Designation: D5411 – 05

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 D5411; 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 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units, which are provided for information only and are not considered standard.

1.3 *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:*[2]

D1066 Practice for Sampling Steam
D1129 Terminology Relating to Water
D3370 Practices for Sampling Water from Closed Conduits
D3648 Practices for the Measurement of Radioactivity

2.2 *Code of Federal Regulations:*

10CFR100 Reactor Cite Criteria[3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this practice, refer to Terminology D1129.

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**).[4] 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 by charged particles and photons 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 (37 kBq) 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

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

Current edition approved Dec. 1, 2005. Published December 2005. Originally approved in 1993. Last previous edition approved in 2005 as D5411 – 93 (2005)$^{\epsilon 1}$. DOI: 10.1520/D5411-05.

[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.

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

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

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 with several half-lives and are no longer considered a significant contributor to Ē.

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 Ē 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 D1066, D3370, and D3648.

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 D3648.

9. Procedure

9.1 Conduct all analyses in support of this practice in accordance with the applicable sections of Practice D3648.

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 (37kBq/cc) or µCi/g (37kBq/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, Ē, in MeV according to the following equation:

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

where:

Ē = 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 (37 kBq/cc) or µCi/g (37 kBq/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:

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

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 ($E_{\text{Xe-133}}$) follows.

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

10.4.2 First, calculate $E_{\text{Xe-133}}$(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 isotope may be found in the literature (**4-6**). Or, it may be