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Bowing effects on isotopic concentrations for simplified PWR assemblies and full cores

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ABSTRACT

Fuel assembly bowing effects on isotopic concentrations during depletion are investigated for a range of full-scale fuel assembly bow models for Simplified Pressurized Water Reactor (PWR) assemblies and full cores. First, two-dimensional (2D) 3 × 3 assembly arrays with a central fuel assembly displaced are simulated using both CASMO-5 and SERPENT-2. Investigations are carried out on burn-up evolutions and horizontal re-distributions of nuclide concentrations resulting from assembly bowing effects. Longitudinal distributions of the fuel content changes are also illustrated by simulating a three-dimensional (3D) assembly bowed in C-shape with SERPENT-2. Progressive deformations, varied bowing magnitudes and orientations are considered as influential factors for studying the impact of bowing. Finally, by implementing a measured bowing map from an operating reactor, simulations for 2D PWR full cores are performed with CASMO-5 to reveal the bowing impacts in terms of assembly locations.

1. Introduction

Irradiation growth is a well known mechanism under which fuel pins and guide tubes can deform during reactor irradiation (Hofman et al., 1997). The elongation of the length of fuels and thimbles is constrained by forces exerted from the hold down springs and by the friction forces from the spacer grids. In PWR cores the deformation of fuel bundles is known as the assembly bow, while it is called the channel bow in Boiling Water Reactor (BWR) cores (Inozemtsev, 2010). The deformation of fuel assembly geometries can lead to incomplete control rod insertion and axial offset anomaly, for example. Compared to the observation of single pin bow (Schrire et al., 2014), assembly and channel bow are more commonly observed, characterized mainly by the inter-assembly pitch deformation.

Geometry changes are observed with a variety of deformation types (Jeon et al., 2012; Andersson et al., 2004). They can be simulated in a first approximation with constant deformations, progressive deformations as a function of the irradiation and abrupt changes between reactor cycles. They can result in modifications of the widths of inter-assembly water gaps. Due to the variations of fuel-to-moderator ratios, particularly at the peripheral pins of the assembly, pin depletion is affected by a change of the neutron flux spectrum and power distributions (Grimm, 2006). Simulations of such changes on fuel isotopic content can be useful for the understanding of Post Irradiation Examination (PIE) results and for uncertainty analyses in depleted fuels. With advanced evaluations on the isotope inventories, the spent fuel processing (such as transportation and storage) can be sensibly improved. In this paper we are performing simulations on bowing models used for PIE evaluation to help quantifying the impact of PWR assembly bow.

In comparison to the 3 × 3 PWR pin-cell lattice simulated in Li (2017), a full 3 × 3 PWR assembly array with a central assembly's geometry deformed has the benefit of being more representative of actual irradiation conditions and of reducing the effects of the imposed boundary conditions. With 2D models on the full assembly scale, comparisons of the simulation results from CASMO-5 and SERPENT-2 are presented for four specific isotopes: ^{235}U, ^{239}Pu, ^{244}Cm and ^{148}Nd. General characteristics and evolutions of the isotope inventories are illustrated for the assembly bowing models with UO_2 fuel and constant deformations along burn-up. Following the 2D models, a 3D constant C-shaped PWR assembly in a 3 × 3 assembly array is simulated with SERPENT-2 as well, for illustrat-

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ing the longitudinal distributions of bowing effects, as also presented in Li (2017) for a 3 × 3 pin-cell lattice.

In the next section, the bowing effects are investigated with CASMO-5 in PWR assembly models, using a progressive deformation type as a function of the burn-up values, various bowing amplitudes and orientations, respectively. Finally, by implementing a realistic bowing map measured from an operating reactor (Inozemtsev, 2010), simplified 2D full PWR core models are simulated with various bowing amplitudes and orientations for each assembly. The distributions of modeling biases are thereby illustrated on the full core layout to reveal the influence originating from varied local burn-up values.

2. Methodology and modeling

2.1. Simulation codes

CASMO-5, as a state-of-art physics lattice code using deterministic algorithms, is mainly used in this work (CASMO-5, 2012). It includes the ENDF/B-VII.0 nuclear data library (Chadwick et al., 2006) for 2D transport calculation, implementing 19 energy groups for UO_2 lattices. In this context, SERPENT-2 (SERPENT, 2015), as a stochastic code with Monte Carlo methodologies including the ENDF/B-VII.1 libraries (Chadwick et al., 2011), is used to verify the CASMO-5 results for the isotopic concentrations of the four mentioned isotopes.

Regarding the modeling capabilities, SERPENT-2 can model irregular assembly configurations in both 2D and 3D models. Due to its modeling flexibility, the displacement amplitude is only constrained by the contact of pins or assembly boxes. In the case of CASMO-5, the displacements of fuel pins cannot exceed the pin-cell boundaries in the PWR assembly models.

As for the computing requirements, CASMO-5 calculations are faster than the ones from SERPENT-2, which allows more extensive simulations in terms of the core size. One can also perform depletion calculations to higher burn-up values with finer burn-up intervals, given the existing limitations of the physical models.

2.2. Model configurations

In the 2D model of a 3 × 3 assembly configuration, the mechanical deformation is represented by the displacement of the central assembly with respect to the nominal position. With a displacement of the central assembly parallel to one of its borders, one can achieve assembly bow along a single orientation as sketched in Fig. 1. For a displacement occurring along two orthogonal borders simultaneously, a more realistic bowing model with an arbitrary orientation can be obtained. To visualize the displacement, only the regions adjacent to the central, displaced assembly out of the full 3 × 3 assembly model are shown in Fig. 1. The fuel compositions, assembly dimensions and operation conditions are listed in Table 1, same as the examples provided in the CASMO-5 manual for the MxN model (CASMO-5, 2012). For simplification, only fresh fuels in Table 1 are considered in the assembly array and full core models.

Each simulation case is composed of a bowing model and its corresponding nominal model without any deformation used as reference. All 2D calculations with SERPENT-2 and CASMO-5 were carried out with reflective boundary conditions. 2D and 3D simulations using SERPENT-2, are performed with the same neutron histories of 100,000 neutrons per cycle, 500 active and 250 inactive cycles inducing both statistical uncertainties of k_{eff} below 10 pcm (one standard deviation). To model the 3D C-shaped bow, each fuel pin with a full length of 320 cm in the central assembly is divided into 20 axial zones, as also performed in Li (2017).

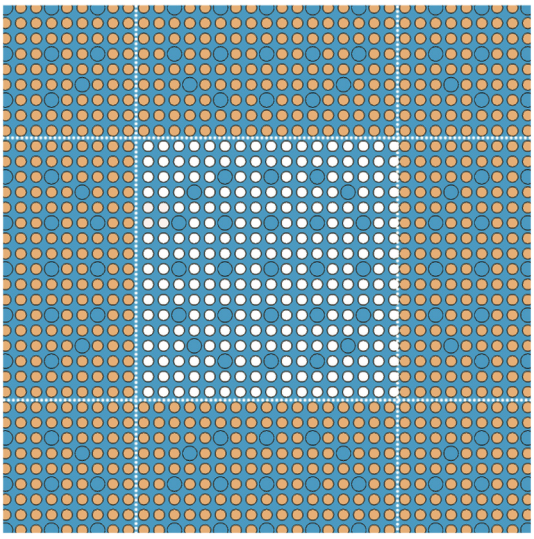

Fig. 1. A rightwards displaced central assembly and 8 surrounding assemblies with same UO_2 fuels (only regions adjacent to the central assembly are shown for PWR).

As for displacement magnitudes, rightward displacements of 1.5 mm for the assembly models are considered. For the full core models, displacements on each border are scaled from the bowing map to be no larger than 1.5 mm. These values are kept constant for the whole irradiation calculation. In assembly models, one progressive deformation is also investigated with a linear increase of the displacement as a function of the burn-up, starting with 0 mm at 0 MWd/kgU, and reaching 1.5 mm at the end of irradiation. For the 3D assembly simulations, amplitudes of the C-shaped bow follow a parabola function, starting with 0 mm at both fuel ends and evolving to 1.5 mm in the middle axial layer, similar to Li (2017).

All the simulation cases are listed below.

- Simulations of 2D nominal and constantly displaced models in a 3 × 3 assembly array using SERPENT-2 and CASMO-5,
- Simulations of 3D nominal and constantly C-shaped bowing models in a 3 × 3 assembly array using SERPENT-2,
- Simulations of 2D progressive and diagonal displaced models in a 3 × 3 assembly array using CASMO-5,
- Simulations of 2D PWR full core models containing 193 nominal or displaced assemblies with various constant amplitudes and orientations using CASMO-5,

Additionally, the assembly depletion calculations with CASMO-5 are performed up to 80 MWd/kgU, whereas the full core models stop at 20 MWd/kgU, both with burn-up intervals of 0.5 MWd/kgU after 1 MWd/kgU. With SERPENT-2 the burn-up calculations are performed up to 40 MWd/kgU. The burn-up intervals start with 0.5 MWd/kgU after 1 MWd/kgU, increase to 1 MWd/kgU after 15 MWd/kgU and to 2 MWd/kgU after 30 MWd/kgU.

3. 2D assembly bow

The bowing effects can be quantified by the relative deviations of the isotopic concentrations between the nominal and bowing models, as illustrated in the following equation:

$$\Delta_i = \frac{C_i^D - C_i^N}{C_i^N}, \tag{1}$$