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Standard Guide for
Neutron Irradiation of Unbiased Electronic Components[1]

This standard is issued under the fixed designation F1190; 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 guide strictly applies only to the exposure of unbiased silicon (Si) or gallium arsenide (GaAs) semiconductor components (integrated circuits, transistors, and diodes) to neutron radiation from a nuclear reactor source to determine the permanent damage in the components. Validated 1-MeV displacement damage functions codified in National Standards are not currently available for other semiconductor materials.

1.2 Elements of this guide, with the deviations noted, may also be applicable to the exposure of semiconductors comprised of other materials except that validated 1-MeV displacement damage functions codified in National standards are not currently available.

1.3 Only the conditions of exposure are addressed in this guide. The effects of radiation on the test sample should be determined using appropriate electrical test methods.

1.4 This guide addresses those issues and concerns pertaining to irradiations with reactor spectrum neutrons.

1.5 System and subsystem exposures and test methods are not included in this guide.

1.6 This guide is applicable to irradiations conducted with the reactor operating in either the pulsed or steady-state mode. The range of interest for neutron fluence in displacement damage semiconductor testing range from approximately 10^9 to 10^{16} 1-MeV n/cm^2.

1.7 This guide does not address neutron-induced single or multiple neutron event effects or transient annealing.

1.8 This guide provides an alternative to Test Method 1017.3, Neutron Displacement Testing, a component of MIL-STD-883 and MIL-STD-750. The Department of Defense has restricted use of these MIL-STDs to programs existing in 1995 and earlier.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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
E668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices
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
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
E1854 Practice for Ensuring Test Consistency in Neutron-Induced Displacement Damage of Electronic Parts
E1855 Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors
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

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[1] This guide is under the jurisdiction of ASTM Committee F01 on Electronics and is the direct responsibility of Subcommittee F01.11 on Nuclear and Space Radiation Effects.

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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.

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2.2 *Other Documents:*

2.2.1 The Department of Defense publishes every few years a compendium of nuclear reactor facilities that may be suitable for neutron irradiation of electronic components:

DASIAC SR-94-009, April 1996, Guide to Nuclear Weapons Effects Simulation Facilities and Techniques[3]

2.3 *The Office of the Federal Register, National Archives and Records Administration publishes several documents that delineate the regulatory requirements for handling and transporting radioactive semiconductor components:*

Code of Federal Regulations: Title 10 (Energy), Part 20, Standards for Protection Against Radiation[4]

Code of Federal Regulations: Title 10 (Energy), Part 30, Rules of General Applicability to Domestic Licensing of Byproduct Material[4]

Code of Federal Regulations: Title 49 (Transportation), Parts 100 to 177[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *1-MeV equivalent neutron fluence* $\Phi_{eq,\,1\,MeV,\,Si}$ —this expression is used by the radiation-hardness testing community to characterize an incident energy-fluence spectrum, $\Phi(E)$, in terms of monoenergetic neutrons at a specific energy, $E_{ref} = 1$ MeV, required to produce the same displacement damage in a specific irradiated material, denoted by the subscript as "matl" (see Practice E722 for details).

3.1.1.1 *Discussion*—Historically, the material has been assumed to be silicon (Si). The emergence of gallium arsenide (GaAs) as a significant alternate semiconductor material, whose radiation damage effects mechanisms differ substantially from Si based devices, requires that future use of the 1-MeV equivalent fluence expression include the explicit specification of the irradiation semiconductor material.

3.1.2 *equivalent monoenergetic neutron fluence* ($\Phi_{eq,Eref,\,matl}$)—an equivalent monoenergetic neutron fluence that characterizes an incident energy-fluence spectrum, $\Phi(E)$, in terms of the fluence of monoenergetic neutrons at a specific energy, E_{ref}, required to produce the same displacement damage in a specified irradiated material, matl (see Practice E722 for details).

3.1.2.1 *Discussion*—The appropriate expressions for commonly used 1-MeV equivalent fluence are $\Phi_{eq,\,1\,MeV,\,Si}$ for silicon semiconductor devices and $\Phi_{eq,\,1\,MeV,\,GaAs}$ for gallium arsenide based devices. See Practice E722 for a more thorough treatment of the meaning and significant limitations imposed on the use of these expressions.

3.1.3 *silicon damage equivalent (SDE)*—expression synonymous with "1-MeV(Si) equivalent fluence in silicon."

4. Summary of Guide

4.1 Evaluation of neutron radiation-induced damage in semiconductor components and circuits requires that the following steps be taken:

4.1.1 Select a suitable reactor facility where the radiation environment and exposure geometry desired are both available and currently characterized (within the last 15 months). Practice E1854 contains detailed guidance to assist the user in selecting a reactor facility that is certified to be adequately calibrated.

4.1.2 Prepare test plan and fixtures,

4.1.3 Conduct pre-irradiation electrical test of the test sample,

4.1.4 Expose test sample and dosimeters,

4.1.5 Retrieve irradiated test sample,

4.1.6 Read dosimeters,

4.1.7 Conduct post-irradiation electrical tests, and

4.1.8 Repeat 4.1.4 through 4.1.7 until the desired cumulative fluence is achieved or until degradation of the test device will not allow any further useful data to be taken.

4.2 Operations addressed in this guide are only those relating to reactor facility selection, irradiation procedure and fixture development, positioning and exposure of the test sample, and shipment of the irradiated samples back to the parent facility. Dosimetry methods are covered in existing ASTM standards referenced in Section 2, and many pre- and post-exposure electrical measurement procedures are contained in the literature. Dosimetry is usually supplied by the reactor facility, see Practice E1854.

5. Significance and Use

5.1 Semiconductor devices can be permanently damaged by reactor spectrum neutrons (**1, 2**)[5]. The effect of such damage on the performance of an electronic component can be determined by measuring the component's electrical characteristics before and after exposure to fast neutrons in the neutron fluence range of interest. The resulting data can be utilized in the design of electronic circuits that are tolerant of the degradation exhibited by that component.

5.2 This guide provides a method by which the exposure of silicon and gallium arsenide semiconductor devices to neutron irradiation may be performed in a manner that is repeatable and which will allow comparison to be made of data taken at different facilities.

5.3 For semiconductors other than silicon and gallium arsenide, applicable validated 1-MeV damage functions are not available in codified National standards. In the absence of a validated 1-MeV damage function, the non-ionizing energy loss (NIEL) or the displacement kerma, as a function incident neutron energy, normalized to the response in the 1 MeV energy region, may be used as an approximation. See Practice E722 for a description of the method used to determine the damage functions in Si and GaAs (**3**).

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[3] Available from Defense Special Weapons Agency, Washington, DC 20305-1000.

[4] Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

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

6. Interferences

6.1 *Gamma Effects:*

6.1.1 All nuclear reactors produce gamma radiation coincident with the production of neutrons. Prompt gamma rays are produced directly in the fission process, from neutron transmutation reactions with reactor support materials and test objects. Delayed gamma rays are emitted by fission products and activated materials. Furthermore, these gamma rays can produce secondary gamma rays and fluorescence photons in reactor fuel, moderator, and surrounding materials. Since degradation in piece part performance may be produced by gamma rays as well as neutrons, and because of the softer photon spectra dose enhancement may be a problem. If a separation of neutron (n) and gamma ray (γ) degradation is desired, either the n/γ ratio must be increased to the point at which gamma effects are negligible or the test sample degradation must first be characterized in a "pure" gamma ray environment and one must have a basis for believing that the damage mode of concern does not exhibit any synergy between the neutron and gamma response. The use of such data from a gamma ray exposure to separate neutron and gamma effects obtained during a neutron exposure may be a complex task. If this approach is taken, Guide F1892 should be used as a reference. Guides E1249 and E1250 should be used to address dose enhancement issues.

6.1.2 TRIGA-type reactors (Training Research and Isotope production reactor manufactured by General Atomics) deliver gamma dose during neutron irradiations that can vary considerably depending on the immediately preceding operating history of the reactor. A TRIGA-type reactor that has been operating at a high power level for an extended period prior to the semiconductor component neutron irradiation will contain a larger fission product inventory that will contribute significantly higher gamma dose than a reactor that has had no recent high level operations. The experimenter must determine the maximum gamma dose his experiment can tolerate, and advise the facility operator to provide sufficient shielding to meet this limit.

6.2 *Temperature Effects*—Annealing of neutron damage is enhanced at elevated temperatures. Elevated temperatures may occur during irradiation, transportation, storage, or electrical characterization of the test devices.

6.3 *Dosimetry Errors*—Neutron fluence is typically reported in terms of an equivalent 1-MeV monoenergetic neutron fluence in the specified irradiated material ($\Phi_{eq,\ 1\ MeV,\ Si}$ or $\Phi_{eq,\ 1\ MeV,\ GaAs}$) in units of neutrons per square centimeter. ASTM guidelines and standards exist for calculating this value from measured reactor characteristics. However, reactor facilities may not routinely re-measure the neutron spectrum, (using Guide E720 and Method E721) at the test sample exposure sites. A currently valid determination of the neutron spectrum is needed to provide the essential data to accurately ascertain the equivalent 1-MeV monoenergetic neutron fluence in the specified irradiated material. Lack of this critical data can result in substantial error. Therefore, the experimenter must request a current valid determination of the 1-MeV equivalent fluence in silicon or GaAs, as needed, from the reactor facility operator. This may require a re-characterization of the reactor test facility, or the particular test configuration. Practice E1854 discusses the roles of the facility, dosimetrist, and user.

6.4 *Recoil Ionization Effects*—Ionization effects from neutron-induced recoils of the lattice atoms within a semiconductor device may be significant for some device types at some reactor configurations, although under normal conditions, ionization due to the gamma radiation from the source will be much greater than the ionization from neutron-induced recoils.

6.5 *Test Configuration Effects*—Extraneous materials in the vicinity of the test specimens can modify the radiation environment at the test sample location. Both the neutron spectrum and the gamma field can be altered by the presence of such material even if these materials are not directly interposed between the reactor core and the test devices.

6.6 *Thermal Neutron Effects*—Fast Burst Reactor (FBR) neutron spectra have a small thermal neutron component; however, TRIGA reactors inherently produce a very large thermal neutron flux from the water moderation of the fission neutrons. Neutrons interact with the materials of the devices being irradiated causing them to become radioactive. Thermal neutrons generally induce higher levels of radioactivity. As a consequence, parts irradiated to moderate or high fluence levels at TRIGA reactors should not be handled or measured soon after exposure. It is therefore common practice at TRIGA reactors to shield test parts from the thermal neutrons with borated polyethylene or cadmium shields. Cadmium capture of thermal neutrons produces more gamma rays than boron capture, thus producing a lower n/γ ratio when such a shield is used. In addition, whereas cadmium has a strong capture cross section for neutrons with incident energies less than 0.3 eV, boron-10 has a significant (n,α) reaction with a 1/E energy fall-off that extends into the keV energy region. For these reasons, borated polyethylene shields are preferred. While most facilities providing neutron irradiation for semiconductor parts will automatically provide the thermal neutron shields, it is the experimenter's responsibility to verify that use of such a shield is considered during the irradiation.

7. Procedure

7.1 *Reactor Facility Selection :*

7.1.1 *Reactor Operating Modes and Fluence Levels*—Two types of reactors are generally used for evaluating the displacement effects of neutrons on electronic components. These reactors, the FBR and the TRIGA types, can be operated in either a pulsed or a steady-state mode. The minimum pulse width for the FBR is approximately 50 µs and the TRIGA type has a nominal pulse width >10 ms. No rate dependence of permanent displacement damage has been observed at these facilities. In the single-pulse mode, the FBR typically has a maximum fluence ($\Phi_{eq,\ 1\ MeV,\ Si}$) up to 8×10^{13} n/cm^2 outside the core and 6×10^{14} n/cm^2 inside the core. TRIGA-type reactors have a maximum single pulse fluence that varies with the reactor and the exposure position within the core, but ranges from 5×10^{13} to 6×10^{15} n/cm^2. The volumes (in-core for a TRIGA and in leakage mode for a FBR) available for semiconductor components for most FBR reactors and TRIGA type reactors are on the order of 100 cm^3. Significantly larger core volumes are available at some facilities. Higher fluences can be achieved by exposing the sample to multiple bursts or by operating the reactor in a steady-state mode. In the steady-state mode, the FBR can deliver fluxes on the order of 1.8×10^{11} n/(cm^2 s) outside the core and 7.8×10^{11} n/(cm^2 s) inside the core, while the water-moderated or TRIGA-type reactor can deliver maximum fluxes ranging from approximately 2.2×10^{11} to 4.0×10^{13} n/(cm^2 s).

7.1.2 *Neutron Fluence/Gamma Dose (η/γ) Ratio.* In addition to a neutrons fluence, reactors produce a gamma-ray environment. In order to be sure that the observed radiation effects are due to neutrons, it is necessary that the η/γ ratio is sufficiently large that the gamma damage is small compared to the neutron displacement damage. In the pulse mode, the inherent η/γ ratios for the FBR and TRIGA-type reactors are approximately 4.5×10^9 and 3×10^8 [n/cm^2 per rad(Si)], respectively. These ratios can be increased or decreased by interposing shielding between the sample and the reactor. In general, due to neutron interactions with the room and reactor support structures, the η/γ ratio decreases as the distance from the reactor core is increased. The η/γ ratio tends to be lower for exposures using TRIGA-type reactors in the steady-state rather than pulse mode of operation, and also for exposures at lower rather than higher steady-state power levels as the fraction of the total gamma dose attributable to the preexisting fission product inventory increases as the total exposure time increases.

7.1.3 *Dosimetry and Field Mapping.* Mechanical supports or reactor control elements may cause localized perturbation of the neutron flux; therefore, mapping of the area in which samples are to be exposed is required to verify uniformity. Use sulfur or nickel dosimetry for mapping in accordance with Test Method E264 or E265. Report the resulting neutron fluence in terms of the 1-MeV equivalent neutron fluence in the specified irradiated material ($\Phi_{eq,\ 1\ MeV,\ Si}$ or $\Phi_{eq,\ 1\ MeV,\ GaAs}$) in accordance with Practice E722.

7.1.4 In the absence of a validated 1-MeV damage function, the non-ionizing energy loss (NIEL) as a function incident neutron energy, normalized to the NIEL at 1 MeV, may be used as an approximation of displacement damage. See Practice E722 for a description of the methodology applied to the determination of the Si and GaAs damage functions. Concurrent with the neutron mapping, determine the gamma total dose at the exposure location using CaF_2:Mn Thermoluminescent Dosimeter (TLD) dosimetry. Practice E668 provides good general guidance on the handling and use of TLDs; however, it specifically excludes use in a mixed neutron/gamma exposure field. Practice E2450 provides guidance on the interpretation of CaF_2:Mn TLDs in a mixed neutron/photon environment. The facility should make appropriate independent measurements to derive a correction factor for the effect of neutrons in the TLD readings and should provide this data to the experimenter (**4-6**). Because the neutron energy spectrum extends to thermal energy levels and because lithium (^{6}Li) has a large absorption cross section for thermal neutrons, the use of CaF_2:Mn rather than LiF TLD's is recommended to avoid a potential error in the gamma dose measurement. CaF_2 is also a better match for energy absorption of semiconductor materials. Keep in mind the warning in 6.1.2.

7.2 *Test Plan and Fixtures:*

7.2.1 All reactor facilities require a test procedure or test plan. The procedure should specify the location of the test sample relative to the reactor core and the desired 1-MeV equivalent fluence. The test facility may need only the required fluence, from which the location of the sample and burst temperature will be determined by facility operating personnel. In the steady-state mode, the power level and duration of exposure are required. This too can be provided by facility operators if the desired fluence is given. Plan the exposures such that placement of the test sample in the exposure area can be accomplished quickly with minimal reentry requirements to minimize radiation exposure of test personnel.

7.2.2 Design test fixtures to enable accurate and repeatable positioning of the test sample for tests in which multiple exposures are made. Also design the test fixture with minimum mass to prevent perturbation of the radiation field. Avoid hydrogenous materials because of the resulting degradation in *n*/γ ratio and the softening of the neutron spectrum. In addition, at FBR facilities large amounts of hydrogenous material will reflect neutrons back to the core and may require considerable effort by the facility operator in order to characterize, and hence control, the operation of the reactor with the test fixture in place. The experimenter should also be aware that certain materials, some of which are used as electrical insulation (for example, TFE-fluorocarbon), degrade in a reactor environment. High atomic number materials generally activate to a large degree and can raise the radiation dose to experimenters when handling the fixture after the neutron irradiation. Aluminum is commonly used to construct test fixtures.

7.3 *Exposure of Test Sample and Dosimeters:*

7.3.1 Mount test samples on panels of convenient dimensions for ease in handling. Sulfur (or nickel) and TLD dosimeters may be attached, as required, to the panels prior to exposure. In general, use an array of dosimeters if the nonuniformity of the environment is expected to exceed ±10 % over the test article or sample group. An exposure geometry should be chosen such that the total variation in fluence observed at the test sample sites does not exceed ±20 %.

7.3.2 Semiconductor piece parts may be irradiated passively because displacement damage is independent of applied bias.

NOTE 1—Transient annealing of damage immediately following exposure of parts to pulsed neutron environment may be strongly affected by bias conditions following exposure. Displacement damage in GaAs is particularly sensitive to the charge-injection annealing. Refer to Guide F980 for a method of characterizing rapid annealing effects. Mount the test samples unbiased. For MOS devices or any microcircuit containing an MOS element, all leads shall be shorted. For all other device technologies, the leads may be either open or shorted.

7.3.3 If static-sensitive parts are to be irradiated, use standard electrostatic discharge (ESD) protective procedures in handling these parts. However, as a general rule, protect the leads of *all* semiconductor devices during irradiation to prevent damage resulting from electrostatic discharge. This protection usually consists of placing the devices in conductive foam or shorted sockets.

7.3.4 All exposures shall be conducted at ambient temperatures between room temperature (that is, 24 ± 6° C) and 50° C unless otherwise specified.

7.3.5 The temperature of the sample devices should be maintained below 50° C from the time of the exposure until the post-electrical tests are made. If the temperature exceeds 50° C between the time of irradiation and the electrical measurements some correction may be required to account for annealing. The post-exposure electrical tests as specified shall be made within 30 days.

7.3.6 Significant postirradiation annealing of damage occurs immediately following irradiation (seconds through ~2 days depending on device composition and structure) and then continues at a much slower rate for months (**2**). The amount and rate of annealing depends on the semiconductor temperature and on the time duration at elevated temperatures. Such annealing will affect the results of the post-exposure electrical tests. It is recommended that postirradiation electrical tests be performed within 2 days of the exposure. For silicon devices, when electrical testing within 2 days is not feasible due to the shipment of the activated parts to a remote facility where the electrical characterization can be performed, it is recommended that a displacement damage stabilization annealing, as described in Section 8.1.6 of Test Method E1855, be performed.

7.4 *Retrieval and Return of Test Sample*—Following exposure of the test samples, the parts may be retrieved after the radioactivity of the test chamber has reached a safe level. Facility Health Protection (Radiation Safety) personnel typically determine when re-entry is permissible based upon the hazard exposure limits in CFR 20. Retrieve the test samples and dosimeters quickly to minimize personnel radiation exposure. Following retrieval, separate the dosimeters and turn them over to dosimetry personnel responsible for reading the dosimeters. This service is generally facilitated by the reactor facility staff by prior arrangement.

7.5 *Electrical Characterization :*

7.5.1 Pre- and post-irradiation electrical measurements are made in accordance with the appropriate electrical test procedures. Selection of test parameters and bias conditions requires knowledge of basic radiation effects on the device technology being tested and may require knowledge of the intended application of the test device.

7.5.2 Electrical tests may be performed at the reactor facility or another facility. After exposure, the samples are likely to be radioactive for a period ranging from several days to months and must be handled in accordance with appropriate health safety procedures, referenced in 10 CFR 20, or until declared nonradioactive by a certified radiation health physicist.

8. Packaging and Package Marking

8.1 Radioactive test samples that are to be shipped to another facility must be packaged in accordance with applicable regulations pertaining to the shipment of radioactive material, referenced in 49 CFR 100-177. It is also important to note that the receiving facility must be licensed in accordance with governing Federal Regulations, referenced in 10 CFR 30, to receive radioactive material.

9. Report

9.1 In describing the results of a neutron irradiation report the following information:

9.1.1 Reactor identification,

9.1.2 Reactor operating mode—pulse or steady-state,

9.1.3 Core configuration used for irradiation,

9.1.4 Times and number of pulses or steady-state runs,

9.1.5 Shielding details,

9.1.6 Sulfur (or nickel) dosimeter readings, including measurement uncertainties,

9.1.7 TLD dosimeter readings, if any, and the corrections required to adjust for the neutron sensitivity of the TLD,

9.1.8 1-MeV fluence as determined using Practice E722, and including an uncertainty estimate that takes into account the knowledge of the neutron spectrum,

9.1.9 Total or ionizing dose, or both, in the relevant material (that is, Si, GaAs, or SiO_2) and measurement uncertainty as determined using Practice E668 and correlated to current exposure,

9.1.10 Sample identification (including part type number, serial number, manufacturer, controlling specification, the date code, and any other identifying numbers given by the manufacturer),

9.1.11 Date and time of exposure to neutrons,

9.1.12 Diagrams of the electrical parameter measurement circuits,

9.1.13 Electrical measurement data before and after irradiation, along with uncertainty details on the measurements and details on the calibration of any equipment used for the electrical measurements,

9.1.14 Date, time, and temperature at which electrical measurements were made,

9.1.15 Date, time, and temperature history (particularly important is the maximum temperature and its duration) of any periods between the time of irradiation and the post-exposure electrical measurements where the samples exceeded 50°C.

9.1.16 Reactor facility and exposure site radiation environment characterization, with uncertainties, based on Practice E1854, method used, and date completed,

9.1.17 Core configuration used for calibration,

9.1.18 Sulfur (or nickel) fluence multiplier, and associated uncertainty, used to calculate the 1-MeV equivalent fluence for the irradiated material associated with the current reactor facility calibration for the specific exposure site used, and

9.1.19 Geometry of radiation exposure.

9.1.20 Any anomalous incidents during the test shall be fully documented.

10. Keywords

10.1 dosimetry; electronic component; equivalent monoenergetic neutron fluence; fast burst reactor (FBR); gallium arsenide; gamma dose; gamma effects; irradiation; neutron fluence; neutron flux; nickel; 1 MeV equivalent fluence; radiation; reactor; semiconductor; silicon; sulfur; thermoluminescent dosimeter (TLD); TRIGA-type reactor

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