Proposed Revision of the Decay Heat Standard ANSI/ANS-5.1-2005

I. C. Gauld, M. C. Brady Raap, F. Schmittroth, W. B. Wilson

Oak Ridge National Laboratory[1]*, Oak Ridge, TN, 37831-6170, gauldi@ornl.gov*

INTRODUCTION

The ANSI/ANS-5.1 [1] standard on decay heat in light water reactors is one of the most widely used standards for reactor design and safety analysis. The standard was last revised and issued in 2005. The 2005 revision included several important accomplishments, including incorporation of ENDF/B-VI nuclear data in the development of correction factors implemented in the standard, and revisions to the "simplified method."

The status of the 2005 ANS-5.1 standard has been summarized previously [2]. Future revisions of the standard under consideration, as proposed by the working group, were to (a) improve the neutron capture effect specification, (b) include contributions from actinides not already addressed by the standard, and (c) specify values for the total recoverable decay energy *Q* for major fissionable elements. These items are carried over from recommendations by Dickens et al. [3] during development of the 1994 revision. The current working group has also identified the representation of decay heat uncertainties as an area for improvement.

This paper discusses recent development activities to further improve and extend the utility of the ANS-5.1 decay heat standard. These developments are in progress, and this paper summarizes the status of the activities. The proposed revisions discussed in this paper are being considered by the working group for adoption in the next publication of the standard.

PROPOSED REVISIONS

Neutron Capture Effect

The standard representation of fission product decay heat following fission does not include the effect due to neutron capture by the fission products during irradiation. In the current version of the ANS 5.1 standard, this capture effect is treated using a parameter, *G(t)*, that is multiplied by the fission product decay heat without capture. This factor is based on a very conservative reactor operating history and generally produces bounding estimates of the neutron capture effect. An alternative treatment of the neutron capture effect is implemented in the 1992 international decay heat standard [4], ISO 10645. The International Organization for Standardization (ISO) standard treats ^{134}Cs explicitly using analytical expressions and then lumps the remainder of the fission products into a single correction factor. This practice has been shown to greatly reduce conservatism in treating the capture effect. Cesium-134 is the dominant neutron capture fission product, accounting for more than 90% of the peak total capture effect at cooling times near 10^8 s. The ISO 10645 analytical expression for decay heat power from ^{134}Cs following an irradiation time *T* and cooling time *t* is

$$P_c(t,T) = Y\ E\ \lambda_4\ \frac{P}{Q}\left[\frac{1-e^{-(\lambda_4+\sigma_4\phi)T}}{\lambda_4+\sigma_4\phi} + \frac{e^{-\sigma_3\phi T} - e^{-(\lambda_4+\sigma_4\phi)T}}{\sigma_3\phi-(\lambda_4+\sigma_4\phi)}\right]e^{-\lambda_4 t},$$

where *Y* is the effective fission yield for ^{133}Cs, *E* is the recoverable decay energy for ^{134}Cs, λ_4 is the decay constant for ^{134}Cs, *P* is the fission power, *Q* is the energy per fission, ϕ is the flux, and σ is the effective (1-group) cross section for ^{133}Cs and ^{134}Cs (σ_3 = 10.7 barns and σ_4 = 16.8 b, respectively).

The analytical expressions from ISO 10645 were evaluated for implementation as an alternative to the method currently in ANS 5.1. The equations and associated nuclear data recommended in ISO 10645 (fission yields, decay constants, and cross sections) were first evaluated by comparing calculated ^{134}Cs concentrations obtained from the analytic expressions against measured radiochemical assay data for 27 spent fuel samples. The analytical results showed trends that were consistent with summation codes that use ENDF/B-V and –VI-based cross sections but are not in good agreement with the measurements. Specifically, the ^{134}Cs content was systematically underpredicted relative to experiment by 15 to 20%.

The effective (n,γ) neutron cross sections for ^{133}Cs and ^{134}Cs were reevaluated using ENDF/B-VII data, which include new evaluations for both of these nuclides. The revised cross section values were σ_3 = 11.3 b and σ_4 = 10.9 b. The ENDF/B-VII cross sections significantly improved the predicted ^{134}Cs results, as shown in Fig. 1, and effectively removed the nonconservative bias observed using the ISO data.

The neutron capture contribution from the remaining aggregate fission products (except ^{134}Cs) is calculated using summation codes, e.g., ORIGEN, which is extensively validated against measurements [5].

Actinide Decay Heat Power

ANS 5.1 explicitly considers decay heat power from only ^{239}U and ^{239}Np, which are the dominant decay heat

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sources for decay times less than about 20 d, but there is no provision to include other actinides either explicitly or in some lumped form. This limitation requires users of the standard to augment the ANS 5.1 decay heat values with actinide values obtained from other calculations. Beyond typically 30- to 50-year (10^9 s) cooling times, the actinide contribution generally exceeds that of the fission products. An expanded treatment of actinide contributions is essential to expanding the applicability of the ANSI/ANS-5.1 to spent fuel handling and interim storage applications.

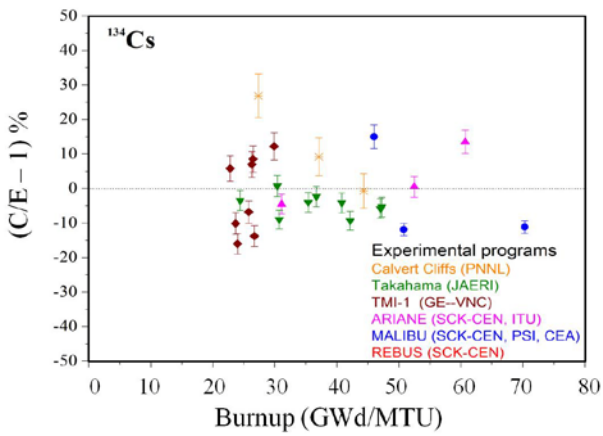

Fig.1. Deviations of ^{134}Cs concentrations calculated (C) using a methodology proposed for ANS 5.1 vs. experiment (E).

One of the objectives of the standard has always been to enable decay heat power to be calculated to the precision of summation methods without requiring the need for complicated calculations. Developing representations of the actinide content of the fuel without making them overly complex to implement presents a challenge. In the proposed revision, tabulated actinide values (^{239}U and ^{239}Np) are developed as a function of cooling time using validated summation calculations. The calculations are based on a conservative irradiation history with $\psi < 1.3$ (fissions per initial heavy metal atom), e.g., 5 wt % ^{235}U enrichment fuel with a burnup < 63 GWd/t. This ψ value is conservative for the vast majority of typically used reactor fuel but is not overly conservative to the point that the standard would produce decay heat estimates that were grossly overestimated for most applications. These actinide content values are illustrated in Fig. 2 as a fraction of the fission product decay heat power versus time for reactor-fuel specific operating powers of 20 and 32 W/g.

For cooling times for which the standard is routinely used in reactor analysis codes to calculate decay heat for thermal-hydraulic and safety-system performance assessment, this actinide contribution increases from about 1% of the fission product decay heat power after 1 s, to about 10% after 10^5 s of cooling.

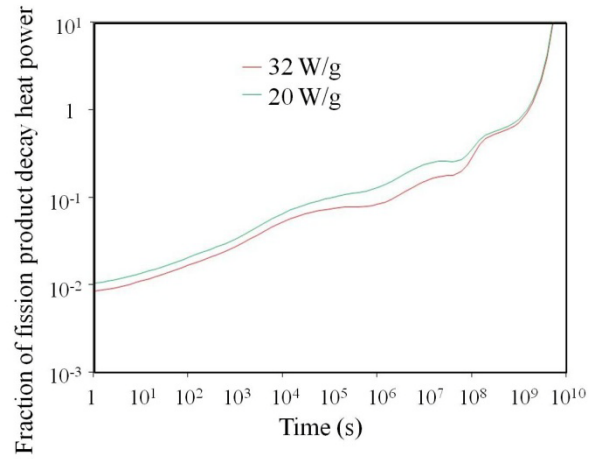

Fig. 2. Actinide contribution (excluding ^{239}U and ^{239}Np) shown as a fraction of the fission product decay heat power for specific fission powers of 20 and 32 W/g.

Uncertainty Representation

The uncertainties in ANS 5.1 are currently represented in tabular form for the decay heat functions f(t) and F(t, ∞), the fission product decay heat power as a function of time (t) after fission for a pulse and infinite irradiation, respectively. Values for intermediate times are obtained by interpolation. The interpolation required when using the tabular data in the standard, particularly the F(t, ∞) values, can make the method sensitive to the interpolation scheme used at longer decay times. To improve the accuracy and flexibility of the uncertainty representation, the tabulated uncertainty values for f(t) have been fit to a function having the same exponential series form as that used for f(t) itself. In the fitting procedure, the same λ coefficients from f(t) are used, and new α coefficients are obtained using a multivariate linear least squares regression analysis. The results from fitting the tabulated uncertainty data for ^{235}U are illustrated in Fig. 3 as a function of time after fission.

The proposed functional representation of the uncertainties will enable decay heat uncertainties to be rapidly evaluated using procedures that are exactly equivalent to those used to calculate fission product decay heat without the need to perform interpolation.

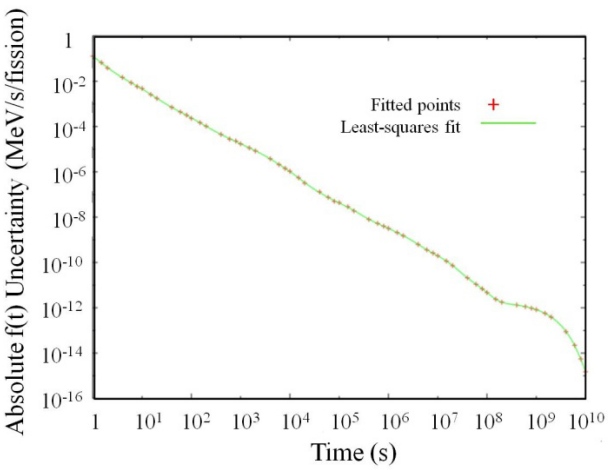

Fig. 3 Fitting results obtained from a parameterized representation of the decay heat uncertainty for ^{235}U.

CONCLUSIONS

The ANS 5.1 working group is currently updating and expanding the standard in preparation for the next revision. These activities are in progress, and recommendations to adopt any of the proposed changes in the next revision are expected to be complete this year. Several of the changes discussed in this paper were adapted from methodologies developed in the ISO 10645 standard, with nuclear data and irradiation assumptions that were modified to reflect newer data or more realistic operating conditions.

The proposed revision represents an important milestone for this standard. Most of the recommendations made by the working group during development of the 1994 standard will have been addressed by the 2005 revision and the proposed revisions described here. Several other minor improvements are also being considered, including the addition of an appendix that describes computer codes that can be used to provide additional data and components of decay heat not addressed by the standard, e.g., activation product decay heat. As nuclear data continue to improve and the ability of computer codes to accurately represent fission product decay heating at very short time intervals increases, computer summation models will likely become more predominant for decay heat calculations. This is particularly true as new advanced fuels, e.g., mixed-oxide fuel, and next-generation reactor concepts, are evaluated that are currently outside the scope and ability of the existing standard. Some initiatives in the area of developing a standard for nuclear data requirements for summation codes have already been initiated under the ISO [6]. However, even with the likely increased reliance on complex computer models in the future, standards such as ANS 5.1 will continue to provide a valuable benchmark because the basis of the standard values is experimental data.

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