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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 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 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 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:* [2]

E 170 Terminology Relating to Radiation Measurements and Dosimetry

E 181 Test Methods for Detector Calibration and Analysis of Radionuclides

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

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

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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.

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron
E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel
E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32
E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum
E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters
E 496 Test Method for Measuring Neutron Fluence and Average Energy from ^{3}H(d,n) ^{4}He Neutron Generators by Radioactivation Techniques
E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238
E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237
E 721 Guide for Determining Neutron Energy Spectra from Neutron Sensors for Radiation-Hardness Testing of Electronics
E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706(IIC)
E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)
E 1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E 706 (IIB)
E 1297 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 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, 2)**,and IRDF-90 **(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 **(4)** and "TRIGA **(5)** 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 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. Ref **(6)** 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,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 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

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
					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,I,J
$^{45}Sc(n,\gamma)^{46}Sc$	4.25 – 7	1.00 + 0	4.00 – 7	4.75 – 4	889.3	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,K,L
$^{235}U(n,f)^{95}Zr$	9.20 – 2	4.70 + 0	6.30 – 4	3.80 + 0	724.2	0.441 (6.363)	64.02 days	0.60	E,L
$^{239}Pu(n,f)^{140}La$	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	1596.2	0.954 (5.326)	40.27 h	1.00	E,K,L
$^{239}Pu(n,f)^{95}Zr$	1.43 – 1	4.80 + 0	8.80 – 4	4.30 + 0	724.2	0.441 (4.685)	64.02 days	0.60	E,L
$^{93}Nb(n,n')^{93m}Nb$	8.40 – 1	5.70 + 0	1.00 + 0	5.50 + 0	16.6	0.115	16.13 years		M
$^{103}Rh(n,n')^{103m}Rh$	5.50 – 1	5.70 + 0	6.90 – 1	5.70 + 0	39.8	0.068	56.1 min		M
$^{237}Np(n,f)^{140}La$	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	1596.2	0.954 (5.489)	40.27 h	0.60	E,K,L,N
$^{237}Np(n,f)^{95}Zr$	5.75 – 1	5.60 + 0	6.60 – 1	5.50 + 0	724.2	0.441 (5.699)	64.02 days	0.60	E,L
*$^{115}In(n,n')^{115m}In$	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,K,L,O
$^{238}U(n,f)^{95}Zr$	1.50 + 0	6.90 + 0	1.50 + 0	6.60 + 0	724.2	0.441 (5.105)	64.02 days	1.00	E,L
$^{232}Th(n,f)^{140}Ba$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	537.3	0.244 (7.704)	12.75 days	1.00	E,K,P
$^{232}Th(n,f)^{95}Zr$	1.50 + 0	7.40 + 0	1.50 + 0	7.10 + 0	724.2	0.441 (5.374)	64.02 days	1.00	E,L
$^{54}Fe(n,p)^{54}Mn$	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,Q,R
$^{32}S(n,p)^{32}P$	2.40 + 0	7.50 + 0	2.30 + 0	7.30 + 0	1710.(beta)	1.00 (beta)	14.28 days	...	S
$^{64}Zn(n,p)^{64}Cu$	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	889.3	1.00	83.81 days	0.15	E,Q
$^{56}Fe(n,p)^{56}Mn$	5.50 + 0	1.14 + 1	5.50 + 0	1.10 + 1	846.8	0.989	2.58 h	0.15	E,T
$^{24}Mg(n,p)^{24}Na$	6.50 + 0	1.17 + 1	6.50 + 0	1.13 + 1	1368.6	1.00	14.96 h	0.03	E,J
$^{27}Al(n,\alpha)^{24}Na$	6.50 + 0	1.21 + 1	6.50 + 0	1.17 + 1	1368.6	1.00	14.96 h	0.30	E,J
$^{48}Ti(n,p)^{48}Sc$	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,M
*$^{63}Cu(n,2n)^{62}Cu$	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 Refs **(7,8)**. The foils are assumed to have Cd covers as described in Footnote *E*.

[B] Data taken from Refs **(9-11)**. Ref **(11)** takes precedent, but it only addresses reactions used in detector calibration. In other cases, Ref **(9)** provides the half-life and Ref **(10)** provides the gamma yields.

[C] Fission yields can be found in Ref **(12)**.

[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] Use in the form of NaCl.

[J] The 1986 edition of Ref **(13)** 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 **(9)**.

[K] 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).

[L] 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).

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

[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 **(14)** and **(15)**.

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

[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.

cross-section sets; (*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 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