INTERNATIONAL

Designation: ~~E844 – 09 (Reapproved 2014)$^{\varepsilon 2}$~~ E844 – 18

Standard Guide for Sensor Set Design and Irradiation for Reactor Surveillance[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.

~~ε^1 NOTE—Figures 1 and 2 were updated and editorial changes were made in September 2014.~~
~~ε^2 NOTE—The title and Referenced Documents were udpated in May 2017.~~

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 SI units are to be regarded as standard. Values in parentheses are for information only.

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

1.4 *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:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry
E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance
E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance
E1005 Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance
E1018 Guide for Application of ASTM Evaluated Cross Section Data File
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

3. Terminology

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.

3.2 For definitions or other terms used in this guide, refer to Terminology 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 in nuclear reactors. Each dosimeter is sensitive to a specific energy range, and, if desired, increased accuracy in a fluence-rate spectrum can be achieved by the use of several dosimeters each covering specific neutron energy ranges.

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

Current edition approved ~~June 1, 2014~~June 1, 2018. Published ~~July 2014~~July 2018. Originally approved in 1981. Last previous edition approved in ~~2009~~2014 as ~~E844 – 09.~~E844 – 09(2014)$^{\varepsilon 2}$. DOI: ~~10.1520/E0844-09R14E02.~~10.1520/E0844-18.

[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* volume information, refer to the standard's Document Summary page on the ASTM website.

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 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 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 fluence-rate 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 fluence-rate ~~perturbations)~~variations) as follows:

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

where:

A = expected disintegration rate (dps) for the product nuclide at the time of counting,
N_o = number of target element atoms,
~~φ = estimated fluence-rate density level,~~
φ = estimated fluence rate,
$\bar{\sigma}$ = 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,~~
$(1 - e^{-\lambda t_1})$ = buildup of the nuclide during the irradiation period, t_1,
$e^{-\lambda t_2}$ = decay after irradiation to the time of counting, t_2, and
λ = decay constant for the product nuclide.

5.1.5 Eq 1 should not be used for the analysis of dosimetry measurements unless it is known that the fluence rate was approximately constant over the duration of the irradiation, or that the total duration of the irradiation was short compared to the half life of the product nuclide.

5.1.6 If the fluence rate during the irradiation period is variable, a valid monitor of the fluence rate variation at the dosimeter location is essential. The validity of the fluence rate monitoring method should be demonstrated by transport calculations or other evidence.

5.1.7 When the requirements of 5.1.6 are met, then the total irradiation period can be divided into a continuous series of periods during each of which φ is essentially constant. Equations that replace Eq 1 for this case are given in Practice E261.

5.1.8 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.

5.1.9 Fission detectors shall be chosen that have accurately known fission yields. Refer to Method E1005.

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

5.1.11 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.

5.1.12 Dosimeters with half-lives as short as one third of the irradiation duration have been used in power reactor surveillance when the power history in nearby reactor channels was available in accordance with 5.1.6 and 5.1.7.

5.1.13 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 95 % response ranges (an energy range that includes most 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 0.51 to 1.27 mm (0.020 to 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 thickness of the shield material must be selected to account for burnout from high fluences.

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 (**4**).[3]

6. Design of Neutron Dosimeters, Thermal Neutron Shields, and Capsules

6.1 *Neutron Dosimeters*—Procedures for handling dosimeter materials during preparation must be developed to ensure personnel safety and accurate nuclear environment characterization. During dosimeter fabrication, care must be taken in order to achieve desired neutron fluence-rate results, especially in the case of thermal and resonance-region dosimeters. A number of factors must be considered in the design of a dosimetry set for each particular application. Some of the principal ones are discussed individually as follows:

6.1.1 *Self-Shielding of Neutrons*—The neutron self-shielding phenomenon occurs when high cross-section atoms in the outer layers of a dosimeter reduce the neutron fluence rate to the point where it significantly affects the activation of the inner atoms of the material. This is especially true of materials with high thermal cross sections and essentially all resonance detectors. This can be minimized by using low weight percentage alloys of high-cross-section material, for example, Co-Al, Ag-Al, B-Al, Li-Al. It is not as significant for the fast region where the cross sections are relatively low; therefore, thermal and resonance detectors shall be as thin as possible. Mathematical corrections can also be made to bring the material to "zero thickness" but, in general, the smaller the correction, the more accurate will be the results. Both theoretical treatments of the complex corrections and experimental determinations are published (**5-17**).

6.1.2 *Self-Absorption of Emitted Radiation*—This effect may be observed during counting of the radiometric dosimeter. If the radiation of interest is a low-energy gamma ray, an X ray, or a beta particle, the thickness of the dosimeter may be of appreciable significance as a radiation absorber (especially for higher atomic number materials). This will lower the counting rate, which would then have to be adjusted in a manner similar to that for the "zero thickness" correction in the case of self-shielding. Therefore, it

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

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

TABLE 2 Dosimeter Elements—Intermediate Neutron Region

Energy of Principal Resonance, eV (17)	Dosimetry Reactions	Element of Interest	Available Forms
[A]	$^{6}Li(n,\alpha)^{3}H$	Li	LiF, Li-Al
[A]	$^{10}B(n,\alpha)^{7}Li$	B	B, B_4C, B-Al, B-Nb
[A]	$^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$	Ni	Ni
1.457	$^{115}In(n,\gamma)^{116m}In$	In	In, In-Al
4.28	$^{181}Ta(n,\gamma)^{182}Ta$	Ta	Ta, Ta_2O_5
4.906	$^{197}Au(n,\gamma)^{198}Au$	Au	Au, Au-Al
5.19	$^{109}Ag(n,\gamma)^{110m}Ag$	Ag	Ag, Ag-Al, $AgNO_3$
21.806	$^{232}Th(n,\gamma)^{233}Th$	Th	Th, ThO_2, $Th(NO_3)_4$
[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, Co-Al, Co-Zr
1038	$^{58}Fe(n,\gamma)^{59}Fe$	Fe	Fe
337.3	$^{55}Mn(n,\gamma)^{56}Mn$	Mn	alloys
579	$^{63}Cu(n,\gamma)^{64}Cu$	Cu	Cu, Cu-Al, $Cu(NO_3)_2$
0.2956243	$^{239}Pu(n,f)FP$	Pu	PuO_2, alloys
2810	$^{23}Na(n,\gamma)^{24}Na$	Na	NaCl, NaF, NaI
3295	$^{45}Sc(n,\gamma)^{46}Sc$	Sc	Sc, Sc_2O_3
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.

TABLE 3 Dosimeter Elements—Fast Neutron Region

Dosimetry Reactions	Element of Interest	Energy Response Range (MeV)[A,B]			Cross Section Uncertainty (%)[A,C]	Available Forms
		Low E_{05}	Median E_{50}	High E_{95}		
$^{237}Np(n,f)FP$	Np	0.684	1.96	5.61	9.34	Np_2O_3, alloys
$^{103}Rh(n,n')^{103m}Rh$	Rh	0.731	2.25	5.73	3.10	Rh
$^{93}Nb(n,n')^{93m}Nb$	Nb	0.951	2.57	5.79	3.01	Nb, Nb_2O_5
$^{115}In(n,n')^{115m}In$	In	1.12	2.55	5.86	2.16	In, In-Al
$^{14}N(n,\alpha)^{11}B$	N	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
$^{232}Th(n,f)FP$	Th	1.45	2.79	7.21	5.11	Th, ThO_2
$^{9}Be(n,\alpha)^{6}Li$	Be	1.59	2.83	5.26	—	Be
$^{47}Ti(n,p)^{47}Sc$	Ti	1.70	3.63	7.67	3.77	Ti
$^{58}Ni(n,p)^{58}Co$	Ni	1.98	3.94	7.51	2.44	Ni, Ni-Al
$^{54}Fe(n,p)^{54}Mn$	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
$^{32}S(n,\alpha)^{29}Si$	S	1.65	3.12	6.06	—	Cu_2S, PbS
$^{58}Ni(n,\alpha)^{55}Fe$	Ni	2.74	5.16	8.72	—	Ni, Ni-Al
$^{46}Ti(n,p)^{46}Sc$	Ti	3.70	5.72	9.43	2.48	Ti
$^{56}Fe(n,p)^{56}Mn$	Fe[D]	5.45	7.27	11.3	2.26	Fe
$^{56}Fe(n,\alpha)^{53}Cr$	Fe	5.19	7.53	11.3	—	Fe
$^{63}Cu(n,\alpha)^{60}Co$	Cu[E]	4.53	6.99	11.0	2.36	Cu, Cu-Al
$^{27}Al(n,\alpha)^{24}Na$	Al	6.45	8.40	11.9	1.19	Al, Al_2O_3
$^{48}Ti(n,p)^{48}Sc$	Ti	5.92	8.06	12.3	2.56	Ti
$^{47}Ti(n,\alpha)^{44}Ca$	Ti	2.80	5.10	9.12	—	Ti
$^{60}Ni(n,p)^{60}Co$	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] Energy response range was derived using the 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)**.
[B] One half of the detector response occurs below an energy given by E_{50}; 95 % of the detector response occurs below E_{95} and 5 % below E_{05}.
[C] Uncertainty metric only reflects that component due to the knowledge of the cross section and is reported at the 1σ level.
[D] Low manganese content necessary.
[E] Low cobalt content necessary.
[F] Low iron content necessary.

would again be desirable to use thin dosimeters in cases where the count rate is affected by dosimeter thickness. In the case of thick pellets, it is usually possible to perform chemical separation of the radionuclide.

6.1.3 *Fission Fragment Loss*—It has been observed that fission foils of 0.0254-mm (0.001-in.) thickness lose a significant fraction (approximately 7 %) of the fission fragments. Increasing the thickness to 0.127 mm (0.005 in.) will reduce this loss to about 1 %.

6.1.4 *Dosimeter Size:*

6.1.4.1 The size of dosimeters and dosimetry sets is often limited by space available, especially in reactor applications where volume in high fluence-rate regions is very limited and in great demand for experimental samples. This fact, coupled with the desirability of minimizing perturbations to the reactor environment due to the presence of the dosimetry set, of minimizing self-shielding corrections, and of minimizing corrections to obtain reaction rates at a common point in space, creates the need for miniaturized dosimeters.