of the neutron spectrum. A device that is particularly vulnerable to thermal neutrons will be more strongly affected by the pool-type ACRR configuration. Therefore, a device with gold contacts will become more activated in the pool-type reactor cavity, and this may result in a delay in the characterization tests. A boron filter can be used to reduce this activation.

X5.3 In order to aid both operators and experimenters in evaluating and choosing appropriate experimental configurations, it is recommended that master parameter charts that characterize all the reactor configurations that are available for tests be constructed by each facility.

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