



Designation: E 1005 – 03

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

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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 Dosimetry in 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, γ) ²⁴ Na	0.62356 (17) d	1368.633 2754.030	99.9936 99.855	1.00	NTR	(24-30)
²⁷ Al(n, α) 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 _{β} >=694.9	100.	0.9502 (9)	TR	E 265
⁴⁵ Sc(n, γ) 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, γ) 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, γ) 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, γ) 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 2158.77	0.24 0.00072			
⁶³ Cu(n,γ) ⁶⁴ Cu	12.700 (2) h	1345.77	0.47336	0.6917 (3)	NTR	(24-30)
⁶³ Cu(n,α) ⁶⁰ Co	1925.5 (5) d 10.467 (6) m (meta)	1173.238	99.857	0.6917 (3)	TR	E 523
		1332.502	99.983			
		58.603	2.01			
		826.33	0.0058			
		1332.501 2158.86	0.25 0.00088			
⁹³ Nb(n,n') ^{93m} Nb	5.89 (5) × 10 ³ d	30.77 16.52 (K _{α1,2})	0.000549 9.25	1.00	TR	(11, 24-30)
¹⁰³ Rh(n,n') ^{103m} Rh	56.114 (9) m	39.755	0.0684	1.00	TR	(24-30)
¹⁰⁹ Ag(n,γ) ^{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,γ) ^{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,γ) 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,γ) ¹⁹⁸ Au	2.69517 (21) d	1087.6904	0.159045	1.00	NTR	E 261, E 262 (24-30)
		675.8874	0.8038278			
		411.804	95.57			
²³² Th(n,γ) 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			
		312.17	38.6			
... ⇒ ²³³ Pa	26.967 (2) d					
FM(n,f) ¹⁴⁴ Ce	284.893 (8) d	133.515 80.120	11.09 1.36407 (see Table 2)	— ^E	NTR, TR	E 704, E 705 (24-30)
FM(n,f) ¹⁴⁰ Ba	12.752 (3) d	537.261	24.4 (see Table 2)	— ^E	NTR, TR	E 393, E 704, E 705
¹⁴⁰ Ba⇒ ¹⁴⁰ La	1.6781 (3) d	1596.21 815.772 487.021	95.4 23.2776 45.5058 (see Table 2)			(24-30)
FM(n,f) ¹³⁷ Cs	30.07 (3) y	661.660	85.1 (see Table 2)	— ^E	NTR, TR	E 320, E 704, E 705
¹³⁷ Cs⇒ ^{137m} Ba	2.552 (1) m	661.660	90.11 (see Table 2)			(24-30)
FM(n,f) ¹⁰⁶ Ru	373.59 (15) d	—	— (see Table 2)	— ^E	NTR, TR	E 704, E 705 (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→ ⁹⁵ Nb	34.997 (6) d	765.807	99.81 (see Table 2)			

^AThe 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.

^BNTR = Non-Threshold Response, TR = Threshold Response.

^CThe time units listed for half-life are years (y), days (d), hours (h), minutes (m), and seconds (s).

^DThe 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.

^EFM = 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 not identified in 1.2, including those for individual RM monitors:

2.2 *ASTM Standards*:

E 170 Terminology Relating to Radiation Measurements and Dosimetry⁴

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods⁵

E 181 General Methods for Detector Calibration and Analysis of Radionuclides⁴

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 Techniques⁴

E 262 Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques⁴

E 263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron⁴

E 264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel⁴

E 265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32⁴

E 266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum⁴

E 267 Test Method for Uranium and Plutonium Concentrations and Isotopic Abundances⁴

E 320 Test Methods for Cesium-137 in Nuclear Fuel Solutions by Radiochemical Analysis⁴

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 Dosimeters⁴

E 393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 from Fission Dosimeters⁴

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 (IC)⁴

E 523 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper⁴

E 526 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Titanium⁴

E 704 Test Method for Measuring Reaction Rates by Radioactivation of Uranium-238⁴

E 705 Test Method for Measuring Reaction Rates by Radioactivation of Neptunium-237⁴

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IC)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 Fields⁴

E 2006 Guide for the Benchmark Testing of Light Water Reactor Calculations⁴

2.3 *ANSI Standard*:

N42.14 Calibration and Usage of Germanium Detectors for Measurement of Gamma-Ray Emission Rates of Radionuclides⁶

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 Data⁴

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 %
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 %
	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 %

⁴All 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 keV⁶⁰Co 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, scalars, 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