RADIAL VARIATION OF BURNUP AND SOURCE TERMS IN HIGH BURNUP LWR FUEL

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1. INTRODUCTION

Oak Ridge National Laboratory (ORNL), under the direction of the US Nuclear Regulatory Commission (NRC), has completed a study of the spatial variation in the burnup and resulting source terms in high-burnup pressurized water reactor (PWR) and boiling water reactor (BWR) fuel. In the context of the present study, ”source terms” refers to the nuclide concentrations, radionuclide activities, and decay energy release (decay heat) in the spent fuel, and does not apply to the *released* source terms.

For this study, a Westinghouse 17 $\times$ 17 (W17) fuel assembly was selected as a representative modern PWR fuel assembly, and a GE14 (10 $\times$ 10) fuel assembly was chosen as a representative BWR fuel assembly. These fuel assemblies were depleted up to 80 GWd/MTHM burnup, and source terms were analyzed for decay times up to 500 years after discharge. This work significantly extends previous studies [1] of spent fuel source terms to include, in addition to the extended burnup and cooling time range, source term information at a highly detailed spatial resolution to enable consequence analysis radionuclide release caused by localized fuel and containment failure. This paper documents the fuel inventories and associated source terms for

- the assembly average
- the peak power fuel pin
- the outer radial region (rim) of a fuel pin
- the peak power axial location

2. METHODOLOGY

The W17 fuel assembly model was taken from the SCALE6.1 ORIGEN library template files[2]. Fuel enrichments of 1.5, 4.0, and 5.0 wt % U-235 were used. Due to lattice symmetry, only 1/4 of the W17 fuel assembly is modeled. No burnable absorbers were used in the assembly, and all pins contained a uniform enrichment. The W17 assembly was depleted using a moderator density of 0.7194 g/cm^3 with a constant soluble boron concentration of 630 ppm. The fuel temperature (805 K) was held constant during depletion.

The GE14 fuel assembly is a highly heterogeneous 10×10 fuel assembly containing 92 fuel pins with a range of fuel enrichments; various fuel pins contain both UO_2 and Gd_2O_3 (gadolinia-bearing pins). Modern BWR fuel assemblies typically contain part-length rods, the axial zone that includes the part-length rods is referred to as the ”full” zone and above the part-length rods the ”vanished” zone. These two zones comprise approximately 3/4 of the axial length of the assembly, with the other 1/4 of the fuel assembly composed of fuel pin plenum zones and natural uranium blanket zones. The vanished zone is located above the full zone and above any part-length fuel rods in the assembly. and one lattice for the vanished zone to represent an entire assembly. It is important to model the full and vanished zones separately, as certain fuel pins in the vanished lattice experience localized increased moderation because of the presence of additional water due to the empty lattice locations.

3. RESULTS

3.1. Identification of High-Power Pins

The W17 and GE14 (full and vanished) models were run using TRITON to obtain assembly-average data and to determine the highest power (also referred to as ”peak power”) fuel pin in the assembly. The fuel pin burnup distribution was extracted at end-of-life (EOL) to determine the peak power pin over the depletion interval.

Figure 1 presents the time-averaged relative pin power distribution for the W17 fuel assembly. The fuel pin with the highest average power over the depletion interval is identified with a yellow box in Figure 1. It can be seen that the highest-power pins (red shaded in Figure 1) tend to be located inside the outer ring of guide tubes and adjacent to guide tubes. The highest-power fuel pin is located directly adjacent to one guide tube and diagonally adjacent to another guide tube, leading to increased neutron moderation relative to other fuel pins in the lattice. In Figure 1, two pin locations are identified as they are identical symmetric fuel pins and have the same power.

In the full and vanished GE14 lattices, the highest-power pins were determined at void fractions of 0%, 40% and 80%. As a result of depletion of the gadolinium poison, the power shifted throughout the assembly as a function of burnup. Figure 2 shows the burnup-averaged power distribution for the

0.963	0.961	0.964	0.969	0.977	0.984	0.983	0.982	0.985
0.961	0.959	0.967	0.977	0.989	1.008	0.995	0.993	1.007
0.964	0.967	0.983	1.010	1.021	GT	1.018	1.016	GT
0.969	0.977	1.010	GT	1.029	1.027	1.006	1.003	1.020
0.977	0.989	1.021	1.029	1.019	1.028	1.008	1.005	1.022
0.984	1.008	GT	1.027	1.028	GT	1.026	1.024	GT
0.983	0.995	1.018	1.006	1.008	1.026	1.009	1.007	1.024
0.982	0.993	1.016	1.003	1.005	1.024	1.007	1.006	1.023
0.985	1.007	GT	1.020	1.022	GT	1.024	1.023	IT

Figure 1. W17 fuel assembly burnup-averaged relative power distribution with highest-power pins identified.

full and vanished lattices that assumes a 40% void fraction. Unlike for the PWR, for the BWR lattices, the highest-power pins at beginning-of-life do not always correspond to the highest-burnup fuel pins at EOL owing to shifting of the power distribution during depletion. In all cases—full and vanished lattices with 0%, 40%, and 80% void fractions—the highest-power fuel pins were those of relatively high enrichment located along the assembly edge near the corners of the fuel assembly. Yellow boxes in Figure 2 highlight these high-power fuel pins. The highest-average-power pin varied for the three simulated void fractions. All yellow highlighted fuel pins in Figure 2 had a very similar power and burnup, meaning they produced very similar isotopics and source terms. The fuel pin highlighted with a red box produced the highest power for both the full and vanished lattice for the 0% void case and was used as the peak power in further analysis in the analysis of all void fractions.

1.044	1.029	1.051	1.061	1.051	1.051	1.059	1.075	1.072	1.035
1.029	0.960	1.014	0.989	0.893	0.988	0.995	0.880	0.968	1.052
1.051	1.014	0.880	0.983	0.989	1.018	1.022	1.006	0.864	1.074
1.061	0.989	0.983	0.977	1.010	W	W	1.009	0.966	1.046
1.051	0.893	0.989	1.010	1.043	W	W	0.994	0.983	1.058
1.051	0.988	1.018	W	W	1.032	0.989	0.953	0.967	1.050
1.059	0.995	1.022	W	W	0.989	0.943	0.934	0.963	1.053
1.075	0.880	1.006	1.009	0.994	0.953	0.934	0.941	0.851	1.066
1.072	0.968	0.864	0.966	0.983	0.967	0.963	0.851	1.020	1.043
1.035	1.052	1.074	1.046	1.058	1.050	1.053	1.066	1.043	1.011

(a) GE14 full lattice burnup-averaged power distribution

0.985	0.996	1.019	1.039	1.019	1.019	1.038	1.045	1.044	0.982
0.996	V	1.036	V	0.901	1.001	V	0.896	V	1.028
1.019	1.036	0.890	1.005	1.000	1.023	1.036	1.021	0.882	1.051
1.039	V	1.005	0.996	1.036	W	W	1.027	V	1.034
1.019	0.901	1.000	1.036	V	W	W	1.005	1.003	1.038
1.019	1.001	1.023	W	W	V	1.019	0.974	0.991	1.032
1.038	V	1.036	W	W	1.019	0.972	0.972	V	1.047
1.045	0.896	1.021	1.027	1.005	0.974	0.972	0.974	0.883	1.046
1.044	V	0.882	V	1.003	0.991	V	0.883	V	1.026
0.982	1.028	1.051	1.034	1.038	1.032	1.047	1.046	1.026	0.968

(b) GE14 vanished lattice burnup-averaged power distribution

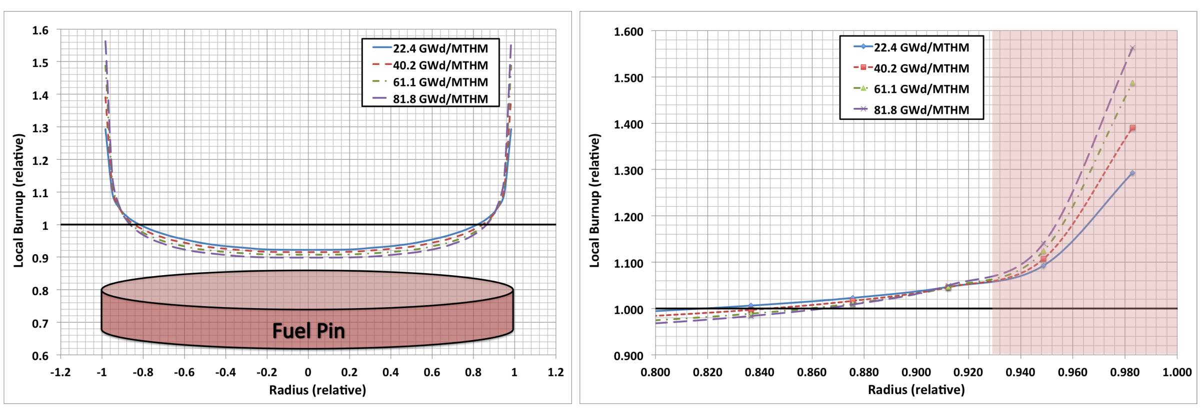
Figure 2. GE14 fuel assembly burnup-averaged relative power distribution with highest-power pins identified.

3.2. Analysis of the Radial Burnup Profile

The W17 high-power fuel pin identified in Figure 1 was modeled using 15 equal-area radial rings. A radial heat conduction model[3] was used to determine the fuel temperature in each of the radial rings so that the average fuel temperature (805 K) was reproduced. All other fuel pins in the lattice were modeled using a single depletion zone. I.e., only the fuel pin identified with the yellow box in Figure 1 was modeled with greater detail.

In Figure 3(a), the normalized radial burnup distribution in the pin was plotted for four burnup points corresponding to approximately 20, 40, 60 and 80 GWd/MTHM. The data were normalized to the average burnup. The burnup increases sharply near the outer edge, near the center of the fuel pin, the burnup is nearly constant. Figure 3(b) is a plot of the radial burnup distribution with the outer edge of the fuel pin is expanded to show greater detail. The 250 micron region near the edge of the fuel pin is highlighted with a red-shaded box. As seen in Figure 3(b), as the pin-average burnup increases, ratio of burnup in the other rim to the average burnup also increases.

Fuel pin depletion can be modeled only as the average over a finite volume, rather than at a singular point or along a line; consequently, the fuel depletion on the surface of a fuel pin cannot be directly calculated. However, a pin cell calculation using a greater number of rings showed that the fuel burnup very near the edge of the fuel pin (within the first 50 microns) could be as high as two times the average at high average burnup values. The research presented herein uses a 250 micron ring for additional analyses because the most significant variation in the radial burnup profile is captured by a ring of this size, as observed in Figure 3. A corresponding BWR fuel pin was not analyzed at the same level of detail, but it is expected that a similar radial burnup profile would be observed.



(a) Radial burnup profile

(b) Radial burnup profile expanded in the outer rim region, with the outher 250 μm highlighted in red.

Figure 3. Radial burnup profile in the PWR high-power pin for selected burnup points.

One item of interest is the level of modeling detail required to produce the proper burnup and isotopic distribution in the fuel rings. For the first part of this study, the fuel pin of interest was modeled in significant detail; 15 radial rings in the fuel region, additional rings in the water to increase spatial flux resolution, and a detailed temperature distribution were applied to the rings of the fuel pin to ensure accurate results. To further understand the impact of a more simplified modeling approach, a simple mini-lattice model (four fuel pins in total) was used to simulate the detailed fuel pin treatment and a more simplified treatment. In the simplified model, the fuel pin of interest was modeled with only two regions—the inner region consists of the 13 innermost rings in the detailed model, and the outer region consists of the 2 outermost rings in the detailed model. The additional rings in the moderator surrounding the detailed model were removed for the simplified model. The radial variation in temperature was also removed.

The detailed and simplified mini-lattice models were depleted to greater than 80 GWd/MTU, and the accrued burnup in the various regions in the pin of interest was examined. In particular, the burnup ratio within the fuel pin (ratio of outer ring burnup to inner ring burnup), which is a measure of how severely the burnup is skewed toward the edge of the fuel pin, was analyzed. The burnup ratio increased with increasing burnup, but the difference in the burnup ratio between the simplified and the detailed model was less than 0.5% over the entire burnup range tested; the simplified model predicted a slightly more skewed burnup profile than the detailed model. Overall, there is very little difference between the models. Based on these results it can be concluded that using two rings (one for the inner portion of the fuel pin and one for the rim region) may be sufficient to quantify the average behavior at the edge of the fuel pin. However, the size of the outer ring may vary for specific applications. This simulation also indicates that the radial burnup profile is relatively insensitive to a detailed radial temperature distribution.

3.3. Decay Characteristics

The fuel radioactivity and decay heat characteristics were also analyzed for the assembly average, the peak power pin, and the outer 250 micron region of the peak power pin. These results will be presented in the full paper.

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