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Decay heat uncertainty for BWR used fuel due to modeling and nuclear data uncertainties ☆

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HIGHLIGHTS

- Evaluate uncertainty in calculated decay heat for a typical BWR fuel assembly.
- Include uncertainties in nuclear data and selected manufacturing and operation parameters.
- Compare to decay heat measurement data for the studied assembly.
- Demonstrate practical approach for evaluating uncertainty in calculated decay heat.

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ABSTRACT

Characterization of the energy released from radionuclide decay in nuclear fuel discharged from reactors is essential for the design, safety, and licensing analyses of used nuclear fuel storage, transportation, and repository systems. There are a limited number of decay heat measurements available for commercial used fuel applications. Because decay heat measurements can be expensive or impractical for covering the multitude of existing fuel designs, operating conditions, and specific application purposes, decay heat estimation relies heavily on computer code prediction. Uncertainty evaluation for calculated decay heat is an important aspect when assessing code prediction and a key factor supporting decision making for used fuel applications. While previous studies have largely focused on uncertainties in code predictions due to nuclear data uncertainties, this study discusses uncertainties in calculated decay heat due to uncertainties in assembly modeling parameters as well as in nuclear data. Capabilities in the SCALE nuclear analysis code system were used to quantify the effect on calculated decay heat of uncertainties in nuclear data and selected manufacturing and operation parameters for a typical boiling water reactor (BWR) fuel assembly. The BWR fuel assembly used as the reference case for this study was selected from a set of assemblies for which high-quality decay heat measurements are available, to assess the significance of the results through comparison with calculated and measured decay heat data.

1. Introduction

Characterization of energy released from radionuclide decay in nuclear fuel discharged from reactors (i.e., nuclear decay heat) is essential for the design, safety, and licensing analyses of used nuclear fuel storage in pools, transportation, interim dry storage, and repository systems. Because measurements of decay heat can be expensive or impractical for covering the multitude of existing fuel designs, operating conditions, and specific application purposes, decay heat estimation for commercial used fuel applications relies heavily on computer code predictions.

Decay heat generated in used nuclear fuel is determined by accounting for all contributions of recoverable energy released from the decay of radionuclides in fuel after its discharge from the reactor. Decay heat is driven by the isotopic composition in fuel at the end of irradiation and varies with the decay time after discharge (also known as cooling time). Calculation of decay heat can be performed with computational tools that simulate the nuclide transmutations and decay processes during fuel irradiation in the reactor, as well as the decay from discharge to a designated cooling time. The SCALE nuclear analysis code system (Bowman,

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2011) is a computational system used internationally to support used nuclear fuel transportation and storage applications. The used fuel analysis capabilities in SCALE, particularly those in the ORIGEN isotopic depletion and decay code (Gauld et al., 2011), have been thoroughly validated against measurement data. These validation studies included analysis of nuclide inventories for over a hundred measured used fuel samples (Ilas et al., 2012) and of decay heat measurements (Ilas and Gauld, 2008; Ilas et al., 2014) performed for both pressurized water reactor (PWR) and boiling water reactor (BWR) used fuel assemblies.

Uncertainty in calculated decay heat is needed to assess the reliability in code predictions and to support decision making for used fuel applications for which decay heat has a significant impact on thermal performance. Bias and uncertainty in calculated metrics for a system of interest is generally estimated by direct comparison of calculated and experimental data, where available for the used fuel metric of interest. However, existing measurement data provide limited coverage of the parametric space (i.e., burnup, enrichment, cooling time) relevant to specific, current, or planned used fuel applications. The knowledge gap is greatly supplemented through computer simulations.

During the past decade, several institutions worldwide have developed computational approaches, complementing well-established methodologies that rely on direct or adjoint-based perturbation theory, to assess the effect of uncertainty in basic evaluated nuclear data on metrics of interest for used fuel applications. Many of these new uncertainty analysis approaches—known as stochastic sampling methods—include random sampling of nuclear data uncertainties, applying the perturbed nuclear data to the system of interest in repeated simulations, and processing the obtained response to determine its uncertainty due to the perturbed nuclear data uncertainties. The nuclear data uncertainty sampling can rely on covariance matrices (Klein et al., 2011) or nuclear reaction models (Rochman et al., 2016). The stochastic sampling methods are computationally intensive, requiring generally hundreds of repeated simulations for ensuring meaningful, adequately converged responses.

Stochastic sampling methods for applications involving isotopic depletion analysis have applied various random sampling approaches using existing cross section covariance files (Klein et al., 2011; Wieselquist et al., 2013a) and different depletion simulation systems such as CASMO (Leray et al., 2016), MCNP (García-Herranz et al., 2008), SCALE (Williams et al., 2013), or Serpent (Rochman et al., 2016). Most of the results published to date that are related to used fuel applications have focused more on propagating nuclear data uncertainties on uncertainty in isotopic compositions and less on uncertainty in integral responses such as decay heat (Williams et al., 2013; Fiorito et al., 2014).

While previous used fuel studies performed with the stochastic sampling capability in SCALE, which is named *Sampler*, were largely focused on response uncertainty due to nuclear data uncertainties (Williams et al., 2013; Wieselquist et al., 2013b), this study addresses uncertainties in calculated decay heat due to both nuclear data and assembly modeling parameters uncertainties. Sampler was used to quantify these uncertainties for a typical BWR fuel assembly configuration. The selected assembly modeling parameters include fuel material data (fuel density and enrichment, gadolinium content in gadolinia fuel rods), fuel rod geometry data (pellet radius, fuel rod radius), and operating data (coolant density, specific power, fuel temperature). The BWR fuel assembly used as the reference case for this study was selected from a set of previously analyzed assemblies (Ilas et al., 2014) for which high-quality decay heat measurements are available, to assess the significance of the results through comparison with calculated and measured decay heat data.

2. Assembly description and data

The reference BWR assembly has an 8×8 design, one of the most common fuel designs in the worldwide BWR fuel inventory. In the United States, ~45% of BWR assemblies discharged from reactors before 2013 (Hu et al., 2016) have an 8×8 lattice design. The selected assembly was measured at the Swedish Central Interim Storage Facility for Spent Nuclear Fuel, also called *Clab*. A comprehensive experimental program initiated and managed by Svensk Kärnbränslehantering AB (SKB), the Swedish Nuclear Fuel and Waste Management Company, is ongoing at Clab. Under this program, full-assembly decay heat measurements were performed for both PWR and BWR assemblies. In the past few years, SKB has closely collaborated with institutions in Europe and the United States under the Next Generation Safeguards Initiative – Spent Fuel (NGSI-SF) project, to develop new measurement technologies for verifying used nuclear fuel attributes (Humphrey et al., 2012). For testing of instruments and techniques developed under this project, 25 PWR and 25 BWR fuel assemblies stored at Clab were selected as a test bed, with 9 of the selected BWR assemblies having an 8×8 design (Vaccaro et al., 2016). Decay heat measurements are planned to be completed for each of these 50 assemblies.

2.1. Assembly geometry and operating data

Previous analyses (Ilas et al., 2014) of decay heat measurements performed at Clab included one 8×8 BWR assembly for which 10 measurements were performed at different cooling times—the largest number of measurements for an assembly in that analyzed set. This assembly, identified as *6432R1*, is used for uncertainty analyses in this study. Detailed data for this assembly can be found in (SKB Report R-05-62, 2006). The assembly has an average enrichment of 2.9 wt% ^{235}U, an average burnup at discharge of 36.9 GWd/MTU, and an average (over all irradiation cycles and axial locations in the assembly) coolant density of 0.453 g/cm^3. The assembly includes 63 fuel rods — 59 regular fuel (UO_2) rods and 4 gadolinia (UO_2-Gd_2O_3) rods, and one water rod. The fuel rods located at the corners of the assembly (corner rods) have a diameter smaller than the remaining fuel rods in the assembly. The fuel enrichment map and assembly layout are illustrated in Fig. 1. The assembly has fuel rods with five enrichments: 1.38, 1.98, 2.49, 3.17, and 3.37 wt% ^{235}U. Unique rod colors in Fig. 1 indicate unique enrichment values, while the white rod indicates the water rod. The rods shown as containing multiple rings are the gadolinia rods. Fig. 2 shows the cumulative burnup of the assembly and the assembly-average specific power as a function of the irradiation cycle.

2.2. Assembly measurement data

Table 1 shows the experimental decay heat data obtained from 10 measurements (SKB Report R-05-62, 2006) performed over a period of almost 6 years that correspond to cooling times between 14.8 and 20.6 years. Five of these 10 measurements were completed within an 18-day period at ~15.6 years cooling time. At this cooling time, the change in decay heat over 18 days is less than 0.1% and these five measurements can be considered as repeat measurements of the same assembly at a specific cooling time. The measured decay heat used as the reference is 183.21 W (mean of the five measurements) at 5681-day decay time, with a standard deviation (1σ) of 1.54 W or 0.8% of the mean measured value. This experiment-based, derived measurement uncertainty of 1.54 W is close to the measurement uncertainty reported for BWR assemblies. The reported measurement uncertainty (SKB Report R-05-62, 2006) at a 95% confidence level (2σ) was 4.2 W at 50 W decay