Designation: E3084 – 17 (Reapproved 2022)$^{\varepsilon 1}$

Standard Practice for Characterizing Particle Irradiations of Materials in Terms of Non-Ionizing Energy Loss (NIEL)[1]

This standard is issued under the fixed designation E3084; 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.

ε[1] NOTE—A misspelling in Section 5 was editorially corrected in July 2022.

1. Scope

1.1 This practice describes a procedure for characterizing particle irradiations of materials in terms of non-ionizing energy loss (NIEL). NIEL is used in published literature to characterize both charged and neutral particle irradiations.

1.2 Although the methods described in this practice apply to any particles and target materials for which displacement cross sections are known (see Practice E521), this practice is intended for use in irradiations in which observed damage effects may be correlated with atomic displacements. This is true of some, but not all, radiation effects in electronic and photonic materials.

1.3 Procedures analogous to this one are used for calculation of displacements per atom (dpa) in charged particle irradiations (see Practice E521) or neutron irradiations (see Practice E693).

1.4 Guidance on calculation of dpa from NIEL is provided.

1.5 Procedures related to this one are used for calculation of 1-MeV equivalent neutron fluence in electronic materials (see Practice E722), but in that practice the concept of damage efficiency, based on correlation of observed damage effects, is included.

1.6 Guidance on conversion of NIEL in silicon to monoenergetic neutron fluence in silicon (see Practice E722), and vice versa, is provided.

1.7 The application of this standard requires knowledge of the particle fluence and energy distribution of particles whose interaction leads to displacement damage.

1.8 The correlation of radiation effects data is beyond the scope of this standard. A comprehensive review (**1**)[2] of displacement damage effects in silicon and their correlation with NIEL provides appropriate guidance that is applicable to semiconductor materials and electronic devices.

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E521 Practice for Investigating the Effects of Neutron Radiation Damage Using Charged-Particle Irradiation

E693 Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA)

E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

3. Terminology

3.1 Definitions of some terms used in this practice can be found in Terminology E170.

3.2 *Definitions:*

3.2.1 *tracked particles*—those particles whose position-dependent fluence spectra are calculated in a particle transport calculation for a specific target geometry.

3.2.1.1 *Discussion*—In calculating displacement damage energy and NIEL, the tracked particles should include neutrons, photons, protons, and ions up to Z = 2, unless their contributions are known to be negligible. Heavier ions may also be tracked in some Monte Carlo codes. Except in the case

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

[3] 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.

of neutrons, particles below a specified minimum energy are not tracked, and are treated as *non-tracked particles*.

3.2.2 *tracked-particle fluence spectrum,* $\Phi_p(E)$—the fluence spectrum of particles, of species p and at particle energy E, that are tracked in a particle transport calculation. For each species of tracked particle other than neutrons there is a specified minimum energy. Particles at lower energy are non-tracked particles.

3.2.3 *secondary particles*—those particles produced in a material by interaction with the tracked particles. Secondary particles may include tracked particles and non-tracked particles.

3.2.4 *non-ionizing energy loss,* $NIEL_p(E)$—the quotient of $d\bar{\varepsilon}_d$ by $\Phi_p(E).dE.dm$, where $\Phi_p(E)dE$ is the tracked-particle fluence in the energy interval E to E+dE of particle species p in a volume element containing material of mass dm, and $d\bar{\varepsilon}_d$ is that part of the mean energy imparted to matter by the tracked particle radiation which produces atomic displacements and lattice phonons (that is, excluding the part that produces ionization and excitations of electrons).

$$NIEL_p(E) = d\bar{\varepsilon}_d / \Phi_p(E)dEdm \quad (1)$$

Unit: MeV·m^2·kg^{-1}. (also used are keV·cm^2·g^{-1}, and MeV·cm^2·g^{-1})

3.2.4.1 *Discussion*—For silicon, using the atomic mass 28.086 g/mol, a displacement kerma cross section 100 MeV·mbarn is equivalent to 2.144 MeV·cm^2/g **(2)**. Microscopic displacement kerma cross sections (see Practice E722) having units with dimensions equal to the product of energy and area (for example, MeV·mbarn) are sometimes used to apply to single target atoms, and may be thought of as the microscopic version of NIEL. For 1-MeV neutrons the reference value of the displacement damage function in silicon is defined in Practice E722 as equal to 95 MeV·mbarn, equivalent to a NIEL value of 2.037 MeV·cm^2/g (0.2037 Mev·m^2·kg^{-1}).

3.2.4.2 *Discussion*—In Eq 1, $NIEL_p(E)$ is to be interpreted as a function dependent on the particle energy, on the species of particle, and on the material in which the particle fluence is present. Its use requires knowledge of NIEL for all energies and tracked-particle species that contribute significantly to the total displacement damage energy in a given material.

3.2.4.3 *Discussion*—In the definition, Eq 1, the volume element in which the tracked-particle fluence Φ_p is present does not necessarily contain all of the atomic displacements produced by the energy transferred, $d\bar{\varepsilon}_d$. The quantity is calculated *as if* the extended volume, dependent on the particle energy, in which displacements occur is homogeneous and of the same composition as the volume element in which the tracked-particle fluence is present. This assumption is justified in cases in which secondary particle equilibrium applies for the non-tracked particles: the number and energy distribution of secondary particles entering a volume element is the same as for those leaving that element. See the analogous description of "charged particle equilibrium" in the definition of **kerma**, Terminology E170.

3.2.4.4 *Discussion*—Damage energy per unit mass, $d\bar{\varepsilon}_d / dm$, is calculated from NIEL by integrating the product of the NIEL with the tracked-particle fluence spectrum over all energies, and summing over all species of tracked particle:

$$d\bar{\varepsilon}_d / dm = \sum_p \int_0^\infty NIEL_p(E)\Phi_p(E)dE \quad (2)$$

3.2.4.5 *Discussion*—The 1 MeV equivalent neutron fluence (cm^{-2}) in silicon may be calculated by dividing the damage energy per unit mass (MeV/g) in Eq 2 by 2.037 MeV cm^2/g (see 3.2.4.1).

3.2.4.6 *Discussion*—The dpa may be calculated from the damage energy per unit mass by multiplying by the average atomic mass of the target and by $\beta/2T_d$, where β is an atomic scattering correction factor equal to 0.8 and T_d is the displacement threshold. This approximation to the Norgett, Robinson, and Torrens **(3)** model is consistent with the method recommended in Practice E521 (14.5.2.1).

3.2.4.7 *Discussion*—In cases where secondary particle equilibrium does not apply due to inhomogeneities in the target material, the damage energy that can be calculated from NIEL values is not necessarily equivalent to the local value of the absorbed dose that leads to displacements. The scale of the relevant inhomogeneities depends on the energies and actual ranges of the non-tracked secondary particles. Detailed Monte Carlo modeling in which tracked particles include all those secondary particles whose range is comparable with or greater than the scale of the material inhomogeneity in the target geometry is necessary. Suitable codes include MCNP6, Geant, and SRIM **(4-9)**.

4. Significance and Use

4.1 A radiation-hardness assurance program requires a methodology for relating radiation-induced changes in materials exposed to a variety of particle species over a wide range of energies, including those encountered in spacecraft and in terrestrial environments as well as those produced by particle accelerators and nuclear fission and fusion reactors.

4.2 A major source of radiation damage in electronic and photonic devices and materials is the displacement of atoms from their normal lattice site. An appropriate exposure parameter for such damage is the damage energy calculated from NIEL by means of Eq 2. Other analogous measures, which may be used to characterize the irradiation history that is relevant to displacement damage, are damage energy per atom or per unit mass (**displacement kerma**, when the primary particles are neutral), and **displacements per atom (dpa)**. See Terminology E170 for definitions of those quantities.

4.3 Each of the quantities mentioned in the previous paragraph should convey similar information, but in a different format. In each case the value of the derived exposure parameter depends on approximate nuclear, atomic, and lattice models, and on measured or calculated cross sections. If consistent comparisons are to be made of irradiation effects caused by different particle species and energies, it is essential that these approximations be consistently applied.

4.4 No correspondence should be assumed to exist between damage energy as calculated from NIEL and a particular change in a material property or device parameter. Instead, the damage energy should be used as a parameter which describes