Designation: D 5411 – 93 (Reapproved 1999)

Standard Practice for Calculation of Average Energy Per Disintegration ($\bar{E}$) for a Mixture of Radionuclides in Reactor Coolant[1]

This standard is issued under the fixed designation D 5411; 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 practice applies to the calculation of the average energy per disintegration ($\bar{E}$) for a mixture of radionuclides in reactor coolant water.

1.2 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1066 Practice for Sampling Steam[2]

D 1129 Terminology Relating to Water[2]

D 3370 Practices for Sampling Water from Closed Conduits[2]

D 3648 Practices for the Measurement of Radioactivity[3]

2.2 *Code of Federal Regulations:*

10 CFR 100 Reactor Cite Criteria[4]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this practice, refer to Terminology D 1129.

4. Summary of Practice

4.1 The average energy per disintegration, $\bar{E}$ (pronounced *E bar*), for a mixture of radionuclides is calculated from the known composition of the mixture. $\bar{E}$ is computed by calculating the total beta/gamma energy release rate, in MeV, and dividing it by the total disintegration rate. The resultant $\bar{E}$ has units of MeV per disintegration.

5. Significance and Use

5.1 This practice is useful for the determination of the average energy per disintegration of the isotopic mixture found in the coolant of a nuclear reactor **(1)**.[5] The resultant value is periodically reported upon, by the operators of nuclear power plants, in order to ensure that the 2-h radiation dose, measured at the plant boundary, will not exceed an appropriately small fraction of the Code of Federal Regulations, Title 10, part 100 dose guidelines.

5.2 In calculating $\bar{E}$, all the energy dissipated in each nuclear radioactive transformation is included. This accounting includes the energy released in the form of beta particles and gamma rays as well as energy released from extra-nuclear transitions in the form of X-rays, Auger electrons, and conversion electrons. However, not all radionuclides present in a sample are included in the calculation of $\bar{E}$.

5.3 Individual, nuclear reactor, technical specifications vary and each nuclear operator must be aware of limitations affecting their operation. Typically, radio-iodines, radionuclides with half lives of less than 10 min (except those in equilibrium with the parent), and those radionuclides, identified using gamma spectrometry, with less than a 95 % confidence level, are not typically included in the calculation. However, the operator must account for at least 95 % of the remaining activity. There are individual bases for each exclusion.

5.3.1 Radio-iodines are typically excluded from the calculation of $\bar{E}$ because many commercial nuclear reactors are required to operate under a more conservative restriction of 1 microCurie per gram dose equivalent I-131 in the reactor coolant.

5.3.2 Excluding radionuclides with half-lives less than 10 min, except those in equilibrium with the parent, has several bases.

5.3.2.1 The first basis considers the nuclear characteristics of a typical reactor coolant. The radionuclides in a typical reactor coolant have half-lives of less than 4 min or have half-lives greater than 14 min. This natural separation provides a distinct window for choosing a 10 min half-life cutoff.

5.3.2.2 The second consideration is the predictable time delay, approximately 30 min, which occurs between the release of the radioactivity from the reactor coolant to its release to the environment and transport to the site boundary. In this time, the short lived radionuclides have undergone the decay associated

[1] This practice is under the jurisdiction of ASTM Committee D-19 on Water and is the direct responsibility of Subcommittee D19.04 on Methods of Radiochemical Analysis.

Current edition approved May 15, 1993. Published November 1993.

[2] *Annual Book of ASTM Standards*, Vol 11.01.

[3] *Annual Book of ASTM Standards*, Vol 11.02.

[4] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

[5] The boldface numbers in parentheses refer to a list of references at the end of this practice.

with several half-lives and are no longer considered a significant contributor to $\bar{E}$.

5.3.2.3 A final practical basis is the difficulty associated with identifying short-lived radionuclides in a sample that requires some significant time, relative to 10 min, to collect, transport, and analyze.

5.3.3 Radionuclides identified using less than a 95 % confidence level are not typically included in the calculation to improve the accuracy of the calculation **(2)**.

6. Interferences

6.1 There are no true interferences to this practice. However, errors may result in the calculation of $\bar{E}$ from incorrectly analyzing the sample mixture.

7. Sampling

7.1 If samples are collected for analysis in support of this practice they should be representative of the matrix, be of sufficient volume to ensure adequate analysis, and be collected in accordance with Practices D 1066, D 3370, and D 3648.

7.2 In addition to the requirements of 7.1, if samples of reactor coolant are required in support of this practice, they should typically be collected only after a minimum of 2 effective full-power days and 20 days of power operation have elapsed since the reactor was subcritical for 48 h or longer. Individual nuclear operator technical specifications vary and should be reviewed to determine specific requirements.

8. Calibration and Standardization

8.1 Any calibrations and standardizations required in support of this practice should be in accordance with the applicable sections of Practice D 3648.

9. Procedure

9.1 Conduct all analyses in support of this practice in accordance with the applicable sections of Practice D 3648.

9.2 Perform sufficient gamma isotopic analyses of the liquid, gaseous, and suspended fractions of the sample to ensure that at least 95 % of the coolant activity due to gamma emitting isotopes has been quantified. Samples should be analyzed at approximately 2 h, 24 h, and 7 days following sample collection. Multiple sample analyses are required to ensure accurate quantification of the longer-lived isotopes because of masking caused by the high initial activity of the sample. If interferences continue to be a concern with the results of the analysis conducted on Day 7, it may be necessary to conduct additional gamma isotopic analyses of the sample at approximately 30 days after collection.

9.3 Perform sufficient isotopic analyses of the liquid, gaseous, and suspended fractions of the sample to ensure that at least 95 % of the coolant activity due to nongamma emitting isotopes has been quantified.

9.4 Tabulate the concentrations, uniformly measured in µCi/cc or µCi/g, of all applicable gamma and nongamma emitting radioisotopes identified in the sample. Some examples of the radioisotopes or types of radioisotopes found in a typical sample are the radioactive noble gases, pure beta emiter such as tritium, carbon-14, strontium-89 and 90, and yttrium-90, beta/gamma emitters such as cobalt-60, electron capture isotopes such as iron-55, and reactor coolant suspended and particulate material (commonly referred to as *crud*).

10. Calculation

10.1 Calculate the average energy per disintegration, $\bar{E}$, in MeV according to the following equation:

$$\bar{E} = \frac{\sum_{n=1}^{n} (A_i * E_i)}{\sum_{n=1}^{n} A_i} \quad (1)$$

where:

$\bar{E}$ = average energy per disintegration, MeV/disintegration,

A_i = activity of the *i*th radionuclide uniformly measured, µCi/cc or µCi/g, and

E_i = isotopic energy emission for the ith radionuclide, MeV/disintegration.

10.2 The values for A_i are simply the measured activity levels, uniformly measured in µCi/cc or µCi/g, for each appropriate radionuclide identified in the sample (for example, Co-60, Sr-90, Xe-133, etc.).

10.3 The values for E_i are constant for each radionuclide and depend upon the decay scheme for that radioisotope. E_i is calculated from the following equation:

$$E_i = E_i(\text{beta}) + E_i(CE) + E_i(A) + E_i(\text{gamma}) + E_i(X) \quad (2)$$

where:

E_i (beta) = the average, abundance weighted, beta energy per disintegration, MeV/disintegration,

E_i *(CE)* = the average, abundance weighted, conversion electron energy per disintegration, MeV/disintegration,

E_i *(A)* = the average, abundance weighted, Auger electron energy per disintegration, MeV/disintegration,

E_i(gamma) = the average, abundance weighted, gamma energy per disintegration, MeV/disintegration, and

E_i *(X)* = the average, abundance weighted, X-ray energy per disintegration, MeV/disintegration.

10.4 An example for the calculation of E_i for the disintegration of xenon-133 ($E_{Xe\text{-}133}$) follows.

10.4.1 The decay scheme for Xe-133 **(3)** is given in Fig. 1.

10.4.2 First, calculate $E_{Xe\text{-}133}$(beta).

10.4.2.1 To determine each E_i(beta), multiply the average energy per disintegration for each beta emitted by its abundance and sum the products. The average beta energies for each

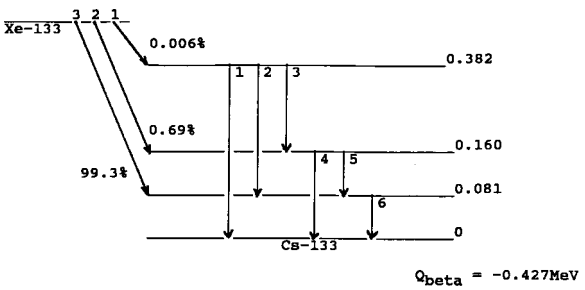

FIG. 1 Delay Scheme for Xe-133

isotope may be found in the literature **(4-6)**. Or, it may be approximated by multiplying the maximum beta particle energy per transformation by a factor of one-third. Only one-third of the maximum beta energy is included in the calculation because the remaining two-thirds of the energy is dissipated by neutrino emission **(7)**. Neutrinos are very unreactive and relinquish their energy very slowly. Therefore, their contribution is ignored when considering the total energy available for absorption at the site boundary.

10.4.2.2 The average energies and abundances of the major beta emissions for the decay of Xe-133 are **(6)**:

beta #	Average Energy	Abundance
2	0.0751 MeV	0.69 %
3	0.101 MeV	99.3 %

10.4.2.3 Therefore, $E_{Xe\text{-}133}$(beta) is:

$E_{Xe\text{-}133}$(beta) = (beta #2 average energy) * (beta 2 abundance)
+ (beta #3 average energy) * (beta 3 abundance)
$E_{Xe\text{-}133}$(beta) = 0.0751 * 0.0069 + 0.101 * 0.993,
$E_{Xe\text{-}133}$(beta) = 0.1055 MeV/disintegration.

10.4.3 Next, calculate E_i (CE).

10.4.3.1 Unlike beta particle emissions, conversion electrons are monoenergetic emissions and are not accompanied by neutrino emission. Therefore, their contributions to E_i (beta) is included at their full emission energy minus the binding energy of the emitted electron. Here again the abundance for each transformation is an included factor.

10.4.3.2 The energies and abundances of the major conversion electron emissions for the decay of Xe-133 are **(6)**:

CE #	Energy	Abundance
K-2	0.0450 MeV	53.3 %
L-2	0.0753 MeV	8.14 %

10.4.3.3 Therefore, $E_{Xe\text{-}133}$(CE) is:

$E_{Xe\text{-}133}$(CE) = (K-2 energy) * (K-2 abundance)
+ (L-2 energy) * (L-2 abundance)
$E_{Xe\text{-}133}$(CE) = 0.0450 * 0.533 + 0.0753 * 0.0814,
$E_{Xe\text{-}133}$(CE) = 0.0301 MeV/disintegration.

10.4.4 Next, calculate $E_{Xe\text{-}133}$(A).

10.4.4.1 Similar to conversion electron emissions, Auger electrons are monoenergetic emissions and are not accompanied by neutrino emission. Therefore, their contribution to E_i is also included at their full emission energy minus the binding energy of the emitted electron. Here again the abundance for each transformation is an included factor.

10.4.4.2 The energies and abundances of the major Auger electron emissions for the decay of Xe-133 are **(6)**:

Auger Electron	Energy	Abundance
L	0.00355 MeV	49.7 %
K	0.0255 MeV	5.6 %

10.4.4.3 Therefore, $E_{Xe\text{-}133}$(A) is:

$E_{Xe\text{-}133}$(A) = (L energy) * (L abundance)
+ (K energy) * (K abundance)
$E_{Xe\text{-}133}$(A) = 0.00355 * 0.497 + 0.0255 * 0.056,
$E_{Xe\text{-}133}$(A) = 0.00319 MeV/disintegration.

10.4.5 Next, calculate $E_{Xe\text{-}133}$(gamma). The energies and abundances of the major gamma emissions for the decay of Xe-133 are **(6)**:

gamma #	Energy	Abundance
5	0.0796 MeV	0.217 %
6	0.0810 MeV	37.6 %

10.4.5.1 Therefore, $E_{Xe\text{-}133}$(gamma) is:

$E_{Xe\text{-}133}$(gamma) = (gamma #5 energy) * (gamma #5 abundance)
+ (gamma #6 energy) * (gamma #6 abundance)
$E_{Xe\text{-}133}$(gamma) = 0.0796 * 0.00217 + 0.081 * 0.376,
$E_{Xe\text{-}133}$(gamma) = 0.0306 MeV/disintegration.

10.4.6 Next, calculate $E_{Xe\text{-}133}$(X). The energies and abundances of the major X-rays emissions for the decay of Xe-133 are **(6)**:

X-ray #	Energy	Abundance
K_{alpha2}	0.0306 MeV	13.3 %
K_{alpha1}	0.0310 MeV	24.6 %

10.4.6.1 Therefore, $E_{Xe\text{-}133}$(X) is:

$E_{Xe\text{-}133}$(X) = (K_{alpha2} energy) * (K_{alpha2} abundance)
+ (K_{alpha1} energy) * (K_{alpha1} abundance)
$E_{Xe\text{-}133}$(X) = 0.0306 * 0.133 + 0.0310 * 0.246,
$E_{Xe\text{-}133}$(X) = 0.0116 MeV/disintegration.

10.4.7 The final step in the calculation of $E_{Xe\text{-}133}$ is:

$E_{Xe\text{-}133}$ = $E_{Xe\text{-}133}$(beta) + $E_{Xe\text{-}133}$(CE) + $E_{Xe\text{-}133}$(A) + $E_{Xe\text{-}133}$(gamma) + $E_{Xe\text{-}133}$(X)
$E_{Xe\text{-}133}$ = 0.106 MeV/dis + 0.0301 MeV/dis + 0.00319 MeV/dis + 0.0306 MeV/dis + 0.0116 MeV/dis
$E_{Xe\text{-}133}$ = 0.181 MeV/disintegration.

10.5 To calculate the value of $\bar{E}$ for the entire sample then, an E_i value for each radionuclide is calculated. The product E_i and A_i are determined for each isotope and summed. This sum is then divided by the total activity of the sample to give $\bar{E}$.

10.6 The decay energies for several nuclides, typically found in reactor coolants, are given in Appendix X1 **(4)**. The table is condensed to show the measured, total average energy for all emitted electrons (the sum of the abundance weighted average energy for the beta, conversion electron, and Auger electron energies = E_i(beta) + E_i(CE) + E_i(A)) and the total average photon energy (the sum of the abundance weighted gamma and X-ray energies = E_i(gamma) + E_i(X)), rather than each individual contributor. It is important to note that the table uses the measured, average beta energy per disintegration rather than the approximated ⅓ of beta max. Values calculated by nuclear operators may differ from those of Appendix X1 due to rounding and variations found in the literature for the energies of each emanation.

11. Keywords

11.1 average energy per disintegration; disintegration; E bar; MeV per disintegration; nuclear reactor; radioactivity; reactor coolant; technical specifications

APPENDIX

(Nonmandatory Information)

X1. See Table X1.1 below.

TABLE X1.1 Average Fission Product Decay Energies for Different Radiation Types (4)

Isotope	Average Total Electron Energy Emitted	Average Total Photon Energy Emitted	Half-Life
	Mev/decay	Mev/decay	
Br-84	1.2492	1.7874	31.8 min
Kr-85	0.2505	0.0022	10.72 years
Kr-85m	0.2553	0.1577	4.48 h
Kr-87	1.3235	0.7931	76.3 min
Kr-88	0.3648	1.9545	2.84 h
Rb-89	2.0711	0.6364	17.8 min
Rb-89	1.0202	2.0683	15.44 min
Sr-89	0.5829	0.0001	50.55 days
Sr-90	0.1958	0.0	28.6 years
Sr-91	0.6531	0.6867	9.5 h
Sr-92	0.1999	1.3391	2.71 h
Y-90	0.9347	0.0	64.1 h
Y-91	0.6023	0.0036	58.51 days
Y-91m	0.0269	0.5306	49.71 min
Y-92	1.4449	0.2516	3.54 h
Zr-95	0.1161	0.7349	64.02 days
Zr-97	0.6974	0.1806	16.9 h
Nb-95	0.0444	0.7644	35.06 days
Nb-95m	0.1805	0.0663	86.6 h
Nb-97	0.4674	0.6648	72.1 min
Mo-99	0.3962	0.1550	66.02 h
Tc-99m	0.0156	0.1266	6.02 h
Ru-103	0.0697	0.4830	39.35 days
Ru-105	0.4035	0.7842	4.44 h
Rh-106	1.4120	0.2073	29.92 h
Te-131	0.7186	0.4204	25.0 min
Te-131m	0.1899	1.4263	30.0 h
Te-132	0.0984	0.2307	78.2 h
Te-133m	0.7094	2.2181	55.4 min
Te-134	0.1465	0.8738	41.8 min
I-131	0.1904	0.3811	8.04 days
I-132	0.4904	2.2913	2.30 h
I-133	0.4099	0.6067	20.8 h
I-134	0.6077	2.6253	52.6 min
I-135	0.3689	1.5751	6.61 h
Xe-131m	0.1422	0.0201	11.84 days
Xe-133	0.1355	0.0453	5.25 days
Xe-133m	0.1902	0.0415	2.19 days
Xe-135	0.3182	0.2479	9.11 h
Xe-135m	0.0958	0.4307	15.36 min
Cs-134	0.1620	1.5551	2.06 years
Cs-136	0.1329	2.1681	13.16 days
Cs-137	0.1708	0.0	30.17 years
Cs-138	1.2227	2.3610	32.2 min
Ba-137m	0.0637	0.5978	2.552 min
Ba-139	0.9024	0.0353	83.1 min
Ba-140	0.3039	0.1910	12.79 days
Ba-141	0.8579	0.8908	18.27 min
La-140	0.5326	2.3163	40.22 h
La-142	0.8472	2.7189	95.4 min
Ce-141	0.1698	0.0769	32.50 days
Ce-143	0.4369	0.2734	33.0 h
Ce-144	0.0925	0.0193	284.3 days
Pr-144	1.2072	0.0319	17.28 min

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