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

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This standard has been approved for use by agencies of the U.S. 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 E170.

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 E721.

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 Test Methods E181. In addition, an alternative method in which the sensors are activated in the known spectrum of a benchmark neutron field is discussed in Guide E1018.

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.

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[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 Dosimetry for Radiation Effects on Materials and Devices.

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1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this 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~~safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 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 General considerations of neutron-activation detectors discussed in Practice E261, Test Method E262, and Guides E721 and E844 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:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry
E181 Test Methods for Detector Calibration and Analysis of Radionuclides
E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E262 Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques
E263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron
E264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel
E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum
E393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters
E496 Test Method for Measuring Neutron Fluence and Average Energy from $^{3}H(d,n)^{4}He$ Neutron Generators by Radioactivation Techniques
E704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238
E705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237
E721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics
E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance
E1018 Guide for Application of ASTM Evaluated Cross Section Data File
E1297 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Niobium

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 E496 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;~~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 E170 and Test Methods E181. Determination of neutron spectra with activation sensor data is discussed in Guides E721 and E944.

4. Foil Sets

4.1 *Reactions Considered:*

[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.

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 (**1, 2**)[3], and IRDFF n1.05 (**3**) cross-sections. These recommendations may change modestly as revisions are made in the ENDF/B and IRDF 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~~"fast burst" (**13**) and "TRIGA Type" (**14**) ~~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,γ)^{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~~six to nine 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 E264 the waiting period for ^{58}Co should be ~~4~~four days. For ^{32}P, Test Method E265 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. Ref (**15**) provides a 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,γ)^{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~~regions 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; or (*3*) assign wide error bars or low statistical weight to these reactions. It is recommended that the first option be chosen because ~~a sufficient number of~~ enough 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~~ (based on inconsistencies among recommended cross sections) may be upgraded when more recent evaluations are applied to a wide range of neutron spectra.

[3] The boldface numbers in parentheses refer to the list of references at the end of this guide.

TABLE 1 Activation Foils

Reaction	Fast Burst[A] E_L, MeV	Fast Burst[A] E_H, MeV	TRIGA Type[A] E_L, MeV	TRIGA Type[A] E_H, MeV	$E\gamma^B$ (keV)	Gamma Emission Probability[B]	Fast Fission Yield,[C] %	$T_{1/2}{}^B$	Recommended Foil Mass, g[D]	Footnotes
$^{197}Au(n,\gamma)^{198}Au$	4.00 – 6	7.20 – 4	3.80 – 6	9.20 – 6	411.80205	95.62		2.6943 days	0.06	E,F,G
$^{59}Co(n,\gamma)^{60}Co$	7.60 – 6	4.50 – 4	6.90 – 7	1.43 – 4	1173.228	99.85		5.2711 years	0.06	E,G
					1332.492	99.9826				
*$^{58}Fe(n,\gamma)^{59}Fe$	1.00 – 6	2.10 + 0	5.25 – 7	1.00 – 2	1099.245	56.51		44.494 days	0.15	E,H
					1291.590	43.23				
$^{55}Mn(n,\gamma)^{56}Mn$	5.25 – 7	6.60 – 1	4.75 – 7	1.10 – 3	846.7638	98.85		2.57878 h	0.05	E,F
					1810.726	26.9				
*$^{63}Cu(n,\gamma)^{64}Cu$	1.15 – 6	2.30 + 0	5.25 – 7	9.60 – 3	1345.77	0.4748		12.7004 h	0.15	E
$^{23}Na(n,\gamma)^{24}Na$	6.30 – 7	2.00 + 0	5.25 – 7	3.00 – 3	1368.630	99.9934		14.4958 h	0.10	E,I,J
					2754.049	99.862				
$^{45}Sc(n,\gamma)^{46}Sc$	4.25 – 7	1.00 + 0	4.00 – 7	4.75 – 4	889.271	99.98374		83.787 days	0.05	E
					1120.537	99.97				
$^{235}U(n,f)^{140}La$	9.20 – 2	4.70 + 0	6.30 – 4	3.80 + 0	1596.203	95.40	5.9599	1.67858 days	0.30	E,K,L
$^{235}U(n,f)^{95}Zr$	9.20 – 2	4.70 + 0	6.30 – 4	3.80 + 0	724.192	44.27	6.3488	64.032 days	0.60	E,L
					756.725	54.438				
$^{239}Pu(n,f)^{140}La$	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	1596.203	95.40	5.3244	1.67858 days	1.00	E,K,L
$^{239}Pu(n,f)^{95}Zr$	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	724.192	44.27	4.6825	64.032 days	0.60	E,L
					756.725	54.38				
$^{93}Nb(n,n')^{93m}Nb$	8.40 – 1	5.70 + 0	1.00 + 0	5.50 + 0	30.77	0.000591		16.12 years		M
$^{103}Rh(n,n')^{103m}Rh$	5.50 – 1	5.70 + 0	6.90 – 1	5.70 + 0	39.755	0.068		56.114 min		M
$^{237}Np(n,f)^{140}La$	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	1596.203	95.40	5.74440	1.67858 days	0.60	E,K,L,N
$^{237}Np(n,f)^{95}Zr$	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	724.192	44.27	5.61470	64.032 days	0.60	E,L
					756.725	54.38				
*$^{115}In(n,n')^{115m}In$	1.00 + 0	6.00 + 0	1.20 + 0	5.80 + 0	336.241	45.8		4.486 h	0.12	
$^{238}U(n,f)^{140}La$	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	1596.203	95.40	5.9718	40.28 h	1.00	E,K,L,O
$^{238}U(n,f)^{95}Zr$	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	724.192	44.27	5.1883	64.032 days	1.00	E,L
					756.725	54.38				
$^{232}Th(n,f)^{140}Ba$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	537.303	24.39	7.7121	12.753 days	1.00	E,K,P
$^{232}Th(n,f)^{95}Zr$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	724.192	44.27	5.5230	64.032 days	1.00	E,L
					756.725	54.38				
$^{54}Fe(n,p)^{54}Mn$	2.30 + 0	7.70 + 0	2.30 + 0	7.40 + 0	834.848	99.9752		312.19 days	0.15	E
$^{58}Ni(n,p)^{58}Co$	2.00 + 0	7.60 + 0	2.00 + 0	7.30 + 0	810.7602	99.44		70.85 days	0.30	E
$^{47}Ti(n,p)^{47}Sc$	1.90 + 0	7.60 + 0	1.90 + 0	7.30 + 0	159.373	68.1		3.3485 days	0.15	E,Q,R
$^{32}S(n,p)^{32}P$	2.40 + 0	7.50 + 0	2.30 + 0	7.30 + 0	1710.66	100. (beta)		14.284 days	...	S
$^{64}Zn(n,p)^{64}Cu$	2.60 + 0	7.70 + 0	2.60 + 0	7.40 + 0	1345.77	0.4748		12.7004 h	0.30	E
$^{27}Al(n,p)^{27}Mg$	3.50 + 0	9.40 + 0	3.40 + 0	9.20 + 0	843.76	71.800		9.458 min	0.30	E
					1014.4	28.0				
$^{46}Ti(n,p)^{46}Sc$	3.80 + 0	9.60 + 0	3.70 + 0	9.20 + 0	889.3	99.983		83.787 days	0.15	E,Q
					1120.5	99.986				
$^{56}Fe(n,p)^{56}Mn$	5.50 + 0	1.14 + 1	5.50 + 0	1.10 + 1	846.7	98.85		2.57878 h	0.15	E,T
					1810.7	26.9				
$^{24}Mg(n,p)^{24}Na$	6.50 + 0	1.17 + 1	6.50 + 0	1.13 + 1	1368.6	99.993		14.958 h	0.03	E,J
					2754.1	99.872				
$^{27}Al(n,\alpha)^{24}Na$	6.50 + 0	1.21 + 1	6.50 + 0	1.17 + 1	1368.6	99.993		14.958 h	0.30	E,J
					2754.1	99.872				
$^{48}Ti(n,p)^{48}Sc$	5.90 + 0	1.24 + 1	5.90 + 0	1.20 + 1	983.5	100.1		43.67 h	0.15	E
					1037.5	97.56				
					1312.1	100.1				
$^{93}Nb(n,2n)^{92m}Nb$	9.70 + 0	1.45 + 1	9.40 + 0	1.40 + 1	934.4	99.1		10.15 days		
$^{127}I(n,2n)^{126}I$	9.70 + 0	1.47 + 1	9.70 + 0	1.43 + 1	388.633	35.6		12.93 days	0.25	E
					666.331	32.9				
$^{65}Cu(n,2n)^{64}Cu$	1.08 + 1	1.57 + 1	1.07 + 1	1.53 + 1	1345.7	0.475		12.7004 h	0.15	E,M
*$^{63}Cu(n,2n)^{62}Cu$	1.19 + 1	1.66 + 1	1.19 + 1	1.63 + 1	875.7	0.150		9.67 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	99.0		78.42 h	0.10	
$^{58}Ni(n,2n)^{57}Ni$	1.32 + 1	1.71 + 1	1.31 + 1	1.69 + 1	1377.6	81.2		35.9 h	0.30	

TABLE 1 Activation Foils

Reaction	Fast Burst[A] E_L, MeV	Fast Burst[A] E_H, MeV	TRIGA Type[A] E_L, MeV	TRIGA Type[A] E_H, MeV	$E\gamma_1{}^B$ (keV)	Gamma Emission Probability[B]	Fast Fission Yield,[C] %	$T_{1/2}{}^B$	Recommended Foil Mass, g[D]	Footnotes
$^{197}Au(n,\gamma)^{198}Au$	4.00 – 6	7.20 – 4	3.80 – 6	9.20 – 6	411.80205 (17)	95.62 (6)		2.6943 (3) d	0.06	E,F,G
$^{59}Co(n,\gamma)^{60}Co$	7.60 – 6	4.50 – 4	6.90 – 7	1.43 – 4	1173.228 (3)	99.85 (3)		5.2711 (8) y	0.06	E,G
					1332.492 (4)	99.9826 (6)				
*$^{58}Fe(n,\gamma)^{59}Fe$	1.00 – 6	2.10 + 0	5.25 – 7	1.00 – 2	1099.245 (3)	56.51 (31)		44.494 (12) d	0.15	E,H
					1291.590 (6)	43.23 (33)				
$^{55}Mn(n,\gamma)^{56}Mn$	5.25 – 7	6.60 – 1	4.75 – 7	1.10 – 3	846.7638 (19)	98.85 (3)		2.57878 (46) h	0.05	E,F
					1810.726 (4)	26.9 (4)				
*$^{63}Cu(n,\gamma)^{64}Cu$	1.15 – 6	2.30 + 0	5.25 – 7	9.60 – 3	1345.77 (6)	0.4748 (34)		12.7004 (20) h	0.15	E

TABLE 1 *Continued*

Reaction	Fast Burst[A]		TRIGA Type[A]		$E\gamma$,[B] (keV)	Gamma Emission Probability[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						
^{23}Na(*n*,γ)^{24}Na	6.30 – 7	2.00 + 0	5.25 – 7	3.00 – 3	1368.630 (5) 2754.049 (13)	99.9934 (5) 99.862 (3)		14.958 (2) h	0.10	E,I,J
^{45}Sc(*n*,γ)^{46}Sc	4.25 – 7	1.00 + 0	4.00 – 7	4.75 – 4	889.271 (2) 1120.537 (3)	99.98374 (25) 99.97 (2)		83.787 (16) d	0.05	E
^{235}U(*n,f*)^{140}Ba	9.20 – 2	4.70 + 0	6.30 – 4	3.80 + 0	1596.203 (13)	95.40 (5)	6.0586 ± 0.0067	12.753 (5) d	0.30	E,K,L
^{235}U(*n,f*)^{95}Zr	9.20 – 2	4.70 + 0	6.30 – 4	3.80 + 0	724.193 (3) 756.729 (12)	44.27 (22) 54.38 (22)	6.4589 ± 0.0084	64.032 (6) d	0.60	E,L
^{239}Pu(*n,f*)^{140}Ba	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	1596.203 (13)	95.40 (5)	5.2916 ± 0.0794	12.753 (5) d	1.00	E,K,L
^{239}Pu(*n,f*)^{95}Zr	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	724.193 (3) 756.729 (12)	44.27 (22) 54.38 (22)	4.6909 ± 0.1173	64.032 (6) d	0.60	E,L
^{93}Nb(*n,n'*)^{93m}Nb	8.40 – 1	5.70 + 0	1.00 + 0	5.50 + 0	30.77 (2)	0.000591 (9)		16.12 (15) y		M
^{103}Rh(*n,n'*)^{103m}Rh	5.50 – 1	5.70 + 0	6.90 – 1	5.70 + 0	39.755 (12)	0.068 (35)		56.114 (9) min		M
^{237}Np(*n,f*)^{140}Ba	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	1596.203 (13)	95.40 (5)	5.7593 ± 0.1152	12.753 (5) d	0.60	E,K,L,N
^{237}Np(*n,f*)^{95}Zr	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	724.193 (3) 756.729 (12)	44.27 (22) 54.38 (22)	5.6715 ± 0.1532	64.032 (6) d	0.60	E,L
*^{115}In(*n,n'*)^{115m}In	1.00 + 0	6.00 + 0	1.20 + 0	5.80 + 0	336.241 (25)	45.9 (1)		4.486 (4) h	0.12	
^{238}U(*n,f*)^{140}Ba	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	1596.203 (13)	95.40 (5)	6.0457 ± 0.0781	12.753 (5) d	1.00	E,K,L,O
^{238}U(*n,f*)^{95}Zr	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	724.193 (3) 756.729 (12)	44.27 (22) 54.38 (22)	5.2506 ± 0.0842	64.032 (6) d	1.00	E,L
^{232}Th(*n,f*)^{140}Ba	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	1596.203 (13)	95.40 (5)	7.6222 ± 0.2431	12.753 (5) d	1.00	E,K,P
^{232}Th(*n,f*)^{95}Zr	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	724.193 (3) 756.729 (12)	44.27 (22) 54.38 (22)	5.4494 ± 0.1582	64.032 (6) d	1.00	E,L
^{54}Fe(*n,p*)^{54}Mn	2.30 + 0	7.70 + 0	2.30 + 0	7.40 + 0	834.848 (3)	99.9752 (5)		312.19 (3) d	0.15	E
^{58}Ni(*n,p*)^{58}Co	2.00 + 0	7.60 + 0	2.00 + 0	7.30 + 0	810.7602 (20)	99.44 (2)		70.85 (3) d	0.30	E
^{47}Ti(*n,p*)^{47}Sc	1.90 + 0	7.60 + 0	1.90 + 0	7.30 + 0	159.373 (12)	68.1 (5)		3.3485 (9) d	0.15	E,Q,R
^{32}S(*n,p*)^{32}P	2.40 + 0	7.50 + 0	2.30 + 0	7.30 + 0	1710.66 (21)	100 (beta)		14.284 (36) d	. . .	S
^{64}Zn(*n,p*)^{64}Cu	2.60 + 0	7.70 + 0	2.60 + 0	7.40 + 0	1345.77 (6)	0.4748 (34)		12.7004 (20) h	0.30	E
^{27}Al(*n,p*)^{27}Mg	3.50 + 0	9.40 + 0	3.40 + 0	9.20 + 0	843.76 (10) 1014.52 (10)	71.80 (2) 28.20 (2)		9.458 (12) min	0.30	E
^{46}Ti(*n,p*)^{46}Sc	3.80 + 0	9.60 + 0	3.70 + 0	9.20 + 0	889.271 (2) 1120.537 (3)	99.98374 (25) 99.97 (2)		83.787 (16) d	0.15	E,Q
^{56}Fe(*n,p*)^{56}Mn	5.50 + 0	1.14 + 1	5.50 + 0	1.10 + 1	846.7638 (19) 1810.726 (4)	98.85 (3) 26.9 (4)		2.57878 (46) h	0.15	E,T
^{24}Mg(*n,p*)^{24}Na	6.50 + 0	1.17 + 1	6.50 + 0	1.13 + 1	1368.630 (5) 2754.049 (13)	99.9934 (5) 99.862 (3)		14.997 (12) h	0.03	E,J
^{27}Al(*n*,α)^{24}Na	6.50 + 0	1.21 + 1	6.50 + 0	1.17 + 1	1368.630 (5) 2754.049 (13)	99.9934 (5) 99.862 (3)		14.997 (12) h	0.30	E,J
^{48}Ti(*n,p*)^{48}Sc	5.90 + 0	1.24 + 1	5.90 + 0	1.20 + 1	983.526 (12) 1037.522 (12) 1312.120 (12)	100.0 (2) 97.56 (3) 100.0 (3)		43.71 (9) h	0.15	E
^{93}Nb(*n*,2*n*)^{92m}Nb	9.70 + 0	1.45 + 1	9.40 + 0	1.40 + 1	934.44 (10)	100.0		10.15 (2) days		

TABLE 1 *Continued*

Reaction	Fast Burst[A]		TRIGA Type[A]		Eγ,[B] (keV)	Gamma Emission Probability[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						
$^{127}I(n,2n)^{126}I$	9.70 + 0	1.47 + 1	9.70 + 0	1.43 + 1	388.633 (11) 666.331 (12)	16.84 (1) = 35.6 (5) x 0.473 (5) 0.1734 (1) = 0.329 (13) x 0.527 (5)		12.93 (5) days	0.25	E
$^{65}Cu(n,2n)^{64}Cu$	1.08 + 1	1.57 + 1	1.07 + 1	1.53 + 1	1345.77 (6)	0.4748 (34)		12.7004 (20) h	0.15	E,M
$^{*63}Cu(n,2n)^{62}Cu$	1.19 + 1	1.66 + 1	1.19 + 1	1.63 + 1	875.66 (7)	0.147 (1) = 43 (2) x 0.00342(17)		9.67 (3) min	0.15	E,H
$^{90}Zr(n,2n)^{89}Zr$	1.28 + 1	1.69 + 1	1.27 + 1	1.67 + 1	908.97 (3)	99.03 (2)		78.42 (13) h	0.10	
$^{58}Ni(n,2n)^{57}Ni$	1.32 + 1	1.71 + 1	1.31 + 1	1.69 + 1	1377.62 (4)	81.2 (6)		35.9 (3) h	0.30	

[A] Energy limits which describe the 5 –to 95 % region of the detector response occurs for each reaction (see Practice E261 and Refs **(4, 5)**. The foils are assumed to have Cd covers as described in Footnote *E*.
[B] Data taken from Refs **(6-8)**. Ref **(8)** takes precedent, but it only addresses reactions used in detector calibration. In other cases, Ref **(6)** provides the half-life and Ref **(7)** provides the gamma yields. Many gamma-ray energies rounded to the nearest 0.1 keV. For uncertainties on values, see references. When the emission process is beta decay, the quoted energy is the maximum beta energy.
[C] Fission yields can be found in Ref **(9)**.
[D] Choice of mass is based on assumed foil diameter of 1.27 cm.
[E] Cd covers 0.5 to ~~1 mm~~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] Use in the form of NaCl.
[J] The 1986 edition of Ref **(10)** 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 **(6)**.
[K] This is the 1.67858 days daughter of 12.753-day ^{140}Ba. Wait ~~5~~five days for maximum decay rate (see Test Method E393).
[L] E_{β} = 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).
[M] Precautions must be taken in counting because of the low gamma-ray energy. See Test Method E1297 for details of ^{93m}Nb use. For ^{103m}Rh, X-rays are typically counted rather than listed gamma ray. See Ref **(7)**.
[N] 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.
[O] 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.
[P] Radioactivity of ^{232}Th interferes with the ^{140}La line.
[Q] At high energies (>10 MeV), account for (*n,np*) contributions from higher atomic number *Ti* isotopes.
[R] See Refs **(11)** and **(12)**.~~,~~
[S] Requires β counting techniques, see Test Method E265.
[T] 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.

4.2 *Foil Impurities:*

4.2.1 Foil impurities are especially serious for a moderated source (TRIGA reactor) when an 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 ^{24}Mn (^{23}Na).

4.2.2 For a soft spectrum, such as the TRIGA J-tube spectrum [boral ~~(boron-aluminum~~ (that is, a 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~~ 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 $^{55}Mn(n,\gamma)^{56}Mn$ 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 1596.203-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 537.303-keV transition from the ^{140}Ba precursor of ^{140}La, having a gamma-transition probability of 0.2439 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 537.303-keV line can be seen above competing lines. See Test Method E393.

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 537.303-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 E844, Practice E261, and Test Methods E262, E263, E264, E265, E266, E704, and E705.

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, $\sum_i$ 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 i^{th} 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 recommended for all (n,γ) and (n,f) reactions. A pure gold foil is an example of a ~~self-shielding~~ self-shielding foil with its highly absorbing resonance at about 5 eV. The correction for a ~~0.025-mm~~0.025 mm thick foil being about a factor of two for epicadmium neutrons (that is, neutrons with energies greater than 0.5 eV) (**16**).

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