Designation: E481 – 23

Standard Practice for Measuring Neutron Fluence Rates by Radioactivation of Cobalt and Silver[1]

This standard is issued under the fixed designation E481; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers a suitable means of obtaining the thermal neutron fluence rate, or fluence, in nuclear reactor environments where the use of cadmium, as a thermal neutron shield as described in Test Method E262, is undesirable for reasons such as potential spectrum perturbations or due to temperatures above the melting point of cadmium.

1.2 The reaction $^{59}Co(n,\gamma)^{60}Co$ results in a well-defined gamma emitter having a half-life of 5.2711 years[2] (8)[3] (**1**).[4] The reaction $^{109}Ag(n,\gamma)^{110m}Ag$ results in a nuclide with a well-known, complex decay scheme with a half-life of 249.78 (2) days (**1**). Both cobalt and silver are available either in very pure form or alloyed with other metals such as aluminum. A reference source of cobalt in aluminum alloy to serve as a neutron fluence rate monitor wire standard is available from the National Institute of Standards and Technology (NIST) as Standard Reference Material (SRM) 953.[5] The competing activities from neutron activation of other isotopes are eliminated, for the most part, by waiting for the short-lived products to die out before counting. With suitable techniques, thermal neutron fluence rate in the range from 10^8 $cm^{-2}{\cdot}s^{-1}$ to 3×10^{15} $cm^{-2}{\cdot}s^{-1}$ can be measured. Two calculational practices are described in Section 9 for the determination of neutron fluence rates. The practice described in 9.3 may be used in all cases. This practice describes a means of measuring a Westcott neutron fluence rate in 9.2 (Note 1) by activation of cobalt- and silver-foil monitors (see Terminology E170). For the Wescott Neutron Fluence Convention method to be applicable, the measurement location must be well moderated and be well represented by a Maxwellian low-energy distribution and an $(1/E)$ epithermal distribution. These conditions are usually only met in positions surrounded by hydrogenous moderator without nearby strongly multiplying or absorbing materials.

NOTE 1—Westcott fluence rate $= v_0 \int_0^\infty n(v)dv$

1.3 The values stated in SI units are to be regarded as the standard, except in the case of nuclear data where the source referenced units are retained in order to preserve the integrity of the referenced uncertainty values.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *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:*[6]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E181 Guide for Detector Calibration and Analysis of Radionuclides in Radiation Metrology for Reactor Dosimetry

E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques

E262 Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques

3. Significance and Use

3.1 This practice uses one monitor (cobalt) with a nearly $1/v$ absorption cross-section curve and a second monitor (silver)

[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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[2] One year is defined to be 365.242198 days (31 556 926 seconds) (**1**).

[3] The value of uncertainty, in parentheses, refers to the corresponding last digits, thus 14.958 (2) corresponds to 14.958 ± 0.002.

[4] The boldface numbers in parentheses refer to references listed at the end of this test method.

[5] Standard Reference Material 953 is available from National Institute of Standards and Technology, U.S. Dept. of Commerce, Washington, DC 20234.

[6] 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.

with a large resonance peak so that its resonance integral is large compared to its thermal cross section. The pertinent data for these two reactions are given in Table 1. The equations are based on the Westcott formalism ((**2, 3**) and Practice E261) and determine a Westcott 2200 m/s neutron fluence rate nv_0 and the Westcott epithermal index parameter $r\sqrt{\frac{T}{T_0}}$. References (**4-6**) contain a general discussion of the two-reaction test method. In this practice, the absolute activities of both cobalt and silver monitors are determined. This differs from the test method in the references wherein only one absolute activity is determined.

3.2 The advantages of this approach are the elimination of four difficulties associated with the use of cadmium: (*1*) the perturbation of the field by the cadmium; (*2*) the inexact cadmium cut-off energy; (*3*) the low melting temperature of cadmium; and (*4*) the potential for high dose-rate encountered when handling activated cadmium. In addition, the reactivity changes accompanying the rapid insertion and removal of cadmium may prohibit the use of the cadmium-ratio method. Self-shielding corrections are only important if the concentrations of cobalt and silver are large, but may be neglected for diluted alloys (<1 %). Studies indicate that the accuracy of the two-reaction method for determination of thermal neutron fluence is comparable to the cadmium-ratio method (**16**).

3.3 The long half-lives of the two monitors permit the determination of fluence for long-term monitoring.

4. Apparatus

4.1 *Germanium Gamma-Ray Spectrometer* (using a multichannel analyzer)—See Guide E181.

4.2 *Precision Balance.*

5. Materials and Manufacture

5.1 The two monitors required for this test method are cobalt and silver. Although these two materials are available commercially in very pure form, they have been used (**17**) alloyed with aluminum (≤1 % cobalt and ≤1 % silver) to minimize the self-shielding effect and to permit insertion into a high thermal-neutron fluence rate (>10^{15} $cm^{-2}{\cdot}s^{-1}$) facility (**6, 18**). Typical alloys contain 0.1 % silver or cobalt in aluminum (see 6.1 and 9.1).

5.2 The uncertainties and nonuniformity of alloy concentrations must be established by one or more different test methods. These might include chemical and activation analysis, or spectrometry. The purity of the aluminum matrix should also be established.

5.3 Whenever possible, the alloys should be tested for interfering impurities by neutron activation.

TABLE 1 Recommended Constants

Symbol	Parameter	Cobalt (^{60}Co)		Silver (^{110m}Ag)	
		Value[A]	Reference	Value[A]	Reference
$t_{1/2}$	Half-life	5.2711 (8)	(**1**)	249.78 (2) days	(**1**)
λ^B	Decay constant	4.1671 (6) × 10^{-9} sec^{-1}	[B]	3.2118 (3) × 10^{-8} sec^{-1}	[B]
A	Abundance of parent isotope	100 % (^{59}Co)	(**7**)	48.161 (8) % (^{109}Ag)	(**7**)
σ_a	Absorption 2200 m/s cross section for target ^{59}Co and ^{109}Ag	37.18 ± 0.06 b	(**8**)	93.4 ± 0.6 b	(**8**)
σ_0	2200 m/s cross section for formation of ^{60}Co and ^{110m}Ag	37.18 ± 0.06 b	(**8**)	4.12 ± 0.10 b	(**9**)
S_0	Correction factor which describes the departure of the cross section from the 1/v law in the epithermal region	1.80 [^{59}Co(n,γ)^{60}Co]	[C]	18.1 (7) [^{109}Ag(n,γ)^{110m}Ag]	(**9**)
I_0	Resonance integral	75.8 ± 2.00 b [^{59}Co(n,γ)$^{60(m+g)}$Co]	(**8**)	67.9 ± 3.1 b [^{109}Ag(n,γ)$^{110(m+g)}$Ag]	(**9**)
σ_2	Effective absorption cross section for product nuclide (reactor spectrum)	2 b	(**10**)	82 b	(**11**)
G_{th}	Thermal neutron self-shielding factor	Table 3	(**12**)	≅ 1 – 4/3 $R\sum_a$	(**4**)
G_{res}	Resonance neutron self-shielding factor	Table 3	(**12**)	Fig. 1[D]	—
g	Correction factor which describes the departure of the cross section from 1/v law in thermal region	1.0	(**2**)	See Table 4	(**2**)

[A] The numbers in parentheses following given values are the uncertainty in the last digit(s) of the value; 0.729 (8) means 0.729 ± 0.008, 70.8(1) means 70.8 ± 0.1.
[B] The decay constant, λ, is defined as ln(2) / $t_{1/2}$ with units of sec^{-1}, where $t_{1/2}$ is the nuclide half-life in seconds.
[C] Calculated using Eq 10.
[D] In Fig. 1, $\Theta = 4E_r kT/\Delta\Gamma^2 = 0.2$ corresponds to the value for ^{109}Ag for T = 293 K, $\sum_r = N_0\sigma_{r,max,T=0K}\sigma_{r,max,T=0K}$ = 31138.03 barn at 5.19 eV (**13**). The value of $\sigma_{r,max,T=0K}$ = 31138.03 barns is calculated using the Breit-Wigner single-level resonance formula $\sigma_\gamma(E_0) = 2.6039\times10^6 \cdot \frac{(A+1)^2}{A^2 \cdot E_0} \cdot \frac{\Gamma_n\Gamma_\gamma}{\Gamma\cdot\Gamma} \cdot g$ where the ^{109}Ag atomic mass is A = 108.9047558 amu (**14**), the ENDF/B-VIII.0 (MAT = 4731) (**13**) resonance parameters are: resonance total width Γ = 0.1427333 eV, formation neutron width Γ_n = 0.0127333 eV, and radiative/decay width Γ_γ = 0.13 eV, with a resonance spin J=1, and the statistical spin factor $g = \frac{(2J+1)}{(2s_1+1)\cdot(2s_2+1)} = \frac{3}{2\cdot2} = 0.75$ where s_1 = ½ and s_2 = ½ are the spins of the two particles (neutron and ^{109}Ag ground state (**15**)) forming resonance.

5.4 The method of encapsulating the monitors for irradiation depends upon the characteristics of the facility in which the measurements are to be made. The monitors have essentially the same chemical characteristics as pure aluminum; therefore, an environment in which aluminum would not be adversely affected would be generally satisfactory for the alloys. However, the low mechanical strength of the monitors requires, in many instances, that it be encapsulated or shielded from physical disturbances by some type of container. Aluminum cans or tubing are satisfactory for many cases of interest, but for hostile environments, stainless steel or vanadium may be preferable. Perturbation due to the presence of the container must be accounted for, especially in the case of stainless steel. The container should be constructed in such a manner that it will not create a significant flux perturbation and that it may be opened easily, especially if the monitors must be removed remotely.

6. Westcott Neutron Fluence Convention

6.1 The Westcott neutron fluence convention is designed primarily for calculations involving reactions rather than those involving scattering or diffusion. It states that the reaction rate per atom present, R, is equal to the product of an effective cross section, $\hat{\sigma}$, with the Westcott neutron fluence $\varphi_w = nv_0$, where n = the neutron density, including both thermal and epithermal neutrons, cm^{-3}, and v_0 = 2200 m/s.

Thus:

$$R = \varphi_w \hat{\sigma} = nv_0 \hat{\sigma} \tag{1}$$

The true equation for reaction rate is given by the equation:

$$R = \int_0^\infty n(v) v \sigma(v) dv \tag{2}$$

where:

$n(v)$ = neutron density per unit velocity,
v = neutron velocity, and
$\sigma(v)$ = cross section for neutrons of velocity v.

Therefore, the effective cross section is defined by the equation:

$$\hat{\sigma} = \int_0^\infty \frac{n(v) v \sigma(v)}{nv_0} dv \tag{3}$$

The neutron spectrum assumed by Westcott has the form: $n(v) = n(1 - f)P_m(v) + n\, f\, P_e(v)$, where P_m and P_e are the Maxwellian and epithermal density distribution functions normalized so that: $\int_0^\infty P_m(v)\mathrm{d}v = \int_0^\infty P_e(v)\mathrm{d}v = 1$. The quantity f is the fraction of the total density, n, in the epithermal distribution. The epithermal distribution is assumed proportional to $1/E$ per unit energy interval. This distribution is terminated by a cut-off function at a suitable lower limit of energy. Based on the above spectrum, one obtains the following relation for the effective cross section:

$$\hat{\sigma} = \sigma_0(g + rs) \tag{4}$$

where:

σ_0 = cross section of 2200 m/s neutrons,
g = a measure of the departure of the cross section from $1/v$ dependence in the thermal region,
s = $S_0\sqrt{\frac{T}{T_0}}$, a factor which describes the departure of the cross section from the $1/v$ law in the epithermal region, including resonance effects, and
r = a measure of the proportion of epithermal neutrons in the reactor spectrum.

More specifically:

$$r = f\sqrt{\frac{\pi\mu_n}{4}} \tag{5}$$

where:

f = fraction of the total density in the epithermal distribution, and
μ_n = a factor chosen to give the proper normalization to the epithermal density distribution. A suitable factor for water moderated systems is 5 (**2**).

6.2 *Limitation of the Westcott Convention*—Sufficient conditions for the applications of the Westcott convention are that:

$$\frac{\Sigma_a}{\xi\Sigma_s} < 0.1 \tag{6}$$

and:

$$\frac{T}{T_m} < 1.07 \tag{7}$$

where:

$\sum_a$ = macroscopic absorption cross section averaged over all materials affecting spectrum,
ξ = average logarithmic energy decrement per collision,
$\sum_s$ = macroscopic scattering cross section averaged over all materials affecting spectrum,
T = neutron temperature, K, and
T_m = temperature of the moderator, K.

If, as a result of neutron captures (for example, in the fuel), the quantity $\frac{\Sigma_a}{\xi\Sigma_s}$ becomes too great or if the neutron temperature T is too great relative to the moderator temperature T_m, the Maxwell spectrum hypothesis fails, the neutron energy spectrum must be determined, and the effective cross section determined with this spectrum.

6.3 The conventional 2200 m/s thermal neutron-fluence rate, φ_0, and the epithermal fluence-rate parameter, φ_e, as defined in Test Method E262, can be obtained from the Westcott neutron-fluence rate, φ_w, and the Westcott epithermal index, $r\sqrt{\frac{T}{T_0}}$, by means of Eq 8 and Eq 9:

$$\varphi_0 = \left(1 - \frac{4r}{\sqrt{\pi\mu_n}}\right)\varphi_w \tag{8}$$

$$\varphi_e = \frac{2}{\sqrt{\pi}} r \sqrt{\frac{T}{T_0}}\,\varphi_w \tag{9}$$

6.4 In Eq 8, it is necessary to estimate the neutron temperature, T, to obtain the value of r from the index $r\sqrt{\frac{T}{T_0}}$. Provided that the inequality (Eq 7) is satisfied, only a slight error is introduced by assuming $T = T_m$, the moderator temperature.

6.5 Although the $Ag^{109}(n,\lambda)Ag^{110m}$ S_0 value in Table 1 is a measured value, S_0 can be calculated by the following equation:

$$S_0 = \frac{2}{\sqrt{\pi}}\frac{I''_0}{\sigma_0} = \frac{2}{\sqrt{\pi}}\left(\frac{I_0}{\sigma_0} - 2g\sqrt{\frac{E_0}{E_{Cd}}}\right) \quad (10)$$

where:

I''_0 = reduced resonance integral excess over the 1/*v* cross section value, cm^2,
σ_0 = 2200 m/s cross-section value, cm^2,
I_0 = resonance integral, $\int_{E_{Cd}}^{\infty}\frac{\sigma(E)}{E}dE$
E_0 = 0.0253 eV, and
E_{Cd} = 0.5 eV.

7. Determination of Effective Interaction Cross Sections by Modeling

7.1 The effective interaction cross section, $\sigma_i(E)$, for a particular energy range from a lower energy bound, E_{li}, to an upper energy bound, E_{ui}, can be found using the tabulated energy-dependent cross sections $\sigma(E)$ and *a priori* neutron flux estimate $\varphi(E)$. The *a priori* neutron flux estimate, $\varphi(E)$, may be determined via any of several well-established neutron transport modeling techniques and nuclear data libraries of the user's choosing. A typical approach involves the computation of application-specific effective interaction cross sections and *a priori* fluxes for each dosimeter in the neutron field using continuous-energy Monte Carlo techniques (for example, MCNP). This is especially important if self-shielding or mutual shielding (as in a stack of foils) is significant, and if the measurement location is not appropriately thermalized (as described in 1.2). The reaction rates (R_i) and group cross sections can then be computed for each foil as follows:

$$R_i = \int_{E_{li}}^{E_{ui}}\sigma(E)\varphi(E)dE \quad (11)$$

$$\sigma_i = \frac{\int_{E_{li}}^{E_{ui}}\sigma(E)\varphi(E)dE}{\int_{E_{li}}^{E_{ui}}\varphi(E)dE} \quad (12)$$

7.2 Energy group structure can be computed over any number of desired multi-group energy regions as specified by the user. The neutron fluence and reaction rate values are typically provided by user specified tallies in Monte Carlo codes; however, the user must refer to the specific code documentation for the method of their choosing.

8. Procedure

8.1 Decide on the size and shape of the monitors to be irradiated, taking into consideration the size and shape of the irradiation space. The mass and irradiation period are parameters which can be varied to obtain a desired disintegration rate for a given neutron fluence rate level. To facilitate the convergence of the two activity equations for the fluence rate and the epithermal index, the concentration of the alloys should be chosen so that the ratio of the disintegration rates is on the order of one with a minimum activity of 100 dps.

8.2 Weigh the samples to a precision of at most ±1.0 % (1S %) as defined in Practice E177.

TABLE 2 Gamma Radiations of ^{110m}Ag (1)[A]

	Energy of Gamma (keV)	Intensity (%)
1.	657.7600 (11)	94.38 (8)
2.	884.6781 (13)	74.0 (11)
3.	937.485 (3)	34.51 (27)
4.	1384.2931 (20)	24.7 (5)
5.	763.9424 (17)	22.31 (9)
6.	706.6760 (15)	16.49 (8)
7.	1505.0280 (20)	13.16 (16)
8.	677.6217 (12)	10.56 (6)
9.	818.0244 (18)	7.33 (4)
10.	687.0091 (18)	6.45 (3)
11.	744.2753 (18)	4.71 (3)
12.	1562.294 (18)	1.21 (3)

[A] The number of parentheses following some given values is the uncertainty in the last digit(s) of the value: 0.729 (8) means 0.729 ± 0.008, 80.8 (1) means 70.8 ± 0.1.

TABLE 3 Self-Shielding Factors for Cobalt Wires (12)

Wire Diameter in. (mm)	Cobalt Content, (mass %)	G'_{res}(132 eV)	G_{th}
0.050 (1.27)	0.104	1.00	1.00
0.050 (1.27)	0.976	0.95 ± 0.04	0.99 ± 0.01
0.001 (0.03)	100	0.81 ± 0.03	0.99 ± 0.02
0.005 (0.13)	100	0.52 ± 0.02	0.97 ± 0.01
0.010 (0.25)	100	0.42 ± 0.02	0.94 ± 0.01
0.015 (0.38)	100	0.38 ± 0.01	0.92 ± 0.02
0.020 (0.51)	100	0.34 ± 0.01	0.90 ± 0.02
0.025 (0.64)	100	0.32 ± 0.01	0.88 ± 0.03

8.3 Irradiate the samples for the predetermined amount of time. Record the power level and any changes in power during the irradiation, the time at the beginning and end of the irradiation, and the relative position of the monitors in the irradiation facility.

8.4 A waiting period is necessary between termination of the irradiation period and start of counting when using Co-Al and Ag-Al monitors. The activation of ^{27}Al (by fast-neutron reaction) and of ^{23}Na impurities in the monitors produces ^{24}Na with a 14.958 (2) h half-life (1). The waiting period should be sufficient to allow the ^{24}Na to decay below levels at which interferences may be caused (typically one week is sufficient). It is sometimes advisable to count the samples periodically and follow the decay of the portions of the activities due to the ^{24}Na.

8.5 With the gamma-ray spectrometer, analyze the silver sample for ^{110m}Ag and the cobalt sample for ^{60}Co. Obtain the net count rate in each full-energy gamma-ray peak of interest, that is, 657.7600 (11) keV or 884.6781 (13) keV for ^{110m}Ag, 1332.492 (4) keV for ^{60}Co (see Guide E181). See Table 2 for gamma radiations of ^{110m}Ag.

9. Calculation

9.1 Measure the activities of ^{110m}Ag and ^{60}Co in disintegrations per second.

9.2 *Calculation Using the Westcott Neutron Fluence Rate:*

9.2.1 A Westcott 2200 m/s neutron fluence rate, nv_0 or φ_w, and the Westcott epithermal index parameter $r\sqrt{\frac{T}{T_0}}$ are related to the measured activities of the silver and cobalt monitors by the following equation: