Designation: E 720 – 02

Standard Guide for Selection and Use of Neutron Sensors for Determining Neutron Spectra Employed in Radiation-Hardness Testing of Electronics[1]

This standard is issued under the fixed designation E 720; 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.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This guide covers the selection and use of neutron-activation detector materials to be employed in neutron spectra adjustment techniques used for radiation-hardness testing of electronic semiconductor devices. Sensors are described that have been used at many radiation hardness-testing facilities, and comments are offered in table footnotes concerning the appropriateness of each reaction as judged by its cross-section accuracy, ease of use as a sensor, and by past successful application. This guide also discusses the fluence-uniformity, neutron self-shielding, and fluence-depression corrections that need to be considered in choosing the sensor thickness, the sensor covers, and the sensor locations. These considerations are relevant for the determination of neutron spectra from assemblies such as TRIGA- and Godiva-type reactors and from Californium irradiators. This guide may also be applicable to other broad energy distribution sources up to 20 MeV.

NOTE 1—For definitions on terminology used in this guide, see Terminology E 170.

1.2 This guide also covers the measurement of the gamma-ray or beta-ray emission rates from the activation foils and other sensors as well as the calculation of the absolute specific activities of these foils. The principal measurement technique is high-resolution gamma-ray spectrometry. The activities are used in the determination of the energy-fluence spectrum of the neutron source. See Guide E 721.

1.3 Details of measurement and analysis are covered as follows:

1.3.1 Corrections involved in measuring the sensor activities include those for finite sensor size and thickness in the calibration of the gamma-ray detector, for pulse-height analyzer deadtime and pulse-pileup losses, and for background radioactivity.

1.3.2 The primary method for detector calibration that uses secondary standard gamma-ray emitting sources is considered in this guide and in General Methods E 181. In addition, an alternative method in which the sensors are activated in the known spectrum of a benchmark neutron field is discussed in Guide E 1018.

1.3.3 A data analysis method is presented which accounts for the following: detector efficiency; background subtraction; irradiation, waiting, and counting times; fission yields and gamma-ray branching ratios; and self-absorption of gamma rays and neutrons in the sensors.

1.4 The values stated in SI units are to be regarded as the standard.

1.5 *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 General considerations of neutron-activation detectors discussed in Practice E 261, Test Method E 262, and Guides E 721 and E 844 are applicable to this guide. Background information for applying this guide are given in these and other relevant standards as follows:

2.2 *ASTM Standards:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[2]

E 181 Test Methods for Detector Calibration and Analysis of Radionuclides[2]

E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra by Radioactivation Techniques[2]

E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques[2]

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron[2]

E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel[2]

[1] This guide is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.07 on Radiation Effects on Electronic Materials and Devices and Pulsed Radiation Effects.

Current edition approved June 10, 2002. Published September 2002. Originally published as E 720 – 80. Last previous edition E 720 – 94.

[2] *Annual Book of ASTM Standards*, Vol 12.02.

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32[2]
E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum[2]
E 343 Test Method for Measuring Reaction Rates by Analysis of Molybdenum-99 Radioactivity from Fission Dosimeters[2]
E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters[2]
E 496 Test Method for Measuring Neutron Fluence Rate and Average Energy from $^{3}H(d,n)$ ^{4}He Neutron Generators by Radioactivation Techniques[2]
E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238[2]
E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237[2]
E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics[2]
E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[2]
E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E706 (IIA)[2]
E 1018 Guide for Application of ASTM Evaluated Cross Section Data File, E 706 (IIB)[2]
E 1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium[2]

3. Significance and Use

3.1 Because of the wide variety of materials being used in neutron-activation measurements, this guide is presented with the objective of bringing improved uniformity to the specific field of interest here: hardness testing of electronics primarily in critical assembly reactor environments.

NOTE 2—Some of the techniques discussed are useful for 14-MeV dosimetry. See Test Method E 496 for activation detector materials suitable for 14-MeV neutron effects testing.

NOTE 3—The materials recommended in this guide are suitable for ^{252}Cf or other weak source effects testing provided the fluence is sufficient to generate countable activities.

3.2 This guide is organized into two overlapping subjects; the criteria used for sensor selection, and the procedures used to ensure the proper determination of activities for determination of neutron spectra. See Terminology E 170 and General Methods E 181. Determination of neutron spectra with activation sensor data is discussed in Guides E 721 and E 944.

4. Foil Sets

4.1 *Reactions Considered*:

4.1.1 Neutron-induced reactions appropriate for this guide are listed in Table 1. The table includes most of the reactions used in this field. Those not marked with an asterisk are recommended because of their demonstrated compatibility with other reactions used in spectrum adjustment determinations. This compatibility is primarily based on experience with the ENDF/B-VI **(, 1)**,and IRDF-90 **(2)** cross-sections. These recommendations may change modestly as revisions are made in the ENDF/B-VI and IRDF-90 dosimetry cross sections. Other reactions may be useful in particular circumstances with appropriate care. It is important that the user take full account of both the footnotes attached to each reaction and the discussions in the body of the text about individual reactions when implementing the foil-activation technique.

4.1.2 The four paired columns under the labels fast burst **(3)** and "TRIGA **(4)** Type" list the energy ranges within which 95 % of the response occurs for these two representative spectra. These limits are just a guide because the response often varies widely within each range. The response limits for an idealized fission spectrum with no $1/E$ tail can be much different (shifted toward higher energy) for resonance reactions. For example, in a Watt fission spectrum the $^{197}Au(n,\gamma)^{198}Au$ has a 95 % response between 5.0×10^{-2} and 2.7 MeV. The recommended foil mass column gives values that are designed to minimize self-absorption, self-shielding, and other corrections, provided the foils are 1.27 cm in diameter. The $E_t \cong 0$ fission foils, ^{235}U and ^{239}Pu, have similar cross-section shapes. However, the ^{235}U foil is preferred since it is less expensive and is much less of a health hazard than ^{239}Pu. In addition, when measuring soft (TRIGA) spectra, the ^{235}U foil is useful in determining the correction for the ^{235}U impurity in the ^{238}U foil (which is readily available with about 400 ppm or less ^{235}U impurity).

4.1.3 Although sulfur is listed and is used widely as a monitor foil, it is the only recommended sensor requiring beta particle detection and, therefore, requires a different calibration and counting technique. The $^{58}Ni(n,p)^{58}Co$ reaction has about the same threshold energy and, therefore, can be used instead of the $^{32}S(n,p)^{32}P$ if it acquires sufficient activity. Many facilities use sulfur as a routine monitor because its two-week half-life allows a convenient period for counting and permits reuse of the sensor after 6 to 9 months. Automated beta counters are commercially available. Neither nickel nor sulfur should be counted for the (n,p) reaction products immediately after irradiation because for nickel the ^{58}Co must build up through a metastable state, and for sulfur there are competing reactions. According to Test Method E 264 the waiting period for ^{58}Co should be 4 days. For ^{32}P, Test Method E 265 recommends waiting 24 h. Corrections can be made for shorter waiting periods.

4.1.4 In selecting dosimetry reactions one should consider the validation of the cross sections and associated uncertainty as demonstrated in the ^{235}U thermal fission and the ^{252}Cf spontaneous fission benchmark neutron fields. **20** provides a recent comparison of the measured and calculated spectrum-averaged cross sections for these benchmark fields.

4.1.5 Some frequently used reactions have shown relatively consistent deviations of measured to calculated activity ratios in many different spectra determinations. For example, when ENDF/B-V cross sections are used in the reaction $^{63}Cu(n,\gamma)^{64}Cu$, the calculated activity is usually low, and an adjustment code will try to raise the spectrum in the vicinity of Cu resonances. In fact, however, this consistent behavior indicates that the tabulated cross-section values in some important energy region are too small. The analyst must then choose one of the following alternatives: (*1*) leave out reactions which have demonstrated consistent deviations; (*2*) seek better cross-section sets; (*3*) assign wide error bars or low statistical

TABLE 1 Activation Foils

Reaction	Fast Burst[A]		TRIGA Type[A]		Eγ, keV	Gamma/Reaction[B] (Fast Fission Yield,%[C])	$T_{1/2}$[B]	Recommended Foil Mass, g[D]	Footnotes
	E_L, MeV	E_H, MeV	E_L, MeV	E_H, MeV					
$^{197}Au(n,\gamma)^{198}Au$	4.00 − 6	7.20 − 4	3.80 − 6	9.20 − 6	411.8	0.956	2.694 days	0.06	E,F,G
$^{59}Co(n,\gamma)^{60}Co$	7.60 − 6	4.50 − 4	6.90 − 7	1.43 − 4	1173.2	0.9998	5.271 years	0.06	E,G
					1332.5	0.9998			
*$^{58}Fe(n,\gamma)^{59}Fe$	1.00 − 6	2.10 + 0	5.25 − 7	1.00 − 2	1099.2	0.565	44.5 days	0.15	E,H
					1291.6	0.432			
$^{55}Mn(n,\gamma)^{56}Mn$	5.25 − 7	6.60 − 1	4.75 − 7	1.10 − 3	846.8	0.989	2.58 h	0.05	E,F,I
					1810.7	0.272			
*$^{63}Cu(n,\gamma)^{64}Cu$	1.15 − 6	2.30 + 0	5.25 − 7	9.60 − 3	1345.9	0.0049	12.7 h	0.15	E
$^{23}Na(n,\gamma)^{24}Na$	6.30 − 7	2.00 + 0	5.25 − 7	3.00 − 3	1368.6	1.00	14.96 h	0.10	E,J,K
$^{45}Sc(n,\gamma)^{46}Sc$	4.25 − 7	1.00 + 0	4.00 − 7	4.75 − 4	1120.5	1.00	83.81 days	0.05	E
$^{235}U(n,f)^{140}La$	9.20 − 2	4.70 + 0	6.30 − 4	3.80 + 0	1596.2	0.954 (6.105)	40.27 h	0.30	E,L,M
$^{235}U(n,f)^{95}Zr$	9.20 − 2	4.70 + 0	6.30 − 4	3.80 + 0	724.2	0.441 (6.363)	64.02 days	0.60	E,M
$^{239}Pu(n,f)^{140}La$	1.43 − 1	4.80 + 0	8.80 − 4	4.30 + 0	1596.2	0.954 (5.326)	40.27 h	1.00	E,L,M
$^{239}Pu(n,f)^{95}Zr$	1.43 − 1	4.80 + 0	8.80 − 4	4.30 + 0	724.2	0.441 (4.685)	64.02 days	0.60	E,M
$^{93}Nb(n,n')^{93m}Nb$	8.40 − 1	5.70 + 0	1.00 + 0	5.50 + 0	16.6	0.115	16.13 years		N
$^{103}Rh(n,n')^{103m}Rh$	5.50 − 1	5.70 + 0	6.90 − 1	5.70 + 0	39.8	0.068	56.1 min		N
$^{237}Np(n,f)^{140}La$	5.75 − 1	5.60 + 0	6.60 − 1	5.50 + 0	1596.2	0.954 (5.489)	40.27 h	0.60	E,L,M,O
$^{237}Np(n,f)^{95}Zr$	5.75 − 1	5.60 + 0	6.60 − 1	5.50 + 0	724.2	0.441 (5.699)	64.02 days	0.60	E,M
*$^{115}In(n,n')^{115m}In$	1.00 + 0	6.00 + 0	1.20 + 0	5.80 + 0	336.2	0.459	4.49 h	0.12	
$^{238}U(n,f)^{140}La$	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	1596.2	0.954 (5.948)	40.27 h	1.00	E,L,M,P
$^{238}U(n,f)^{95}Zr$	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	724.2	0.441 (5.105)	64.02 days	1.00	E,M
$^{232}Th(n,f)^{140}Ba$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	537.3	0.244 (7.704)	12.75 days	1.00	E,L,Q
$^{232}Th(n,f)^{95}Zr$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	724.2	0.441 (5.374)	64.02 days	1.00	E,M
$^{54}Fe(n,p)^{54}Mn$	2.30 + 0	7.70 + 0	2.30 + 0	7.40 + 0	834.8	1.00	312.1 days	0.15	E
$^{58}Ni(n,p)^{58}Co$	2.00 + 0	7.60 + 0	2.00 + 0	7.30 + 0	810.8	0.995	70.8 days	0.30	E
$^{47}Ti(n,p)^{47}Sc$	1.90 + 0	7.60 + 0	1.90 + 0	7.30 + 0	159.4	0.683	3.35 days	0.15	E,R,S
$^{32}S(n,p)^{32}P$	2.40 + 0	7.50 + 0	2.30 + 0	7.30 + 0	1710.(beta)	1.00 (beta)	14.28 days	...	T
$^{64}Zn(n,p)^{64}Cu$	2.60 + 0	7.70 + 0	2.60 + 0	7.40 + 0	1345.9	0.0049	12.7 h	0.30	E
$^{27}Al(n,p)^{27}Mg$	3.50 + 0	9.40 + 0	3.40 + 0	9.20 + 0	843.8	0.718	9.46 min	0.30	E
$^{46}Ti(n,p)^{46}Sc$	3.80 + 0	9.60 + 0	3.70 + 0	9.20 + 0	1120.5	1.00	83.81 days	0.15	E,R
$^{56}Fe(n,p)^{56}Mn$	5.50 + 0	1.14 + 1	5.50 + 0	1.10 + 1	846.8	0.989	2.58 h	0.15	E,U
$^{24}Mg(n,p)^{24}Na$	6.50 + 0	1.17 + 1	6.50 + 0	1.13 + 1	1368.6	1.00	14.96 h	0.03	E,K
$^{27}Al(n,\alpha)^{24}Na$	6.50 + 0	1.21 + 1	6.50 + 0	1.17 + 1	1368.6	1.00	14.96 h	0.30	EK
$^{48}Ti(n,p)^{48}Sc$	5.90 + 0	1.24 + 1	5.90 + 0	1.20 + 1	983.5	1.00	43.7 h	0.15	E
					1037.5	0.975			
					1312.1	1.00			
$^{93}Nb(n,2n)^{92m}Nb$	9.70 + 0	1.45 + 1	9.40 + 0	1.40 + 1	934.4	0.992	10.15 days		
$^{127}I(n,2n)^{126}I$	9.70 + 0	1.47 + 1	9.70 + 0	1.43 + 1	388.6	0.341	13.02 days	0.25	E
					666.	0.331			
$^{65}Cu(n,2n)^{64}Cu$	1.08 + 1	1.57 + 1	1.07 + 1	1.53 + 1	1345.9	0.0049	12.7 h	0.15	E,N
*$^{63}Cu(n,2n)^{62}Cu$	1.19 + 1	1.66 + 1	1.19 + 1	1.63 + 1	875.7	0.00150	9.74 min	0.15	E,H
$^{90}Zr(n,2n)^{89}Zr$	1.28 + 1	1.69 + 1	1.27 + 1	1.67 + 1	909.1	0.999	78.4 h	0.10	
$^{58}Ni(n,2n)^{57}Ni$	1.32 + 1	1.71 + 1	1.31 + 1	1.69 + 1	1377.6	0.80	1.49 days	0.30	

[A] Energy limits inside of which 95 % of the detector response occurs for each reaction (see Practice E 261 and Ref **6**). The foils are assumed to have Cd covers as described in Footnote *E*.

[B] Data from Ref for isotopes with atomic weight greater than or equal to 45, from Ref for isotopes with atomic weight less than 45.

[C] Fission yields can be found in Ref **7**. Because Ref **7** documentation is still in draft form, the fission yield data in the table is taken from Ref .

[D] Choice of mass is based on assumed foil diameter of 1.27 cm.

[E] Cd covers 0.5 to 1-mm thicknesses. Pairs of bare and Cd-covered foils are advantageous for resonance reactions.

[F] Use ^{59}Co instead of ^{197}Au and ^{55}Mn for very long irradiations.

[G] Use dilute aluminum-gold alloy (<0.2 % Au) when possible.

[H] Do not count the 0.511 line.

[I] Resonance structure differs in ENDF/B-VI from ENDF/B-V.

[J] Use in the form of NaCl.

[K] The 1986 edition of Ref has a typographical error for the half-life of ^{24}Na. The correct number can be found in previous editions. The correct number can also be found in Ref **10**.

[L] This is the 40.27-h daughter of 12.75-day ^{140}Ba. Wait 5 days for maximum decay rate (see Test Method E 393).

[M] E_t = 0.01 MeV shielded with ^{10}B sphere. (Use of ^{10}B shield is important for soft (TRIGA) spectra where $\Phi(E < 0.01$ MeV) will otherwise dominate).

[N] Precautions must be taken in counting because of the low gamma-ray energy. See Test Method E 1297.

[O] If a ^{10}B sphere is used for the ^{239}Pu foil, then a ^{10}B sphere should also be used for the ^{237}Np foil so that correction for ^{239}Pu impurity in the ^{237}Np foil can be made.

[P] If a ^{10}B sphere is used for the ^{235}U foil, then a 10^B sphere should also be used for the ^{238}U foil so that correction for ^{235}U impurity in the ^{238}U foil can be made.

[Q] Radioactivity of ^{232}Th interferes with the ^{140}La line.

[R] At high energies (>10 MeV), account for (*n,np*) contributions from higher atomic number *Ti* isotopes.

[S] See Refs **8** and **9**.

[T] Requires β counting techniques, see Test Method E 265.

[U] Maximum Mn impurity = 0.001 %, Cd covered. Do not use ^{56}Fe foil for long irradiations.

* Not recommended for use at this time either because of large uncertainties or because of conflicts with other reactions during spectrum adjustment procedures.

weight to these reactions. It is recommended that the first option be chosen because a sufficient number of well-established cross sections do exist to satisfactorily determine fast reactor spectra. Furthermore, if the cross section for a particular reaction is not well established, and it is assigned too large a weight in the spectrum adjustment procedure, the final

spectrum can be severely distorted. Other suspect reactions are noted in Table 1 with an asterisk.

NOTE 4—Some of the reactions not recommended at this time (on the basis of inconsistencies among recommended cross sections) may be upgraded when more recent evaluations are applied to a wide range of neutron spectra.

4.2 *Foil Impurities*:

4.2.1 Foil impurities are especially serious for a moderated source (TRIGA reactor) when impurity leads to the same reaction product by way of thermal-neutron capture. Some examples of these foils, with impurities in parentheses, are $_{238}$U (^{235}U),^{27}Al (^{23}Na),^{56}Fe (^{55}Mn), and ^{27}Mg(^{23}Na).

4.2.2 For a soft spectrum, such as the TRIGA J-tube spectrum [boral (boron-aluminum alloy) shielded], the number of fissions in the^{235}U foil (Cd covered) is about 100 times the number occurring in the ^{238}U foil; therefore, the ^{238}U must have an impurity level of ^{235}U of no more than about 200 ppm for an uncertainty of 2 % or less in determining accurately the $_{238}$U activity. Higher impurity levels of^{235}U can be tolerated for Godiva-type reactors where the fluence below 10 keV is much lower, or with TRIGA-type reactors if the ^{235}U foil data are used for correcting the ^{238}U activity.

4.2.3 When the^{56}Fe foil (Cd covered) is used in a TRIGA spectrum, it should have no more than 10 ppm^{55}Mn impurity to keep the contribution from the^{55}Mn(n,γ)^{56}Mn reaction to less than 2 %. Similarly, the^{55}Mn impurity should be no more than 100 ppm when using the^{56}Fe foil at 50 cm from a Godiva-type reactor (which is approximately 2 m above the concrete floor) in order to achieve the same level of accuracy. Data from a^{55}Mn foil (Cd covered) can be used to correct the^{56}Fe data if the impurity correction is ≤20 % of the total (n,p) activation, and the percent of manganese in iron is accurately known.

4.3 *Influence of Nuclear Data on Foil Selection*:

4.3.1 Since the total number of interactions is deduced from an absolute specific activity determination, that activity should be determined with good accuracy (of the order of 5 %), and the foils selected should have gamma-ray yields known to the same or better accuracy. Some of the factors involved in determining these yields include conversion-electron production, branching ratio to a given energy level, and fission yield.

4.3.2 The 1596-keV gamma-ray transition from ^{140}La produced by ^{232}Th fission is not usually useful because of interference from ^{232}Th radioactivity. This often has led to the use of the 537-keV transition from the ^{140}Ba precursor of ^{140}La, having a gamma-transition probability of 0.244 per ^{140}Ba decay. The use of ^{140}Ba generally requires the chemical separation of this isotope from the rest of the fission products so that the 537-keV line can be seen above competing lines. See Test Method E 393.

4.3.3 The choice of element, and hence the gamma-ray transition, directly influences the accuracy of determining the specific activity induced by neutron irradiation. It also influences the final choice of foil thickness, in that the selection of an element resulting in a low-energy gamma ray may lead to a large self-absorption correction. For example, the ^{232}Th foil of Table 1 has a maximum attenuation of 22 %, or an average correction of about 11 %, for the 537-keV transition. This represents an upper limit for the thickness of that foil. Therefore, the self-attenuation of gamma rays, as well as the neutron self-shielding discussed later, will influence the foil selection.

NOTE 5—For other considerations in the selection of specific foils, see Guide E 844, Practice E 261, and Test Methods E 262, E 263, E 264, E 265, E 266, E 704, and E 705.

5. Apparatus

5.1 The gamma-ray detector should be a germanium-type detector (either Ge(Li) or intrinsic) with an energy resolution of 2.5 keV or better (full-width at half-maximum (FWHM) at 1173 keV). Associated equipment would include a multichannel pulse-height analyzer and a precision pulse generator with calibrated pulse-height and pulse-rate inputs into the detection system.

5.2 Foil and source holders should be used to provide precise positioning of a gamma-ray standard source and of each activated foil with respect to the detector. Required precision is about 0.2 mm or better in distance from the window of the detector or in lateral alignment.

5.3 National standard sources that are traceable to NIST (or their equivalent) should be used for calibration of the detection system.

6. Precautions

6.1 *Scattering Problems*—A sensor with a strong resonance absorption, such as a thick ^{235}U foil, should not be placed in front of a 1/v detector, and thick foils with covers should not be stacked because accurate corrections for the resultant scattering are difficult to determine. With an isotropic neutron-fluence, Φ_o, incident on stacked foils, the reduction in the fluence rate caused by scattering at a given foil can be estimated by using the following equation:

$$\Phi = \Phi_o e^{-\Sigma_i \sigma_i X_i}$$

where Φ is the attenuated fluence, Σ_i is a summation-over-i symbol, σ_i is the total macroscopic scattering cross section in cm−1, and X_i is the thickness of the ith foil in centimetres. The summation is up to the foil of interest, located at its appropriate depth (distance from source) in the foil stack. For best results, the reduction in fluence rate should be less than 10 % for the foil located at the maximum depth.

6.2 *Foil Self-Shielding*—For the thicknesses of the foils recommended, the correction for self-shielding is appreciable only for pure gold foils (with its highly absorbing resonance at about 5 eV), the correction for a 0.025-mm thick foil being about a factor of two for epicadmium neutrons (that is, neutrons with energies greater than 0.5 eV) **(15)**.

NOTE 6—Dilute aluminum-gold alloys are available and do not generally require self-shielding corrections.

6.3 *Fluence Nonuniformity*—If all the foils cannot be located in a region of uniform fluence rate (as determined by symmetry considerations), they can be located at different positions (and, hence, with different fluence rates) as long as the neutron energy spectrum is constant. If the fluence varies by more than 3 % from point to point, fluence monitors should be used with each foil. Around a Godiva-type reactor, sulfur foils can serve as monitors near the individual foils. Where

space is more limited, then nickel [^{58}Ni(n,p)^{58}Co], iron [^{54}Fe(n,p)^{54}Mn], or even aluminum [^{27}Al(n,α)^{24}Na] should be considered for monitors. (See Practice E 261 for other relevant considerations.) Often a better solution is obtained by mounting all foils on a rotating disk or ring to ensure that they receive the same fluence.

6.4 *Fluence Rate Depression*—At low energies, fluence rate depression can be significant for bare thermal-neutron detectors near cadmium-covered foils if both are embedded in a moderator. This is because the cover on one foil can shadow adjacent bare foils. At high energies, depression can be significant for foils irradiated under the same conditions if the moderator contains reactor fuel. However, this is ordinarily not a problem, since in the sizable irradiation volumes normally used for radiation damage studies, the cadmium covers (as well as the foils) generally subtend a negligibly small solid angle at the point of any surrounding moderator or fuel. Fluence rate depression is usually insignificant for irradiation in a Godiva reactor glory hole.

7. General Handling Procedures

7.1 *Foil Encapsulation*—Fission foils should be encapsulated in sealed containers to avoid oxidation, loss of material, and for health-safety requirements. If a ^{239}Pu foil is used (instead of the much safer ^{235}U foil), it will require special encapsulation and periodic monitoring to check for leakage of the material. Copper encapsulation has been found satisfactory for^{235}U, ^{238}U, ^{237}Np, and^{232}Th foils. The thickness of the copper capsule should be about 0.1 to 0.25 mm at the flat surfaces and soldered at the periphery.

7.2 *Foil Covers*:

7.2.1 As noted in Table 1, cadmium covers of 0.5 to 1-mm thickness are prescribed for all fission foils and 1/v detectors. Cadmium covers also should be used for finite-threshold foils with trace impurities that yield the same reaction product by means of thermal-neutron capture. Examples are foils such as ^{238}U, ^{56}Fe,^{58}Ni, and ^{27}Al with impurities of^{235}U, ^{55}Mn, ^{59}Co, and^{23}Na, respectively. Depending on the concentration, such impurities can lead to large correction factors. For large correction factors (that is, greater than 5 %), cadmium-covered foils made of the impurity materials should be irradiated. Then, corrections can be made with good accuracy if the impurity concentration in the primary threshold foil is accurately known. If the impurity concentration is not known, a thermal-neutron activation analysis of the foil can provide data for the necessary correction. Cadmium covers may not be required for foils irradiated in the empty "glory hole" of a fast-pulse reactor, a cavity in which little or no moderator material is normally present (that is, less than 0.5 g/cm^2).

7.2.2 Covers of ^{10}B for fission foils are useful when measuring a soft TRIGA spectrum. However, if a boral shield that provides good 4-π geometry surrounds the irradiation cavity, and if a negligible amount of moderator is contained within the shield, then the^{10}B covers may not be required. The effect of the boral shielding should be accounted for properly when the neutron spectrum is adjusted with a proper computer code. More is said about boron cover corrections in 7.2.4.

NOTE 7—Spectra adjustment codes are discussed in Guides E 721 and E 944.

7.2.3 If no ^{10}B covers are used for the foils, and if the TRIGA irradiation cavity is only partially shielded by boral, then it will be difficult to determine the neutron spectrum from 10^{-2} MeV down to about 3×10^{-7} MeV. If the TRIGA irradiation cavity has only partial boral shielding, it is important that all the fission foils, all the 1/v foils, and the foils with important 1/v impurities be placed in a boral "box" or a^{10}B cover. For best results, a^{10}B cover of 1 to 1.8 g/cm^2 of (93 %)^{10}B should be used. In this way, the fraction of activations arising from neutrons in the energy range from 3×10^{-7} MeV to 10^{-2} MeV will be reduced greatly. The effect of the cover thickness can be accounted for by a spectrum adjustment code provided that the effective attenuation cross section that accounts for scattering in the cover is available. See 7.2.5.

7.2.4 For a Godiva-type reactor, ^{10}B covers may not be required, and cadmium covers may be sufficient for irradiation distances of less than 1 m from the reactor when the reactor is located a few metres above the concrete floor. Cadmium covers also may be used in the glory hole where the number of low-energy neutrons is insignificant. If ^{10}B covers are used, activities may require correction for scattering by the ^{10}B. The correction can be determined either experimentally with pure finite-threshold fission foils (^{237}Np or ^{232}Th) that contain negligible zero-threshold impurities, or with a neutron transport calculation that takes into account the thickness of the material.

7.2.5 The attenuation by a boron cover of the neutron fluence is not adequately treated by many of the spectrum adjustment codes **(18)**. Some versions of the spectrum adjustment code, SAND II **(11)**, for example, uses a simple exponential attenuation function versus energy, and because most irradiations are conducted in wide-beam or isotropic configurations, scattered neutrons are not in general lost from the beam. As a result, the absorption cross section of the boron should generally be used to determine the attenuation. However, in many configurations (such as narrow-beam geometry or down scattering of the neutrons to lower energy) the scattering portion of the cross section can remove additional neutrons and the true effective removal cross section value will fall somewhere in between the total and the absorption cross section. This is especially noticeable if the response of the foil is concentrated above the 10-keV limit where the B^{10} absorption ceases to dominate the cross section. Thus, for high-threshold fission foils such as ^{238}U and^{237}Np or a normal threshold foil such as nickel, the additional scattering will result in additional attenuation. For example, some experiments and calculations indicate that these corrections are of the order of 10 % for a 1.65-g/cm^2 ^{10}B cover and a thin 12.7-mm diameter fission foil **(12)**. Other work indicates that these scattering corrections may be somewhat larger **(13)**. Strictly speaking, a calculation of the transport in the full-experiment geometry through the boron cover should be performed for each geometry **(18)**. Measurements with a high-threshold foil, ^{58}Ni(n,p) ^{58}Co, have shown a transmission factor of 0.9 in a Godiva-type exposure geometry **(23)**. This compares with a

calculated value (for which only the boron capture cross section is used) of 0.96.

NOTE 8—A monitor foil such as nickel used both inside and outside a boron ball can be used to normalize the boron-covered-fission-foil exposure to that of the rest of the foil set in case positioning errors are likely to be significant. The nickel ratio is not very sensitive to spectrum shape. The procedure is to multiply the fission foil activities by a factor that ensures that the ratio of nickel activities inside and outside the boron ball is about 0.9.

7.2.6 Another advantage of using covers (B, Cd) on broad energy-response foils is that it restricts that response and permits improved definition of the spectrum during the adjustment process. If both bare and Cd-covered resonance materials (such as Au and Na) are exposed, much better definition of the shape of the spectrum in the epithermal and thermal region can be obtained.

NOTE 9—Some versions of spectrum adjustment codes handle covers through th e use of auxiliary codes that apply an energy-dependent-cover correction factor to the dosimetry cross section.

7.2.7 If the spectrum is to be well defined, then the foil set must contain a large fraction of the reactions from Table 1 and possess response functions spread as uniformly over energy as is possible. This is necessary to ensure that the spectrum adjustment codes can arrive at sufficiently restricted solutions. With broad response functions the calculated fluence at one energy can influence the calculated spectrum values at distant energies. If at all possible include ^{237}Np, and ^{239}Pu or ^{235}U to provide sensitivity between 10 keV and 1 MeV where few other reactions have significant response. Silicon devices are also sensitive in this energy region and can be used as spectrum sensors **(14)**.

8. Certification of Foil Purity

8.1 The foil purity analysis results should be recorded permanently so that appropriate impurity corrections can be made. The acceptable uncertainty in the results mainly dictates what impurity concentrations are acceptable. It also depends on the nature and source of the neutron spectrum being measured (see 4.2). If, for example, the percentage impurity of ^{235}U in a foil of ^{238}U is known to be 400 ppm to an accuracy of 10 %, a separate ^{235}U foil can be irradiated in the same way as the primary foil to determine a proper correction factor. In this case, the impurity effect can be reduced to 10 % of its stated value (40 ppm) ^{235}U in ^{238}U by applying the correction factor. In determining the activity of a ^{238}U foil irradiated with a TRIGA spectrum to an uncertainty of 2 % or less, up to 2000 ppm of ^{235}U impurity could be tolerated (see 4.2).

9. Determination of Activities

9.1 A suitable set of sensors is placed in the neutron field under study. After irradiation, the specific activities of the sensor are determined by counting the gamma-ray emissions from each foil and applying appropriate corrections.

NOTE 10—Other energy response functions appropriate for spectrum adjustment procedures measured by detection of other effects, such as emulsion tracks or even displacement damage, can also be used successfully. See Guide E 944, 4.1.

9.2 The measured specific activities of the activation foils are related to the incident neutron energy-fluence spectrum by the following equation:

$$R_j = \int_\sigma^\infty \sigma_j(E)\Phi(E)\,dE \qquad 1 \le j \le n \tag{1}$$

where:

R_j = measured specific activity of an activated foil isotope j,
$\sigma_j(E)$ = neutron cross section at energy E for isotope j,
$\Phi(E)$ = incident neutron fluence differential in energy, and
n = number of reactions.

9.3 The differential neutron energy-fluence spectrum $\Phi(E)$ is calculated by means of a computer code that utilizes the specific activity data from the activation foil set. A number of these codes have been developed for this purpose and are available from the Oak Ridge National Laboratory Radiation Shielding Information Center **(16)**.

10. Detector Calibration Procedures

10.1 Follow the general considerations in General Methods E 181 and Test Method E 265 on energy and efficiency calibration of the detector.

10.2 The germanium detector is usually operated at low temperatures (near the boiling point of liquid nitrogen). This requires the detector to be in a cryostat under vacuum. Normally, a thin window separates the detector's face from the outside environment. In such an enclosure, the exact position of the effective center of the active volume of the detector with respect to the cryostat window may not be known precisely.

10.3 Very low-activity foils must be placed close to the detector window in order to achieve a reasonable count rate. For such close foil-detector spacing, two problems occur that can affect the detector efficiency. One concerns the effects of finite source size on the effective detector solid angle, and the other concerns coincidence photon summing. Coincidence summing occurs when a radionuclide emits two or more cascade photons within the resolving time of the detector system. These problems are considered in the following sections that deal with determining detector efficiency.

10.3.1 Measure the count rate under each energy peak from a small diameter (about 2 mm) standard source at some specified distance, d (100 mm or greater), from the detector window. Use a long-lived mixed radionuclide standard source or several single radionuclide standard sources (or their equivalents) for these measurements (see Note 11). Determine the detector efficiency, $\epsilon(d)_s$, at this distance, d, from the source. The detector efficiency is defined as the ratio of the net count rate under the selected energy peak to the known gamma-ray emission rate of the standard source at that energy. A log-log plot of these data provides an efficiency-versus-energy curve