Designation: E821 – 16

Standard Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation[1]

This standard is issued under the fixed designation E821; 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.

PART I—EXPERIMENTAL PROCEDURE

1. Scope

1.1 This practice covers the performance of mechanical tests on materials being irradiated with charged particles. These tests are designed to provide an understanding of the effects of neutron irradiation on the mechanical behavior of materials. Practices are described that govern the test material, the particle beam, the experimental technique, and the damage calculations. Reference should be made to other ASTM standards, especially Practice E521. Procedures are described that are applicable to creep and creep rupture tests made in tension and torsion test modes.[2]

1.2 The word simulation is used here in a broad sense to imply an approximation of the relevant neutron irradiation environment. The degree of conformity can range from poor to nearly exact. The intent is to produce a correspondence between one or more aspects of the neutron and charged particle irradiations such that fundamental relationships are established between irradiation or material parameters and the material response.

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E521 Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation

3. Terminology

3.1 *Definitions:*

3.1.1 Descriptions of relevant terms are found in Terminology E170.

4. Specimen Characterization

4.1 *Source Material Characterization:*

4.1.1 The source of the material shall be identified. The chemical composition of the source material, as supplied by the vendor or of independent determination, or both, shall be stated. The analysis shall state the quantity of trace impurities. The material, heat, lot, or batch, etc., number shall be stated for commercial material. The analytical technique and compositional uncertainties should be stated.

4.1.2 The material form and history supplied by the vendor shall be stated. The history shall include the deformation process (rolling, swaging, etc.), rate, temperature, and total extent of deformation (given as strain components or geometrical shape changes). The use of intermediate anneals during processing shall be described, including temperature, time, environment, and cooling rate.

4.2 *Specimen Preparation and Evaluation:*

4.2.1 The properties of the test specimen shall represent the properties of bulk material. Since thin specimens usually will be experimentally desirable, a specimen thickness that yields bulk properties or information relatable to bulk properties should be selected. This can be approached through either of

[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.08 on Procedures for Neutron Radiation Damage Simulation.

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[2] These practices can be expanded to include mechanical tests other than those specified as such experiments are proposed to Subcommittee E10.08.

[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.

two techniques: (*1*) where the test specimen properties exactly equal bulk material properties; (*2*) where the test specimen properties are directly relatable to bulk properties in terms of deformation mechanisms, but a size effect (surface, texture, etc.) is present. For the latter case, the experimental justification shall be reported.

4.2.2 The specimen shape and nominal dimensions shall be stated and illustrated by a drawing. Deviations from ASTM standards shall be stated. The dimensional measurement techniques and the experimental uncertainty of each shall be stated. The method of specimen preparation, such as milling, grinding, etc., shall be stated. The degree of straightness, flatness, surface condition, edges, fillets, etc., shall be described. The method of gripping the specimen during the test shall be stated and, preferably, illustrated by a drawing.

4.2.3 The heat treatment conditions such as time, temperature, atmosphere, cooling rate, etc., shall be stated. Because of the small specimen dimensions, it is essential to anneal in a non-contaminating environment. Reanalysis for O, N, C, and other elements that are likely to change in concentration during heat treatment is recommended.

4.2.4 Special care shall be exercised during specimen preparation to minimize surface contamination and irregularities because of the possible effect the surface can have on the flow properties of small specimens. Visible surface contamination during heat treatment shall be reported as a discoloration or, preferably, characterized using surface analysis technique. It is recommended that surface roughness be characterized.

4.2.5 The preirradiation microstructure shall be thoroughly evaluated and reported, including grain size, grain shape, crystallographic texture, dislocation density and morphology, precipitate size, density, type, and any other microstructural features considered significant. When reporting TEM results, the foil normal and diffracting conditions shall be stated. The specimen preparation steps for optical and transmission electron microscopy shall be stated.

4.2.6 The preirradiation mechanical properties shall be measured and reported to determine deviations from bulk behavior and to determine baseline properties for irradiation measurements. It is recommended that creep rates be measured for each specimen before and after irradiation. The thermal creep rate shall be obtained under conditions as close as possible to those existing during irradiation. The temperature, strain rate, atmosphere, etc., shall be stated.

4.2.7 It is recommended that other material properties including microhardness, resistivity ratio, and density be measured and reported to improve interlaboratory comparison.

4.3 *Irradiation Preconditioning:*

4.3.1 Frequently the experimental step preceding charged-particle irradiation will involve neutron irradiation or helium implantation. This section contains procedures that characterize the environment and the effects of this irradiation preconditioning. For reactor irradiations the reactor, location in reactor, neutron flux (fluence rate), flux history and spectrum, temperature, environment, and stress shall be reported. The methods of determining these quantities shall also be reported. The displacement rate (dpa/*s*) and total displacement (dpa) shall be calculated; see Practice E521 for directions. For ex-reactor neutron irradiation the accelerator, neutron flux and spectrum, temperature, environment, and stress shall be stated, including descriptions of the measurement techniques. The dpa/*s* and dpa should be calculated (see Sections 7 – 10). For helium implantation using an accelerator, the accelerator, beam energy and current density, beam uniformity, degrader system, temperature, environment, stress, helium content, and helium measurement technique and any post-implantation annealing shall be stated. The helium distribution shall be calculated as shall the resulting dpa (or shown to be negligible); see Sections 7 and 8 and Practice E521 for assistance. If another helium implantation technique is used, a description shall be given of the technique. It is recommended that chemical analysis follow any of the above preconditioning procedures.

4.3.2 The microstructure of irradiation preconditioned material shall be characterized with respect to dislocation loop size and density, total dislocation density, voids, and any microstructural changes from the unirradiated condition. Specimen density changes or dimensional changes shall be reported. It is recommended that changes in hardness or tensile strength, or both, be reported. Furthermore, any change in surface condition, including coloration, shall be reported.

4.4 *Analysis After Charged-Particle Irradiation:*

4.4.1 The physical, mechanical, and chemical properties of the specimen should be characterized prior to irradiation and any irradiation-induced changes reported. Practice E521 provides information on post-irradiation specimen preparation and examination.

4.4.2 After charged-particle irradiation, the specimen dimensions and density shall be measured. The microstructure and surface conditions shall be reexamined, with changes being reported. Chemical analysis for those elements likely to change during the mechanical test (O, C, N, H) shall be performed on the test specimen or on a dummy specimen held under conditions closely approximating those during irradiation. It is recommended that changes in hardness, tensile strength, or creep strength, or both, be measured and reported.

5. Particle Beam Characterization

5.1 *Beam Composition and Energy:*

5.1.1 Most accelerator installations include a calibrated magnetic analysis system which ensures beam purity and provides measurement and control of the energy and energy spread, both of which should be reported. A possible exception will occur if analogue beams are accelerated. For example, a cyclotron can produce simultaneous beams of $^{16}O^{4+}(Z/A = ¼)$ and $^{12}C^{3+}(Z/A = ¼)$ at different energies ($E + E_oZ^2/A$) which cannot easily be separated magnetically or electrostatically. This situation, normally only significant for heavy ion beams, can be avoided by judicious choice of charge state and energy. For Van de Graaff accelerators analogue beams of light ions, such as D^+ and He^{++}, can be generated, and under certain circumstances involving two stage acceleration and further ionization (for example, $He^+ \rightarrow 5$ MeV $He^+ \rightarrow 5$ MeV He^{++}), beams of impurity ions can be produced that may not be easily separated from the primary beam (for example, 5 MeV H^+).

5.1.2 For most cases, ion sources are sufficiently pure to remove any concern of significant beam impurity, but this

problem should be considered. Beam energy attenuation and changes in the divergence of the beam passing through windows and any gaseous medium shall be estimated and reported.

5.2 *Spatial Variation in Beam Intensity:*

5.2.1 The quantity of interest is beam intensity/unit area at the specimen. It is usually desirable to produce a uniform beam density over the specimen area so that this quantity can be inferred from a measurement of the total beam intensity and area.

5.2.2 Total beam intensity should be measured using a Faraday cup whenever possible; however, this may not be possible on a continuous basis during irradiation. The Faraday cup shall be evacuated to $P < 10^{-5}$ and shall be electron-suppressed; otherwise, spurious results may be generated. Various secondary beam monitors may then be used, such as ionization chambers, secondary emission monitors, transformers or other induction devices (for pulsed beams), beam scanners, or particles scattered from a foil. All such devices shall be calibrated through Faraday cup measurements or through activation analysis. These calibrations shall be reported.

5.2.3 Displacement rate gradients occur in charged-particle irradiation specimens in the Z (beam) direction because of changes in ion energy and, therefore, displacement cross section with penetration (see 10.5.1), and in the X and Y (lateral and longitudinal specimen axes, respectively) directions because of spatial variations in beam intensity.

NOTE 1—Non-uniform specimen cross section may give rise to displacement rate variations in the x- and y-directions, even under a spatially-uniform beam.

5.2.3.1 Displacement rate ratios of 1.2 to 2.5 (ratio of displacement rate at exit surface to rate at entrance surface of specimen in the Z direction) are common, but it is recommended that this ratio be minimized. In the case of foil specimens it is also recommended that the variations in beam intensity in the X direction be minimized, since a gradient in this direction will affect both the temperature and the creep compliance so as to maximize the stress gradient from specimen center to edge.

5.2.4 The beam may be rastered over the specimen to improve uniformity. The frequency of rastering shall be reported. The beam profile shall be measured regularly during the irradiation experiments, if possible. If this is not possible, some secondary measurement, such as temperature gradient, should be made. Analysis of the variation in specimen activity along the gauge section can provide an integrated average of the spatial variation in beam intensity; this is recommended.

5.3 *Time Variation in Intensity:*

5.3.1 Accelerator beams often have a built-in time-structure which must be accepted; this should be reported. The history of beam interruptions due to occasional electrical breakdown shall be reported. The long-term stability of beam focusing and directing equipment shall be considered. If the beam spot is rastered to produce a uniform intensity profile, a further time dependence will be introduced, depending on the frequency and amplitude of the scan, and the size of the raw beam spot; this should be reported. When scanning a pulsed beam at a subharmonic of its natural frequency, it should be noted that the beam spot will strike the specimen at discrete locations, rather than be distributed continuously across the specimen. The raw beam spot must therefore be considerably larger than the distance between these locations or a very non-uniform intensity distribution will result. It is most desirable to use a continuous rather than rastered beam. If a rastered beam is used, the degree of defect annealing between pulses shall be considered.

6. Mechanical Testing Apparatus

6.1 *Strain Measurement:*

6.1.1 The strains measured during light ion irradiation tests, for measurement periods ~1 day and for conditions where the irradiation has a significant effect on the elongation rate, are very small (typically $\sim 10^{-3}$ to 10^{-5}). Therefore, the strain resolution normally required for continuous measurements is 1 to 10×10^{-6}. The strain resolution as well as displacement resolution shall be reported.

6.1.2 Normally for these experiments the limiting factor in strain measurement is not the resolution of the actual displacement measuring device (for example, LVDT, LVDC, strain gage, laser extensometer, etc.); it is the ability of the apparatus to transmit the displacement with fidelity. To minimize these displacement measurement errors it is recommended that the temperature be monitored or controlled, or both, on each critical part of the apparatus and that thermal sensitivity experiments be performed; that is, a local temperature fluctuation should be imposed on individual elements of the strain measuring system while the strain signal is monitored. It is recommended that the strain sensitivity to ambient temperature fluctuations be recorded. It is recommended that the strain sensitivity to vibrations and coolant flow rates be monitored and reported. The strainmeasuring resolution, linearity, and reproducibility should be examined at several test temperatures on a regular basis using calibrated standards developed for such a purpose.

6.1.3 The sensitivity of the strain measurement shall be considered with respect to large magnetic or electrostatic fields, both of which may be present in these experiments. The effect of stray ion currents caused by secondary radiation should also be considered. The effect of lead length and shielding between the strain transducer(s) and the indicating device should be considered. Grounding may give rise to problems, especially with long lead lengths and associated ground potential differences.

6.1.4 The means of defining the deforming gage length of the specimen should be reported along with the accuracy of its measurement. Possible errors arising from deformation occurring outside the gauge section should be reported. It is also recommended that strain measurement errors caused by specimen bending be evaluated and reported.

6.2 *Load Application and Measurement:*

6.2.1 The requirements for load measurement in these experiments are much less stringent than those for strain measurements; accuracies of $\leq 1\ \%$ are recommended. Temperature, pressure, and vibration sensitivity measurements

should be performed on the load measuring device. The load-measuring resolution, linearity, and reproducibility should be examined on a regular basis using calibrated standards.

6.2.2 The effect of secondary radiation, electric, or magnetic fields on the load transducer should be considered, along with lead length and shielding. Variations in ground potentials shall be considered.

6.2.3 Possible loading errors associated with misalignment shall be evaluated and reported. Frictional forces shall be measured where applicable, since friction anywhere in a mechanical load train may affect the strain measurement. The hysteresis in load application and measurement should be reported in relation to the strain measurement.

6.3 *Temperature Monitoring and Control*—For these experiments temperature monitoring and control capabilities may be the dominant factors that limit the overall accuracy and resolution of the primary strain measurement. For uniaxial tension the temperature dependence of the strain error arises from thermal expansion ($d\varepsilon/dT \sim 10^{-5}$/K) and, to a lesser degree, from the temperature dependence of the modulus ($d\varepsilon/dT \sim 10^{-7}$/K). For torsion experiments, the temperature dependent strain error is that of the modulus only. Primary emphasis will be given to uniaxial tension experiments, since strain resolution requirements are likely to limit the allowable temperature variations to less than 1 K over the desired temperature range (from room temperature to about 1000 K). The overall reproducibility from experiment to experiment may not be so stringent, however. If this reproducibility is 5 K or less, reasonably good agreement between thermal creep rates will be obtained, and very good agreement should be obtained on radiation-induced mechanical property changes.

6.3.1 *Temperature Monitoring*—This section is devoted to the description of techniques for detecting the absolute temperature of the specimen (accuracy) and for detecting changes in specimen temperature from some set point (resolution). Each of the following techniques may be important for either the accuracy or resolution of the temperature measurement, or both. In a given experiment, one technique may be utilized for estimating the overall specimen temperature to within several K; whereas, in another experiment the same technique may be used to resolve small (~0.1 K) temperature fluctuations (presumably in conjunction with the temperature control function). However, it should be kept in mind that beam heating at high beam currents can adversely affect the temperature resolution. It is recommended that direct monitoring of the specimen temperature be performed. If, however, an indirect monitoring technique is used (for example, a dummy specimen or an ambient heat sink temperature measurement is used) then it should be demonstrated that the factors controlling the heat transfer from the specimen to the point where temperature is monitored remain constant. For example, if heat transfer must occur through an oxide film on the specimen or, perhaps, on an adjacent heat sink, the stability of this film during an experiment should be evaluated. Three temperature-monitoring techniques have been applied to these experiments, (*1*) thermocouples, (*2*) infrared pyrometry, and (*3*) resistance thermometry. The method for absolute calibration of any of these techniques used shall be reported.

6.3.1.1 *Thermocouples*—There are several problems associated with the use of thermocouples applied directly to specimens for these experiments. The thin specimens normally used are subject to local perturbations in temperature through heat conduction from specimen to thermocouple wire. Thermal analysis shall be performed to determine the magnitude of temperature error associated with this thermal shunting. Another difficulty with applying the thermocouple directly to the specimen is the effect on the specimen material at the point where the thermocouple is welded. The "heat-affected" zone shall be minimized, and the percent of the total cross section that is affected by the welding of two thermocouple wires shall be reported. Radiation can affect the performance of thermocouples. Radiation damage and, to a lesser degree, transmutation will affect thermocouple calibration. Therefore, it is recommended that thermocouples that are irradiated during an experiment should be calibrated before and after each experiment. Radiation can also affect the temperature of the thermocouple junction. Radiation heating shall be included in the thermal analysis mentioned above. Another possibly important effect of radiation is ionization events which can occur in the thermocouple wire, in its insulation, or in the medium surrounding a bare thermocouple wire. In all these cases spurious voltages or currents can give rise to errors (only, of course, when the two thermocouple wires are ionized to dissimilar degrees). Furthermore, thermocouples that are not directly in the beam, but that receive significant gamma radiation, will undergo ionization. These effects should be considered. Special problems can arise when split thermocouples are employed. For example, when an electrical heating current passes through the specimen, the output voltage of the thermocouple will reflect the IR drop between the two points of contact of the thermocouple wires. Caution shall be exercised in the use of split thermocouples for the following reasons: (*1*) the specimen, with its radiation-sensitive Seebeck coefficient, may undergo the equivalent of thermocouple decalibration, (*2*) split thermocouples can mask temperature spikes or hot spots between the wire contact points, and (*3*) the averaging of temperature gives rise to error, except under the ideal condition of linear variation in temperature between the contact points.

6.3.1.2 *Infrared Pyrometers*—The accuracy of infrared pyrometers is dependent upon several factors. First, the surface emissivity must remain constant. This shall be demonstrated in pre- and post-experimental evaluation. If specimen preoxidation is necessary for keeping the emissivity constant, it shall be demonstrated that thermal creep properties in the temperature and stress range of interest are not affected by the oxidation treatment. Second, since instruments will receive a significant level of gamma radiation during some experiments, these infrared pyrometers shall be regularly calibrated.

6.3.1.3 *Resistance Thermometry*—Resistance thermometry is potentially a very high accuracy approach to temperature measurement. A comprehensive reference on this subject is Ref (**1**).[4] A major source of error is associated with a change in the intrinsic or low-temperature specimen resistance. This change

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

results from microstructural changes caused by annealing or irradiation, or both. It must be demonstrated that the appropriate *T* versus *R* curve is known during the period measurements are taken. Also, compensation must be provided for resistance changes associated with specimen deformation. Specimen voltage leads present a problem area similar to that for thermocouples. Thermal shunting and specimen structural changes at the points of lead welding shall be minimized. Since resistance thermometry is an averaging technique, the temperature shall be monitored at several discreet points over the entire specimen to detect thermal spikes.

6.3.2 *Temperature Control:*

6.3.2.1 The types of temperature control may be grouped as direct or indirect methods. These terms refer to the specimen heating or cooling technique applied. An indirect technique is one in which the electrical control signal heats or cools (or changes the flow of) some intermediary substance which in turn changes the specimen temperature. It is recommended that an indirect control method not be used in conjunction with an indirect monitoring technique; see 6.3.1. If this is done, it shall be demonstrated that relevant heat transfer coefficients remain constant throughout an experiment. The temperature-control technique shall be described, including information on the thermal time constant of the specimen, as well as the time constants of adjacent heat sinks (including grips). Furthermore, the techniques used to control the ambient temperature of the overall apparatus shall be described.

6.3.3 *Temperature Gradients:*

6.3.3.1 Temperature gradients can arise from four primary factors associated with charged-particle irradiation of specimens: (*1*) spatial variations in beam intensity; (*2*) non-uniform beam energy deposition through the specimen thickness; (*3*) non-uniform thermal heat input or removal; and (*4*) changes in heat loss mechanisms to the surroundings. Because the temperature profile is dependent on a number of experimental parameters and is potentially a major source of experimental error, efforts to minimize and record the temperature profile are considered important.

6.3.3.2 A major effect of a non-uniform temperature profile is the difficulty in maintaining a constant profile with the beam on and off. This effect can limit strain resolution and introduce an uncertainty in the baseline thermal creep strain associated with the thermal conditions during an irradiation creep experiment. Another major consideration is the possible temperature measurement error which could result from a nonsteady profile, an unrepresentative monitoring point, or a temperature that is averaged over a highly nonuniform profile.

6.3.3.3 Since specimens are quite thin in the *Z* (parallel to beam) direction, thermal gradients in this direction are generally small relative to axial and lateral gradients. Thermal gradients in the *X* (lateral) direction are generally not large, provided significant heat flow does not occur in this direction. In any case the three dimensional temperature profile shall be estimated or measured and reported for each experiment. Given a measure of the temperature distribution an estimate shall be made and reported of the stress distribution throughout the specimen.

6.4 *Specimen Environment Monitoring:*

6.4.1 Experiments shall be designed to maintain a high-purity environment in contact with the specimen. This is particularly true for reactive metals such as Nb, Mo, Zr, etc., but is also recommended for other metals.

6.4.2 Vacuum system capabilities of the irradiation chamber shall be stated. Details shall include a description of the chamber, type of seals, and bake-out capabilities. A bakeable ultra-high vacuum chamber is recommended for those cases where impurities desorbed from the walls present a contamination problem. The types of vacuum pumps used, including roughing and high vacuum, shall be described.

6.4.3 Precautions against the effects of back-streaming from pumps are necessary and shall be described. It is also important to indicate the types and locations of pressure monitors used in the vacuum system.

6.4.4 Methods used to process internal surfaces of the vacuum system should be described.

6.4.5 Descriptions of those aspects of the cooling system which affect the purity of the coolant shall be given. This includes the type of coolant (gas, liquid metal, other), initial purity, purification system, type of circulating pump, and flow rate.

6.4.6 The environment shall be of such a purity that changes in bulk chemistry are minimized during irradiation. This shall be determined by chemical analyses of specimens crept under light irradiation or thermally crept under conditions closely approximating those during irradiation.

6.4.7 The specimens shall be thoroughly cleaned before irradiation, and any surface discoloration or oxide formation during irradiation shall be noted.

6.4.8 It is recommended that continuous monitoring of vacuum or gas environments be performed. Continuous oxygen analysis shall be the minimum analysis, with complete residual gas analysis preferred. Details of the analysis system shall be reported. This shall include information on differential pumping systems, backstreaming precautions, and calibration. The source and nominal composition of gaseous or liquid metal coolants shall be reported.

6.5 *Other Monitoring:*

6.5.1 In cases where dosimetry is used to determine the fluence, details of the dosimeter foil, reaction, reaction cross section, and counting procedure must be stated.

6.5.2 All electronic devices associated with the experiment shall be examined with respect to line voltage sensitivity.

PART II—RADIATION DAMAGE CALCULATIONS

7. Scope

7.1 Part II of this practice follows naturally Part I on Experimental Procedure and describes recommended methods for calculating particle ranges, damage energy, damage rates, and damage gradients. In addition, consistent methods for comparing ion damage with neutron damage are recommended. Particles that either have been used or are expected to be used in mechanical property testing are covered, namely, ions with atomic weight $A \leq 4$ in the energy range from 1 to 100 MeV, henceforth referred to as light ions. It is anticipated

that as techniques are developed using other particles or energies, or both, the techniques will be incorporated into the standards.

8. Terminology

8.1 *Definitions:*

8.1.1 *displacement*—the process of dislodging an atom from its normal site in the lattice.

8.1.2 *range*—the distance from the point of entry at the surface of the target to the point at which the particle comes to rest.

8.1.3 *stopping power* (*or stopping cross section*)—the energy lost per unit path length due to a particular process; usually expressed in differential form as $-\mathrm{d}E/\mathrm{d}x$.

8.1.4 *straggling*—the statistical fluctuation due to atomic or electronic scattering of some quantity such as particle range or particle energy at a given depth.

8.2 *Symbols:*

8.2.1 A_1, Z_1—the atomic weight and number of the bombarding ion.

8.2.2 A_2, Z_2—the atomic weight and number of the atoms of the medium undergoing irradiation.

8.2.3 *damage energy,* T_{dam}—that portion of the energy lost by an ion moving through a solid that is transferred as kinetic energy to atoms of the medium; strictly speaking, the energy transfer in a single encounter must exceed T_d.

8.2.4 *depa*—damage energy per atom; a unit of radiation exposure. It can be expressed as the product of $\bar{\sigma}_{\mathrm{de}}$ and the fluence.

8.2.5 *dpa*—displacements per atom; a unit of radiation exposure giving the mean number of times an atom is displaced from its lattice site. It can be expressed as the product of $\bar{\sigma}_{\mathrm{d}}$ and the fluence.

8.2.6 E_d—the threshold displacement energy.

8.2.7 *light ion*—an arbitrary designation used here for convenience to denote an ion of $A \leq 4$.

8.2.8 T_d—an effective value of the energy required to displace an atom from its lattice site.

8.2.9 $\sigma_d(E)$—an energy-dependent displacement cross section. Usual unit is barns.

8.2.10 $\sigma_{de}(E)$—an energy-dependent damage energy cross section. Usual unit is barns-eV or barns-keV.

9. Particle Ranges

9.1 The range straggling and energy straggling of light ions with energies greater than 1 MeV is small except near end of range and can usually be ignored. For this reason range-energy tables (**2-8**) or analytical approximations (**9, 10**) thereto can be applied. In recent years, it has been common to use the SRIM Monte Carlo code to compute these values (**11**). In addition, these tables, their approximations, or SRIM can be used to determine the energy, E, of a light ion at the depth, x, by making use of the relationship:

$$R(E_x) = R(E_i) - x \tag{1}$$

where:

E_x = the energy at the depth, x,
E_i = the initial energy, and
$R(E)$ = the range of an ion with energy E.

For a more complete discussion on available range-energy tables consult Practice E521. For approximate calculations the range of deuterons and alpha particles can be estimated, if the range of protons is known, by the following:

$$R_\alpha(E) \cong R_p(E/4) \tag{2}$$

$$R_d(E) \cong 2R_p(E/2). \tag{3}$$

Since these expressions are derived from an electronic stopping power equation (**12**) (that is, Bethe Bloch formulism), they are valid to the extent the electronic stopping power approximates the total stopping power. Agreement with tabular values is within 5 % for deuteron energies greater than 2 MeV and alpha particle energies above 8 MeV and improves with energy. Generally, these errors will be tolerable in view of the fact that end of range is usually avoided in mechanical property testing. It is near end of range that the stopping power is varying most rapidly and the energy and range straggling is greatest. Furthermore, it is near end of range that the influence of foreign atoms introduced by ions coming to rest will be greatest.

10. Damage Calculations

10.1 In calculations involving light ion radiation damage, it is recommended that models consistent with those recommended for use in calculating neutron damage be used wherever practicable (**13**). Therefore, consistency in the choice of energy partition theory and secondary displacement models will be recommended and discussed in this section. More detail in certain areas can be obtained by consulting Practice E521.

10.1.1 It is likely that mechanical property testing may be conducted at some future date using energetic electrons, light ions with $E > 100$ MeV, or very energetic heavy ions ($A > 4$). It is anticipated that as experimental techniques using these particles evolve, the standards will be amended to include damage calculations covering them.

10.2 *Damage Regimes:*

10.2.1 The interaction between an energetic light ion ($E > 1$ MeV) and target nuclei has generally been assumed to be due to pure Coulomb scattering, leading to the Rutherford scattering cross section for purposes of calculating displacement damage. This is only true, however, over a limited region of particle energy and energy transfer where the limits of validity are determined by both the incident light ion and target material. For small energy transfers or low energies, or both, the electronic screening of the nuclei becomes important. A sufficient criteria for the neglect of screening corresponds to (**14**):

$$E > E_s \sim 0.4(A_1/A_2)Z_1{}^2 Z_2{}^2 (Z_1{}^{2/3} + Z_2{}^{2/3}) \times (\mathrm{leV}/E_d)\mathrm{MeV} \tag{4}$$

Recommended values of E_d have been tabulated in Practice E521, Table 1. Representative values of E_s for several materials are listed in Table 1 of this practice. In practice, the influence of screening may be neglected at somewhat lower energies depending upon accuracy desired. As an approximate rule, the screening correction to the damage is less than 5 % if $E > E_s/5$. For large energy transfers or high energy, or both, nuclear forces may cause deviations from Rutherford scattering. The

TABLE 1 Values of the Screening Energy, E_s, MeV

Material	$1p^1$	$1d^2$	$2He^3$	$2He^4$
Al	0.82	1.6	11	14
Cu	2.9	5.8	37	49
Ag	5.5	11	68	91
Au	7.0	14	87	120

energy, in megaelectronvolts, where nuclear forces become significant is approximated by the coulomb barrier and is of the order of:

$$E_c \cong \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} \tag{5}$$

Representative values of E_c are given in Table 2.

Therefore, the expression:

$$E_s < E < E_c \tag{6}$$

establishes a criterion for the use of Rutherford scattering. In some cases $E_s > E_c$ (for example, alpha particles on copper) in which case there are deviations from Rutherford scattering for small and large energy transfers. In general, however, there is a limited energy range over which Rutherford scattering may be assumed. Later sections will discuss in greater detail the calculation of displacement damage in cases where Rutherford scattering is inappropriate.

10.3 *Primary Recoil Spectrum:*

10.3.1 It is recommended that the primary recoil spectrum be adopted as an interim measure of the degree by which light ions simulate neutrons. Other parameters such as damage energy, displacement cross section, and mean primary knock-on atom (PKA) energy can easily be derived from the primary recoil spectrum once known and should also be calculated and reported. It should be recognized, however, that these calculated parameters, such as mean PKA energy, can be misleading. In other words, different irradiating particles can have the same mean primary recoil energy and at the same time have quite different PKA spectra. These differences could lead, as an example, to an entirely different type of residual defect structure with implications on mechanical property changes. The PKA spectrum, on the other hand, may be expected to form the basis from which both empirical property change models (for example, damage functions) and analytical models (for example, short-term annealing effects) may be derived. In reporting PKA spectra it is important to state assumptions made and contributing damage processes included.

10.4 *Radiation Damage Parameters:*

10.4.1 The PKA spectrum is simply the sum of all differential cross sections that can lead to a PKA of energy T, by an incident particle of energy, E, as a function of T and can be expressed as:

TABLE 2 Values of Coulomb Barrier Energy, E_c, MeV

Material	$1p^1$	$1d^2$	$2He^3$	$2He^4$
Al	3.2	3.0	5.9	5.7
Cu	5.8	5.5	10.5	10.4
Ag	8.1	7.8	15.1	14.8
Au	11.6	11.2	21.7	21.3

$$\frac{d\sigma}{dT}(E, T) = \sum_i \frac{d\sigma_i(E, T)}{dT} \tag{7}$$

for i different contributions. The PKA expression has the units of recoils/atom-incident particle-keV. One assumption often made is that a differential cross section can be approximated by the Rutherford scattering cross section. This assumption allows one to determine directly the PKA spectrum and other damage parameters. (See Practice E521 for an expression for damage energy using the Rutherford scattering formula.) However, as previously described, there is a rather narrow damage regime for most particles and energies for which Rutherford scattering is valid. At lower energies, coulomb screening should be accounted for. In this domain, the Thomas-Fermi model as used in the E-Dep-1 code is recommended.

NOTE 2—It is necessary to insert the appropriate electronic stopping power into E-Dep-1. At particle energies greater than those for which Rutherford scattering is valid, the situation becomes more difficult. It is in this energy regime that nuclear effects predominate. The nuclear interactions can be divided into elastic scattering, nonelastic scattering, and nuclear reactions. Elastic scattering at higher energies, especially for large angle scattering, is dominated by potential nuclear scattering. In order to calculate the contribution of this process to the damage, one must rely on either experimentally obtained differential cross sections or optical model computer codes. It is recommended that a combination of the two be used. The use of an optical model code is especially important for very small and very large angle scattering where experimental cross sections are largely unavailable. Also the optical model is useful for evaluating the total cross section. Rigorous calculations of nonelastic scattering have not been made; however, there are several codes available that model the nucleus in various degrees of detail, the ultimate choice usually depending upon a tradeoff between detail desired and computation time available. Protons are the simplest of the light ions to model and are in many ways directly analogous to neutrons in so far as their nuclear interaction is concerned. An evaporation model by Grimes **(15)** that has been applied by Logan et al **(16)** to 14 to 23 MeV protons is a good example. Unfortunately, evaporation models assume that particles are emitted isotropically in the center of mass which is not necessarily the case. This assumption has the effect of distorting the shape of the PKA spectrum. Also, since the partial cross sections are not considered explicitly, a separate calculation must be performed to estimate transmutation product production rates (for example, $2He^4$ and $1H^1$). For deuterons and alpha particles the evaporation model is less adequate. High-energy light ions are also capable of undergoing nuclear reactions [for example, (d, α)] which produce neutrons or charged particles, or both, as reaction products. As was the case for nonelastic scattering, the experimental cross-section data is scarce and no specific computer code is recommended at this time to calculate the damage resulting from nuclear reactions. As additional work is done in this area, data or models, or both, will be recommended. Existing data for elastic, nonelastic, and nuclear reactions are tabulated in Ref **(17)**. To extend these cross sections to the calculation of damage energy, see Practice E521. In Practice E521, procedures are described for damage energy calculation, displacement cross-section calculation, and a secondary displacement model. The mean PKA energy in kiloelectronvolts, $\bar{T}_{dam}$, can be calculated as follows:

$$\bar{T}_{dam} = \frac{\int_{T_d}^{T_m} T_{dam} \frac{d\sigma(T, E)}{dT} dT}{\int_{T_d}^{T_m} \frac{d\sigma(T, E)}{dT} dT} = \frac{\sigma_{de}(E)}{\sigma(E)} \tag{8}$$

where:

$$T_m = \frac{4A_2A_1}{(A_2 + A_1)^2} \text{ E}$$

the maximum possible PKA energy (in the absence of charged particle emission).

10.5 *Damage Gradients:*

10.5.1 As light ions pass through material, they give up energy by both electronic excitation of the lattice and nuclear interaction. This loss in energy gives rise to a gradient in both heat dissipated and displacement energy deposited which if significant could affect the outcome of a mechanical properties test. It is recommended that this gradient be calculated using range-energy tables to calculate the particle energy, *E*, at the depth, *x*. For ease of computation it may be expedient to use an analytical approximation thereto (**9**). Once the energy, *E*, is known as a function of depth it is possible to calculate the damage energy or displacement damage as a function of depth. Also, use of the electronic stopping power (for example, Bethe Bloch formula) allows the calculation of the heat deposition gradient.

11. Correlation with Neutron Spectra

11.1 It is recommended that displacement damage created by light ions be compared with that created by neutrons using the same energy partition theory and secondary displacement model as described previously. In general, the formulas for calculating the radiation damage resulting from neutrons are directly analogous to those given previously; however, Practice E521 should be consulted for further detail. In time, other effects such as those due to shortterm annealing should be incorporated into the calculation for light ion and neutron irradiations on a consistent basis.

12. Keywords

12.1 accelerators; beam heating; in situ measurements; ion irradiation; mechanical properties; radiation damage simulation

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