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Progress of in-core fuel management system for PWR reactors: Use of macroscopic cross sections generated by SCALE 6.0 in a developed nodal code

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1. Introduction

Nuclear fuel management relates to the decisions pursuing the optimal strategy of fuel assembly (FA), replacement and reposition after each cycle of operation. It comprises three decisions: the choice of FA that are exhausted and will be withdrawn after an operational cycle; the position or reposition of the partially burnt fuel assemblies and the type and position of new FA to be inserted in the reactor. This operation aims to restore reactivity for a new operational cycle, optimizing the performance of the reactor and complying with all safety criteria. This whole process is known as In-Core Fuel Management (ICFM) (1).

In order to model and perform ICFM, a valid reactor physics code is required. This calculation code, which shall be very efficient (low computational time usage) due to large number of variables, constrains and viable solutions, interacts with the optimization algorithm (1). Therefore, a 2-dimensional (2D) coarse mesh nodal code, called NOD2ABC, was developed using the *nodal expansion method* (NEM) (2), solving the neutron diffusion equation with two energy groups, fast and thermal neutrons.

Inside the core of an active PWR reactor, there are several types of FAs with different enrichments, concentrations, burnable poisons and burnup conditions. Besides the FAs, the reactor operation is highly influenced by parameters such as fuel and moderator temperatures and boron concentration. Under these various conditions, the SCALE 6.0 code was used to homogenize the FAs characteristics based on the reactor's construction parameters and its operation condition. SCALE 6.0 is able to collapse homogenized macroscopic cross sections of FAs in two energy groups, which are used in the developed nodal code.

To validate the generated cross sections, an International Atomic Energy Agency (IAEA) benchmark was used (3). This benchmark presents calculations and experimental data from the Nuclear Power Plant Almaraz-II, currently in operation in Spain, which has a 2686 MWth thermal reactor. The published benchmark does not present the cross sections of the FAs, but describes the reactor operation, the position of the FAs at the beginning of reactor's life (BOL), the soluble boron concentration (C_b) for each reactor burn step and the k_∞ (infinity multiplication factor) calculations of each FA that will be used to compare with the calculations performed by SCALE 6.0.

The main objective of this work is to present the validation of the methodology used in the

generation of these homogenized cross sections, together with their use in the developed nodal code, NOD2ABC. This will also be validated using the benchmark available at (3).

This paper is organized as follows: the next section presents the Methodology used in this work. Results and Discussion are presented in Section 3, and the Conclusions can be found on Section 4.

2. Methodology

The elaboration of the library with the FAs' cross sections for several operating conditions is a very important step for the evaluation of the nodal code used in ICFM (4). In order to determine these cross sections it is necessary to collect operational data, dimensions and actual materials that compose each FA. Therefore, the cross sections of the FA's Almaraz-II were generated using SCALE 6.0. SCALE is a set of modeling and simulation suite for nuclear safety analysis developed by the Reactor and Nuclear Systems Division (RNSD) from the Oak Ridge National Laboratory (ORNL) (5). The cross sections were generated in two energy groups i.e. for fast and thermal neutrons.

The PWR core of Almaraz-II power plant has 157 fuel assemblies. For the first cycle, the distribution of fuel assemblies in the symmetric quarter of the reactor core in the BOL is shown in Fig. 1. Each FA has 264 fuel rods arranged in the form of 17 × 17 rods' slots, some of which has 12, 16 or 20 burnable poison rods (BPR). The structure of FA with BPR is shown in the Fig. 2 .

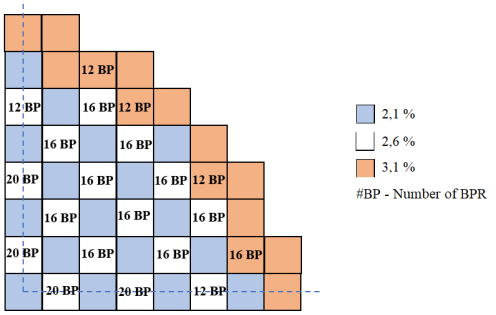

Figure 1: First cycle distribution of fuel assemblies in a symmetric quarter of Almaraz-II reactor's core

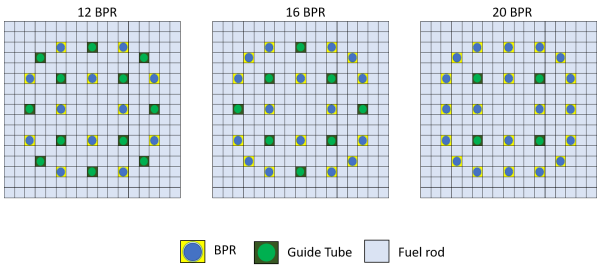

Figure 2: Burnable poison rod position in each FA

As shown in Fig. 1, the Almaraz-II core has three types of FAs with different enrichments, 2.1%, 2.6% and 3.1%. The element with 2.6% enrichment can have a set with 12, 16 or 20 rods with PYREX burnable poisons while the element with 3.1% enrichment will have only 12 or 16 BPR. The position of the BPR in the elements is shown in Fig. 2. More details of FA's composition, dimensions and operational conditions of Almaraz-II are available in IAEA benchmark (3).

There are six institutes that took part in Almaraz-II benchmark (3). Each of them evaluates k_∞ in a different way for each FA. Thus, the homogenized cross sections generated in this work by SCALE were compared to the average (avg.) of the evaluations of k_∞ performed in each institutes, along with their respective *standard deviation* (std.). In order to include more recent data from the Almaraz-II benchmark, the results of this work were also compared with the work of Pinem *et. al.* (3) and (4) evaluated with SRAC2006 program package (6).

The NOD2ABC was developed by the *nodal expansion method* (NEM) for this research. In NEM, for each node, the three-dimensional diffusion equation is integrated over transversal directions, generating one-dimensional equations for each direction in the Cartesian plane (7) and (8). These equations are solved by approximating a polynomial expansion of the fourth degree (7) and (8). With an iterative process, NEM is able to quickly and accurately provide the average of neutron fluxes at the nodes, neutron currents on the faces of these nodes and the effective multiplication factor.

3. Results and Discussion

The results obtained from modeling performed with SCALE 6.0 for the k_∞ value as a function of the fuel burnup are shown in the Figures 3 and 4. These figures present the result for one FA considering 2.1% enrichment with 1000 ppm of soluble boron concentration without BPR (Fig. 3) and another FA with the same enrichment and soluble boron concentration but with 12 BPR (Fig. 4). These calculations were performed under hot full power (HFP) conditions and the results were compared with average results found in Almaraz II benchmark, with their respective std. (3), and with SRAC2006 results (4).

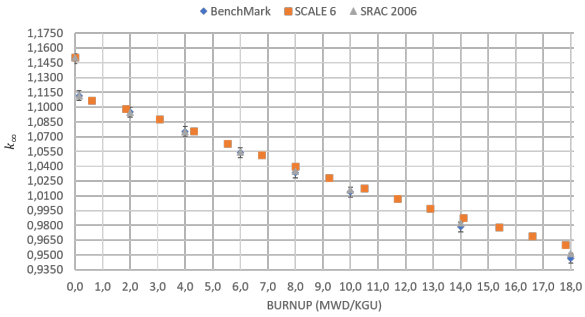

Figure 3: k_∞ value as a function of the fuel burnup for 2.1% enrichment FA, with 1000 ppm of boron

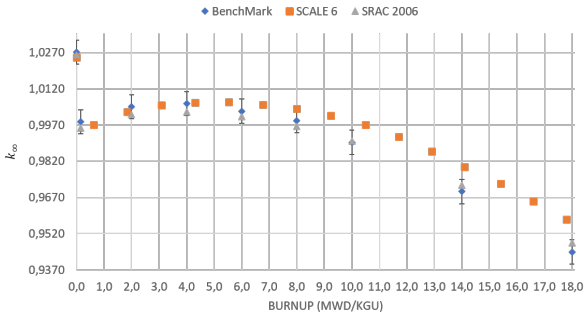

Figure 4: k_∞ value as a function of the fuel burnup for 2.6% enrichment FA, with 12 BPR and 1000 ppm of boron

NOD2ABC uses the cross sections generated for all types of FAs. Thus, it is possible to calculate the critical boron concentration curve as a function of the burnup of the entire first cycle of reactor operation. The distribution of FAs in the core of the Almaraz II reactor in the first operating cycle is shown in Fig. 1. Using the calculations of NOD2ABC, the soluble boron concentration results were compared with the Almaraz II benchmark as shown in Fig. 5.

4. Conclusions

Considering the results obtained with SCALE 6.0, the generated macroscopic cross sections constants for each FA according to its burnup level were considered acceptable. Using these cross sections, NOD2ABC was able to reproduce the soluble boron curve with minor punctual differences in some burnup level steps. So, it is concluded that the presented methodology was acceptable and with good accuracy. Thus, SCALE 6.0 code and NOD2ABC can be used in the ICFM proposed methodology, that will be applied in future works.

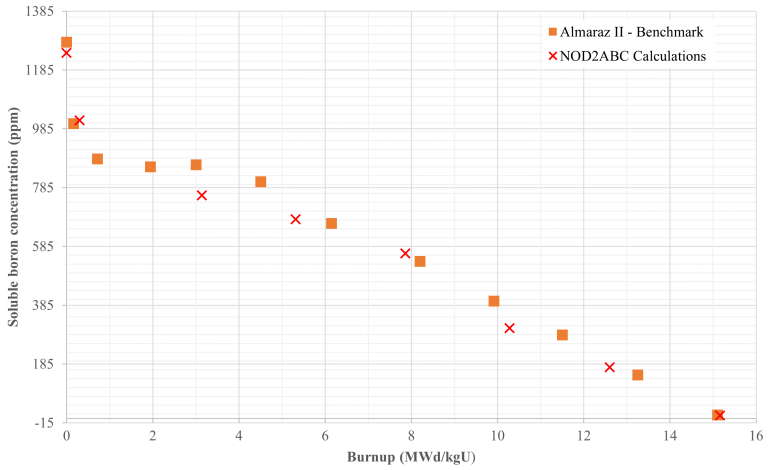

Figure 5: The critical boron concentration curve as function of the burnup for Almaraz-II first cycle

Acknowledgments

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