



Designation: E 261 – 98

Standard Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques¹

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1. Scope

1.1 This practice describes the general procedures for the determination of neutron fluence rate, fluence, and energy spectra from the radioactivity that is induced in a detector specimen.

1.2 The practice is directed toward the determination of these quantities in connection with radiation effects on materials.

1.3 For application of these techniques to reactor vessel surveillance, see also Test Methods E 1005.

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.*

NOTE 1—Detailed methods for individual detectors are given in the following ASTM test methods: E 262, E 263, E 264, E 265, E 266, E 343, E 393, E 418, E 481, E 523, E 526, E 704, E 705, and E 854.

2. Referenced Documents

2.1 ASTM Standards:

E 170 Terminology Relating to Radiation Measurements and Dosimetry²

E 181 Test Methods for Detector Calibration and Analysis of Radionuclides²

E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques²

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron²

E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel²

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32²

E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum²

E 343 Test Method for Measuring Reaction Rates by Analysis of Molybdenum-99 Radioactivity from Fission Dosimeters²

E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters²

E 418 Method for Measuring Fast-Neutron Flux by Track-Etch Technique³

E 481 Test Method for Measuring Neutron Fluence Rate by Radioactivation of Cobalt and Silver²

E 523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper²

E 526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium²

E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238²

E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237²

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

E 854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance, E 706(IIIB)²

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

E 1005 Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance, E 706 (IIIA)

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

2.2 ISO Standard:

Guide in the Expression of Uncertainty in Measurement

3. Terminology

3.1 Descriptions of terms relating to dosimetry are found in Terminology E 170.

4. Summary of Practice

4.1 A sample containing a known amount of the nuclide to be activated is placed in the neutron field. The sample is removed after a measured period of time and the induced activity is determined.

5. Significance and Use

5.1 *Transmutation Processes*—The effect on materials of bombardment by neutrons depends on the energy of the

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² Annual Book of ASTM Standards, Vol 12.02.

³ Discontinued—see 1984 Annual Book of ASTM Standards, Vol 12.02.

E 261

neutrons; therefore, it is important that the energy distribution of the neutron fluence, as well as the total fluence, be determined.

6. Counting Apparatus

6.1 A number of instruments are used to determine the disintegration rate of the radioactive product of the neutron-induced reaction. These include the scintillation counters, ionization chambers, proportional counters, Geiger tubes, and solid state detectors. Recommendations of counters for particular applications are given in General Methods E 181.

7. Requirements for Activation-Detector Materials

7.1 The general considerations concerning the suitability of a material for use as an activation detector are found in Guide E 844.

7.2 The amounts of fissionable material needed for fission threshold detectors are rather small and the availability of the material is limited. Licenses from the U.S. Nuclear Regulatory Commission are required for possession.

7.3 A detailed description of procedures for the use of fission threshold detectors is given in Test Methods E 343, E 393, and E 854, and Guide E 844.

8. Irradiation Procedures

8.1 The irradiations are carried out in two general ways depending upon whether the instantaneous fluence rate or the fluence is being determined. For fluence rate, irradiate the detector for a short period at sufficiently low power that handling difficulties and shielding requirements are minimized. Then extrapolate the resulting fluence rate value to the value anticipated for full reactor power. This technique is sometimes used for the fluence mapping of reactors (1, 2).

8.2 The determination of fluence is most often required in experiments on radiation effects on materials. Irradiate the detectors for the same duration as the experiment at a position in the reactor where, as closely as possible, they will experience the same fluence, or will bracket the fluence of the position of interest. When feasible, place the detectors in the experiment capsule. In this case, long-term irradiations are often required.

8.3 It is desirable, but not required, that the neutron detector be irradiated during the entire time period considered and that a measurable part of the activity generated during the initial period of irradiation be present in the detector at the end of the irradiation. Therefore, the effective half-life, $t'_{1/2} = 0.693/\lambda'$, of the reaction product should not be much less than the total elapsed time from the initial exposure to the final shutdown.

8.4 As mentioned in 9.11 and 9.12, the use of cadmium-shielded detectors is convenient in separating contributions to the measured activity from thermal and epithermal neutrons. Also, cadmium-shielding is helpful in reducing activities due to impurities and the loss of the activated nuclide by thermal-neutron absorption. The recommended thicknesses of cadmium is 1 mm. When bare and cadmium-shielded samples are placed in the same vicinity, take care to avoid partial shielding of the bare detectors by the cadmium-shielded ones.

9. Calculation

9.1 The activity of the sample, A , at the end of the exposure

period is calculated as follows:

$$A = \lambda D / [(1 - \exp(-\lambda t_c)) \exp(-\lambda t_w)] \quad (1)$$

where:

λ = decay constant for the radioactive nuclide,

t_c = time interval for counting,

t_w = time elapsed between the end of the irradiation period and the start of the counting period, and

D = number of disintegrations (net number of counts corrected for background, random and true coincidence losses, efficiency of the counting system, and fraction of the sample counted) in the interval t_c .

9.1.1 If, as is often the case, the counting period is short compared to the half-life ($= 0.693/\lambda$) of the radioactive nuclide, the activity is well approximated as follows:

$$A = D / [t_c \exp(-\lambda t_w)] \quad (2)$$

9.2 For irradiations at constant fluence rate, the saturation activity, A_s , is calculated as follows:

$$A_s = A / (1 - \exp(-\lambda' t_i)) \quad (3)$$

where:

t_i = exposure duration, and

λ' = effective decay constant during the irradiation.

NOTE 2—The saturation activity corresponds to the number of disintegrations per foil per unit time for the steady-state condition in which the rate of production of the radioactive nuclide is equal to the rate of loss by radioactive decay and transmutation.

9.2.1 The effective decay constant, which may be a function of time, is related to the decay constant as follows:

$$\lambda' = \lambda + \int_0^\infty \sigma_a(E) \phi(E) dE \quad (4)$$

where:

$\sigma_a(E)$ = neutron absorption cross section for the product nuclide, and

$\phi(E)$ = neutron fluence rate per unit energy.

9.2.2 Application of the effective decay constant for irradiations under varying fluence rates is discussed in this section and in the detailed methods for individual detectors.

9.3 The reaction rate is calculated as follows:

$$R_s = A_s \lambda' / N \lambda \quad (5)$$

where:

N = number of target nuclei in the detector at time of irradiation.

9.3.1 The number of target nuclei can often be assumed to be equal to N_o , the number prior to irradiation.

$$N_o = N_A F m / M \quad (6)$$

where:

N_A = Avogadro's number
= 6.022×10^{23} mole⁻¹,

F = atom fraction of the target nuclide in the target element,

m = mass of target element, g, and

M = atomic mass of the target element.

9.3.2 Calculations of the isotopic concentration after irradiation is discussed in 9.6.6 and in the detailed methods for individual detectors.



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ASTM E 261

9.4 The neutron fluence rate, ϕ , is calculated as follows:

$$\phi = R_s / \bar{\sigma} \quad (7)$$

where:

$\bar{\sigma}$ = the spectral weighted neutron activation cross section.

9.4.1 Cross sections should be processed from an appropriate cross-section library that includes covariance data. Guide E 1018 provides information and recommendations on how to select the cross section library. The International Reactor Dosimetry File (IRDF-90) (38) is one good source for cross sections. The SNLRML cross section compendium (25) provides a processed fine-group representation of recommended dosimetry cross sections and covariance matrices.

9.4.2 If spectral-averaged cross-section or spectrum data are not available, one of the alternative procedures discussed in 9.10 to 9.13 may be used to calculate an approximate neutron fluence rate from the saturation activity.

9.5 The neutron fluence, Φ , is related to the time varying differential neutron fluence rate $\phi(E, t)$ by the following expression:

$$\Phi = \int_0^\infty \int_{t_1}^{t_2} \phi(E, t) dt dE \quad (8)$$

where:

$t_2 - t_1$ = duration of the irradiation period.

9.5.1 Long irradiations usually involve operation at various power levels, and changes in isotopic content of the system; under such conditions $\phi(E, t)$ can show large variations with time.

9.5.2 It is usual to assume, however, that the neutron fluence rate is directly proportional to reactor power; under these conditions, the fluence can be well approximated by:

$$\Phi = \left(\frac{\phi}{P} \right) \sum_{i=1}^n P_i t_i \quad (9)$$

where:

ϕ/P = average value of the neutron fluence rate, ϕ , at a reference power level, P ,

t_i = duration of the i^{th} operating period during which the reactor operated at approximately constant power, and

P_i = reactor power level during that operating period.

9.5.2.1 Alternate methods include measuring the power generation rate in a fraction of the reactor volume adjacent to the volume of interest.

9.6 Transmutation Processes:

9.6.1 The neutron fluence rate spectrum, $\phi(E)$, can be determined by computer calculations using neutron transport codes, and adjustment techniques using radioactivation data from multiple foil irradiations.

9.6.2 The reaction rate is related to the fluence rate by the following equation:

$$R_s = \int_0^\infty \sigma(E) \phi(E) dE \quad (10)$$

where:

$\sigma(E)$ = activation cross section at energy E , and

$\phi(E)$ = differential neutron fluence rate, that is the fluence per unit energy per unit time for neutrons with energies between E and $E + dE$.

9.6.3 The production rate of a radioactive nuclide is related to the reaction rate by the following equation:

$$dn/dt = N R_s - n \lambda' \quad (11)$$

9.6.4 Solution of Eq 11, for the case where R_s and N are constant, yields the following expression for the activity of a foil:

$$A = (\lambda/\lambda') N R_s (1 - \exp(-\lambda' t)) \quad (12)$$

9.6.5 The saturation activity of a foil is defined as the activity when $dn/dt = 0$; thus Eq 11 yields the following relationship for the saturation activity:

$$A_s = (\lambda/\lambda') N R_s \quad (13)$$

9.6.6 The isotopic content of the target nuclide may be reduced during the irradiation by more than one transmutation process and it may be increased by transmutation of other nuclides so that the rate of change of the number of target nuclei with time is described by a number of terms:

$$dN/dt = N (R_s + \sum_{i=1}^n R_i) - \sum_{j=1}^m N_j R_j \quad (14)$$

where:

i = discrete transmutation path for removal of the target isotope, and

j = discrete transmutation reaction whereby the target isotope is produced from isotope N_j and each of the R_i and R_j terms could be calculated from equations similar to Eq 10, using the appropriate cross sections.

9.6.6.1 The R_s term may predominate and, if R_s is constant, Eq 14 can be solved as $N = N_o \exp(-R_s t)$. The change in the target composition may be negligible and N may be approximated by N_o .

9.6.7 During irradiation, the effective decay rate is increased by transmutations of the product isotope (see Eq 4).

9.7 Long Term Irradiations:

9.7.1 Long irradiations for materials testing programs and reactor pressure vessel surveillance are common. Long irradiations usually involve operation at various power levels, including extended zero-power periods; thus, appropriate corrections must be made for depletion of the target nuclide, decay and burnout of the radioactive nuclide, and variations in neutron fluence rate. Multiple irradiations and nuclide burnup must also be considered in short-irradiation calculations where reaction-product half-lives are relatively short and nuclide cross sections are high.

9.7.2 The total irradiation period can be divided into a continuous series of periods during each of which $\phi(E)$ is essentially constant. Then the activity generated during the i^{th} irradiation period is:

$$A_i = [\lambda N_i (R_s/\lambda')] [1 - \exp(-\lambda' t_i)] \quad (15)$$

where:

N_i = number of target atoms, and

t_i = duration of the i^{th} period.

9.7.2.1 The activity remaining from the i^{th} period at the end of the n^{th} period can be calculated as the following equation: