Designation: ~~E1854 – 07~~ E1854 – 13

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

This standard is issued under the fixed designation E1854; 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~~ sources, accelerator-based neutron sources, such as 14-MeV DT sources, and ^{252}Cf ~~testing when this source is used for this application.~~ sources. 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.~~ to recognize, minimize or eliminate these problems. 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~~ whole. Electrical measurements are addressed in other ~~standards.~~ standards, such as Guide F980. Additional information on conducting irradiations can be found in Practices E798 and F1190. This practice also may be of use to test sponsors ~~(that is, organizations~~ (organizations that establish test specifications or otherwise have a vested interest in the performance of electronics in neutron environments).

1.3 Methods for the evaluation and control of undesired ~~contributors~~contributions to damage are discussed in this ~~practice, and references~~ practice. 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 and recommendations are addressed in Appendix X1 ~~through X1.3.1~~(Nonmandatory ~~information)..~~information).

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 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.

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

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2.2 *ASTM Standards:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry
E181 Test Methods for Detector Calibration and Analysis of Radionuclides
E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E262 Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques
E263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron
E264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel
E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters
E481 Test Method for Measuring Neutron Fluence Rates by Radioactivation of Cobalt and Silver
E482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E706 (IID)
E496 Test Method for Measuring Neutron Fluence and Average Energy from ^{3}H(d,n)^{4}He Neutron Generators by Radioactivation Techniques
E523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper
E526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium
~~E665 Practice for Determining Absorbed Dose Versus Depth in Materials Exposed to the X-Ray Output of Flash X-Ray Machines (Withdrawn 2000)[3]~~
E666 Practice for Calculating Absorbed Dose From Gamma or X Radiation
E668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices
E704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238
E705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237
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
E798 Practice for Conducting Irradiations at Accelerator-Based Neutron Sources
E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)
E1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E706 (IIB)
E1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources
E1250 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
E1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium
E1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors
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
F980 Guide for Measurement of Rapid Annealing of Neutron-Induced Displacement Damage in Silicon Semiconductor Devices
F1190 Guide for Neutron Irradiation of Unbiased Electronic Components

3. ~~The Roles of the Participants~~ Functional Responsibilities

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~~who 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,

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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.

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~~ specialist, who may be 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 of record 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~~who 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.

~~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;~~ operate (the operational environment); 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 F1190.

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~~ produced by 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~~effects are presented in (non-mandatory) Appendix ~~X2~~X1 and Appendix ~~X3~~X2, but compliance is not required.

4.4 Some neutron tests are performed with ~~an~~ a specific end application ~~of~~for 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 the data that is obtained in the test environments. If ~~these~~ the operational and test environments differ materially from each other, then damage equivalence methodologies are required in order to make the required correspondences. ~~The~~This process is shown schematically in Fig. 1. The part of the process (A, in Fig. 1) that establishes the operational 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~~1 MeV equivalent fluence specification level, it is ~~Fig. 1), it is important that this~~important that the process (B, in Fig. 1~~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~~may not ~~ensured.~~ be met. 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 E722 (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 E722 reference outdated versions of the silicon damage function and do not include GaAs damage functions. However, when comparing test specifications and test results from data obtained in historical tests, it may be necessary to adjust specifications and test data to account for changes in damage functions which have evolved through the years as more accurate and reliable damage functions have become available.

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~~ 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 E722.

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 the 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~~X1).

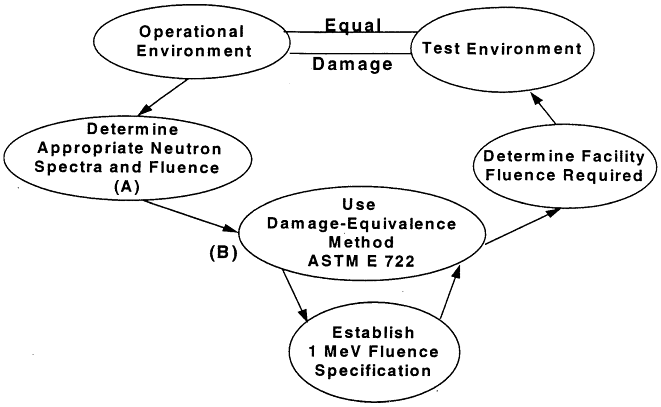

FIG. 1 Process for Damage Equivalence

5.4 *Environment ~~Characterization~~ Characterization—~~(Facility Operator and Test Specialist)—~~*It is assumed ~~in this section~~ throughout the standard that the primary damage mechanism being investigated is the neutron displacement damage. If secondary effects (such as those caused ~~be~~by 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 5.12.1 and 5.12.2. 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 E720 and E721.) A free-field spectrum based solely upon neutron transport calculations for a reactor irradiation is not acceptable. ~~If~~ Physics constraints associated with some accelerator-based neutron sources may be sufficient for spectrum characterization when used in conjunction with normalization measurements such as are described in Test Method E496 for 14-MeV DT sources. Neutron spectra from isotopic sources, such as ^{252}~~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.~~Cf, may be used to leverage spectrum determinations performed at other facilities as long as the irradiation source and geometry are sufficiently similar. It is acceptable that the experimental measurements supporting the spectrum characterization be performed at a different, but near-by, location rather than the characterized position, as long as one can use calculations to relate the sensor response between the characterized position and the location where the sensors are fielded and if the analysis is accompanied by a high fidelity assessment of the calculated ratio of the sensor response in the two positions.

5.4.1.1 If the fixtures used by the experimenter significantly perturb the free-field environment that was characterized by the facility, then the experimenter shall be responsible for properly relating the irradiation environment impacting the device-under-test to the freefield radiation environment characterization that is provided by the facility.

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 E181, E262, E393, E481, E523, E526, E704, E705, and E1297, Practice E261, and Guide E844.

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 boron-covered fission foils, ^{235}~~U,~~ U and ^{239}Pu, ~~and~~ as well as the ^{237}~~Np.~~ Np fission foil. 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.~~ sensors responsive within this energy range. It is suggested that both fission foils and silicon devices be used for mutual confirmation (**1**,**2**).[3]

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~~ an 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.~~ fluence rate. 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~~ Equivalence—~~(Facility operator, Validator)—~~*The facility shall provide, at 15-month intervals or less, experimental confirmation that the equivalent fluence is ~~equal to~~consistent with that predicted by the ~~spectrum. This~~ facility-provided spectrum. The emphasis here is on the stability and consistency of the neutron field since the time of the complete spectrum characterization. One way that this may be done is by demonstrating that the ~~damage measured in a standardized and~~ displacement damage, as measured with 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~~ device calibration could be an irradiation in a reference neutron environment, see 5.6~~as the PHI1 monitor to distinguish it from the DUT.~~, or a reference calibration can be obtained by irradiating the device within the same time period (not necessarily in the same irradiation) as when the baseline experimentally supported spectrum characterization referenced in 5.4 was performed. Two devices appropriate to this application, because of extensive investigations of their responses, are 2N2222A transistors (see Test Method E1855) 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 reproducible, but nonlinear, way (The shape of the calibration curve is the same for all of the diodes.) ~~(see 5.9 and Practice E722). Thus, 2N2222A transistors and DN-156~~

~~[3] The last approved version of this historical standard is referenced on www.astm.org.~~

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

~~diodes are appropriate PHI1 monitors if they are calibrated in the environments whose spectra (and consequently Φ_T) are well established.~~ The environment is considered to be satisfactorily characterized for electronic parts testing if the ratio of the Φ_1~~,~~ ~~measured with~~ damage value to a reference monitor, such as the ^{58}~~pHI1~~Ni(n,p)^{58} ~~monitors,~~ Co activity obtained from the simultaneous irradiation of a nickel foil is within 10 % of that predicted using the spectrum and fluence reported by the test facility for that location (see Note 3). Another acceptable way to demonstrate this stability and consistency of the neutron field is to irradiate a subset of sensors that were used in the baseline experimentally supported spectrum characterization (see 5.4) and demonstrate the consistency in the ratio of the sensor response values to a reference/monitor reaction, such as ^{58}Ni(n,p)^{58}Co, with the values obtained during the baseline spectrum characterization. The subset of sensors used must be one that includes sensors with good energy coverage over the range of neutron energies that are important to the displacement damage metric of interest, typically between 10 keV and 5 MeV.

NOTE 3—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 *Reference Environment*—~~The~~ If a reference environment is used for the calibration of the PHI1 monitors used in 5.5, this reference neutron field shall be either a standard fast neutron benchmark field **(4)** or a reference neutron benchmark field (see ~~Guide 2005~~Guide E2005 and the definitions of "standard neutron field" and "reference neutron field" in Terminology E170) designated for neutron effects testing in semiconductors. ~~Suitable standard fast neutron fields are ^{252}Cf spontaneous fission neutron fields realized in a low-scattering environment: either the one implemented at NIST (4) or one which has been demonstrated by intercomparison to be equivalent with respect to its neutron field characteristics.~~ Reference benchmark fields that may be designated for this application are generated by bare fast-fission reactors, either in an in-core cavity or in a nearby leakage environment that is not substantially modified by room-return neutrons. The relevant neutron field parameters must be established by calculation and spectrum measurement in the manner described in Guide E721, and, in addition, must be experimentally verified ~~by exposure,~~ within an interval no longer than five ~~years, of a PHI1 monitor or other fluence transfer monitor that is calibrated to a standard~~ years and the basis for the experimental verification documented and made available by facility users.^{252}~~Cf field.~~

5.7 *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 E722), 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.

5.8 *Controls and ~~Auditability~~ Auditability—~~(Facility Operator)—~~*The facility (including the reference source FBRs) must provide written assurance that an adequate radiation 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:

5.8.1 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.

5.8.2 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.

5.8.3 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.

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

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

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

5.9.2 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 convenient half-lives.

5.9.3 Suitable gamma dose sensors shall be used to monitor the gamma-ray ~~dose.~~ dose discussed in Practice E666. If thermoluminescence dosimeters are selected as the gamma sensor, Practice E668 provides useful information on the calibration and use of TLDs in gamma environments. ~~In~~Practice E2450 provides useful information on the use of TLDs in mixed neutron and gamma ray ~~fields,~~ fields. The sensor selected to monitor the gamma ~~sensor~~environment should have a demonstrated low neutron sensitivity. CaF$_2$:Mn TLDs are an appropriate sensor for ~~most applications.~~application in most mixed neutron/gamma ray fields.

5.9.4 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.

5.10 *Damage ~~Correlations~~ 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 E722. 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 (**5,6**). 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 E722~~, 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.~~

5.11 *Test Device Response ~~Function~~ 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~~ The latest functions from Practice E722 ~~should be used.~~ shall be used for neutron displacement damage functions. 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 5.12.1 and 5.12.2.

5.11.1 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 gamma filters such as lead or bismuth surround the test object, the neutron spectrum will be modified and must be determined for that configuration.

5.11.2 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.

5.12 *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.

5.12.1 *Secondary Gamma-Ray ~~Effects~~ 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~~ fluence rate 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~~X1. 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 E668. ~~Details on~~Practice E2450 ~~gamma sources can be found in Practices~~describes a procedure for measuring gamma-ray absorbed ~~E665 and~~dose in ~~E666.~~CaF_2(Mn) TLDs exposed to mixed neutron-photon environments.

5.12.2 *Other Secondary Effects*—Other potential contributors to measured DUT performance include displacement damage annealing (which can actually aid in device performance recovery), the temperature and device electrical currents 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 alpha particles can result from these 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 E1249 and Test Method E1250.

5.12.3 *Measurements for the DUT ~~Environment~~ 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~~co-located 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 E263, E264, and E265. 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 E720 or E721 or Practice E722 or their equivalent.

~~5.12.3.1 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 E720 or E721 or Practice E722 or their equivalent.~~

5.12.4 The determination of (*1*) the spectrum shape from the environment characterization, and (*2*) the magnitude of the 1-MeV fluence (derived ~~form~~from 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 E482 and E1018, and Practice E944.

~~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.~~

5.13 *Test Documentation*—The user, with the assistance of the other participants, is responsible for making certain that all the tasks listed above (in 5.1-5.12) 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.

~~5.13.1 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.~~

5.13.1 In the usual mode of operation, as discussed in 5.7, 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.

~~5.13.3 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.~~

~~5.14 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;~~reactors; test consistency ; 1 MeV-equivalence

~~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 E722. Instead of directly relating the total displacement energy in two neutron environments, Practice E722 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 E722 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 E722 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:~~

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

~~where:~~

~~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 F^{-}_{D} × Φ is the total displacement damage, a fluence of neutrons that would produce an equivalent amount of displacement damage is given by:~~

$$\Phi_{E_{ref}} \times F_{D,E_{ref}} = \bar{F}_D \times \Phi \quad \text{(X1.2)}$$

~~where:~~

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

~~When E_{ref} = 1 MeV, then $F_{D,1\ \text{MeV}}$ = average damage produced by a 1-MeV neutron. For silicon, $F_{D,1\ \text{MeV}}$ 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:~~

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

~~where Φ_1 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, Φ(E> 3 MeV) equals the fluence of neutrons with energy greater than 3 MeV.~~

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

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

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

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

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

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

~~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 Φ = Φ(E> 3MeV) × 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 E720 and E721).~~

~~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 (**7,8**)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}Pin 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.~~

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

~~This is the same procedure as is described in Practice E722.~~

~~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 γ,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 E722. 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.~~

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

~~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~~