ANSI/ANS-5.1-2005

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American Nuclear Society

WITHDRAWN

November 7, 2014
ANSI/ANS-5.1-2005 (W2014)

decay heat power in light water reactors

an American National Standard

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ANSI/ANS-5.1-2005

published by the
American Nuclear Society
555 North Kensington Avenue
La Grange Park, Illinois 60526 USA

ERRATUM

ANSI/ANS-5.1-2005
Decay Heat Power in Light Water Reactors

The total uncertainty values listed for Examples 1 and 2 in Appendix B (page 32) were found to be incorrect. The corrected tables are below.

Table B.1—Example 1: Decay heat power relative to operating power

	^{235}U		^{239}Pu		^{238}U		^{241}Pu		Total					
Time after shutdown (s)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{d}/P	One sigma (%)	$G(t)$	P_d/P	P_{dHE}/P	$(P_d + P_{dHE})/P$
1.00E+00	2.454E-02[1)]	2.8	2.128E-02	4.5	5.880E-03	9.0	5.993E-03	5.4	5.769E-02	4.3	1.00488	5.797E-02	2.678E-03	6.065E-02
1.00E+01	1.877E-02	2.0	1.704E-02	3.6	4.108E-03	5.7	4.498E-03	4.5	4.441E-02	3.2	1.00489	4.463E-02	2.672E-03	4.730E-02
1.00E+02	1.218E-02	1.8	1.166E-02	3.6	2.509E-03	5.2	2.822E-03	5.1	2.918E-02	3.1	1.00496	2.932E-02	2.611E-03	3.193E-02
1.00E+03	7.374E-03	1.8	7.109E-03	3.6	1.440E-03	5.0	1.646E-03	6.2	1.757E-02	3.2	1.00567	1.767E-02	2.126E-03	1.980E-02
1.00E+04	3.600E-03	1.7	3.352E-03	4.3	6.761E-04	4.7	7.519E-04	9.2	8.380E-03	3.7	1.01276	8.487E-03	1.234E-03	9.721E-03

[1)] Read as 2.454×10^{-2}.

Table B.2—Example 2: Decay heat power relative to operating power

	^{235}U		^{239}Pu		^{238}U		^{241}Pu		Total					
Time after shutdown (s)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{di}/P	One sigma (%)	P'_{d}/P	One sigma (%)	$G(t)$	P_d/P	P_{dHE}/P	$(P_d + P_{dHE})/P$
1.00E+05	1.722E-03[1)]	2.0	1.704E-03	4.9	3.276E-04	3.8	3.821E-04	10.0	4.136E-03	4.1	1.144	4.732E-03	9.001E-04	5.632E-03
1.00E+06	8.854E-04	1.9	7.984E-04	5.0	1.558E-04	3.6	1.794E-04	10.0	2.019E-03	4.0	1.169	2.359E-03	4.182E-05	2.401E-03
1.00E+07	2.695E-04	1.9	2.294E-04	5.1	4.389E-05	3.9	5.227E-05	10.0	5.951E-04	4.0	1.206	7.179E-04		7.179E-04
1.00E+08	3.049E-05	2.2	2.031E-05	5.5	4.020E-06	4.5	4.561E-06	9.5	5.938E-05	4.0	1.497	8.887E-05		8.887E-05
1.00E+09	8.016E-06	2.0	2.510E-06	4.9	6.891E-07	4.3	4.145E-07	9.8	1.163E-05	3.0	1.000	1.163E-05		1.163E-05

[1)] Read as 1.722×10^{-3}.

ANSI/ANS-5.1-2005

American National Standard
Decay Heat Power
in Light Water Reactors

Secretariat
American Nuclear Society

Prepared by the
American Nuclear Society
Standards Committee
Working Group ANS-5.1

Published by the
American Nuclear Society
555 North Kensington Avenue
La Grange Park, Illinois 60526 USA

Approved April 1, 2005
by the
American National Standards Institute, Inc.

American National Standard

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Published by

American Nuclear Society
555 North Kensington Avenue
La Grange Park, Illinois 60526 USA

Printed in the United States of America

Foreword

(This Foreword is not a part of American National Standard "Decay Heat Power in Light Water Reactors," ANSI/ANS-5.1-2005.)

The American Nuclear Society Nuclear Power Plant Standards Committee approved the American National Standard "Decay Heat Power in Light Water Reactors" in August 1994, which was released in 1995 [1] [1)], superceding the 1979 version. The standard was developed to fulfill a need for evaluations of fission reactor performance dependent upon knowledge of decay heat power in the fuel elements. The standard replaced a 1971 draft standard [2] (see Appendix A).

The 1994 revision to the standard incorporated additional measurements of decay heat that were published [3–6] and updated evaluations of decay heat using summation calculations based on improved nuclear databases [7,8]. In 1991, comparisons of elements of the standard with results of the new measurements and the new summation calculations were published [9]. In that report, proposed improvements to the standard were outlined. In response to that report, the tabular data in the tables entitled "Data for Standard Decay Heat Power" and associated uncertainties were reevaluated for the three fuel isotopes ^{235}U, ^{238}U, and ^{239}Pu and evaluated for the fuel isotope ^{241}Pu and were then added to the 1994 revision.

In the interim between the release of the 1994 standard and this revision, few new decay heat measurements have been reported in the literature. At the time this revision was completed, these new data had been integrated into the JENDL files [10]. These data were not incorporated into the fission yield evaluations for ENDF/B-VI since they were direct fission yield measurements. However, decay heat values calculated using the updated JENDL libraries have been compared with the recommended decay heat values in the 1994 standard [1] and were found to agree within the uncertainties cited in the standard [11].

The revised 2005 standard contains the main features of the 1994 standard except that the specific "simplified method" as described in the 1994 standard is incorporated in the 2005 standard in a new Appendix D as one example of a simplified model. A correction for Eq. (D.2) [formerly Eq. (13) in the 1994 standard] is included in the Appendix D example. Section 3.6 has been modified to permit substitution of a user-provided simplified model under the conditions specified. Minor corrections have also been made to Eqs. (10) and (C.6) and to the text in Section 3.5. The $G_{max}(t)$ values reported in Table 13 have been recalculated using CINDER'90 and ENDF/B-VI data [12]. The 1994 G_{max} values [13] were based on calculations performed with ENDF/B-IV data. The empirical representation of the correction factor for short times [Eq. (11)] is based on a parametric study of the influence of neutron capture on fission products as reported by Spinrad and Tripathi [14] and is not changed from the 1994 version of the standard.

The revised 2005 standard is the same as the previous versions of the standard in that

(1) the standard prescribes fission product decay heat power and its uncertainty for reactor operating histories;

(2) the standard prescribes data that are applicable to light water reactors (LWRs) of the type currently operating in the United States;

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1) Numbers in brackets refer to corresponding numbers in "Foreword References" on p. iv.

(3) the standard prescribes the recoverable energy release rates from fission product decay but does not specify the spatial distribution of the deposition of the energy in reactor materials;

(4) decay heat power for ^{239}U and ^{239}Np are separately prescribed and are to be added to the fission product decay heat power;

(5) in the standard, the uncertainty is expressed in a statistical sense as one standard deviation in a normal distribution;

(6) the standard presents decay power for two irradiation conditions: (a) a fission pulse and (b) an irradiation of 10^{13} s to represent infinite reactor operation;

(7) the effect of neutron capture in fission products during reactor operation is accounted for in the revised standard. An upper bound for the effect of neutron capture in fission products that provides conservative values of decay heat power is given for the case of a long operation of a ^{235}U-fueled LWR at high neutron flux;

(8) for cooling times greater than 10^5 s, the standard is based solely upon summation calculations rather than empirical data and summation calculations as at shorter decay times;

(9) the formulations are based upon the assumption that the energy release per fission during operation Q_i for each nuclide is independent of time;

(10) a method is prescribed for obtaining decay heat power for arbitrary reactor operating histories from the standard;

(11) the decay heat power is related to the operating power of the reactor via the fission rate and the recoverable energy per fission during operation;

(12) decay heat power from activation products in reactor materials is not specified in the standard.

Features that distinguish the revised standard from the 1979 standard but are consistent with the 1994 standard are the following:

(1) The cooling-time region of validity has been extended to 10^{10} s. In the 1979 standard the time region of validity was 10^9 s;

(2) Data are prescribed for decay heat power from fission products from fissioning of the major fissionable nuclides present in LWRs, i.e., ^{235}U, ^{239}Pu, and ^{241}Pu thermal, and ^{238}U fast, and methods are prescribed for evaluating the total fission product decay heat power from the data given for these specific fuel nuclides. The 1979 standard gave standard curves for ^{235}U and ^{239}Pu thermal, and ^{238}U fast;

(3) The standard values adopted for ^{238}U are based upon an evaluation of new experimental data and summation calculations. In the 1979 standard, the values for ^{238}U were obtained solely from summation calculations;

(4) The standard values adopted for ^{241}Pu are based upon evaluation of experimental data and summation calculations. The 1979 standard did not give a separate set of values and prescribed that ^{235}U values should be used for contributions from all other fissioning actinides other than ^{239}Pu and ^{238}U;

(5) Standard values and uncertainties for pulse thermal fission ^{235}U have been revised for times after shutdown of 1.0, 1.5, and 2.0 s, based upon a recently published evaluation by Tobias [15] of all available experimental data for ^{235}U.

These changes involve increases of decay heat power of 16.2, 8.0, and 3.3%, respectively. Corresponding uncertainties have been reduced for these values from those given in the 1979 standard, also based on the Tobias evaluation;

(6) Standard values and uncertainties for pulse thermal fission of ^{235}U have been revised for times after shutdown greater than 1.5×10^9 s. These changes reflect improved nuclear data and uncertainties used in summation calculations for long-lived fission products, principally ^{99}Tc and ^{126}Sn;

(7) Standard uncertainties for pulse thermal fission of ^{239}Pu have been revised for times after shutdown of 1.0, 1.5, and 2.0 s and between 20 and 15,000 s, based on the Tobias evaluation [15] of all available experimental data for ^{239}Pu, as well as the excellent agreement of the experimental results of Akiyama et al. [5] with the results of Dickens et al. [3];

(8) Standard values and uncertainties for pulse thermal fission of ^{239}Pu have been revised for times after shutdown greater than 5×10^9 s, reflecting improved nuclear data and uncertainties used in summation calculations for long-lived fission products, principally ^{99}Tc and ^{126}Sn.

Summation calculations by Ryman et al. [16] for long cooling times in support of U.S. Nuclear Regulatory Commission Regulatory Guide (RG) 3.54 [17] on spent-fuel storage are in good agreement with data predicted by the 1979 standard; RG 3.54 accepts the use of the 1979 standard in its cooling-time region of validity. Isotope inventory codes [13] that use summation techniques to predict decay heat power have been subjected to a controlled intercomparison [18,19] and found to provide essentially equivalent results. Dickens et al. [9] compare the 1979 standard with international decay heat power standards or proposed standards [20–22].

Further revisions of the standard are planned to

(1) improve the capture effect specification;

(2) include contributions from actinides not already included;

(3) specify total recoverable energy Q for major elements;

(4) separate beta-ray and gamma-ray components;

(5) complete separate data sets for other fuel elements and other neutron energies.

The foregoing items (1), (2), and (3) were included in the recommendations for near-term improvements to the standard by Dickens et al. [9].

The formal presentation of the revised standard is the same as for the 1994 standard, thus allowing ease in upgrading computer programs. Users applying the standard to reactor safety analysis should justify that the inputs (e.g., the recoverable energy Q) to the standard are appropriate.

Fission product yields and uncertainties used in summation calculations for the revised standard are consistent with ANS-19.8, "Fission-Product Yields for ^{235}U, ^{238}U, and ^{239}Pu" (in draft form).

The American National Standard ANSI/ANS-5.1-1994 [1] is superseded by the present revision.

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The working group acknowledges and appreciates the substantial efforts of earlier working groups in establishing and maintaining this standard. The changes from the previous version to this were minor and do not alter the technical basis of the standard. In this respect, we have included the names of the working group that established the 1994 version of the standard.

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Contents

Appendices

Decay Heat Power in Light Water Reactors

1 Scope and purpose

1.1 Scope

This standard sets forth values for the decay heat power from fission products and ^{239}U and ^{239}Np following shutdown of light water reactors (LWRs) containing ^{235}U, ^{238}U, and plutonium. The decay heat power from fission products is presented in tables and equivalent analytical representations. Methods are described that account for the reactor operating history, for the effect of neutron capture in fission products, and for assessing the uncertainty in the resultant decay heat power.

Decay heat power from other actinides and activation products in structural materials, and fission power from delayed neutron–induced fission are not included in this standard and shall be evaluated by the user and appropriately included in any analysis of shutdown power.

1.2 Purpose and application

This standard provides bases for determining the shutdown decay heat power and its uncertainty following shutdown of LWRs. The information in this standard can be used in the design, performance evaluation, and assessment of the safety of LWRs. This standard can be used as the basis for comparison with the results of alternate methods of determining fission product decay heat power.[1)]

2 Limitations

2.1 General

The standard methods of evaluating decay heat described herein are applicable to LWRs containing ^{235}U as the initial major fissile material and ^{238}U as the fertile material. The contributions from ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu are treated explicitly; account is made for other fissionable nuclides by treating them as ^{235}U.

2.2 Limitations on use of standard fission product decay heat power representation

Standard fission product decay heat power values are provided in tabular form for thermal reactor neutron spectrum fission of ^{235}U, ^{239}Pu, and ^{241}Pu and for fast fission of ^{238}U at various times after shutdown following two limiting reactor operating periods: one for a fission pulse and one for a reactor operated at a constant fission rate for an infinite period of time and then instantaneously shut down.

These standard values do not account for neutron capture by fission products. Uncertainties are provided for each shutdown time for each of the tabulations. Methods are prescribed for obtaining the total fission product decay heat power and the associated uncertainty for finite operating times from either the pulse or infinite operation representations. A method is prescribed to account for the effect of neutron capture in fission products for shutdown times less than 10^4 s; it uses a multiplying factor that depends upon reactor operating time, total fissions per initial fissile atom, and the time after shutdown. The upper bound for this factor is also prescribed for shutdown times up to 10^{10} s. The user has the option of computing and justifying the capture correction.

2.3 Spatial distribution

The variation of the spatial distribution of the decay heat power deposition is left to the users of this standard. This standard relates local production of decay heat power in the shutdown condition to local fission power in the operating condition. Time dependence of radiation spectra in the shutdown reactor can cause variations in the spatial distribution of the gamma-ray energy deposition. This influence is beyond the scope of this standard.

[1)] Examples of the use of the standard methods are presented in Appendix B.