



Designation: E1005 – 21

Standard Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance¹

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1. Scope

1.1 This test method describes procedures for measuring the specific activities of radioactive nuclides produced in radiometric monitors (RMs) by nuclear reactions induced during surveillance exposures for reactor vessels and support structures. More detailed procedures for individual RMs are provided in separate standards identified in 2.1 and in Refs (1-5).² The measurement results can be used to define corresponding neutron induced reaction rates that can in turn be used to characterize the irradiation environment of the reactor vessel and support structure. The principal measurement technique is high resolution gamma-ray spectrometry, although X-ray photon spectrometry and Beta particle counting are used to a lesser degree for specific RMs (1-29).

1.1.1 The measurement procedures include corrections for detector background radiation, random and true coincidence summing losses, differences in geometry between calibration source standards and the RMs, self absorption of radiation by the RM, other absorption effects, radioactive decay corrections, and burn out of the nuclide of interest (6-26).

1.1.2 Specific activities are calculated by taking into account the time duration of the count, the elapsed time between start of count and the end of the irradiation, the half life, the mass of the target nuclide in the RM, and the branching intensities of the radiation of interest. Using the appropriate half life and known conditions of the irradiation, the specific activities may be converted into corresponding reaction rates (2-5, 28-30).

1.1.3 Procedures for calculation of reaction rates from the radioactivity measurements and the irradiation power time history are included. A reaction rate can be converted to neutron fluence rate and fluence using the appropriate integral cross section and effective irradiation time values, and, with other reaction rates can be used to define the neutron spectrum through the use of suitable computer programs (2-5, 28-30).

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

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² The boldface numbers in parentheses refer to the list of references appended to this method.

1.1.4 The use of benchmark neutron fields for calibration of RMs can reduce significantly or eliminate systematic errors since many parameters, and their respective uncertainties, required for calculation of absolute reaction rates are common to both the benchmark and test measurements and therefore are self canceling. The benchmark equivalent fluence rates, for the environment tested, can be calculated from a direct ratio of the measured saturated activities in the two environments and the certified benchmark fluence rate (2-5, 28-30).

1.2 This test method is intended to be used in conjunction with ASTM Guide E844 and existing or proposed ASTM practices, guides, and test methods that are also directly involved in the physics-dosimetry evaluation of reactor vessel and support structure surveillance measurements.

1.3 The procedures in this test method are applicable to the measurement of radioactivity in RMs that satisfy the specific constraints and conditions imposed for their analysis. More detailed procedures for individual RM monitors are identified in 2.1 and in Refs 1-5 (see Table 1).

1.4 This test method, along with the individual RM monitor standard methods, are intended for use by knowledgeable persons who are intimately familiar with the procedures, equipment, and techniques necessary to achieve high precision and accuracy in radioactivity measurements.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard, except for the energy units based on the electron volt, keV and MeV, and the time units: minute (min), hour (h), day (d), and year (a).

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.*

TABLE 1 Radiometric Monitors Proposed for Reactor Vessel Surveillance

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance ^A Ref (31)	Detector Response ^B	ASTM Standard or Ref
	Half-life ^{C,A,D}	E_{γ}^D (keV)	Yield ^D (%) γ /Reaction			
²³ Na(n, γ) ²⁴ Na	14.958 (2) h	1368.630 (5) 2754.049 (13)	99.9934 (5) 99.862 (3)	1.00	NTR	(2-5, 28-32)
²⁷ Al(n, α) ²⁴ Na	14.958 (2) h	1368.630 (5) 2754.049 (13)	99.9934 (5) 99.862 (3)	1.00	TR	(32) E266
³² S(n,p) ³² P	14.284 (36) d	<E _p >=695.5 (3)	100.0	0.9499 (26)	TR	E265
⁴⁵ Sc(n, γ) ⁴⁶ Sc	83.787 (16) d	889.271 (2) 1120.537 (3)	99.98374 (25) 99.97 (2)	1.00	NTR	(2-5, 28-32)
⁴⁶ Ti(n,p) ⁴⁶ Sc	83.787 (16) d	889.271 (2) 1120.537 (3)	99.98374 (25) 99.97 (2)	0.0825 (3)	NTR	(32) E526
⁴⁷ Ti(n,p) ⁴⁷ Sc	3.3485 (9) d	159.373 (12)	68.1 (5)	0.0744 (2)	TR	E526
⁴⁸ Ti(n,p) ⁴⁸ Sc	43.67 (9) h	983.526 (12) 1037.522 (12) 1312.120 (12)	100.0 (3) 97.5 (5) 100.0 (5)	0.7372 (3)	TR	E526
⁵⁵ Mn(n,2n) ⁵⁴ Mn	312.19 (3) d	834.848 (3)	99.752 (5)	1.00	TR	E261, E263 (2-5, 28-30)
⁵⁴ Fe(n,p) ⁵⁴ Mn	312.19 (3) d	834.848 (3)	99.752 (3)	0.05845 (35)	TR	E263
⁵⁴ Fe(n, γ) ⁵⁵ Fe	2.747 (8) a	5.88765 5.89875 6.49045	8.45 (14) 16.57 (27) 3.40 (7)	0.05845 (35)	NTR	(2-5, 28-30)
⁵⁶ Fe(n,p) ⁵⁶ Mn	2.57878 (46) h	846.7638 (19) 1810.726 (4) 2113.092 (6)	98.85 (3) 26.9 (4) 14.2 (3)	0.91754 (36)	TR	(2-5, 28-30)
⁵⁸ Fe(n, γ) ⁵⁹ Fe	44.494 (12) d	1099.245 (3) 1291.590 (6) 1481.70 (12)	56.51 (31) 43.23 (33) 0.059 (6)	0.00282 (4)	NTR	(2-5, 28-30)
⁵⁹ Co(n, γ) ⁶⁰ Co	5.2711 (8) a 10.467 (6) min (meta)	1173.228 (3) 1332.492 (4) 58.603 (7) 826.10 (3) 1332.492 (4) 2158.57 (3)	99.85 (3) 99.9826 (6) 2.07 (3) 0.00775 (3) 0.25 (3) 0.00075 (3)	1.00	NTR	E262, E481
⁵⁸ Ni(n,p) ⁵⁸ Co	70.85 (3) d 9.10 (9) h (meta)	810.7602 (20) 863.958 (6) 1674.705 (6) 24.889 (21)	99.44 (2) 0.700 (22) 0.528 (13) 0.0397 (6)	0.68077 (9)	TR	E264
⁶⁰ Ni(n,p) ⁶⁰ Co	5.2711 (8) a 10.467 (6) min (meta)	1173.228 (3) 1332.492 (4) 58.603 (7) 826.10 (3) 1332.492 (4) 2158.57 (3)	99.85 (3) 99.9826 (6) 2.07 (3) 0.00775 (3) 0.25 (3) 0.00075 (3)	0.26223 (8)	TR	(2-5, 28-30)
⁶³ Cu(n, γ) ⁶⁴ Cu	12.7004 (20) h	1345.77 (6)	0.4748 (34)	0.6915 (15)	NTR	(2-5, 28-30)
⁶³ Cu(n, α) ⁶⁰ Co	5.2711 (8) a 10.467 (6) min (meta)	1173.228 (3) 1332.492 (4) 58.603 (7) 826.10 (3) 1332.492 (4) 2158.57 (3)	99.85 (3) 99.9826 (6) 2.07 (3) 0.00775 (3) 0.25 (3) 0.00075 (3)	0.6915 (15)	TR	E523
⁹³ Nb(n,n') ^{93m} Nb	16.12 (15) a	30.77 (2) 16.52 (K _{α1,2})	0.000591 (9) 9.25	1.00	TR	(1-5, 28-30)
¹⁰³ Rh(n,n') ^{103m} Rh	56.114 (20) min	39.755 (12)	0.0684 (35)	1.00	TR	(2-5, 28-30)
¹⁰⁹ Ag(n, γ) ^{110m} Ag	249.78 (2) d	116.48 (5) 884.6781 (13)	0.0080 (3) 74.0 (12)	0.48161 (8)	NTR	E481

TABLE 1 *Continued*

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance ^A Ref (31)	Detector Response ^B	ASTM Standard or Ref
	Half-life ^{C,A,D}	E_{γ}^D (keV)	Yield ^D (%) γ /Reaction			
¹¹⁵ In(n, γ) ^{116m} In	54.29 (17) min	937.485 (3)	34.51 (27)	0.9571 (5)	NTR	E261, E262
		1384.2931 (20)	24.7 (5)			
		1475.7792 (23)	4.03 (5)			
		1505.028 (2)	13.16 (16)			
		1293.56 (2)	84.8			
		1097.28 (2)	58.512			
¹¹⁵ In(n,n') ^{115m} In	4.486 (4) h	818.68 (2)	12.126	0.9571 (5)	TR	(2-5, 28-30)
		2112.29 (2)	15.094			
¹⁸¹ Ta(n, γ) ¹⁸² Ta	114.61 (13) d	336.241 (25)	45.9 (1)	0.9998799 (32)	NTR	E262
		497.370 (29)	0.047 (1)			
		1121.290 (3)	35.17 (33)			
¹⁹⁷ Au(n, γ) ¹⁹⁸ Au	2.6943 (3) d	1189.040 (3)	16.58 (16)	1.00	NTR	E261, E262 (2-5, 28-30)
		1221.395 (3)	27.27 (27)			
		1087.6842 (7)	0.1591 (21)			
²³² Th(n, γ) ²³³ Th	22.15 (8) min	675.8836 (7)	0.804 (5)	1.00	NTR	(2-5, 28-30)
		411.80205 (17)	95.62 (6)			
		890.1 (5)	0.1052 (14)			
²³³ Th \Rightarrow ²³³ Pa	26.98 (2) d	499.02 (4)	0.1078 (16)	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
		699.901	0.1576 (21)			
		764.55 (6)	0.68			
FM(n,f) ¹⁴⁴ Ce	284.89 (6) d	311.904 (5)	38.3 (5)	— ^E	NTR, TR	E393, E704, E705
		133.5152 (20)	10.83 (12)			
		80.120 (4)	1.40 (5) (see Table 2)			
FM(n,f) ¹⁴⁰ Ba	12.753 (5) d	537.261 (25)	24.6 (5) (see Table 2)	— ^E	NTR, TR	E393, E704, E705
		1596.203 (13)	95.40 (5)			
		815.784 (6)	23.72 (20)			
¹⁴⁰ Ba \Rightarrow ¹⁴⁰ La	1.67858 (21) d	487.022 (6)	46.1 (5) (see Table 2)	— ^E	NTR, TR	(2-5, 28-30)
		661.657 (3)	84.99 (20) (see Table 2)			
		661.657 (3)	90.07 (20) (see Table 2)			
FM(n,f) ¹³⁷ Cs	30.05 (8) a	—	—	— ^E	NTR, TR	E704, E705
¹³⁷ Cs \Rightarrow ^{137m} Ba	2.552 (1) min	—	—	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
FM(n,f) ¹⁰⁶ Ru	371.5 (21) d	—	—	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
¹⁰⁶ Ru \Rightarrow ¹⁰⁶ Rh	30.1 (3) s	511.8534 (23)	20.52 (23) (see Table 2)	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
FM(n,f) ¹⁰³ Ru	39.247 (13) d	497.085 (10)	91.0 (see Table 2)	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
FM(n,f) ⁹⁵ Zr	64.032 (6) d	756.729 (12)	54.38 (22)	— ^E	NTR, TR	E704, E705 (2-5, 28-30)
		724.193 (3)	44.27 (22) (see Table 2)			
⁹⁵ Zr \Rightarrow ⁹⁵ Nb	34.991 (6) d	765.803 (6)	99.808 (7) (see Table 2)	— ^E	NTR, TR	E704, E705 (2-5, 28-30)

^A The numbers in parentheses following some given values is the uncertainty in the last digit(s) of the value: 0.729 (8) means 0.729 \pm 0.008, 70.8 (1) means 70.8 \pm 0.1.

^B NTR = Non-Threshold Response, TR = Threshold Response.

^C The time units listed for half-life are years (a), days (d), hours (h), minutes (min), and seconds (s). Note that a "year" herein is considered to be tropical and equivalent to 365.242 days and thus equivalent to 31.556.926 s per Ref (32).

^D The nuclear data has been drawn from several primary sources including Refs (32-35). Reference (36) summarizes the source of the selected nuclear constants, last checked for consistency on March 19, 2014.

^E FM = Fission Monitor: ²³⁵U and ²³⁹Pu (NTR) and ²³⁸U, ²³⁷Np, and ²³²Th (TR) target isotope or weight fraction varies with material batch.

2. Referenced Documents

2.1 ASTM Standards:³

- E181** Test Methods for Detector Calibration and Analysis of Radionuclides
- E185** Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels
- 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
- E481** Test Method for Measuring Neutron Fluence Rates by Radioactivation of Cobalt and Silver
- E482** Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance
- E523** Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper
- E526** Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium
- E636** Guide for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels
- E693** Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA)
- E704** Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238
- E705** Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237
- E844** Guide for Sensor Set Design and Irradiation for Reactor Surveillance
- E853** Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Neutron Exposure Results
- E854** Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance
- E900** Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials
- E910** Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance
- E944** Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance
- E1018** Guide for Application of ASTM Evaluated Cross Section Data File

- E1035** Practice for Determining Neutron Exposures for Nuclear Reactor Vessel Support Structures
- E1214** Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance
- E2005** Guide for Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields
- E2006** Guide for Benchmark Testing of Light Water Reactor Calculations
- E2956** Guide for Monitoring the Neutron Exposure of LWR Reactor Pressure Vessels

2.2 IEEE/ANSI Standard:

- N42.14** Calibration and Use of Germanium Spectrometers for Measurement of Gamma-Ray Emission Rates of Radionuclides⁴

3. Terminology

3.1 Definitions:

3.1.1 *radiometric monitor (RM), dosimeter, foil*—a small quantity of material consisting of or containing an accurately known mass of a specific target nuclide. Usually fabricated in a specified and consistent geometry and used to determine neutron fluence rate (flux density), fluence and spectra by measuring a specific radioactive neutron-induced reaction product. A single RM may contain more than one target nuclide or have more than one specific reaction product.

3.1.2 *calibration standard*—a calibrated radioactive source standardized using an absolute calibration method or by rigorous comparison to a national or certified radioactivity standard source.

3.1.3 *national radioactivity standard source*—a calibrated radioactive source prepared and distributed as a standard reference material by the National Institute of Standards and Technology (NIST) or equivalent national standards and calibration institution.

3.1.4 *certified radioactivity standard source*—a calibrated radioactive source, with stated accuracy, whose calibration is traceable to a national radioactivity measurements system.

3.1.5 *check source, control standard*—a radioactivity source, not necessarily calibrated, which is used as a working reference to verify the continuing satisfactory operation of an instrument.

3.1.6 *FWHM (full width at half maximum)*—a measure of detector/system gamma-ray energy resolution expressed as the width of the gamma-ray peak distribution, in units of energy, measured at one-half the maximum peak height above the background.

3.1.7 *FWTM (full width at tenth maximum)*—identical to FWHM except the width is measured at one tenth the maximum peak height above the background.

3.1.8 *resolution, gamma-ray*—usually expressed as the FWHM and often including a specification for the FWTM.

³ 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 Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, <http://www.ansi.org>.

3.1.9 *peak-to-Compton-ratio*—the ratio of the net height of a Gaussian fit of the gamma-ray peak to average net counts in channels in the relatively flat portion of the Compton continuum.

4. Summary of Test Method

4.1 Appropriate radiation detection-measurement instruments shall be used in conjunction with suitable calibration standards, nuclear parameters, and test data to quantitatively determine the decay rate of selected radioactive nuclides produced in RMs during test and surveillance irradiations in neutron fields. These results together with established cross sections, spectral response data, and known test parameters allow the determination of the neutron fluence rate, fluence, and spectrum. Conversely, by using well-characterized controlled neutron fields to irradiate the selected target foils, cross sections and spectral response data can be determined from the radioactivity measurements.

4.2 The appropriate standard method of analysis identified in Section 2 for the individual RMs shall be followed as the individual problems that may be encountered and the precision and bias of the analysis for that particular RM are more fully discussed in these standards.

4.3 The neutron fluence rate (flux density), fluence, and spectral data shall be correlated to radiation induced change and damage in reactor materials through the use of appropriate analytical/calculational codes (see Guides E482, E693, E844, E853, E900, E944, E1018, E2005, and E2006).

5. Significance and Use

5.1 Radiometric monitors shall provide a proven passive dosimetry technique for the determination of neutron fluence rate (flux density), fluence, and spectrum in a diverse variety of neutron fields. These data are required to evaluate and estimate probable long-term radiation-induced damage to nuclear reactor structural materials such as the steel used in reactor pressure vessels and their support structures.

5.2 A number of radiometric monitors, their corresponding neutron activation reactions, and radioactive reaction products and some of the pertinent nuclear parameters of these RMs and products are listed in Table 1. Table 2 provides data (37) on the cumulative and independent fission yields of the important fission monitors. Not included in these tables are contributions to the yields from photo-fission, which can be especially significant for non-fissile nuclides (2-5, 27-29, 38-41).

6. Apparatus

6.1 A high resolution gamma-ray spectrometry system consisting of, but not limited to the following items:

6.1.1 *Gamma-Ray Detector*—A high purity germanium or lithium drifted germanium diode with its preamplifier and high-voltage (bias) power supply, and liquid nitrogen or electro-mechanically cooled cryostat. The detector (incorporated into the complete spectrometry system) shall have a resolution of ≤ 2.5 keV (FWHM) measured at the 1332 keV ^{60}Co peak with the FWTM no larger than 2 times the FWHM. The peak-to-Compton ratio shall be 25 to 1 or greater.

6.1.1.1 If more than one detector is available, the specifications can be advantageously tailored to optimize performance over the range of radioactivity levels and gamma-ray energies to be measured.

6.1.2 *Linear Amplifier*, for nuclear spectroscopy—multichannel pulse-height analyzer with at least 4000 channels, live time correction, and a hard copy data read out device. A visual display is extremely useful and in many cases essential for efficient operations. A built-in data handling and reduction system is necessary for processing large numbers of samples and to reduce possibility of human error.

6.2 *Thallium Activated Sodium Iodide Scintillation Crystal*—[NaI(Tl)], optically coupled to a photomultiplier tube with preamplifier, high voltage power supply, linear amplifier, multichannel analyzer with at least 400 channel capacity and a suitable data readout device. It is often feasible and advantageous to use a portion of the multichannel analyzer used for the high resolution germanium detector system for the NaI(Tl) detector through use of multiplexing techniques. A 3 by 3-in. integrally mounted NaI(Tl) detector is a good choice for general use.

6.3 *Beta Particle Counting System*, consisting of a suitable detector ranging from a thin end-window Geiger-Mueller type detector, proportional counter, scintillation counter to partially depleted silicon diodes; electronic components such as preamplifiers, amplifiers, discriminator-drivers, scalers, timers and high voltage power supplies to complete the system. Refer to Test Methods E181 for preparation of apparatus and counting procedures.

6.4 *X-ray Spectrometry System*, utilizing high resolution lithium drifted silicon, Si(Li), or germanium X-ray detector with liquid nitrogen or electro-mechanically cooled cryostat, preamplifier, amplifier and multichannel analyzer system with at least 1000 channel capacity and suitable data readout and display devices. Multiplexing could permit use of the same multichannel analyzer used for the high resolution germanium gamma spectrometer if adequate capacity exists or the analyzer could be dedicated to one use or the other to suit analysis schedules and requirements.

6.5 *High-Density Shielding* (usually lead) around the detectors to reduce interferences from background radiations.

6.6 *Sample Positioning Hardware*, to provide a number of reproducible fixed positions which can be calibrated for each detector as appropriate to accommodate different sample activities and sizes.

6.7 *National and Certified Radioactivity Standard Sources*.

6.8 *Calibration and Control Standards*.

6.9 Apparatus and reagents as listed in applicable ASTM standards for RM analysis.

7. Precautions

7.1 Refer to Test Methods E181 and Guide E844. For high fluence irradiations, burn-in or burn-out of target nuclides in the RM must be considered. For decay chains, such as ^{140}Ba – ^{140}La , decay corrections must take into account formation of a radioactive daughter by a radioactive parent. When

TABLE 2 Recommended Fission Yield Data^A

Fissionable Isotope	Reaction Product	Cumulative Fission Yield (Energy Dependent)		Independent Fission Yield (Energy Dependent)	
		Fast ^B	Thermal	Fast ^B	Thermal
²³² Th(n,f)	⁹⁵ Zr	5.4494 ± 2.9 %		1.5399 × 10 ⁻² ± 37.3 %	
	⁹⁵ Nb	5.4461 ± 2.9 %			
	¹⁰³ Ru	0.1518 ± 6.3			
	¹⁰⁶ Ru	0.0532 ± 5.7 %		3.4898 × 10 ⁻⁶ ± 38.0 %	
	¹⁰⁶ Rh	0.0532 ± 5.7 %			
	¹³⁷ Cs	6.1790 ± 5.1 %		2.4501 × 10 ⁻³ ± 35.0 %	
	^{137m} Ba	5.8329 ± 5.2 %			
	¹⁴⁰ Ba	7.6222 ± 3.2 %		2.9420 × 10 ⁻² ± 40.6 %	
	¹⁴⁰ La	7.6222 ± 3.2 %			
¹⁴⁴ Ce	7.6334 ± 6.1 %		1.7491 × 10 ⁻³ ± 42.4 %		
²³⁵ U(n,f)	⁹⁵ Zr	6.4589 ± 1.3 %	6.5042 ± 1.0 %	9.7309 × 10 ⁻² ± 36.6 %	1.0044 × 10 ⁻¹ ± 36.8 %
	⁹⁵ Nb	6.4553 ± 1.3 %	6.5006 ± 1.0 %	2.2939 × 10 ⁻⁴ ± 37.0 %	2.2213 × 10 ⁻⁴ ± 37.1 %
	¹⁰³ Ru	3.2809 ± 1.4 %	3.1118 ± 2.1 %	1.5966 × 10 ⁻⁴ ± 35.5 %	1.0372 × 10 ⁻⁴ ± 36.4 %
	¹⁰⁶ Ru	0.4660 ± 7.6 %	0.4096 ± 2.3 %	1.5698 × 10 ⁻² ± 35.6 %	5.4091 × 10 ⁻³ ± 79.9 %
	¹⁰⁶ Rh	0.4660 ± 7.6 %	0.4096 ± 2.3 %	7.6175 × 10 ⁻⁷ ± 37.1 %	5.2533 × 10 ⁻⁷ ± 46.2 %
	¹³⁷ Cs	5.8572 ± 1.9 %	6.0897 ± 1.0 %	8.3295 × 10 ⁻² ± 35.5 %	8.1095 × 10 ⁻² ± 35.2 %
	^{137m} Ba	5.5295 ± 2.1 %	5.7492 ± 1.4 %	2.4791 × 10 ⁻⁴ ± 35.9 %	4.9138 × 10 ⁻⁴ ± 35.6 %
	¹⁴⁰ Ba	6.0586 ± 1.1 %	6.3444 ± 1.0 %	4.9120 × 10 ⁻¹ ± 32.0 %	5.0254 × 10 ⁻¹ ± 31.6 %
	¹⁴⁰ La	6.0594 ± 1.1 %	6.3450 ± 1.0 %	8.2570 × 10 ⁻⁴ ± 35.5 %	6.4628 × 10 ⁻⁴ ± 35.2 %
	¹⁴⁴ Ce	5.1578 ± 1.8 %	5.4781 ± 0.9 %	4.2616 × 10 ⁻² ± 36.3 %	4.1193 × 10 ⁻² ± 35.9 %
	²³⁷ Np(n,f)	⁹⁵ Zr	5.6715 ± 2.7 %		1.2618 × 10 ⁻¹ ± 35.5 %
⁹⁵ Nb		5.6684 ± 2.7 %		2.8734 × 10 ⁻⁴ ± 36.3 %	
¹⁰³ Ru		5.3778 ± 11.2 %		7.8595 × 10 ⁻⁴ ± 35.3 %	
¹⁰⁶ Ru		2.2333 ± 10.8 %		1.2099 × 10 ⁻¹ ± 35.4 %	
¹⁰⁶ Rh		2.2335 ± 10.8 %		2.2083 × 10 ⁻⁴ ± 36.5 %	
¹³⁷ Cs		6.2129 ± 3.6 %		2.9840 × 10 ⁻¹ ± 34.6 %	
^{137m} Ba		5.8651 ± 3.7 %		1.2288 × 10 ⁻⁴ ± 36.3 %	
¹⁴⁰ Ba		5.7593 ± 2.0 %		4.0794 × 10 ⁻¹ ± 32.8 %	
¹⁴⁰ La		5.7674 ± 2.0 %		8.1060 × 10 ⁻³ ± 35.6 %	
¹⁴⁴ Ce		4.1743 ± 4.8 %		3.7653 × 10 ⁻² ± 34.2 %	
²³⁸ U(n,f)		⁹⁵ Zr	5.2506 ± 1.6 %		1.0941 × 10 ⁻² ± 38.6 %
	⁹⁵ Nb	5.2475 ± 1.6 %			
	¹⁰³ Ru	6.0331 ± 1.8 %		3.6712 × 10 ⁻⁵ ± 34.8 %	
	¹⁰⁶ Ru	2.5063 ± 5.3 %		1.3091 × 10 ⁻² ± 37.8 %	
	¹⁰⁶ Rh	2.5064 ± 5.3 %		5.2394 × 10 ⁻⁵ ± 38.0 %	
	¹³⁷ Cs	6.0045 ± 2.3 %		2.5145 × 10 ⁻³ ± 34.8 %	
	^{137m} Ba	5.6682 ± 2.5 %			
	¹⁴⁰ Ba	6.0457 ± 1.3 %		1.9061 × 10 ⁻² ± 38.3 %	
	¹⁴⁰ La	6.0457 ± 1.3 %			
	¹⁴⁴ Ce	4.6916 ± 2.3 %		1.2708 × 10 ⁻³ ± 38.1 %	
	²³⁹ Pu(n,f)	⁹⁵ Zr	4.6909 ± 2.5 %	4.8805 ± 1.1 %	1.7132 × 10 ⁻¹ ± 34.8 %
⁹⁵ Nb		4.6890 ± 2.5 %	4.8781 ± 1.1 %	7.9095 × 10 ⁻⁴ ± 36.0 %	3.9415 × 10 ⁻⁴ ± 36.2 %
¹⁰³ Ru		6.5709 ± 2.5 %	6.8709 ± 1.2 %	1.6105 × 10 ⁻³ ± 35.7 %	1.6865 × 10 ⁻³ ± 35.0 %
¹⁰⁶ Ru		4.0375 ± 7.8 %	4.3404 ± 2.3 %	4.1824 × 10 ⁻¹ ± 34.0 %	5.2773 × 10 ⁻¹ ± 27.1 %
¹⁰⁶ Rh		4.0394 ± 7.8 %	4.3426 ± 2.3 %	1.8578 × 10 ⁻³ ± 37.4 %	2.1687 × 10 ⁻³ ± 33.4 %
¹³⁷ Cs		6.3098 ± 2.2 %	6.5796 ± 1.2 %	5.0890 × 10 ⁻¹ ± 34.4 %	4.7400 × 10 ⁻¹ ± 34.8 %
^{137m} Ba		5.9624 ± 2.4 %	6.2163 ± 1.5 %	5.9273 × 10 ⁻³ ± 36.5 %	5.1692 × 10 ⁻³ ± 36.1 %
¹⁴⁰ Ba		5.2916 ± 1.5 %	5.2880 ± 1.1 %	1.3323 × 10 ⁰ ± 25 %	1.2357 × 10 ⁰ ± 26.1 %
¹⁴⁰ La		5.3067 ± 1.5 %	5.2989 ± 1.1 %	1.5084 × 10 ⁻² ± 34.4 %	1.0926 × 10 ⁻² ± 34.4 %
¹⁴⁴ Ce		3.4994 ± 1.7 %	3.7623 ± 0.9 %	1.8595 × 10 ⁻¹ ± 31.6 %	1.8624 × 10 ⁻¹ ± 31.9 %

^A All yield data are given as a percentage with associated uncertainties given as percentages of the percentage at the 1 σ level.

^B For this fission yield evaluation (37), "Fast" indicates that the data was extracted from a wide range of reactor-based fission neutron spectra that can be characterized as having an average energy of ~0.4 MeV. Almost all of the fission reactions for U-238 and Th-232 occur above an effective threshold energy of ~1 MeV and, for Np-237, above ~0.2 MeV.

appropriate, round-robin intercalibration tests such as those previously conducted by NIST, the LWR Pressure Vessel Surveillance Dosimetry Improvement Program, or under the Interlaboratory Reaction Rate (ILRR) Program shall be undertaken to detect and eliminate unforeseen sources of error (2-5, 28-30).

8. Preparation of Apparatus

8.1 Follow the manufacturer's instructions for setting up and preliminary testing of equipment. Observe all manufacturer's limitations and cautions.

8.2 When the equipment appears to be operating according to specifications, test the operations of various features, such as energy linearity, live-time correction, pulse pile-up rejection, and tolerance to high counting rates using radioactivity standard sources, calibration and control standards singly and in different combinations to determine equipment limitations ((6-12), Test Methods E181).

8.3 One or more control standards should be measured regularly on each system to verify that the system is operating consistently and properly. A control log including a running record and tolerance limits of each control measurement is an effective way of implementing this method.

9. Calibration and Standardization

9.1 For gamma-ray and X-ray spectrometry systems, refer to procedures given in Test Methods E181.

9.1.1 Obtain or prepare, or both, pure solutions of radionuclides corresponding to the national and certified radioactivity standards available and for as many of the radionuclides to be analyzed as practical.

9.1.2 Using carefully measured aliquots of these solutions, prepare sources that are as identical and as practical in mounting geometry and source strength to the national and certified fixed source standards. At the same time, carefully prepare sources which are as analyzed using multiple and fractional aliquots of the same solutions to optimize the counting rates at the different fixed sample positions with respect to the detector. These sources can be used as secondary standards to obtain calibrations of sample positions for which no suitable national or certified radioactivity standard is available.

9.1.3 If the capabilities or services are available, obtain or prepare calibration standard sources of radionuclides which are not available as national or certified standards. 4π -Beta, 4π -Beta/Gamma coincidence, and 4π -X-ray/Gamma coincidence are some techniques which might be available to standardize solutions for calibration standards. These standards can be used to help fill gaps left by the non-availability of national or certified standards and to help verify efficiency calibration curves for each position to be calibrated (13-15).

9.1.4 An alternative technique for calibration of high resolution gamma spectrometers is the use of a calibrated multiple peak mixed standard source or a multiple gamma emitting nuclide source for which the relative intensities are well known. In the latter case, the shape of the energy versus efficiency curve can be defined over the range of energies available and then the curve can be normalized to an absolute calibration using one or more points obtained with national or certified gamma emission radioactivity standards. NIST Standard Reference Material SRM 4370 (Europium-152 Radioactivity Standard)⁵ and SRM 4274 (Holmium-166m Gamma-ray Emission Rate Standard)⁵ are examples of calibration standards that can be used. Special care must be taken when applying this technique, particularly in the high efficiency counting positions, to correct for true summing effects for

gamma-rays (and X-rays) of different energies emitted in coincidence from the same decay event. Depending upon the calibration source used, the entire efficiency curve shape may be distorted if this correction is not applied.

9.2 Calibration of the beta counting system, which in this method is used only for the measurement of phosphorus-32, is accomplished by preparing a source mount from a national radioactivity standard solution in a manner as identical as possible to the sample mount. The counting efficiency can be readily calculated from the observed background corrected count rate and the known disintegration rate of the standard. A control source of a long-lived beta emitter with comparable beta energy such as a Strontium-Yttrium-90 equilibrium source should be used to verify continued satisfactory operation of the counting system.

10. Counting Procedures

10.1 *Equipment Control and Performance Checks*—Refer to the Performance Testing Section of Test Methods E181. Modify procedures as appropriate for X-ray spectrometry and beta counting systems.

10.2 *Sample Counting:*

10.2.1 The sample shall be counted on the detector system in the position which gives the highest possible count rate without unacceptably high uncertainties due to count loss or geometry corrections. When the calibration has been made using a calibration standard of the sample radionuclide that is nearly identical to the sample in physical configuration, the calculation of the observed measurement is simple and straight forward.

10.2.2 The sample counting time shall be tailored to accumulate at least the counts required to provide adequate counting statistics to obtain results to the required accuracy.

10.2.3 Absorbers can be used to advantage when counting a sample emitting a complex mixture of gamma-rays such as a mixed fission product sample. For example, by placing a suitable absorber between the detector and the sample a much higher usable count rate for the 1596 keV gamma-ray from Lanthanum-140 can be obtained since the absorber(s) keeps the quantities of low-energy gamma-rays in the mixed fission products from reaching and overloading the detector system. When using this technique, extreme care must be used to verify theoretical calculations, see Test Methods E181, or obtain appropriate calibrations with the calibration standard, absorber, and detector in the identical positions used to count the samples.

10.2.4 For sample to detector counting positions that are 15 cm or more apart, most small RMs and “point source” calibration standards can be considered to be equivalent geometries. The effects of the differences in the size and shape of the RMs versus the calibration sources become increasingly pronounced as the distance between the sample counting position and the detector is decreased.

10.3 Procedures for counting samples of the X-ray emitters (for example, iron-55, rhodium-103m, and particularly niobium-93m) present special problems in accurate counting

⁵ Available from the National Institute of Standards and Technology, Gaithersburg, MD 20899.