



Standard Test Method for Measuring Neutron Fluence Rates by Radioactivation of Cobalt and Silver¹

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 test method covers a suitable means of obtaining the thermal neutron fluence rate, or fluence, in well moderated nuclear reactor environments where the use of cadmium, as a thermal neutron shield as described in Method E262, is undesirable because of potential spectrum perturbations or of temperatures above the melting point of cadmium.

1.2 This test method describes a means of measuring a Westcott neutron fluence rate (Note 1) by activation of cobalt- and silver-foil monitors (See Terminology E170). The reaction $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ results in a well-defined gamma emitter having a half-life of 1925.28 days (1).² The reaction $^{109}\text{Ag}(n,\gamma)^{110\text{m}}\text{Ag}$ results in a nuclide with a complex decay scheme which is well known and having a half-life of 249.76 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 953.³ 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 $10^9 \text{ cm}^{-2} \cdot \text{s}^{-1}$ to $3 \times 10^{15} \text{ cm}^{-2} \cdot \text{s}^{-1}$ can be measured. For this method to be applicable, the reactor must be well moderated and be well represented by a Maxwellian low-energy distribution and an $(1/E)$ epithermal distribution. These conditions are usually met in positions surrounded by hydrogenous moderator without nearby strongly absorbing materials. Otherwise the true spectrum must be calculated to obtain effective activation cross sections over all energies.

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

¹ This test method 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.

Current edition approved Jan. 1, 2010. Published May 2010. Originally approved in 1973. Last previous edition approved in 2003 as E481 – 03. DOI: 10.1520/E0481-10.

² The boldface numbers in parentheses refer to references listed at the end of this test method.

³ Standard Reference Material 953 is available from National Institute of Standards and Technology, U.S. Dept. of Commerce, Washington, DC 20234.

1.3 The values stated in SI units are to be regarded as the 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:⁴

E170 Terminology Relating to Radiation Measurements and Dosimetry

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

E181 Test Methods for Detector Calibration and Analysis of Radionuclides

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

3. Significance and Use

3.1 The pertinent data for these two reactions are given in Table 1. This test method uses one monitor (cobalt) with a nearly $1/v$ absorption cross-section curve and a second monitor (silver) with a large resonance peak so that its resonance integral is large compared to the thermal cross section. The equations are based on the Westcott formalism (2, 3) and determine a Westcott 2200 m/s neutron fluence rate nv_0 and the Westcott epithermal index parameter $r \sqrt{T/T_0}$. References 4, 5, and 6 contain a general discussion of the two-reaction test method. In this test method, 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 test method are the elimination of three 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

⁴ 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.

TABLE 1 Recommended Constants

Symbol	Parameter	Cobalt (^{60}Co)		Silver ($^{110\text{m}}\text{Ag}$)	
		Value ^A	Reference	Value ^A	Reference
$t_{1/2}$	Half-life	1925.28 (14) days	(1)	249.76 (4) days	(1)
A	Abundance of parent isotope	100 % (^{59}Co)	(1)	48.161 (8) % (^{109}Ag)	(1)
Δ	Mass excess of residual isotope (scaled to $\Delta [^{12}\text{C}] = 0$) (1 amu = 931.494 MeV) ^B	-61.64904 MeV	(1)	-87.3424 MeV	(1)
σ_a	Absorption 2200 m/s cross section for target ^{59}Co and ^{109}Ag	37.233 b $\pm$ 0.16 %	C,D	91.0 b $\pm$ 1 %	(7)
σ_0	2200 m/s cross section for formation of ^{60}Co and $^{110\text{m}}\text{Ag}$	37.233 b $\pm$ 0.16 %	C,D	4.12 b $\pm$ 2.54 %	(8)
S_0	Correction factor which describes the departure of the cross section from the 1/v law in the epithermal region	1.80 [$^{59}\text{Co}(\text{n},\gamma)^{60}\text{Co}$]	E	18.13 $\pm$ 4 % [$^{109}\text{Ag}(\text{n},\gamma)^{110\text{m}}\text{Ag}$] 17.76 [$^{109}\text{Ag}(\text{n},\gamma)^{110\text{m}+110\text{g}}\text{Ag}$]	(8)
I_0	Resonance Integral	75.421 b $\pm$ 0.77 % [$^{59}\text{Co}(\text{n},\gamma)^{60}\text{Co}$]	(9) ^F	67.9 b $\pm$ 4.5 % [$^{109}\text{Ag}(\text{n},\gamma)^{110\text{m}}\text{Ag}$]	(8)
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)	$\cong 1 - 4/3 R\Sigma_a$	(4)
G'_{res}	Resonance neutron self-shielding factor	Table 3	(12)	Fig. 1 ^G	
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 parenthesis following given values is 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 Isotopic masses may be calculated as $A + 931.49432/\Delta$, where A is the atomic mass number.

^C A 2200 m/s cross section ($E = 0.0253$ eV, $T = 20^\circ\text{C}$) was taken from the sources indicated in Ref (9).

^D Cross section uncertainty data is taken from Ref (7), the cross section comes from the other reference.

^E Calculated using Eq 5.

^F Cross section uncertainty comes from covariance data provided in the cross section source. The other reference indicates the source of the cross section.

^G In Fig. 1, $\Theta = 4E_0 kT/AT^2 = 0.2$ corresponds to the value for ^{109}Ag for $T = 293$ K, $\Sigma_r = N_0\sigma_r$, $\sigma_{r, \text{max}} = 29999$ barn at 5.19 eV (13).

cadmium. In addition, the reactivity changes accompanying the rapid insertion and removal of cadmium may prohibit the use of the cadmium-ratio method. However, the self-shielding corrections remain important unless the concentrations of cobalt and silver are small. Studies indicate that the accuracy of the two-reaction method for determination of thermal neutron fluence is comparable to the cadmium-ratio method (14).

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

4. Apparatus

4.1 *NaI(Tl) or Germanium Gamma-Ray Spectrometer (using a multichannel analyzer)*—For the NaI(Tl) technique and the germanium technique, see Method E181.

4.2 *Precision Balance.*

4.3 *Digital Computer.*

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 (15) 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 ($>10^{15} \text{ cm}^{-2}\text{s}^{-1}$) facility (6, 16). Typical alloys contain 0.1 % silver or cobalt in aluminum) see 6.1 and 8.1).

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.

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. Procedure

6.1 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 exposure time 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 in Section 7, the concentration of the alloys should be chosen so that the ratio of the disintegration rates is on the order of one.

6.2 Weigh the samples to a precision of $\pm 1.0\%$ (1S %) as defined in Practice E177.

6.3 Irradiate the samples for the predetermined time period. 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.

6.4 A waiting period is necessary between termination of the exposure and start of counting when using Co-Al and Ag-Al monitors. This allows the 0.62356 days (17) half-life ^{24}Na which is formed by fast-neutron reactions on ^{27}Al or by thermal-neutron captures by ^{23}Na impurities to decay below levels at which its radiations may cause interferences. It is sometimes advisable to count the samples periodically and follow the decay of the portions of the activities due to the ^{24}Na . The length of the waiting period can be reduced by the use of a germanium detector.

6.5 With the gamma-ray spectrometer, analyze the silver sample for $^{110\text{m}}\text{Ag}$ and the cobalt sample for ^{60}Co . Obtain the net count rate in each full-energy gamma-ray peak of interest, that is, 657.7623 keV or 884.684 keV for $^{110\text{m}}\text{Ag}$; 1332.501 keV for ^{60}Co (see Method E181). See Table 2 for gamma radiations of $^{110\text{m}}\text{Ag}$.

7. Calculation

7.1 Calculate the activities of $^{110\text{m}}\text{Ag}$ and ^{60}Co in disintegrations per second.

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

$$A = N_0 \lambda B F G \hat{\sigma}_1 \phi_w t_i \quad (1)$$

TABLE 2 Gamma Radiations of $^{110\text{m}}\text{Ag}$ (17,18)

Energy of Gamma ^A (keV)	Relative ^{B,A} Emission Probability (%)
1. 657.7600 (11)	100
2. 884.6781 (13)	77.1 (3)
3. 937.485 (3)	36.3 (6)
4. 1384.2931 (20)	26.4 (8)
5. 763.9424 (17)	23.98 (21)
6. 706.6760 (15)	17.31 (5)
7. 1505.0280 (20)	14.42 (19)
8. 677.6217 (12)	11.20 (2)
9. 818.0244 (18)	7.78 (8)
10. 687.0091 (18)	6.83 (5)
11. 744.2753 (18)	5.06 (9)
12. 1562.294 (18)	1.319 (17)

^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 .

^B For absolute intensity multiply emission probabilities by 0.943 ± 0.004 .

where:

- A = measured activity at the end of the exposure time, disintegrations/s,
- N_0 = number of target atoms of ^{59}Co or ^{109}Ag at start of irradiation,
- λ = disintegration constant of product nuclide, s^{-1} ,
- B = Self-absorption factor of the decay gamma ray in the monitor material,
- F = burnup and decay correction factor,
- G = self-shielding factor (see Eq 4, Table 3 and Fig. 1).
- $\hat{\sigma}_1$ = Westcott's effective absorption cross section for production of the product nuclide, cm^2 ,
- ϕ_w (or nv_0) = a 2200 m/s neutron fluence rate in which n is the neutron density (including both thermal and epithermal neutrons) and t_i is 2200 m/s, and
- t_i = exposure time.

7.3 The self-absorption factor, if not known for the gamma rays being measured, can be approximated by the following equation:

$$B \approx 1 - (4/3)(\mu_a R) \quad (2)$$

where:

- μ_a = linear absorption coefficient in monitor, cm^{-1} , and
- R = radius of monitor wire, cm.

7.4 The burnup and decay correction factor is given by:

$$F = \frac{\exp(-\hat{\sigma}_a \phi_w t_i) - \exp(-(\lambda + \hat{\sigma}_2 \phi_w) t_i)}{(\lambda + \hat{\sigma}_2 \phi_w - \hat{\sigma}_a \phi_w) t_i} \quad (3)$$

where:

- $\hat{\sigma}_a$ = Westcott's effective absorption cross section for target nuclide, cm^2 , and
- $\hat{\sigma}_2$ = Westcott's effective absorption cross section for the product nuclide, cm^2 .

7.5 The self-shielding factor is given by:

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

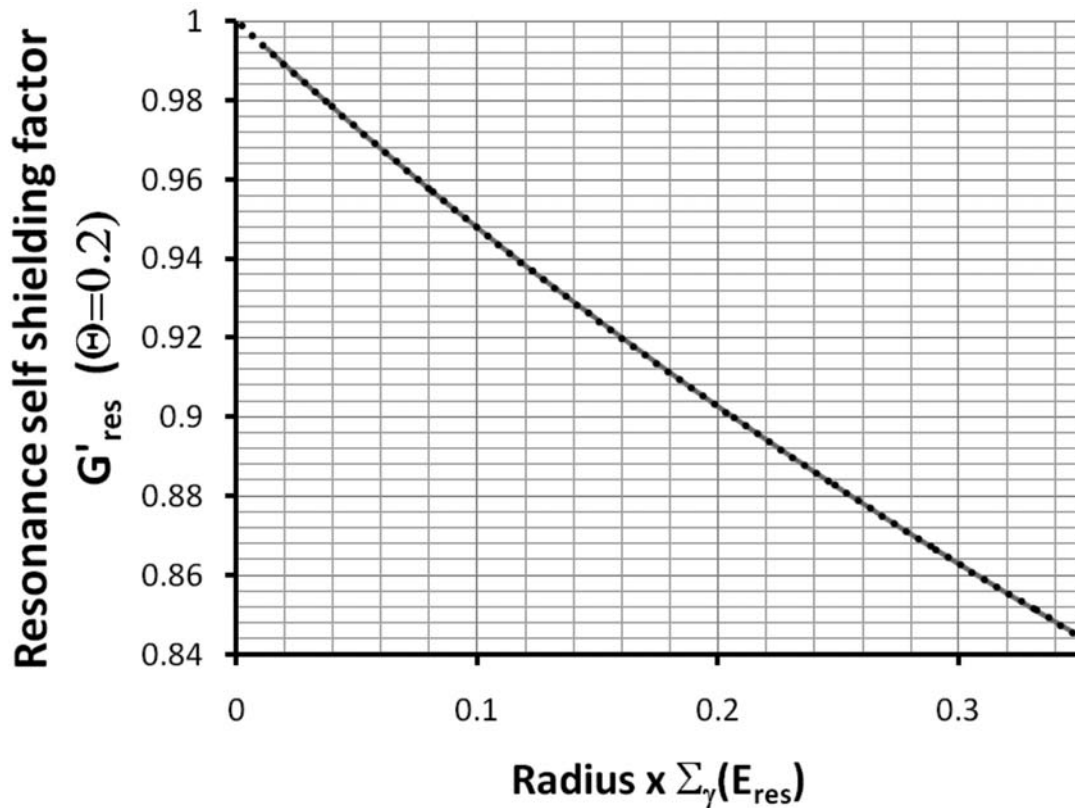


FIG. 1 Resonance Self-Shielding Factor for Cylinders ($\theta = 0.2$) as a Function of Radius $\times$ Macroscopic Absorption Cross Section at the Peak of the Resonance, for ^{109}Ag at 5.19 eV, $\sigma_{\gamma, \max} = 29999$ barn (13)

$$G = \frac{gG_{th} + (r\sqrt{T/T_0})S_0G'_{res}}{g + (r\sqrt{T/T_0})S_0} \quad (4)$$

where:

- g = correction factor which describes the departure of the cross section from the $1/\nu$ law in the thermal region (see Table 4 for silver “ g ” factors),
- G_{th} = thermal neutron self-shielding factor,
- G'_{res} = resonance neutron self-shielding factor,
- r = a measure of the proportion of epithermal neutrons in the reactor spectrum,
- T = neutron temperature, K,
- T_0 = 293.6 K, and
- S_0 = correction factor which describes the departure of the cross section from the $1/\nu$ law in the epithermal region.

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

$$S_0 = \frac{2}{\sqrt{\pi}} \frac{I''_0}{\sigma_0} = \frac{2}{\sqrt{\pi}} \left(\frac{I_0}{\sigma_0} - 2g \sqrt{\frac{E_0}{E_{Cd}}} \right) \quad (5)$$

where:

- I''_0 = resonance integral excess over the $1/\nu$ cross section value, cm^2 ,
- σ_0 = 2200 m/s cross-section value, cm^2 ,
- I_0 = resonance integral,
- E_0 = 0.0253 eV, and
- E_{Cd} = 0.55 eV.

7.7 Substituting the measured activities of the cobalt and the silver monitors into Eq 1 yields two nonlinear equations in the two unknown parameters $r\sqrt{T/T_0}$ and ϕ_w .

7.8 PC software products such as *MathCad* and *Mathematica* can be programmed to solve these two nonlinear equations with a variety of iterative solvers. A FORTRAN IV computer program, COAG2 (19), was written to solve these equations. The program iterates until the epithermal index and the fluence values give calculated activities that are within 0.1 % of their measured values. The constants, cross sections, and other measured values used in the program should be set equal to those listed in Table 1.

7.9 If the burnup corrections are negligible, that is, if the factor F , (Eq 3) is equal to $(1 - \exp(-\lambda t_i))/\lambda t_i$, the equations can be solved in closed form. If the subscripts 1 and 2 refer to the two reactions (in either order) the parameters are calculated as follows:

$$\phi_w = \left(\frac{R_2}{S_{02}G'_{res2}\sigma_{02}} - \frac{R_1}{S_{01}G'_{res1}\sigma_{01}} \right) / \left(\frac{g_2G_{th2}}{S_{02}G'_{res2}} - \frac{g_1G_{th1}}{S_{02}G'_{res1}} \right) \quad (6)$$

$$r\sqrt{\frac{T}{T_0}} = \frac{\frac{g_1G_{th1}}{S_{01}G'_{res1}} - \frac{g_2G_{th2}}{S_{02}G'_{res2}} \left(\frac{R_1}{g_1G_{th1}\sigma_{01}} - \frac{R_2}{g_2G_{th2}\sigma_{02}} \right)}{\frac{R_1}{S_{01}G'_{res1}\sigma_{01}}} \quad (7)$$

where:

- R_1 and R_2 = the measured reaction rates per target atom = $A/N_0\lambda BFt_i$

TABLE 4 “g” Factor for Silver

$T (^{\circ}\text{C})$	$g (\text{Ag})$
20	1.0044
40	1.0053
60	1.0062
80	1.0071
100	1.0080
120	1.0090
140	1.0099
160	1.0108
180	1.0117
200	1.0126
220	1.0136
240	1.0145
260	1.0154
280	1.0164
300	1.0173
330	1.0187
360	1.0201
390	1.0215
420	1.0230
450	1.0244
480	1.0258
510	1.0273
540	1.0287
570	1.0302
600	1.0316
640	1.0336
680	1.0356
720	1.0376
760	1.0395
800	1.0416
840	1.0436
880	1.0456
920	1.0476
960	1.0497
1000	1.0517
1060	1.0549
1120	1.0580
1180	1.0612
1240	1.0644
1300	1.0676

7.10 The Westcott 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, σ , with nv_0 , where n = the neutron density, including both thermal and epithermal neutrons, cm^{-3} , and $v_0 = 2200 \text{ m/s}$.

so that:

$$R = nv_0\hat{\sigma} \quad (8)$$

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

$$R = \int_0^{\infty} n(v)v\sigma(v)dv \quad (9)$$

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:

$$\hat{\sigma} = \int_0^{\infty} n(v)v\sigma(v)dv/nv_0 \quad (10)$$

The neutron spectrum assumed by Westcott has the form: $n(v) = n(1 - f)P_m(v) + nfP_e(v)$, where P_m and P_e are the Maxwellian and epithermal density distribution functions normalized so that: $\int_0^{\infty} P_m(v)dv = \int_0^{\infty} P_e(v)dv = 1$. 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, Δ , at a suitable lower limit of energy. Based on the above spectrum, one obtains the following relation for the effective cross section:

$$\hat{\sigma} = \sigma_0(g + rs) \quad (11)$$

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 = $S_0 \sqrt{T/T_0}$, a factor which describes the departure of the cross section from the $1/v$ law in the epithermal region, and

r = a measure of the proportion of epithermal neutrons in the reactor spectrum.

More specifically:

$$r = f\sqrt{\pi\mu_n}/4 \quad (12)$$

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).

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

$$\Sigma_a/\xi\Sigma_s < 0.1 \quad (13)$$

and:

$$T/T_m < 1.07 \quad (14)$$

where:

Σ_a = macroscopic absorption cross section averaged over all materials affecting spectrum,

ξ = average logarithmic energy decrement per collision,

Σ_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 $\Sigma_a/\xi\Sigma_s$ becomes too great or if the neutron temperature T is too great relative to the moderator temperature T_m , the Maxwell spectrum hypothesis fails and the true spectrum must be calculated and the effective cross section determined with this spectrum.

7.12 The conventional 2200 m/s thermal neutron-fluence rate, ϕ_0 , and the epithermal fluence-rate parameter, ϕ_e , as defined in Method E262, can be obtained from the Westcott neutron-fluence rate, ϕ_w , and the Westcott epithermal index, $r\sqrt{T/T_0}$, by means of equations Eq 15 and Eq 16:

$$\phi_0 = \left(1 - \frac{4r}{\sqrt{\pi\mu_n}}\right) \phi_w \quad (15)$$

$$\phi = \frac{2}{\sqrt{\pi}} r \sqrt{\frac{T}{T_0}} \phi_w \quad (16)$$

7.13 In Eq 15, it is necessary to estimate the neutron temperature, T , in order to obtain the value of r from the index

$r \sqrt{T/T_0}$. Provided inequality (Eq 14) is satisfied, only slight error is introduced by assuming $T = T_m$, the moderator temperature.

8. Precision and Bias

NOTE 2—Measurement uncertainty is described by a precision and bias statement in this standard. Another acceptable approach is to use Type A and B uncertainty components (20,21). This Type A/B uncertainty specification is now used in International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

8.1 There are several sources of errors that affect the precision of this test method. Random errors appear in the determination of the weight percent and homogeneity of low concentrations of cobalt and silver alloyed with some other material such as aluminum, the determination of the cobalt and

silver activities after irradiation, and the measurement of cross sections and other related data. These errors should not exceed $\pm 3\%$ (1σ), $\pm 3\%$ (1σ), and $\pm 5\%$ (1σ) as defined in Practice E177.

8.2 The bias due to trace impurities was calculated to be negligible. Self-shielding and the burnup of the product nuclide are accounted for in the mathematical treatment. Self-shielding may become appreciable unless care is taken to minimize this effect by the use of low concentrations of cobalt and silver in the alloy used, as very thin foils. The burnout of the product nuclide is a very small effect unless the cross section is greatly in error.

9. Keywords

9.1 activation; cobalt; dosimetry; foil; silver; thermal neutron

REFERENCES

- (1) *Nuclear Wallet Cards*, compiled by Jagdish K. Tuli, National Nuclear Data Center, www.nndc.bnl.gov/wallet/wccurrent.html. The data presented here reflects this database as of March 2009.
- (2) Westcott, C. H., "Effective Cross Sections Values for Well-Moderated Thermal Reactor Spectra," CRRP-960, November 1960.
- (3) Westcott, C. H., Walker, W. H., and Alexander, T. K., A/Conf. 15/P/202 "Effective Cross Sections and Cadmium Ratios for the Neutron Spectra of Thermal Reactors."
- (4) Hart, R. G., Bingham, C. B., and Miller, F. C., "Silver-109 as an Epithermal Index Monitor for Use with Cobalt Flux Monitors," CRDC-1083, April 1962.
- (5) Cabell, M. J., and Wilkins, M., "A Comparison of 240Pu and 109Ag as Epithermal Index Monitors for Long Irradiations," AERE-R4866, April 1965.
- (6) Cabell, M. J., and Wilkins, M., "Routine Use of the Silver-Cobalt Activity Ratio Method to Determine Epithermal Indices for Large Neutron Dose Irradiations," AERE-R5122, February 1966.
- (7) Mughabghab, S. F., *Neutron Cross Sections, Vol. 1: Neutron Resonance Parameters and Thermal Cross Sections*, National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, Academic Press Inc., 1984. This report was formerly known as BNL-325.
- (8) Nakamura, S., Hiraoki, W., Shcherbakov, O., Furutaka, K., Harada, H., and Katoh, T., "Measurement of the Thermal Neutron Capture Cross Section and the Resonance Integral of the 109Ag (n,g)110mAg Reaction," *J. Nucl. Sci. and Technology*, Vol 40, No. 3, March 2003 pp. 119-124.
- (9) Griffin, P. J., Kelly, J. G., Luera, T. F., VanDenBerg, J. *SNL RML Recommended Dosimetry Cross Section Compendium*, Sandia National Laboratories, Albuquerque, NM, report SAND92-0094, November 1993.
- (10) Hogg, C. H., and Weber, L. D., "Neutron Activation Cross Sections for the Cobalt-60 Isomers," IN-1024, 1966.
- (11) Goldberg, M. D., et al., "Neutron-Cross Sections," Vol IIB, Z-41 to 60, BNL 325, 2nd Edition, Supplement No. 2, 1966.
- (12) Eastwood, T. A., and Werner, R. D., "Resonance and Thermal Neutron Self-Shielding in Cobalt Foils and Wires," *Nuclear Science and Engineering*, Vol 13, 1962, pp. 385-390.
- (13) Evaluated Nuclear (reaction) Data File, ENDF/B-VII.0 (2006) at <http://www.nndc.bnl.gov/endl/>, Brookhaven National Laboratory.
- The value of 29999 barns is calculated from the resonance parameters.
- (14) van der Meer, K., Delveau, C., and Kriener, B., "Is the Co/Ag method for the simultaneous determination of the thermal and epithermal neutron flux reliable?" Proceedings of the 11th International Symposium on Reactor Dosimetry, in *Reactor Dosimetry in the 21st Century*, Wagemans et al., Eds., World Scientific, 2003, pp. 186-193.
- (15) Walz, K. F., and Weiss, A. M., *Zeitschrift fuer Naturforschung*, Vol 25a, 1971, p. 921.
- (16) Kam, F. B. K., and Swanks, J. H., "Measurements of the Neutron Flux with the HFIR Target Region", *Transactions*, Am. Nuclear Soc., Supplement to Vol 12, October 1969.
- (17) Bé, M. M., Chechev, V. P., Dersch, R., Helene, O. A. M., Helmer, R. G., Herman, M., Hlavác, S., Marcinkowski, A., Molnár, G. L., Nichols, A. L., Shcönfeld, E., Vanin, V. R., and Woods, M. J., *Update of X Ray and Gamma Ray Decay Data Standards for Detector Calibration and Other Applications*, Vol 1, Recommended Decay Data, High Energy Gamma Ray Standards and Angular Correlation Coefficients, Vienna: International Atomic Energy Agency, 2007, ISBN 92-0-113606-4.
- (18) Evaluated Nuclear Structure Data File (ENSDF), a computer file of evaluated nuclear structure and radioactive decay data, which is maintained by the National Nuclear Data Center (NNDC), Brookhaven National Laboratory (BNL), on behalf of The International Network for Nuclear Structure Data Evaluation, which functions under the auspices of the Nuclear Data Section of the International Atomic Energy Agency (IAEA). The data presented here reflects this database as of March 2009, www.nndc.bnl.gov/ENSDF.
- (19) Kam, F. B. K., "COAG2: A FORTRAN IV Program to Determine the Westcott Epithermal Index and the Westcott 2200 m/s Neutron Flux." Available as ID# P000701036000 from the Radiation Safety Information Computation Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- (20) *Guide in the Expression of Uncertainty in Measurement*, International Organization for Standardization, 1993, ISBN 92-67-10188-9.
- (21) Taylor, B. N., Kuyatt, C. E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, National Institute of Standards and Technology, Gaithersburg, MD, 1994.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the ASTM website (www.astm.org/COPYRIGHT/).