Designation: E262 – 17

Standard Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques[1]

This standard is issued under the fixed designation E262; 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 The purpose of this test method is to define a general procedure for determining an unknown thermal-neutron fluence rate by neutron activation techniques. It is not practicable to describe completely a technique applicable to the large number of experimental situations that require the measurement of a thermal-neutron fluence rate. Therefore, this method is presented so that the user may adapt to their particular situation the fundamental procedures of the following techniques.

1.1.1 Radiometric counting technique using pure cobalt, pure gold, pure indium, cobalt-aluminum, alloy, gold-aluminum alloy, or indium-aluminum alloy.

1.1.2 Standard comparison technique using pure gold, or gold-aluminum alloy, and

1.1.3 Secondary standard comparison techniques using pure indium, indium-aluminum alloy, pure dysprosium, or dysprosium-aluminum alloy.

1.2 The techniques presented are limited to measurements at room temperatures. However, special problems when making thermal-neutron fluence rate measurements in high-temperature environments are discussed in 9.2. For those circumstances where the use of cadmium as a thermal shield is undesirable because of potential spectrum perturbations or of temperatures above the melting point of cadmium, the method described in Test Method E481 can be used in some cases. Alternatively, gadolinium filters may be used instead of cadmium. For high temperature applications in which aluminum alloys are unsuitable, other alloys such as cobalt-nickel or cobalt-vanadium have been used.

1.3 This test method may be used to determine the equivalent 2200 m/s fluence rate. The accurate determination of the actual thermal neutron fluence rate requires knowledge of the neutron temperature, and determination of the neutron temperature is not within the scope of the standard.

1.4 The techniques presented are suitable only for neutron fields having a significant thermal neutron component, in which moderating materials are present, and for which the average scattering cross section is large compared to the average absorption cross section in the thermal neutron energy range.

1.5 Table 1 indicates the useful neutron-fluence ranges for each detector material.

1.6 *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.*

1.7 *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:*[2]

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

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

E481 Test Method for Measuring Neutron Fluence Rates by Radioactivation of Cobalt and Silver

3. Terminology

3.1 *cadmium ratio*—see Terminology E170.

3.2 *Calibration Techniques:*

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

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[2] 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 Useful Neutron Fluence Ranges of Foil Material

Foil Material	Form	≈ Useful Range (neutrons/cm^2)
Indium	pure or alloyed with aluminum	10^3 to 10^{12}
Gold	pure or alloyed with aluminum	10^7 to 10^{14}
Dysprosium	pure or alloyed with aluminum	10^3 to 10^{10}
Cobalt	pure or alloyed with aluminum	10^{14} to 10^{20}

3.2.1 *radiometric*—the radiometric technique uses foil properties, decay properties of the activation product, the detector efficiency, and cross section to derive the neutron fluence rate. When beta counting is used, it becomes problematic to determine the absolute detector efficiency, and calibration is usually performed by exposing the foil to a Standard or Secondary Standard field.

3.2.2 *standard comparison*—the standard comparison technique compares activity from a foil irradiated in a standard or reference field to the activity from a foil irradiated in the unknown field to derive the neutron fluence rate.

3.2.3 *secondary standard comparison*—the secondary standard comparison technique is the same as the standard comparison technique, except that the reference field is not a well-calibrated national reference, and is usually local to the facility. This is sometimes done because a foil with a short half-life undergoes too much decay in transit from a standard source.

3.2.3.1 *Discussion*—The standard comparison technique is the most accurate. Among the foils discussed in this standard, only gold has a suitable half-life for standard counting: long enough to allow transport of the foil from the standards laboratory to the facility for counting, and short enough to allow reuse of the foil. One might consider moving the radiation detector to the national standard location to accommodate a short half-life.

3.3 *equivalent 2200 m/s fluence*—see Terminology E170.

3.4 *foil*—material whose induced radioactivity is used to help determine the properties of a neutron field. Typical foil shapes are thin discs or rectangles, but wire segments are another common shape. In this document, all activation materials of every shape will be called “foils” for the sake of brevity. Foils are also often called “radiometric dosimeters” or “radiometric monitors.”

3.5 *Maxwell-Boltzmann distribution*—the Maxwell-Boltzman distribution is a probability distribution which describes the energy or velocity distribution of particles in equilibrium at a given temperature. For neutrons, this is given by:

$$n(E)dE = n_{th}\frac{2}{\sqrt{\pi}}\frac{E^{1/2}}{(kT)^{3/2}}e^{-E/kT}dE$$

or

$$n(v)dv = n_{th}\frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2}v^2e^{-\left(\frac{mv^2}{2kT}\right)}dv$$

where:

n_{th} = the number of thermal neutrons per volume,
m = the neutron mass (931 MeV),
k = Boltzmann’s constant (8.617×10^{-5} ev K^{-1},
T = the neutron temperature,
v and E = the neutron velocity and energy, respectively.

3.6 *thermal neutron fluence rate (Φ_{th})*—

$$\int_0^\infty v\cdot n(v)dv$$

where:

v = the neutron velocity and $n(v)$ is the thermal neutron density as a function of velocity.

3.7 *Thermal neutron fluence rate conventions:*

3.7.1 *Stoughton and Halperin convention*—the neutron spectrum is separated into a thermal part and a 1/E part. The 2200 m/s neutron fluence rate, Φ_0, is the hypothetical neutron fluence rate in which all the thermal neutrons have a velocity of 2200 m/s. The 1/E part of the spectrum is not included. The Stoughton and Halperin convention is followed in this standard.

3.7.2 *Westcott convention*—Φ_0 is the hypothetical neutron fluence rate in which all the neutrons have a velocity of 2200 m/s, which gives the same activation as the total neutron fluence incident on a 1/v detector.

3.7.2.1 *Discussion*—See Theory section and Precision and Bias section for further discussion.

3.7.3 *Hogdahl convention*—the Hogdahl convention is similar to the Stoughton and Halperin convention, but separates out the subcadmium fluence as a separate entitity, φ_{sc}. See Practice E261 for further discussion.

3.8 *thermal neutrons*—See Terminology E170.

3.9 *neutron temperature, T*—an adjustable parameter used to give the best fit of a calculated or measured thermal neutron speed distribution to the Maxwell-Boltzmann distribution. Because of increasing absorption for lower energy neutrons, the neutron temperature is usually higher than the temperature of the moderating materials in the system of interest.

3.10 *2200 m/s cross section*—see Terminology E170.

4. Significance and Use

4.1 This test method can be extended to use any material that has the necessary nuclear and activation properties that suit the experimenter’s particular situation. No attempt has been made to fully describe the myriad problems of counting techniques, neutron-fluence depression, and thick-foil self-shielding. It is assumed that the experimenter will refer to existing literature on these subjects. This test method does offer a referee technique (the standard gold foil) to aid the experimenter when they are in doubt of their ability to perform the radiometric technique with sufficient accuracy.

4.2 The standard comparison technique uses a set of foils that are as nearly identical as possible in shape and mass. The foils are fabricated from any material that activates by an (n, γ) reaction, preferably having a cross section approximately inversely proportional to neutron speed in the thermal energy range. Some of the foils are irradiated in a known neutron field

(at NIST) or other standards laboratory). The foils are counted in a fixed geometry on a stable radiation-detecting instrument. The neutron-induced reaction rate of the foils is computed from the counting data, and the ratio of the known neutron fluence rate to the computed reaction rate is determined. For any given foil, neutron energy spectrum, and counting set-up, this ratio is a constant. Other foils from the identical set can now be exposed to an unknown neutron field. The magnitude of the fluence rate in the unknown field can be obtained by comparing the reaction rates as determined from the counting data from the unknown and reference field, with proper corrections to account for spectral differences between the two fields (see Section 5). One important feature of this technique is that it eliminates the need for knowing the detector efficiency.

4.3 This test method follows the Stoughton and Halperin convention for reporting thermal neutron fluence. Other conventions are the Wescott convention (followed in Test Method E481) and the Hogdahl convention. Practice E261 explains the three conventions and gives conversion formulae relating values determined by the different conventions. Reference **(1)**[3] discusses the three thermal-neutron conventions in detail.

5. Theory

5.1 *1/v Cross Sections*—It is not possible using radioactivation techniques to determine the true thermal neutron fluence rate without making some assumptions about the spectral shapes of both the thermal and epithermal components of the neutron density. For most purposes, however, the information required is only that needed to make calculations of activation and other reaction rates for various materials exposed to the neutron field. For reactions in which the cross section varies inversely as the neutron speed (1/v cross sections) the reaction rates are proportional to the total neutron density and do not depend on the spectrum shape. Many radioactivation detectors have reaction cross sections in the thermal energy range which approximate to 1/v cross sections (1/v detectors). Departures from the 1/v shape can be accounted for by means of correction factors.

5.2 *Fluence Rate Conventions:*

5.2.1 The purpose of a fluence rate convention (formerly called "flux convention") is to describe a neutron field in terms of a few parameters that can be conveniently used to calculate reaction rates. The best known fluence rate conventions relating to thermal neutron fields are the Westcott convention **(2)** and the Stoughton and Halperin convention **(3)**. Both make use of the concept of an equivalent 2200 m/s fluence rate, that is equal to the product of the neutron density and the standard speed, v_0, equal to 2200 m/s which is the most probable speed of Maxwellian thermal neutrons when the characteristic temperature is 293.59°K. In the Westcott convention, it is the total neutron density (thermal plus epithermal) which is multiplied by v_0 to form the "Westcott flux", but in the Stoughton and Halperin convention, the conventional fluence rate is the product of the Maxwellian thermal neutron density and v_0. The latter convention is the one followed in this method:

$$\varphi_0 = n_{th} v_0 \quad (1)$$

where φ_0 is the equivalent (or conventional) 2200 m/s thermal fluence rate and n_{th} represents the thermal neutron density, which is proportional to the reaction rate per atom in a 1/v detector exposed to thermal neutrons:

$$R_0 = n_{th}\sigma_0 v_0 = \sigma_0 \varphi_0 \quad (2)$$

5.2.2 R_0 represents only that part of the reaction rate that is induced by thermal neutrons, which have the Maxwellian spectrum shape. σ_0 is the 2200 m/s cross section. For a non-1/v detector Eq 2 needs to be replaced by:

$$R_0 = n_{th} g \sigma_0 v_0 = g \sigma_0 \varphi_0 \quad (3)$$

where g is a correction factor that accounts for the departures from the ideal 1/v detector cross section in the thermal energy range. The same factor appears in the Westcott convention Ref **(2)**, and is usually referred to as the Westcott g factor. g depends on the neutron temperature, T, and is defined as follows:

$$g = \frac{1}{v_0 \sigma_0} \int_0^\infty \frac{4}{\pi^{1/2}} \left(\frac{v}{v_0}\right)^3 \left(\frac{T_0}{T}\right)^{3/2} \cdot \exp\left[-\left(\frac{v}{v_0}\right)^2 \left(\frac{T_0}{T}\right)\right] \sigma(v) dv \quad (4)$$

5.2.3 If the thermal neutron spectrum truly follows the Maxwellian distribution and if the neutron temperature is known, it is possible to calculate the true thermal neutron fluence rate by multiplying the conventional (equivalent 2200 m/s) thermal fluence rate by the factor:

$$\frac{v}{v_0} = \left(\frac{4T}{\pi T_0}\right)^{1/2} \quad (5)$$

where v is the Maxwellian mean speed for neutron temperature T, and T_0 is the standard temperature of 293.4°K. This conversion is most often unnecessary and is usually not made because the temperature T may be unknown. Naturally, it is essential when reporting results to be absolutely clear whether the true thermal fluence rate or the equivalent 2200 m/s thermal fluence rate or the equivalent 2200 m/s total (Westcott) fluence rate is used. If the true thermal fluence rate is used, then its value must be accompanied by the associated temperature value.

5.3 *Epithermal Neutrons*—In order to determine the effects of epithermal neutrons, that are invariably present together with thermal neutrons, cadmium covered foil irradiations are made. It is important to realize that some epithermal neutrons can have energies below the effective cadmium cut-off energy, E_{cd}. The lowest energy of epithermal neutrons is usually taken to be equal to $5kT$ (where k is Boltzmann's constant) that is equal to 0.13 eV for room temperature (293°K) neutrons **(2)**, though 4 kT has been recommended for some reactors **(4)**. In order to correct for these, it is necessary to make some assumption about the epithermal neutron spectrum shape, and the assumption made in Refs **2** and **3** is that the epithermal neutron fluence rate per unit energy is proportional to 1/E:

$$\varphi_e(E) = \varphi_e / E \qquad E \geq 5kT \quad (6)$$

where φ_e is an epithermal fluence parameter equal to the fluence rate per unit energy, $\varphi_e(E)$, at 1 eV. This assumption is usually adequate for the purpose of correcting thermal neutron

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

fluence rate measurements for epithermal neutrons at energies below the cadmium cut-off. To represent the epithermal fluence more correctly, however, many authors have shown that the use of a $1/E^{(1+\alpha)}$ spectrum shape is preferable, where α is an empirical parameter. Refs (**5-11**).

5.4 *Resonance Integral:*

5.4.1 The resonance integral for an ideal dilute detector is defined as follows:

$$I_0 = \int_{E_{cd}}^{\infty} \sigma(E) \frac{dE}{E} \tag{7}$$

5.4.2 The cadmium cut-off energy is taken to be 0.55 eV for a cylindrical cadmium box of wall thickness 1 mm. (**12**). The data needed to correct for epithermal neutron reactions in the methods described are the values of $I_0/g\sigma_0$ for each reaction (see Table 2). These values, taken from Refs (**13-15**), are based on integral measurements.

5.5 *Reaction Rate:*

5.5.1 The reaction rate per atom, for an isotope exposed to a mixed thermal and epithermal neutron field is given by:

$$R = \varphi_0 g\sigma_0 + \varphi_e g\sigma_0 \left[f_1 + w'/g + I_0/g\sigma_0\right] \tag{8}$$

f_1 is a function that describes the epithermal activation of a 1/v detector in the energy range 5kT to E_{cd}:

$$f_1 = \int_{5kT}^{E_{cd}} \left(\frac{kT_0}{E}\right)^{1/2} \frac{dE}{E} \tag{9}$$

5.5.2 For E_{cd} equal to 0.55eV and T_0 equal to 293.4°K, f_1 = 0.468. w' in Eq 8 is a function which accounts for departure of the cross section from the 1/v law in the energy range 5kT to E_{cd}:

$$w' = \frac{1}{\sigma_0} \int_{5kT}^{E_{cd}} \left[\sigma(E) - g\sigma_0 \left(\frac{kT}{E}\right)^{1/2} \right] \frac{dE}{E} \tag{10}$$

Some values of w' for T equal 293.4°K are given in Table 2.

5.5.3 For a cadmium covered foil, the reaction rate is given as:

$$R_{Cd} = \varphi_e I_0 \tag{11}$$

5.5.4 This can be used to eliminate the unknown epithermal fluence rate parameter, φ_e, from Eq 8. After rearrangement, one obtains an expression for the saturation activity due to thermal neutrons only:

$$\varphi_0 g\sigma_0 = R_0 = R - R_{Cd} \left(1 + \frac{g\sigma_0}{I_0} f_1 + \frac{\sigma_0 w'}{I_0}\right) \tag{12}$$

5.6 *Neutron Self-Shielding:*

5.6.1 Unless extremely thin or dilute alloy materials are used, all of the measurement methods are subject to the effects of neutron self-shielding. The modified version of Eq 12 which takes into account both a thermal self-shielding factor G_{th}, and an epithermal self shielding factor G_{res} is:

$$\varphi_0 g\sigma_0 = \frac{R_0}{G_{th}}$$

$$= \frac{1}{G_{th}} \left[R - R_{Cd} \left(1 + \frac{g\sigma_0}{G_{res} I_0} f_1 + \frac{\sigma_0 w'}{G_{res} I_0}\right) \right] \tag{13}$$

5.6.2 Values of the self-shielding factors G_{th} and G_{res} for several foils and wires are given in Tables 3-7. In the literature, values for the resonance self-shielding factor are given in two ways, and those must not be confused. G_{res}, as used here, is a factor by which multiplies the resonance integral as defined in Eq 7. G'_{res} is a self-shielding factor that multiplies the reduced resonance integral from which the 1/v part of the cross section has been subtracted. The necessary conversion factor that has been applied where needed in Tables 3-7 is:

$$G_{res} = G'_{res} + (1 - G'_{res})\, 0.429 \frac{g\sigma_0}{I_0} \tag{14}$$

5.7 The tables in this test method may be used to provide self-shielding factors. For materials and dimensions not in the tables, neutron transport codes may be used. Reference (**1**) provides formulae for determining self-shielding for foils and wires.

5.8 *Fluence Depression Factors*—Thermal fluence depression is an additional perturbation that occurs when an absorber is surrounded by a moderator. Because the effects are sensitive to the details of individual situations, it is not possible to provide correction factors here. References (**24-32**) describe these effects. The problem is avoided when foils are exposed in cavities of very large volume compared to the detector volume. In other cases, a rough guide is that the external perturbation effect is usually less than the thermal self-shielding effect, and much less when the hydrogenous moderator is absent.

6. Apparatus

6.1 *Radiation-Detection Instruments:*

6.1.1 The radiation detectors that may be used in neutron activation techniques are described in the Standard Methods, E181. In addition, or as an alternative, a calibration high-pressure ionization chamber may be used. Details for its construction and calibration may be found in Ref (**33**).

TABLE 2 Nuclear Data from References

Reaction	σ barns$_0$ [A]	g (T = 300 K)[A]	$\frac{I_0}{g\sigma_0}$	w'
^{59}Co(n,γ) ^{60}Co	37.18 ± 0.16 %	1.000	1.98 ± .034[B]	0[C]
^{197}Au(n,γ) ^{198}Au	98.65 ± 0.09 %	1.005	15.7 ± 0.3[B]	.0500[C]
^{115}In(n,γ) ^{116}In	159 ± 1 %	1.020	16.01 ± 0.51[A]	.2953[C]
^{164}Dy(n,γ) ^{165}Dy	2650 ± 2.6 %	0.987	0.13 ± 0.01[A]	0[D]

[A]Ref 16. σ_0 adjusted from ^{116m}In by 0.79.
[B]Ref 15.
[C]Ref 17.
[D]Ref 13.

TABLE 3 Resonance Self-Shielding Data for Cobalt Foils (Ref (18))

Foil Thickness (in.)	Foil Thickness (cm)	G'_{res} (132 eV)	G_{res}
0.0004	0.001018	0.8264	0.864
0.0010	0.00254	0.7000	0.765
0.0025	0.00635	0.5470	0.645
0.0050	0.0127	0.4395	0.561
0.0075	0.01905	0.3831	0.517
0.010	0.0254	0.3476	0.489
0.015	0.0381	0.3028	0.454
0.020	0.0508	0.2744	0.432

TABLE 4 Thermal and Resonance Self-Shielding Data for Cobalt Wires (Ref (19))

Wire diameter		Cobalt content (mass %)	G'_{res} (132 eV)	G_{th}	G_{res}
(in.)	(cm)				
0.050	0.127	0.104	1.00	1.00	1.00
0.050	0.127	0.976	0.95 ± 0.04	0.99 ± 0.01	0.96
0.001	0.00254	100	0.81 ± 0.03	0.99 ± 0.02	0.85
0.005	0.01270	100	0.52 ± 0.02	0.97 ± 0.01	0.62
0.010	0.0254	100	0.42 ± 0.02	0.94 ± 0.01	0.55
0.015	0.0381	100	0.38 ± 0.01	0.92 ± 0.02	0.51
0.020	0.0508	100	0.34 ± 0.01	0.90 ± 0.02	0.48
0.025	0.0635	100	0.32 ± 0.01	0.88 ± 0.03	0.47

TABLE 5 Resonance Self-Shielding Data for Gold Foils (Refs 20 and 21)

Foil Thickness (cm)	I (barn)	G_{res} (theory)	G_{res} (experiment)	$(G_{theo}-G_{exp})/G_{exp}$ (%)
2×10^{-6}	1556.83	0.9936	. . .	. . .
4×10^{-6}	1550.04	0.9893	. . .	. . .
8×10^{-6}	1577.91	0.9815	. . .	. . .
2×10^{-5}	1507.41	0.9621	0.9644	–0.24
4×10^{-5}	1465.83	0.9355	0.9340	+0.16
8×10^{-5}	1398.77	0.8927	0.8852	+0.85
2×10^{-4}	1252.38	0.7993	0.7852	+1.80
4×10^{-4}	1088.91	0.6950	0.6836	+1.66
8×10^{-4}	890.482	0.5683	0.5612	+1.27
2×10^{-3}	628.570	0.4012	0.3952	+1.51
4×10^{-3}	468.493	0.2990	0.3020	–0.99
8×10^{-3}	347.671	0.2219	0.2219	–0.0036
2×10^{-2}	234.983	0.1450	0.1505	–0.35

TABLE 6 Resonance Self-Shielding Data for Gold Wires (Ref 22)

Wire Diameter		Average (cm)	G_{res}
Nominal (10^{-3} in.)	Average (10^{-3} in.)		
0.5	0.505	0.00128	0.703
1.0	0.98	0.00249	0.552
2.0	1.98	0.00503	0.410
4.0	4.05	0.01029	0.302
6.0	6.02	0.01529	0.258
8.0	7.98	0.02027	0.228
10.0	10.01	0.02542	0.208

6.2 *Precision Punch:*

6.2.1 A precision punch is required to fabricate a set of identical foils for the standard foil technique. The punch must cut foils that have smooth edges. Since finding such a punch commercially available is difficult, it is recommended that the punch be custom made. It is possible to have several dies made to fit one punch so that a variety of foil sizes can be obtained. Normally, foil diameters are 12.7 mm (0.500 in.) or less. The precision punch is one of the most important items in the standard foil technique particularly if the counting technique includes β or soft-photon events.

6.3 *Aluminum and Cadmium Boxes:*

6.3.1 One set of foils must be irradiated in cadmium boxes or covers to determine that part of the neutron activation resulting from absorption of epicadmium neutrons. The cadmium box must be constructed so that the entire foil is surrounded by 1 mm (0.040 in.) of cadmium. This can be accomplished by using a circular cup-shaped design as shown in Fig. 1. To eliminate positioning errors, aluminum boxes identical to the cadmium boxes should be used for the "bare" or total neutron activation measurements. Small-bore cadmium tubing having 1 mm walls is commercially available for use with wires.

7. Materials and Manufacture

7.1 The four materials required for the techniques in this method are cobalt, gold, indium, and dysprosium. These metals are available commercially in very pure form (at least 99.9 %) and can be obtained in either foil or wire form. Cobalt, gold, indium, and dysprosium are also available as an alloy with aluminum, for example NIST Standard Reference Material 953. The alloy dilutions are useful for extending the range of measurement to higher neutron fluences; in the case of indium, the alloy has the additional advantage of mechanical strength. Pure indium is so soft that it must be handled with extreme care to prevent distortions in the precision punched foils. The use of alloys results in uncertainties and nonuniformity of alloy concentrations, but reduces the self-shielding corrections and their uncertainties.

8. Procedure

8.1 *Cobalt Method (Radiometric Technique):*

8.1.1 Pure cobalt wire, 0.127 mm (0.005 in.) in diameter will conveniently monitor thermal neutron fluences in the range of 10^{14} to 10^{18} cm^{-2}. Cobalt-aluminum alloy wire of the same diameter (0.50 % by weight of cobalt or less) can be used for higher fluences. Burn-up of the target material needs to be considered at fluences above 10^{20} cm^{-2}. The neutron reaction involved is $^{59}Co(n,\gamma)^{60}Co$. ^{60}Co emits two gamma rays per disintegration in cascade with energies of 1.17 and 1.33 MeV having a half-life of 1925.23 days (**34**). ^{60m}Co is also formed in the reaction, but this isometric state decays to ^{60}Co by means of a single 0.0586 MeV gamma ray having a half-life of 10.467 min (**35**).

8.1.2 The equivalent 2200 m/s thermal fluence rate in which a thin sample of cobalt has been irradiated may be calculated as follows:

$$\varphi_0 = \frac{R}{g\sigma_0} \tag{15}$$

where:

R = reaction rate per target atom,
σ_0 = 2200 m/s cross section,
g = Wescott g factor.

8.1.3 The reaction rate is given by

$$R = \frac{C\ \exp(\lambda t_w)}{(\varepsilon N_0(1 - \exp(-\lambda t_i)))} \tag{16}$$

TABLE 7 Self-Shielding Calculations for Indium and Gold Foils (Ref 23)

Natural indium foil thickness (mg/cm^2)	G_{res}	G_{th}	G_{res}/G_{th}	Natural gold foil thickness (mg/cm^2)	G_{res}	G_{th}	G_{res}/G_{th}
0.05	0.988	1.000	0.988	0.05	0.994	1.000	0.994
0.1	0.977	1.000	0.977	0.1	0.987	1.000	0.987
0.2	0.959	0.999	0.960	0.2	0.975	1.000	0.975
0.5	0.920	0.998	0.922	0.5	0.950	1.000	0.950
1.0	0.868	0.997	0.870	0.075	0.931	0.999	0.932
2.0	0.796	0.993	0.801	1.0	0.919	0.999	0.920
5.0	0.649	0.987	0.658	2.0	0.867	0.998	0.869
10	0.519	0.976	0.531	3.0	0.828	0.997	0.830
20	0.400	0.956	0.417	5.0	0.763	0.995	0.767
30	0.334	0.939	0.357	7.5	0.698	0.994	0.702
40	0.294	0.924	0.319	10	0.645	0.993	0.650
60	0.243	0.897	0.271	20	0.521	0.985	0.529
100	0.192	0.850	0.226	40	0.410	0.969	0.423
150	0.156	0.800	0.195	60	0.347	0.959	0.362
200	0.134	0.759	0.177	120	0.264	0.930	0.283
250	0.120	0.720	0.167	240	0.202	0.882	0.229

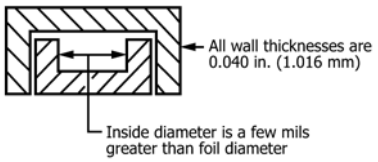

FIG. 1 Side View of Cadmium Box Cross Section

where:

C = net counting rate of ^{60}Co in the sample at the time of measurement, corrected for background radiations,
λ = decay constant of 4.170×10^{-9} s^{-1} corresponding to the half-life of ^{60}Co of 1925.5 days,
N_0 = original number of atoms of nuclide to be activated (given by the product of the weight in grams of ^{59}Co in the sample and Avogadro's number divided by the atomic weight, 58.9332, in g),
ε = efficiency of the detector for ^{60}Co radiation in the given geometry,
t_i = duration of the exposure, and
t_w = elapsed time from the end of the exposure period to the time of counting.

8.1.4 When the exposure time is small compared to the 1925.5-day half-life of ^{60}Co, as is usually the case, we may write

$$1 - \exp(-\lambda t_i) \approx \lambda t_i \tag{17}$$

Eq 15 becomes

$$\varphi_0 = C \exp(\lambda t_w)/\lambda t_i N_0 \sigma_0 \varepsilon \tag{18}$$

8.1.5 The fluence over the irradiation period is

$$\Phi = \varphi_0 t_i = C \exp(\lambda t_w)/\lambda N_0 \sigma_0 \varepsilon \tag{19}$$

8.1.6 If the cobalt sample has been activated in a neutron spectrum that is not totally thermalized, then the reaction rate must be corrected for epithermal neutron activation. This is done by irradiating a similar cobalt sample shielded by cadmium (1 mm (0.040-in.) thick) and using Eq 13 which yields,

$$\Phi = \frac{1}{G_{th}}\left(C_B - C_{cd}\left(1 + \frac{g\sigma_0 f_1}{G_{res} I_0} + \frac{\sigma_0 w'}{G_{res} I_0}\right)\right) \cdot \exp(\lambda t_w)/\lambda N_0 g \sigma_0 \varepsilon \tag{20}$$

where C_B and C_{cd} are the ^{60}Co counting rates in the bare and cadmium-covered samples, respectively. In practice, the 0.127-mm cobalt wire cannot be considered a thin sample. The self-shielding effects of the wire are accounted for by the G_{th} and G_{res} factors in Eq 20 (see also Tables 4 and 5). If the cobalt-aluminum alloy (0.50 % by weight of cobalt or less) is being used, no self-shielding correction factors are needed.

8.1.7 There are two methods for obtaining the detection efficiency for the ^{60}Co in the sample. The first method uses a high-pressure ionization chamber, a heavily shielded well-type counter that almost completely surrounds the sample being counted with an ionization volume, thereby allowing for essentially 4-π geometry to detect the radiation. A voltage placed across the collecting electrodes generates a current proportional to the number of ions produced, which in turn is proportional to the sample source strength. Measure the current, expressed as the voltage drop across precision resistors, with a potentiometer. Calibrate the chamber for ^{60}Co with a ^{60}Co gamma source having a certified activity which is traceable to a National Standard. A calibration constant S, expressed as disintegrations per second per volt, is thereby obtained. Accordingly, the disintegration rate of the cobalt wire sample is the product of S multiplied by the voltage reading obtained.

8.1.8 A second method for determining the disintegration rate in the cobalt sample as described in Method E181, makes use of high resolution gamma detectors for interference-free counting of ^{60}Co. The detection efficiency for the ^{60}Co radiation must be measured using a certified ^{60}Co source, or a multi-gamma-ray reference standard traceable to National Standards as described in Section 12.5 of Test Methods E181. The shape, positioning, and encapsulation of both the standard source and the activation monitor sample must be carefully controlled to ensure the same detection efficiency in each case.