~~Designation:E 844–86 (Reapproved 1991)~~ Designation: E844 – 09

Standard Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[1]

This standard is issued under the fixed designation E844; 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 guide covers the selection, design, irradiation, post-irradiation handling, and quality control of neutron dosimeters (sensors), thermal neutron shields, and capsules for reactor surveillance neutron dosimetry.

1.2 The values stated in ~~inch-pound~~SI units are to be regarded as ~~the~~ standard. ~~The values given~~Values in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E261 Practice for Determining Neutron Fluence, Fluence Rate, ~~Fluence,~~ and Spectra by Radioactivation Techniques

E854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance, ~~E 706(IIB)~~[2]E706(IIIB)

E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, ~~E 706(IIC)~~[2]E706 (IIIC)

E1005 ~~Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance, E 706(IIIA)~~[2] Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance, E 706 (IIIA)

E1018 Guide for Application of ASTM Evaluated Cross Section Data File, Matrix E706 (IIB)

E706(IIID)~~Analysis of Damage Monitors for Reactor Vessel Surveillance~~ 1214 Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance, E 706 (IIIE)

E706(IIIE)~~Analysis of Temperature Monitors for Reactor Vessel Surveillance~~[3] 2005 Guide for Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields

E706(IIE)~~Benchmark Testing of Reactor Vessel Dosimetry~~[3] 2006 Guide for Benchmark Testing of Light Water Reactor Calculations

3. Terminology ~~Definitions~~

3.1 *Definitions:*

3.1.1 *neutron dosimeter, sensor, monitor*—a substance irradiated in a neutron environment for the determination of neutron fluence rate, fluence, or spectrum, for example: radiometric monitor (RM), solid state track recorder (SSTR), helium accumulation fluence monitor (HAFM), damage monitor (DM), temperature monitor (TM).

3.1.2 *thermal neutron shield*—a substance (that is, cadmium, boron, gadolinium) that filters or absorbs thermal neutrons.

~~3.3For~~3.2 For definitions or other terms used in this guide, refer to Terminology ~~E 170~~E170.

4. Significance and Use

4.1 In neutron dosimetry, a fission or non-fission dosimeter, or combination of dosimeters, can be used for determining a fluence-rate, fluence, or neutron spectrum, or both, in nuclear reactors. Each dosimeter is sensitive to a specific energy range, and,

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[1] This guide is under the jurisdiction of ASTM Committee ~~E-10~~ E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

~~Current edition approved Oct. 31, 1986. Published December 1986. Originally published as E 844–81. Last previous edition E 844–81[ε2].~~

Current edition approved June 1, 2009. Published June 2009. Originally approved in 1981. Last previous edition approved in 2003 as E844 – 03. DOI: 10.1520/E0844-09.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* ~~, Vol 12.02.~~volume information, refer to the standard's Document Summary page on the ASTM website.

if desired, increased accuracy in a flu~~x~~ence-rate spectrum can be achieved by the use of several dosimeters each covering specific neutron energy ranges.

4.2 A wide variety of detector materials is used for various purposes. Many of these substances overlap in the energy of the neutrons which they will detect, but many different materials are used for a variety of reasons. These reasons include available analysis equipment, different cross sections for different ~~flux~~fluence-rate levels and spectra, preferred chemical or physical properties, and, in the case of radiometric dosimeters, varying requirements for different half-life isotopes, possible interfering activities, and chemical separation requirements.

5. Selection of Neutron Dosimeters and Thermal Neutron Shields

5.1 *Neutron Dosimeters*:

5.1.1 The choice of dosimeter material depends largely on the dosimetry technique employed, for example, radiometric monitors, helium accumulation monitors, track recorders, and damage monitors. At the present time, there is a wide variety of detector materials used to perform neutron dosimetry measurements. These are generally in the form of foils, wires, powders, and salts. The use of alloys is valuable for certain applications such as (*1*) dilution of high cross-section elements, (*2*) preparation of elements that are not readily available as foils or wires in the pure state, and (*3*) preparation to permit analysis of more than one dosimeter material.

5.1.2 For neutron dosimeters, the reaction rates are usually deduced from the absolute gamma-ray radioanalysis (there exist exceptions, such as SSTRs, HAFMs, damage monitors). Therefore, the radiometric dosimeters selected must have gamma-ray yields known with good accuracy (>98 %). The half-life of the product nuclide must be long enough to allow for time differences between the end of the irradiation and the subsequent counting. Refer to Method ~~E 1005~~E1005 for nuclear decay and half-life parameters.

5.1.3 The neutron dosimeters should be sized to permit accurate analysis. The range of high efficiency counting equipment over which accurate measurements can be performed is restricted to several decades of activity levels (5 to 7 decades for radiometric and SSTR dosimeters, 8 decades for HAFMs). Since flux levels at dosimeter locations can range over 2 or 3 decades in a given experiment and over 10 decades between low power and high power experiments, the proper sizing of dosimeter materials is essential to assure accurate and economical analysis.

5.1.4 The estimate of radiometric dosimeter activity levels at the time of counting include adjustments for the decay of the product nuclide after irradiation as well as the rate of product nuclide buildup during irradiation. The applicable equation for such calculations is (in the absence of ~~flux~~fluence-rate perturbations) as follows:

~~$$A = N_o \bar{\sigma} \phi \alpha (1 - e^{-\lambda t_1})(e^{-\lambda t_2}) \quad (1)$$~~

$$A = N_o \bar{\sigma} \phi \alpha (1 - e^{-\lambda t_1})(e^{-\lambda t_2}) \quad (1)$$

E0844-09_1

where:

A = expected disintegration rate (dps) for the product nuclide at the time of counting,
N_o = number of target element atoms,
φ = estimated flux density level, $\bar{\sigma}$
$\bar{\sigma}$ = spectral averaged cross section,
α = product of the nuclide fraction and (if applicable) of the fission yield,
~~$1 - e^{-\lambda t_1}$~~ = buildup of the nuclide during the irradiation period, t_1,
$e^{-\lambda t_1}$ = decay after irradiation to the time of counting, t_2, and
$e^{-\lambda t_2}$ = decay constant for the product nuclide.

5.1.5 For SSTRs and HAFMs, the same type of information as for radiometric monitors (that is, total number of reactions) is provided. The difference being that the end products (fission tracks or helium) requires no time-dependent corrections and are therefore particularly valuable for long-term irradiations.

5.1.6 Fission detectors shall be chosen that have accurately known fission yields. Refer to Method ~~E 1005~~E1005.

5.1.7 In thermal reactors the correction for neutron self shielding can be appreciable for dosimeters that have highly absorbing resonances (see 6.1.1).

5.1.8 Dosimeters that produce activation or fission products (that are utilized for reaction rate determinations) with half-lives that are short compared to the irradiation duration should not be used. Generally, radionuclides with half-lives less than three times the irradiation duration should be avoided unless there is little or no change in neutron spectral shape or fluence rate with time.

5.1.9 Tables 1-3 ~~present various dosimeter elements. Listed are the element of interest, the nuclear reaction, and the available forms. For the intermediate energy region, the energies of the principal resonances are listed in order of increasing energy. In the case of the fast neutron energy region, the 90% response ranges (that is, energies between which 90% of the activity is produced) for a U-235 neutron spectrum are included.~~ present various dosimeter elements. Listed are the element of interest, the nuclear reaction, and the available forms. For the intermediate energy region, the energies of the principal resonances are listed in order of increasing energy. In the case of the fast neutron energy region, the 95 % response ranges (an energy range that includes most

TABLE 1 Dosimeter Elements—Thermal Neutron Region

Element of Interest	Nuclear Reaction	Available Forms
B	$^{10}B(n,\alpha)^{7}Li$	B, B_4C, B-Al, B-Nb
Co	$^{59}Co(n,\gamma)^{60}Co$	Co, Co-Al, Co-Zr
Cu	$^{63}Cu(n,\gamma)^{64}Cu$	Cu, Cu-Al, $Cu(NO_3)_2$
Au	$^{197}Au(n,\gamma)^{198}Au$	Au, Au-Al
In	$^{115}In(n,\gamma)^{116m}In$	In, In-Al
Fe	$^{58}Fe(n,\gamma)^{59}Fe$	Fe
Fe	$^{54}Fe(n,\gamma)^{55}Fe$	Fe
Li	$^{6}Li(n,\alpha)^{3}H$	LiF, Li-Al
Mn	$^{55}Mn(n,\gamma)^{56}Mn$	alloys
Ni	$^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$	Ni
Pu	$^{239}Pu(n,f)FP$	PuO_2, alloys
Sc	$^{45}Sc(n,\gamma)^{46}Sc$	Sc, Sc_2O_3
Ag	$^{109}Ag(n,\gamma)^{110m}Ag$	Ag, Ag-Al, $AgNO_3$
Na	$^{23}Na(n,\gamma)^{24}Na$	NaCl, NaF, NaI
Ta	$^{181}Ta(n,\gamma)^{182}Ta$	Ta, Ta_2O_5
U (enriched)	$^{235}U(n,f)FP$	U, U-Al, UO_2, U_3O_8, alloys

TABLE 2 Dosimeter Elements—Intermediate Neutron Region

Energy of Principal Resonance, eV (17)	~~Ele~~Dosi~~ment of Inter~~y Resactions	~~Nue~~Elear R~~meaenti~~ of Interest	Available Forms
~~...~~	~~$^{6}Li(n,\alpha)^{3}H$~~		~~LiF, Li-Al~~
[A]	$^{6}Li(n,\alpha)^{3}H$	Li	LiF, Li-Al
~~...~~	~~$^{10}B(n,\alpha)^{7}Li$~~		~~B, B_4C, B-Al, B-Nb~~
[A]	$^{10}B(n,\alpha)^{7}Li$	B	B, B_4C, B-Al, B-Nb
~~...~~	~~$^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$~~	~~Ni~~	~~1.46Ni~~
[A]	$^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$	Ni	Ni
~~In~~	~~$^{115}In(n,\gamma)^{116m}In$~~		~~In, In-Al~~
1.457	$^{115}In(n,\gamma)^{116m}In$	In	In, In-Al
~~4.28~~	~~$^{181}Ta(n,\gamma)^{182}Ta$~~		~~Ta, Ta_2O_5~~
4.28	$^{181}Ta(n,\gamma)^{182}Ta$	Ta	Ta, Ta_2O_5
~~4.91~~	~~$^{197}Au(n,\gamma)^{198}Au$~~		~~Au, Au-Al~~
4.906	$^{197}Au(n,\gamma)^{198}Au$	Au	Au, Au-Al
~~5.20~~	~~$^{109}Ag(n,\gamma)^{110m}Ag$~~		~~Ag, Ag-Al, $AgNO_3$~~
5.19	$^{109}Ag(n,\gamma)^{110m}Ag$	Ag	Ag, Ag-Al, $AgNO_3$
~~24~~	~~$^{232}Th(n,\gamma)^{233}Th$~~		~~Th, ThO_2, $Th(NO_3)_4$~~
21.806	$^{232}Th(n,\gamma)^{233}Th$	Th	Th, ThO_2, $Th(NO_3)_4$
~~1–100~~	~~U (enriched)~~ ~~$^{235}U(n,f)FP$~~		~~U, U-Al, UO_2, U_3O_8, alloys~~
[B]	$^{235}U(n,f)FP$	U	U, U-Al, UO_2, U_3O_8, alloys
~~132~~	~~$^{59}Co(n,\gamma)^{60}Co$~~		~~Co, Co-Al, Co-Zr~~
132	$^{59}Co(n,\gamma)^{60}Co$	Co	Co, Co-Al, Co-Zr
~~220, 340~~	~~$^{58}Fe(n,\gamma)^{59}Fe$~~	~~Fe~~	~~337Fe~~
1038	$^{58}Fe(n,\gamma)^{59}Fe$	Fe	Fe
~~Mn~~	~~$^{55}Mn(n,\gamma)^{56}Mn$~~		~~alloys~~
337.3	$^{55}Mn(n,\gamma)^{56}Mn$	Mn	alloys
~~577~~	~~$^{63}Cu(n,\gamma)^{64}Cu$~~		~~Cu, Cu-Al, $Cu(NO_3)_2$~~
579	$^{63}Cu(n,\gamma)^{64}Cu$	Cu	Cu, Cu-Al, $Cu(NO_3)_2$
~~1000~~	~~$^{239}Pu(n,f)FP$~~		~~PuO_2, alloys~~
0.2956243	$^{239}Pu(n,f)FP$	Pu	PuO_2, alloys
~~2800~~	~~$^{23}Na(n,\gamma)^{24}Na$~~		~~NaCl, NaF, NaI~~
2810	$^{23}Na(n,\gamma)^{24}Na$	Na	NaCl, NaF, NaI
~~3700~~	~~$^{45}Sc(n,\gamma)^{46}Sc$~~		~~Sc, Sc_2O_3~~
3295	$^{45}Sc(n,\gamma)^{46}Sc$	Sc	Sc, Sc_2O_3
~~Fe~~	~~$^{54}Fe(n,\gamma)^{55}Fe$~~	~~Fe~~	~~Fe~~
7788	$^{54}Fe(n,\gamma)^{55}Fe$	Fe	Fe

[A] This reaction has no resonance that contributes in the intermediate energy region and the principle resonance has negative energy (i.e. the cross section is 1/v).
[B] Many resonances contribute in the 1 – 100 eV region for this reaction.

of the response for each dosimeter is specified by giving the energies E_{05} below which 5 % of the activity is produced and E_{95} above which 5 % of the activity is produced) for the ^{235}U neutron thermal fission spectrum are included.

5.2 *Thermal Neutron Shields*:

5.2.1 Shield materials are frequently used to eliminate interference from thermal neutron reactions when resonance and fast neutron reactions are being studied. Cadmium is commonly used as a thermal neutron shield, generally ~~0.020~~0.51 to ~~0.050 in. (0.51~~1.27 mm (0.020 to ~~1.27 mm)~~0.050 in.) thick. However, because elemental cadmium (m.p. = 320°C) will melt if placed within the vessel of an operating water reactor, effective thermal neutron filters must be chosen that will withstand high temperatures of light-water reactors. High-temperature filters include cadmium oxide (or other cadmium compounds or mixtures), boron (enriched in the ^{10}B isotope), and gadolinium. The ~~thicknesses~~thickness of the shield material must be selected to account for burnout from high fluences.

TABLE 3 Dosimeter Elements—Fast Neutron Region

90 % Response Rans	Element of Interest		Energe^A (MeV) (17)			^B	Elementof Int ertainty (%)	Available st	
	Nuclear Reaction	Available Forms	Dosimetry Reactions	Element of Interest		Energy Response Range (MeV)^A (MeV) (17)			
Low E_{05}	Median E_{50}	High E_{95}							
0.67–5.7	Np	^{237}Np(n,f)FP		Np	0.684	1.96	5.61	9.34	Np_2O
	Rh	^{103}Rh(n,n′)^{103m}Rh		Rh		Nb	5.73	3.10	
	Rh	^{103}Rh(n,n′)^{103m}Rh		Rh	0.731	2.25	5.73	3.10	
^{93}Nb(n,n′)^{93m}Nb		Nb	0.951	2.57	5.79	3.01	Nb, Nb_2O_5		
1.16–5.9	In	^{115}In(n,n′)^{115m}In		In, In-Al					
	1.4–4.8^B	N	5.86	2.16	In, In-Al				
	1.12	2.55	5.86	2.16	In, In-Al				
^{14}N(n,α)^{11}B		TiN, ZrN, NbN							
^{14}N(n,α)^{11}B		N, ZrN, NbN							
	1.510–6.7	U (depleted)	5.86	—	TiN, ZrN, NbN				
	1.75	3.39	5.86	—	TiN, ZrN, NbN				
^{238}U(n,f)FP		U (depleted)	1.44	2.61	6.69	0.319	U, U-Al, UO_3, U_3O_8, alloys		
1.518–7.2	Th	^{232}Th(n,f)FP		Th	1.45	2.79	7.21	5.11	Th
1.6–6.7^B	Be	^{9}Be(n,α)^{6}Li		Be	1.87–7.5	Ti	5.26	—	
^B	Be	^{9}Be(n,α)^{6}Li		Be	1.59	2.83	5.26	—	
^{47}Ti(n,p)^{47}Sc		Ti	2.09–7.6	Ni	7.67	3.77	Ti		
^{47}Ti(n,p)^{47}Sc		Ti	1.70	3.63	7.67	3.77	Ti		
^{58}Ni(n,p)^{58}Co		Ni, Ni-Al							
	2.47–7.8	Fe	7.51	2.44	Ni, Ni-Al				
	1.98	3.94	7.51	2.44	Ni, Ni-Al				
^{54}Fe(n,p)^{54}Mn		Fe	2.29–7.4	S	7.54	2.12	Fe		
^{54}Fe(n,p)^{54}Mn		Fe	2.27	4.09	7.54	2.12	Fe		
^{32}S(n,p)^{32}P		S	2.28	3.94	7.33	3.63	$CaSO_4$, Li_2SO_4		
	S	^{32}S(n,α)^{29}Si		S	1.65	3.12	6.06	—	Cu
	Ni	^{58}Ni(n,α)^{55}Fe		Ni, Ni-Al					
	3.86–9.4	Ti	8.72	—	Ni, Ni-Al				
	2.74	5.16	8.72	—	Ni, Ni-Al				
^{46}Ti(n,p)^{46}Sc		Ti	5.44–11	Fe^C	9.43	2.48	Ti		
^{46}Ti(n,p)^{46}Sc		Ti	3.70	5.72	9.43	2.48	Ti		
^{56}Fe(n,p)^{56}Mn		Fe 5.1–11.3^B	Fe	7.27	11.3	2.26	Fe		
^{56}Fe(n,p)^{56}Mn		Fe^D	5.45	7.27	11.3	2.26	Fe		
^{56}Fe(n,α)^{53}Cr		Fe	6.13–11	Cu^D	11.3	—	Fe		
^{56}Fe(n,α)^{53}Cr		Fe	5.19	7.53	11.3	—	Fe		
^{63}Cu(n,α)^{60}Co		Cu, Cu-Al							
^E	6.5–12	Al	11.0	2.36	Cu, Cu-Al				
^E	4.53	6.99	11.0	2.36	Cu, Cu-Al				
^{27}Al(n,α)^{24}Na		Al	6.45	8.40	11.9	1.19	Al, Al_2O_3		
5.7–13	Ti	^{48}Ti(n,p)^{48}Sc		Ti		Ti	12.3	2.56	
5.7–13	Ti	^{48}Ti(n,p)^{48}Sc		Ti	5.92	8.06	12.3	2.56	
^{47}Ti(n,α)^{44}Ca		Ti	4.81–11	Ni^D	9.12	—	Ti		
^{47}Ti(n,α)^{44}Ca		Ti	2.80	5.10	9.12	—	Ti		
^{60}Ni(n,p)^{60}Co	Ni, Ni-Al								
11.0–16	Mn^E	4.72	6.82	10.8	10.3	Ni, Ni-Al			
11.0–16	Ni^E	4.72	6.82	10.8	10.3	Ni, Ni-Al			
^{55}Mn(n,2n)^{54}Mn		Mn^F	11.0	12.6	15.8	13.54	alloys		

^A Energiy res bponsetwee range which 90% ofactivity is p dereived uesing thed (ENDF/B-VI^{235}U fission spectrum, Ref **(1)**, MT = 9228, MF = 5, MT = 18. The cross section and associated covariance sources are identified in Guide E1018 and in Refs **(2**^{3}**5U fission spectrum3)**.

^B ROne half of the detector response occurs below an energy given by E_{50}; 95 % of the detector HAFM response occurs below E_{95} and 5 % below E_{05}.

^C Low maUngcertainty mesetric only reflects that component due to the knowleedge of the cross section and is ryeported at the 1σ level.

^D Low cob maltnganese content necessary.

^E Low cobalt content necessary.

^F Low iron content necessary.

5.2.2 In reactors, feasible dosimeters to date whose response range to neutron energies of 1 to 3 MeV includes the fission monitors ^{238}U, ^{237}Np, and ^{232}Th. These particular dosimeters must be shielded from thermal neutrons to reduce fission product production from trace quantities of ^{235}U, ^{238}Pu, and ^{239}Pu and to suppress buildup of interfering fissionable nuclides, for example,^{238}Np and ^{238}Pu in the ^{237}Np dosimeter,^{239}Pu in the ^{238}U dosimeter, and ^{233}U in the ^{232}Th dosimeter. Thermal neutron shields are also necessary for epithermal spectrum measurements in the 5×10^{-7} to 0.3-MeV energy range. Also, nickel dosimeters used for the fast activation reaction ^{58}Ni(n,p)^{58}Co must be shielded from thermal neutrons in nuclear environments having thermal fluence rates above 3×10^{12} n·cm^{-2}·s^{-1} to prevent significant loss of ^{58}Co and ^{58m}Co by thermal neutron burnout (**14**).[3]

[3] For standards that are in the draft stage and have not received an ASTM designation, see Section 5 as well as Figures 1 and 2 of Matrix E 706E 706(IIID).

[3] The boldface number in parentheses refers to the list of references at the end of the guide.