Designation: E 1005 – 03

Standard Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance, E 706(IIIA)[1]

This standard is issued under the fixed designation E 1005; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This method describes general 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 **11, 24-27**. 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).**[2]

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, and radioactive decay corrections **(1-10, 12-22).**

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 **(24-30).**

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 **(24-30).**

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 **(24-30).**

1.2 This method is intended to be used in conjunction with ASTM Guide E 844, . The following existing or proposed ASTM practices, guides, and methods are also directly involved in the physics-dosimetry evaluation of reactor vessel and support structure surveillance measurements:

Master Matrix for Light-Water Reactor Pressure Vessel Surveillance Standards, E 706 (O) [3]

E 853 Analysis and Interpretation of Light-Water Reactor Surveillance Results, E 706 (IA)[3]

E 560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E 706 (IC)[3]

E 693 Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E 706 (ID)[3]

E 185 Practice for Conducting Surveillance Tests for Light-Water Nuclear Power Reactor Vessels, E 706 (IF)[3]

E 1035 Practice for Determining Radiation Exposure for Nuclear Reactor Vessel Support Structures, E 706 (IG)[3]

E 636 Practice for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels, E 706 (IH)[3]

E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)[3]

E 1018 Guide for Application of ASTM Evaluated Cross Section and Data File, E 706 (IIB)[3]

E 482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E 706 (IID)[3]

E 2005 Guide for the Benchmark Testing of Reactor Vessel Dosimetryin Standard and Reference Neutron Fields

E 2006 Guide for the Benchmark Testing of Light Water Reactor Calculations

[1] This 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.

[3] The reference in parentheses refers to Section 5 as well as Figs. 1 and 2 of Matrix E 706.

E 854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Vessel Surveillance, E 706 (IIIB)[3]

E 910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E 706 (IIIC)[3]

E1214 Application and Analysis of Temperature Monitors for Reactor Vessel Surveillance, E 706 (IIIE) [3]

1.3 The general procedures in this 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 **11, 24-27** (see Table 1).

1.4 This 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 *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.*

TABLE 1 Radiometric Monitors Proposed for Reactor Vessel Surveillance

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance[A] [31]	Detector Response[B]	ASTM Standard or Ref.
	Half-life[C,A,D]	E_γ[D] (keV)	Yield[D] (%) γ/Reaction			
$^{23}Na(n,\gamma)^{24}Na$	0.62356 (17) d	1368.633 2754.030	99.9936 99.855	1.00	NTR	**(24-30)**
$^{27}Al(n,\alpha)^{24}Na$	0.62356 (17) d	1368.633 2754.030	99.9936 99.855	1.00	TR	E 266
$^{32}S(n,p)^{32}P$	14.262 (14) d	$<E_\beta>$=694.9	100.	0.9502 (9)	TR	E 265
$^{45}Sc(n,\gamma)^{46}Sc$	83.79 (4) d	889.277 1120.545	99.9844 99.9874	1.00	NTR	**(24-30)**
$^{46}Ti(n,p)^{46}Sc$	83.79 (4) d	889.277 1120.545	99.9844 99.9874	0.0825 (3)	TR	E 526
$^{47}Ti(n,p)^{47}Sc$	3.3492 (1) d	159.381	68.3	0.0744 (2)	TR	E 526
$^{48}Ti(n,p)^{48}Sc$	43.67 (9) h	983.526 1037.522 1312.120	100.0 97.5 100.0	0.7372 (3)	TR	E 526
$^{55}Mn(n,2n)^{54}Mn$	312.11 (5) d	834.843	99.9758	1.00	TR	E 261, E 263 **(24-30)**
$^{54}Fe(n,p)^{54}Mn$	312.11 (5) d	834.843	99.9758	0.05845 (35)	TR	E 263
$^{54}Fe(n,\gamma)^{55}Fe$	2.73 (3) y	5.888 5.899 6.490	8.2 16.2 2.86	0.05845 (35)	NTR	**(24-30)**
$^{56}Fe(n,p)^{56}Mn$	2.5789 (1) hr	846.754 1810.72 2113.05	98.87 27.18925 14.33615	0.91754 (36)	TR	**(24-30)**
$^{58}Fe(n,\gamma)^{59}Fe$	44.472 (8) d	1099.251 1291.596 1481.7	56.5 43.2 0.059	0.00282 (4)	NTR	**(24-30)**
$^{59}Co(n,\gamma)^{60}Co$	1925.5 (5) d 10.467 (6) m (meta)	1173.238 1332.502 58.603 826.28 1332.501 2158.77	99.857 99.983 2.01 0.00768 0.24 0.00072	1.00	NTR	E 262, E 481
$^{58}Ni(n,p)^{58}Co$	70.82 (3) d 9.15 (10) h (meta)	810.775 863.959 1674.730 24.889	99.45 0.69 0.519 0.0369	0.68077 (9)	TR	E 264
$^{60}Ni(n,p)^{60}Co$	1925.5 (5) d 10.467 (6) m (meta)	1173.238 1332.502 58.603 826.28	99.857 99.983 2.01 0.00768	0.26223 (8)	TR	**(24-30)**

TABLE 1 *Continued*

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance[A] [31]	Detector Response[B]	ASTM Standard or Ref.
	Half-life[C,A,D]	E_γ[D] (keV)	Yield[D] (%) γ/Reaction			
		1332.501	0.24			
		2158.77	0.00072			
$^{63}Cu(n,\gamma)^{64}Cu$	12.700 (2) h	1345.77	0.47336	0.6917 (3)	NTR	**(24-30)**
$^{63}Cu(n,\alpha)^{60}Co$	1925.5 (5) d	1173.238	99.857	0.6917 (3)	TR	E 523
		1332.502	99.983			
	10.467 (6) m	58.603	2.01			
	(meta)	826.33	0.0058			
		1332.501	0.25			
		2158.86	0.00088			
$^{93}Nb(n,n')^{93m}Nb$	$5.89\ (5) \times 10^3$ d	30.77	0.000549	1.00	TR	**(11, 24-30)**
		16.52 ($K_{\alpha 1,2}$)	9.25			
$^{103}Rh(n,n')^{103m}Rh$	56.114 (9) m	39.755	0.0684	1.00	TR	**(24-30)**
$^{109}Ag(n,\gamma)^{110m}Ag$	249.76 (4) d	116.48	0.00799	0.48161 (8)	NTR	E 481
		884.685	72.192			
		937.493	34.1314			
		1384.300	24.1204			
		1505.040	12.9532			
		1475.788	3.96868			
$^{115}In(n,\gamma)^{116m}In$	54.29 (17) m	1293.54	84.4	0.9571 (5)	NTR	E 261, E 262
		1097.3	56.2104			
		818.7	11.4784			
		2112.1	15.5296			
$^{115}In(n,n')^{115m}In$	4.486 (4) h	336.241	45.9	0.9571 (5)	TR	**(24-30)**
		497.370	0.047			
$^{181}Ta(n,\gamma)^{182}Ta$	114.43 (3) d	1121.3008	34.9	0.99988 (2)	NTR	E 262
		1189.0503	16.225			
		1221.4066	26.9777			
$^{197}Au(n,\gamma)^{198}Au$	2.69517 (21) d	1087.6904	0.159045	1.00	NTR	E 261, E 262
		675.8874	0.8038278			**(24-30)**
		411.804	95.57			
$^{232}Th(n,\gamma)^{233}Th$	22.3 (1) m	890.1	0.14	1.00	NTR	**(24-30)**
		490.80	0.17			
		499.02	0.21			
		699.901	0.68			
		764.4	0.120			
. . . .⇒^{233}Pa	26.967 (2) d	312.17	38.6			
$FM(n,f)^{144}Ce$	284.893 (8) d	133.515	11.09	—[E]	NTR, TR	E 704, E 705
		80.120	1.36407			**(24-30)**
			(see Table 2)			
$FM(n,f)^{140}Ba$	12.752 (3) d	537.261	24.4	—[E]	NTR, TR	E 393, E 704,
			(see Table 2)			E 705
$^{140}Ba⇒^{140}La$	1.6781 (3) d	1596.21	95.4			**(24-30)**
		815.772	23.2776			
		487.021	45.5058			
			(see Table 2)			
$FM(n,f)^{137}Cs$	30.07 (3) y	661.660	85.1	—[E]	NTR, TR	E 320, E 704,
			(see Table 2)			E 705
$^{137}Cs⇒^{137m}Ba$	2.552 (1) m	661.660	90.11			**(24-30)**
			(see Table 2)			
$FM(n,f)^{106}Ru$	373.59 (15) d	—	—	—[E]	NTR, TR	E 704, E 705
			(see Table 2)			**(24-30)**
$^{106}Ru⇒^{106}Rh$	29.80 (8) s	511.8605	20.4			

TABLE 1 *Continued*

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance[A] [31]	Detector Response[B]	ASTM Standard or Ref.
	Half-life[C,A,D]	E_γ[D] (keV)	Yield[D] (%) γ/Reaction			
			(see Table 2)			
$FM(n,f)^{103}Ru$	39.26 (2) d	497.084	91.0 (see Table 2)	—[E]	NTR, TR	E 704, E 705 **(24-30)**
$FM(n,f)^{95}Zr$	64.02 (5) d	756.729 724.199	54.46 44.1725 (see Table 2)	—[E]	NTR, TR	E 704, E 705 **(24-30)**
$^{95}Zr \Rightarrow ^{95}Nb$	34.997 (6) d	765.807	99.81 (see Table 2)			

[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± 0.008, 70.8 (1) means 70.8 ± 0.1.
[B]NTR = Non-Threshold Response, TR = Threshold Response.
[C]The time units listed for half-life are years (y), days (d), hours (h), minutes (m), and seconds (s).
[D]The nuclear data has been drawn from several primary sources including References **(31), (33)** and **(34)**. Reference **(32)** summarizes the source of the selected nuclear constants.
[E]FM = Fission Monitor:^{235}U and ^{239}Pu (NTR) and^{238}U, ^{237}Np, and^{232}Th (TR) target isotope or weight fraction varies with material batch.

2. Referenced Documents

2.1 ASTM Standards not identified in 1.2, including those for individual RM monitors:

2.2 *ASTM Standards:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[4]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods [5]

E 181 General Methods for Detector Calibration and Analysis of Radionuclides[4]

E 219 Test Method for Atom Percent Fission in Uranium Fuel (Radiochemical Method)[4]

E 261 Practice for Determining Neutron Fluence Rate, Fluence, and Spectra by Radioactivation Techniques[4]

E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques[4]

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron[4]

E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel[4]

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32[4]

E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum[4]

E 267 Test Method for Uranium and Plutonium Concentrations and Isotopic Abundances[4]

E 320 Test Methods for Cesium-137 in Nuclear Fuel Solutions by Radiochemical Analysis[4]

E 321 Test Method for Atom Percent Fission in Uranium and Plutonium Fuel (Neodymium-148 Method)[4]

E 343 Test Method for Measuring Reaction Rates by Analysis of Molybdenum-99 Radioactivity from Fission Dosimeters[4]

E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters[4]

E 481 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E707 (IID)[4]

E 482 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[4]

E 523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper[4]

E 526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium[4]

E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238[4]

E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237[4]

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[4]

E 944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, (IIA)[4]

E 1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E 706 (IIB)[4]

E 1035 Practice for Determining Radiation Exposure for Nuclear Reactor Vessel Support Structures, E 706 (IG)[4]

E 1214 Application and Analysis of Temperature Monitors for Reactor Vessel Surveillance, E 706 (IIIE)[4]

E 2005 Guide for the Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields [4]

E 2006 Guide for the Benchmark Testing of Light Water Reactor Calculations[4]

2.3 *ANSI Standard:*

N42.14 Calibration and Usage of Germanium Detectors for Measurement of Gamma-Ray Emission Rates of Radionuclides[6]

3. Terminology

3.1 *Definitions:*

3.1.1 *radiometric monitor (RM), dosimeter, foil*—a small quantity of material consisting of or containing an accurately

[4] *Annual Book of ASTM Standards*, Vol 12.02.
[5] *Annual Book of ASTM Standards*, Vol 14.02.
[6] Available from American National Standards Institute, 11 W. 42nd St., 13th Floor, New York, NY 10036.

TABLE 2 Recommended Fission Yield Data[A]

Fissile Isotope	Reaction Product	Cumulative Fission Yield (Energy Dependent)		Independent Fission Yield (Energy Dependent)	
		0.5 MeV	Thermal	0.5 MeV	Thermal
^{232}Th(n,f)	^{95}Zr	5.67313 ± 2.8 %	—	3.84804×10^{-3} ± 64 %	—
	^{95}Nb	5.67313 ± 2.8 %	—	7.49008×10^{-7} ± 64 %	—
	^{103}Ru	0.156332 ± 4.0 %	—	6.12007×10^{-8} ± 64 %	—
	^{106}Ru	0.0537306 ± 11 %	—	1.05001×10^{-4} ± 64 %	—
	^{106}Rh	0.0537306 ± 11 %	—	1.33001×10^{-8} ± 64 %	—
	^{137}Cs	5.84355 ± 4 %	—	8.32609×10^{-3} ± 64 %	—
	^{137m}Ba	5.528 ± 4 %	—	7.63008×10^{-6} ± 64 %	—
	^{140}Ba	7.87647 ± 2.8 %	—	4.82795×10^{-2} ± 64 %	—
	^{140}La	7.87649 ± 2 %	—	2.71003×10^{-5} ± 64 %	—
	^{144}Ce	7.94699 ± 4 %	—	4.80505×10^{-3} ± 64 %	—
^{235}U(n,f)	^{95}Zr	6.42554 ± 1 %	6.49458 ± 1 %	2.93502×10^{-2} ± 64 %	1.2208×10^{-1} ± 16 %
	^{95}Nb	6.42557 ± 0.7 %	6.49471 ± 1 %	2.21002×10^{-5} ± 64 %	1.02003×10^{-4} ± 64 %
	^{103}Ru	3.26185 ± 1 %	3.03144 ± 1.4 %	2.35002×10^{-5} ± 64 %	2.31006×10^{-5} ± 64 %
	^{106}Ru	0.535398 ± 1 %	0.44108 ± 1.4 %	7.55005×10^{-3} ± 64 %	8.90023×10^{-7} ± 64 %
	^{106}Rh	0.535404 ± 1 %	0.400983 ± 1.4 %	6.06004×10^{-6} ± 64 %	0
	^{137}Cs	6.22335 ± 0.5 %	6.18682 ± 0.5 %	1.84879×10^{-1} ± 32 %	5.93635×10^{-2} ± 11 %
	^{137m}Ba	5.88768 ± 0.5 %	5.85286 ± 0.5 %	3.93003×10^{-4} ± 64 %	1.30003×10^{-4} ± 64 %
	^{140}Ba	5.98741 ± 1 %	6.19595 ± 1 %	4.72071×10^{-1} ± 64 %	4.64072×10^{-1} ± 32 %
	^{140}La	5.98872 ± 1 %	6.2012 ± 1 %	1.31401×10^{-5} ± 64 %	5.25214×10^{-3} ± 64 %
	^{144}Ce	5.26689 ± 1.4 %	5.49709 ± 0.7 %	4.35013×10^{-2} ± 64 %	6.27386×10^{-2} ± 64 %
^{237}Np(n,f)	^{95}Zr	5.68896 ± 2.8 %	—	6.1647×10^{-2} ± 64 %	—
	^{95}Nb	5.68907 ± 2 %	—	8.5×10^{-5} ± 64 %	—
	^{103}Ru	5.56212 ± 2.8 %	—	1.44×10^{-4} ± 64 %	—
	^{106}Ru	2.18067 ± 11 %	—	6.0445×10^{-2} ± 64 %	—
	^{106}Rh	2.18077 ± 11 %	—	9.29×10^{-5} ± 64 %	—
	^{137}Cs	6.16977 ± 2.8 %	—	2.74311×10^{-1} ± 64 %	—
	^{137m}Ba	5.83804 ± 2.8 %	—	1.438×10^{-3} ± 64 %	—
	^{140}Ba	5.47246 ± 1.4 %	—	5.83709×10^{-1} ± 64 %	—
	^{140}La	5.47688 ± 2.8 %	—	4.421×10^{-3} ± 64 %	—
	^{144}Ce	4.12987 ± 2 %	—	9.1496×10^{-2} ± 64 %	—
^{238}U(n,f)	^{95}Zr	5.15126 ± 1 %	—	7.88021×10^{-4} ± 64 %	—
	^{95}Nb	5.15126 ± 1 %	—	8.34022×10^{-8} ± 64 %	—
	^{103}Ru	6.26113 ± 1 %	—	3.06008×10^{-7} ± 64 %	—
	^{106}Ru	2.48759 ± 1.4 %	—	3.8101×10^{-7} ± 64 %	—
	^{106}Rh	2.48759 ± 1.4 %	—	0	—
	^{137}Cs	6.02075 ± 1 %	—	9.28724×10^{-3} ± 64 %	—
	^{137m}Ba	5.69564 ± 1 %	—	4.10011×10^{-6} ± 64 %	—
	^{140}Ba	5.84596 ± 1 %	—	2.57317×10^{-2} ± 64 %	—
	^{140}La	5.84597 ± 1 %	—	1.38004×10^{-5} ± 64 %	—
	^{144}Ce	4.55034 ± 1.4 %	—	1.30603×10^{-3} ± 64 %	—
^{239}Pu(n,f)	^{95}Zr	4.65412 ± 1.4 %	4.80834 ± 1.4 %	7.94561×10^{-2} ± 64 %	1.25228×10^{-1} ± 64 %
	^{95}Nb	4.65431 ± 1.4 %	4.80904 ± 1.4 %	1.45002×10^{-4} ± 64 %	5.64006×10^{-4} ± 64 %
	^{103}Ru	6.85701 ± 1.4 %	7.0047 ± 2 %	4.41006×10^{-4} ± 64 %	1.01101×10^{-3} ± 64 %
	^{106}Ru	4.33807 ± 1.4 %	4.32901 ± 2 %	2.00083×10^{-1} ± 64 %	3.2276×10^{-1} ± 32 %
	^{106}Rh	4.33845 ± 1.4 %	4.32923 ± 2 %	3.76005×10^{-4} ± 64 %	2.23002×10^{-4} ± 64 %
	^{137}Cs	6.57917 ± 0.7 %	6.61591 ± 0.5 %	9.9008×10^{-1} ± 16 %	5.94641×10^{-1} ± 16 %
	^{137m}Ba	6.22844 ± 0.7 %	6.26233 ± 0.5 %	4.54506×10^{-3} ± 64 %	3.68004×10^{-3} ± 64 %
	^{140}Ba	5.31538 ± 1 %	5.37475 ± 2 %	9.4334×10^{-1} ± 64 %	1.51518×10^{-0} ± 23 %
	^{140}La	5.32713 ± 1 %	5.38286 ± 1.4 %	1.17572×10^{-2} ± 64 %	8.11109×10^{-3} ± 64 %
	^{144}Ce	3.67369 ± 0.7 %	3.74236 ± 1 %	1.56328×10^{-1} ± 64 %	1.06259×10^{-1} ± 64 %

[A]All yield data is given as a percentage.

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).

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.

3.1.9 *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 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 flux, 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 E 482 E 844, E 944, E 1018, E 2005, and E 2006).

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 **(35)** on the cumulative and independent fission yields of the important fission monitors. Additional fission product reactions that may provide in situ photo fission information will be added to Table 1 as information is developed and verified **(23-29, 36-39).**

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 cryostat, preamplifier and high-voltage (bias) power supply, and liquid nitrogen dewar. 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. The relative full-energy peak counting efficiency shall be about 0.1 **(1).**

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 data read out device such as a printer, teletype, or other hard copy terminal. A CRT display is extremely useful and in many cases essential for efficient operations, as are computer compatible storage devices as punch paper tape, magnetic tape, diskettes, and hard disks. A built in computerized data handling and reduction system is also useful 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 General Methods E 181 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 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 General Methods E 181 and Guide E 844. 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 appropriate, round-robin intercalibration tests such as those conducted by NBS, 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 **(24-30).**

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 **(1-7,** General Methods E 181).

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 general procedures given in General Methods E 181.

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 **(8-10).**

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 4215 (Mixed-Radionuclide Gamma Ray Emission Rate Point-Source Standard),[7] SRM 4275 (Mixed Radionuclide Point-Source Standard for the Efficiency Calibration of Gamma Spectrometer Systems),[7] and SRM 4218 (Point Source Radioactivity Standard Europium-152)[7] are examples of calibration standards which have been 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 General Methods E 181. 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

[7] Available from the National Institute of Standards and Technology, Gaithersburg, MD 20899.

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 General Methods E 181, 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 and interpretation of the data and shall be addressed more fully in separate standards **(11, 22-27),** such as those listed in Section 2.

11. Calculations

11.1 The absolute activity of the nuclide of interest in the RM at the end of irradiation is **(12-21)**:

$$D = A\, I\, S_r\, S_c\, E\, G\, P\, e^{\lambda T}\, C\, B \text{ dps} \quad (1)$$

where:

A = average observed net count rate, cps,
I = correction for absorption of radiation within the sample and the cladding if the sample is encapsulated, see General Methods E 181 and Method E 481,
S_r = correction for random coincidence summing, see General Methods E 181. (In the simplest case this may be a linear function of the gross RM count rate. This shall be determined experimentally for each detector system),
S_c = correction for true coincidence summing losses, see General Methods E 181,
E = reciprocal of the detector efficiency for the photopeak of interest and at the counting position used,
G = sample size/geometry correction,
P = reciprocal of the gammas per disintegration of the radiation of interest, and
λ = decay constant for the nuclide of interest as defined by:

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.69315}{t_{1/2}} \quad (2)$$

where:

$t_{1/2}$ = half life of the nuclide of interest,
T = time between end of irradiation and start of count,
C = correction for radioactive decay during the elapsed counting period as defined by:

$$C = \frac{\lambda t_c}{1 - e^{-\lambda t_c}} \quad (3)$$

where ${}^{t}c$ is the true elasped (clock time) counting period. For $t_c << t_{1/2}$, C approaches 1.0, and
B = correction for burn out of the nuclide of interest, see General Methods E 181, Method E 262, Method E 264, and Method E 481.

11.1.1 For ^{32}P and other beta emitters, the factor S_c is unity but the factor I must also include effects due to self scattering, backscattering, and scattering from the surroundings as well as self absorption. These corrections are discussed more fully in General Methods E 181. Normally, these corrections are minimized by proper preparation of the samples (see General Methods E 181 and Method E 265).

11.2 The saturated specific activity (A_s) of the sample may be calculated from the disintegrate rate (D) in the following manner:

$$A_s = \frac{D}{W(1 - e^{-\lambda t})} \quad (4)$$

where:

W = mass of target element, mg,
t = length of irradiation, and
$1 - e^{-\lambda t}$ = saturation factor.

11.2.1 The assumption is made in Eq 4 that the reaction rate is constant throughout the irradiation. If this is not the case, due to power variations or interruptions to the irradiation, the irradiation period may be divided into shorter time duration intervals, Δt_i, and the equivalent normalized saturated specific activity may be calculated from:

$$A_s = \frac{D}{W \sum_{i=1}^{n} R_i (1 - e^{-\lambda \Delta t i})\, e^{-\lambda (t_e - t_o)}} \text{ dps/mg} \quad (5)$$

where:

R_i = normalization factor, which may involve a time dependent spectral weighting factor, to maximum or full power for the period of Δt_i,
t_e = end time at the end of irradiation, and
t_o = time at the end of the time period Δt_i.

11.3 The reaction rate (R_s) is usually expressed in terms of reactions per target nucleus and is calculated from the saturated specific activity (A_s) and the isotopic assay data for the RM **(22)**.

$$R_s = \frac{A_s\, MS_s \cdot 10^{-3}}{NF} \quad (6)$$

where:

N = Avogadro's number,
M = gram atomic mass of the target element,
F = atom fraction of the target nuclide in RM, and
S_s = correction for neutron self shielding (see Methods E 262 and E 481) to convert to a theoretical infinitely dilute target nuclide matrix.

11.4 The absolute flux density can be calculated if the appropriate spectral averaged cross section (σ) and the fractional fission yield (Y), in the case of fissionable RM, are known. For nonfission monitors Y is 1.0.

$$\phi = \frac{R_s}{\bar{\sigma}\bar{Y}} \tag{7}$$

11.5 When benchmark referencing is utilized and the test field equivalent benchmark fluence rate is subsequently calculated and reported, a number of parameters in Eq 1 and Eq 6 may be common to both sets of measurements and are therefore self cancelling. The RM weight and its associated error may be eliminated from Eq 4 if the same RM is used for both the benchmark and test irradiations. This is satisfactory only if the RM neutron-induced activities are short lived, or a background correction is made on the second count and no appreciable burnup of the target nuclide occurs in the first irradiation. If the RM's are uniformly prepared, and the same counting system and configuration are used in both measurements the absorption (I), true summing (S_c), efficiency (E), geometry (G), and branching intensity (P) factors, along with their associated uncertainties, are again common to both measurements and would cancel from Eq 1. Eq 7 is no longer required as the test field equivalent benchmark flux reduces to a direct ratio relationship and is expressed as:

$$\phi E = \frac{A_s(T)}{A_s(B)}\phi B \tag{8}$$

where:
$A_s(T)$ and $A_s(B)$ = modified test and benchmark field saturated specific activities respectively, and
ϕB = certified benchmark flux.

12. Precision and Bias

NOTE 1—Measurement uncertainty is described by a precision and bias statement in this standard. Another acceptable approach is to use Type A and B uncertainty components (40, 41). This type A/B uncertainty specification is now used in International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

12.1 Refer to General Methods E 181, Guide E 844, the individual RM standards, Table 1, and the appropriate references appended to this standard.

13. Keywords

13.1 activity; fission monitor; monitor foil; neutron fluence; pressure vessel; radiometric monitor; reaction rate; reactor surveillance

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