Designation: ~~E1005 – 16~~ E1005 – 21

Standard Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance[1]

This standard is issued under the fixed designation E1005; 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 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**).

1.1.4 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~~. The following~~ 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:~~measurements.

~~E706 Master Matrix for Light-Water Reactor Pressure Vessel Surveillance Standards, E706 (O)~~ [3]

[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.

E853 Analysis and Interpretation of Light-Water Reactor Surveillance Results, E706 (IA)[3]
E693 Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E706 (ID)[3]
E185 Practice for Conducting Surveillance Tests for Light-Water Nuclear Power Reactor Vessels, E706 (IF)[3]
E1035 Practice for Determining Radiation Exposure for Nuclear Reactor Vessel Support Structures, E706 (IG)[3]
E636 Practice for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels, E706 (IH)[3]
E2956 Guide for Monitoring the Neutron Exposure of LWR Reactor Pressure Vessels[3]
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E706 (IIA)[3]
E1018 Guide for Application of ASTM Evaluated Cross Section and Data File, E706 (IIB)[3]
E482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E706 (IID)[3]
E2005 Guide for the Benchmark Testing of Reactor Vessel Dosimetry in Standard and Reference Neutron Fields
E2006 Guide for the Benchmark Testing of Light Water Reactor Calculations
E854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Vessel Surveillance, E706 (IIIB)[3]
E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E706 (IIIC)[3]
E1214 Application and Analysis of Temperature Monitors for Reactor Vessel Surveillance, E706 (IIIE) [3]

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,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 safety, health, and healthenvironmental 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.*

2. Referenced Documents

2.1 ASTM Standards (some already identified in 1.2), including those for individual RM monitors:

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

[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.

TABLE 1 Radiometric Monitors Proposed for Reactor Vessel Surveillance

Dosimetry Reactions	Residual Nucleus			Target Atom Natural Abundance[A] ~~[31]~~<u>Ref (**31**)</u>	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~~ <u>^{23}Na(n,γ)^{24}Na</u>	~~14.9574 (20) h~~ <u>14.958 (2) h</u>	~~1368.626~~ <u>1368.630 (5)</u> ~~2754.007~~ <u>2754.049 (13)</u>	~~99.9935~~ <u>99.9934 (5)</u> ~~99.872~~ <u>99.862 (3)</u>	~~1.00~~ <u>1.00</u>	~~NTR~~ <u>NTR</u>	~~(2-5, 28-31)~~ <u>(**2-5, 28-32**)</u>
~~^{27}Al(n,α)^{24}Na~~ <u>^{27}Al(n,α)^{24}Na</u>	~~14.9574 (20) h~~ <u>14.958 (2) h</u>	~~1368.626~~ <u>1368.630 (5)</u> ~~2754.007~~ <u>2754.049 (13)</u>	~~99.9935~~ <u>99.9934 (5)</u> ~~99.872~~ <u>99.862 (3)</u>	~~1.00~~ <u>1.00</u>	~~TR~~ <u>TR</u>	~~(31)E266~~ <u>(**32**) E266</u>
~~^{32}S(n,p)^{32}P~~ <u>^{32}S(n,p)^{32}P</u>	~~14.284 (14) d~~ <u>14.284 (36) d</u>	~~<E_{β}>=694.9~~ <u><E_{β}>=695.5 (3)</u>	~~100.~~ <u>100.0</u>	~~0.9502 (9)~~ <u>0.9499 (26)</u>	~~TR~~ <u>TR</u>	~~E265~~ <u>E265</u>
~~^{45}Sc(n,γ)^{46}Sc~~ <u>^{45}Sc(n,γ)^{46}Sc</u>	~~83.788 (22) d~~ <u>83.787 (16) d</u>	~~889.277~~ <u>889.271 (2)</u> ~~1120.545~~ <u>1120.537 (3)</u>	~~99.9844~~ <u>99.98374 (25)</u> ~~99.9874~~ <u>99.97 (2)</u>	~~1.00~~ <u>1.00</u>	~~NTR~~ <u>NTR</u>	~~(2-5, 28-31)~~ <u>(**2-5, 28-32**)</u>
~~^{46}Ti(n,p)^{46}Sc~~ <u>^{46}Ti(n,p)^{46}Sc</u>	~~83.788 (22) d~~ <u>83.787 (16) d</u>	~~889.277~~ <u>889.271 (2)</u> ~~1120.545~~ <u>1120.537 (3)</u>	~~99.9844~~ <u>99.98374 (25)</u> ~~99.9874~~ <u>99.97 (2)</u>	~~0.0825 (3)~~ <u>0.0825 (3)</u>	~~NTR~~ <u>NTR</u>	~~(31)E526~~ <u>(**32**) E526</u>
~~^{47}Ti(n,p)^{47}Sc~~ <u>^{47}Ti(n,p)^{47}Sc</u>	~~3.3492 (6) d~~ <u>3.3485 (9) d</u>	~~159.381~~ <u>159.373 (12)</u>	~~68.3~~ <u>68.1 (5)</u>	~~0.0744 (2)~~ <u>0.0744 (2)</u>	~~TR~~ <u>TR</u>	~~E526~~ <u>E526</u>
^{48}Ti(n,p)^{48}Sc	43.67 (9) h	983.526 <u>(12)</u> 1037.522 <u>(12)</u> 1312.120 <u>(12)</u>	100.0 <u>(3)</u> 97.5 <u>(5)</u> 100.0 <u>(5)</u>	0.7372 (3)	TR	E526
~~^{55}Mn(n,2n)^{54}Mn~~ <u>^{55}Mn(n,2n)^{54}Mn</u>	~~312.13 (3) d~~ <u>312.19 (3) d</u>	~~834.838~~ <u>834.848 (3)</u>	~~99.9758~~ <u>99.752 (5)</u>	~~1.00~~ <u>1.00</u>	~~TR~~ <u>TR</u>	~~E261, E263~~ <u>E261, E263</u> **(2-5, 28-30)**
~~^{54}Fe(n,p)^{54}Mn~~ <u>^{54}Fe(n,p)^{54}Mn</u>	~~312.13 (3) d~~ <u>312.19 (3) d</u>	~~834.838~~ <u>834.848 (3)</u>	~~99.9758~~ <u>99.752 (3)</u>	~~0.05845 (35)~~ <u>0.05845 (35)</u>	~~TR~~ <u>TR</u>	~~E263~~ <u>E263</u>
~~^{54}Fe(n,γ)^{55}Fe~~ <u>^{54}Fe(n,γ)^{55}Fe</u>	~~2.744 (9) a~~ <u>2.747 (8) a</u>	~~5.888~~ <u>5.88765</u> ~~5.899~~ <u>5.89875</u> ~~6.490~~ <u>6.49045</u>	~~8.2~~ <u>8.45 (14)</u> ~~16.2~~ <u>16.57 (27)</u> ~~2.86~~ <u>3.40 (7)</u>	~~0.05845 (35)~~ <u>0.05845 (35)</u>	~~NTR~~ <u>NTR</u>	~~(2-5, 28-30)~~ <u>(**2-5, 28-30**)</u>
~~^{56}Fe(n,p)^{56}Mn~~ <u>^{56}Fe(n,p)^{56}Mn</u>	~~2.57878 (46) h~~ <u>2.57878 (46) h</u>	~~846.764~~ <u>846.7638 (19)</u> ~~1810.73~~ <u>1810.726 (4)</u> ~~2113.09~~ <u>2113.092 (6)</u>	~~98.85~~ <u>98.85 (3)</u> ~~26.8872~~ <u>26.9 (4)</u> ~~14.2344~~ <u>14.2 (3)</u>	~~0.91754 (36)~~ <u>0.91754 (36)</u>	~~TR~~ <u>TR</u>	~~(2-5, 28-30)~~ <u>(**2-5, 28-30**)</u>
~~^{58}Fe(n,γ)^{59}Fe~~ <u>^{58}Fe(n,γ)^{59}Fe</u>	~~44.495 (9) d~~ <u>44.494 (12) d</u>	~~1099.245~~ <u>1099.245 (3)</u> ~~1291.590~~ <u>1291.590 (6)</u> ~~1481.7~~ <u>1481.70 (12)</u>	~~56.5~~ <u>56.51 (31)</u> ~~43.2~~ <u>43.23 (33)</u> ~~0.059~~ <u>0.059 (6)</u>	~~0.00282 (4)~~ <u>0.00282 (4)</u>	~~NTR~~ <u>NTR</u>	~~(2-5, 28-30)~~ <u>(**2-5, 28-30**)</u>
~~^{59}Co(n,γ)^{60}Co~~ <u>^{59}Co(n,γ)^{60}Co</u>	~~1925.28 (14) d~~ <u>5.2711 (8) a</u> 10.467 (6) min (meta)	~~1173.228~~ <u>1173.228 (3)</u> 1332.492 <u>(4)</u> 58.603 <u>(7)</u> 826.10 <u>(3)</u> 1332.492 <u>(4)</u> 2158.57 <u>(3)</u>	~~99.85~~ <u>99.85 (3)</u> 99.9826 <u>(6)</u> 2.07 <u>(3)</u> 0.00775 <u>(3)</u> 0.25 <u>(3)</u> 0.00075 <u>(3)</u>	~~1.00~~ <u>1.00</u>	~~NTR~~ <u>NTR</u>	~~E262, E481~~ <u>E262, E481</u>
~~^{58}Ni(n,p)^{58}Co~~ <u>^{58}Ni(n,p)^{58}Co</u>	~~70.86 (6) d~~ <u>70.85 (3) d</u>	~~810.7593~~ <u>810.7602 (20)</u> ~~863.951~~ <u>863.958 (6)</u> ~~1674.725~~ <u>1674.705 (6)</u>	~~99.45~~ <u>99.44 (2)</u> ~~0.69~~ <u>0.700 (22)</u> ~~0.507~~ <u>0.528 (13)</u>	~~0.68077 (9)~~ <u>0.68077 (9)</u>	~~TR~~ <u>TR</u>	~~E264~~ <u>E264</u>

TABLE 1 *Continued*

Dosimetry Reactions	Residual Nucleus Half-life^{C,A,D}	Residual Nucleus E_{γ}^{D} (keV)	Residual Nucleus Yield^{D} (%) γ/Reaction	Target Atom Natural Abundance^{A} [31]Ref (31)	Detector Response^{B}	ASTM Standard or Ref
	9.10 (9) h (meta)	24.889 (21)	0.0397 (6)			
^{60}Ni(n,p)^{60}Co	1925.28 (14) d	1173.238	99.85	0.26223 (8)	TR	(2-5, 28-30)
^{60}Ni(n,p)^{60}Co	5.2711 (8) a	1173.228 (3)	99.85 (3)	0.26223 (8)	TR	(2-5, 28-30)
		1332.492 (4)	99.9826 (6)			
	10.467 (6) m	58.603	2.07			
	10.467 (6) min (meta)	58.603 (7)	2.07 (3)			
		826.10 (3)	0.00775 (3)			
		1332.492 (4)	0.25 (3)			
		2158.57 (3)	0.00075 (3)			
^{63}Cu(n,γ)^{64}Cu	12.701 (2) h	1345.77	0.475395	0.6917 (3)	NTR	(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	1925.28 (14) d	1173.238	99.85	0.6917 (3)	TR	E523
^{63}Cu(n,α)^{60}Co	5.2711 (8) a	1173.228 (3)	99.85 (3)	0.6915 (15)	TR	E523
		1332.492 (4)	99.9826 (6)			
	10.467 (6) min (meta)	58.603 (7)	2.07 (3)			
		826.10 (3)	0.00775 (3)			
		1332.492 (4)	0.25 (3)			
		2158.57 (3)	0.00075 (3)			
^{93}Nb(n,n')^{93m}Nb	5.89 (5) × 10^{3} d	30.77	0.000591	1.00	TR	(1-5, 28-30)
^{93}Nb(n,n')^{93m}Nb	16.12 (15) a	30.77 (2)	0.000591 (9)	1.00	TR	(1-5, 28-30)
		16.52 ($K_{\alpha 1,2}$)	9.25			
^{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	0.00799	0.48161 (8)	NTR	E481
^{109}Ag(n,γ)^{110m}Ag	249.78 (2) d	116.48 (5)	0.0080 (3)	0.48161 (8)	NTR	E481
		884.6781 (13)	74.0 (12)			
		937.485 (3)	34.51 (27)			
		1384.2931	24.47			
		1384.2931 (20)	24.7 (5)			
		1505.028	13.16			
		1475.7792 (23)	4.03 (5)			
		1475.7792	4.03			
		1505.028 (2)	13.16 (16)			
^{115}In(n,γ)^{116m}In	54.29 (17) min	1293.56 (2)	84.8	0.9571 (5)	NTR	E261, E262
		1097.28 (2)	58.512			
		818.68 (2)	12.126			
		2112.19	15.094			
		2112.29 (2)	15.094			
^{115}In(n,n')^{115m}In	4.486 (4) h	336.241 (25)	45.9 (1)	0.9571 (5)	TR	(2-5, 28-30)
		497.370 (29)	0.047 (1)			
^{181}Ta(n,γ)^{182}Ta	114.74 (12) d	1121.290	35.24	0.9998799 (32)	NTR	E262
^{181}Ta(n,γ)^{182}Ta	114.61 (13) d	1121.290 (3)	35.17 (33)	0.9998799 (32)	NTR	E262
		1189.040	16.485			
		1189.040 (3)	16.58 (16)			
		1221.395	27.230			
		1221.395 (3)	27.27 (27)			
^{197}Au(n,γ)^{198}Au	2.69517 (21) d	1087.6842	0.159	1.00	NTR	E261, E262
^{197}Au(n,γ)^{198}Au	2.6943 (3) d	1087.6842 (7)	0.1591 (21)	1.00	NTR	E261, E262
		675.8836	0.806			(2-5, 28-30)
		675.8836 (7)	0.804 (5)			(2-5, 28-30)
		411.802504	95.54			
		411.80205 (17)	95.62 (6)			
^{232}Th(n,γ)^{233}Th	21.83 (4) min	890.1	0.14	1.00	NTR	(2-5, 28-30)
^{232}Th(n,γ)^{233}Th	22.15 (8) min	890.1 (5)	0.1052 (14)	1.00	NTR	(2-5, 28-30)
		490.80	0.17			
		490.80 (6)	0.1078 (16)			
		499.02	0.21			
		499.02 (4)	0.1576 (21)			
		699.901	0.68			
		764.4	0.120			
		764.55 (6)	0.0891 (13)			
. . . .→^{233}Pa	26.975 (13) d	311.904	38.5			

TABLE 1 *Continued*

Dosimetry Reactions	Residual Nucleus Half-life[C,A,D]	Residual Nucleus E_γ[D] (keV)	Residual Nucleus Yield[D] (%) γ/Reaction	Target Atom Natural Abundance[A] ~~[31]~~Ref (31)	Detector Response[B]	ASTM Standard or Ref
^{233}Th⇒^{233}Pa	26.98 (2) d	311.904 (5)	38.3 (5)			
~~FM(n,f)^{144}Ce~~ FM(n,f)^{144}Ce	~~284.91 (5) d~~ 284.89 (6) d	~~133.515~~ 133.5152 (20) ~~80.120~~ 80.120 (4)	~~11.09~~ 10.83 (12) ~~1.36407~~ 1.40 (5) (see Table 2)	—[E] —[E]	~~NTR, TR~~ NTR, TR	~~E704, E705~~ E704, E705 ~~(2-5, 28-30)~~ (2-5, 28-30)
~~FM(n,f)^{140}Ba~~ FM(n,f)^{140}Ba	~~12.7527 (23) d~~ 12.753 (5) d	~~537.261~~ 537.261 (25)	~~24.439~~ 24.6 (5) (see Table 2)	—[E] —[E]	~~NTR, TR~~ NTR, TR	~~E393, E704,~~ E393, E704, E705
~~^{140}Ba⇒^{140}La~~ ^{140}Ba⇒^{140}La	~~1.67855 (12) d~~ 1.67858 (21) d	~~1596.21~~ 1596.203 (13) ~~815.772~~ 815.784 (6) ~~487.021~~ 487.022 (6)	~~95.4~~ 95.40 (5) ~~23.2776~~ 23.72 (20) ~~45.5058~~ 46.1 (5) (see Table 2)			~~(2-5, 28-30)~~ (2-5, 28-30)
FM(n,f)^{137}Cs	30.05 (8) a	661.657 (3)	84.99 (20) (see Table 2)	—[E]	NTR, TR	E704, E705
~~^{137}Cs⇒^{137m}Ba~~ ^{137}Cs⇒^{137m}Ba	~~2.552 (1) min~~ 2.552 (1) min	~~661.657~~ 661.657 (3)	~~89.90~~ 90.07 (20) (see Table 2)			~~(2-5, 28-30)~~ (2-5, 28-30)
~~FM(n,f)^{106}Ru~~ FM(n,f)^{106}Ru	~~371.8 (18) d~~ 371.5 (21) d	~~—~~ —	~~—~~ — (see Table 2)	—[E] —[E]	~~NTR, TR~~ NTR, TR	~~E704, E705~~ E704, E705 (2-5, 28-30)
~~^{106}Ru⇒^{106}Rh~~ ^{106}Ru⇒^{106}Rh	~~30.07 (35) s~~ 30.1 (3) s	~~511.8605~~ 511.8534 (23)	~~20.4~~ 20.52 (23) (see Table 2)			
~~FM(n,f)^{103}Ru~~ FM(n,f)^{103}Ru	~~39.26 (2) d~~ 39.247 (13) d	~~497.085~~ 497.085 (10)	~~91.0~~ 91.0 (see Table 2)	—[E] —[E]	~~NTR, TR~~ NTR, TR	~~E704, E705~~ E704, E705 (2-5, 28-30)
~~FM(n,f)^{95}Zr~~ FM(n,f)^{95}Zr	~~64.032 (6) d~~ 64.032 (6) d	~~756.725~~ 756.729 (12) ~~724.192~~ 724.193 (3)	~~54.38~~ 54.38 (22) ~~44.27~~ 44.27 (22) (see Table 2)	—[E] —[E]	~~NTR, TR~~ NTR, TR	~~E704, E705~~ E704, E705 ~~(2-5, 28-30)~~ (2-5, 28-30)
^{95}Zr⇒^{95}Nb	34.991 (6) d	765.803 (6)	99.808 (7) (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 (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 (~~31~~32).
[D] The nuclear data has been drawn from several primary sources including Refs (~~31-~~32-~~34~~35). Reference (~~35~~36) summarizes the source of the selected nuclear constants, last checked for consistency on March 19, 2014.
[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.

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 *~~ANSI~~IEEE/ANSI Standard:*
N42.14 Calibration and ~~Usage~~Use of Germanium ~~Detectors~~Spectrometers for Measurement of Gamma-Ray Emission Rates of Radionuclides[4]

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.

3.1.9 *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.

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

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 (~~36~~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, ~~37-~~38-~~40~~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 crystostat. 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.