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Use of Effective Diffusion Homogenization method with the Monte Carlo code for light water reactor

Dušan Ćalić [a,*], Andrej Trkov [b], Marjan Kromar [a], Luka Snoj [a]

[a] Reactor Physics Division, Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[b] International Atomic Energy Agency, Vienna International Centre, PO Box 100, A-1400 Vienna, Austria

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ABSTRACT

The use of Monte Carlo transport method with the Serpent code for generating unit cell cross sections of a light-water reactor is investigated. The geometry is a 3 × 3 array of cells, where homogenization is performed over the central cell, while the neighboring cells represent a kind of color-set scheme to model the radial leakage from the central cell. Instead of the default homogenization method of Serpent, the Effective Diffusion Homogenization method is applied externally, which conserves reaction rates, as well as the boundary partial currents of the central cell. The exercise serves to explore the potential of the Monte Carlo method for core design calculations and to validate and improve the existing computational scheme in which unit-cell calculations are based on the 1-D deterministic transport model in the WIMSD code. The cross sections by both methods are compared and applied to predict the hot-zero-power critical boron concentration and radial power distribution of the Krško NPP in comparison with measured values. The results confirm applicability of Monte Carlo transport calculations with EDH homogenization at the unit-cell level and warrant further extension to burnup and whole-assembly Monte Carlo modeling, at least for validation purposes due to present computational time constraints.

1. Introduction

The Krško nuclear power plant (NPP) is a 2-loop Westinghouse pressurized water reactor (PWR). Recently it has completed its twenty-seventh cycle of operation. Since its operation an independent design verification program has been performed at the Jožef Stefan Institute using the WIMSD–GNOMER system to ensure safe and reliable operation within the limits of the technical specifications. WIMSD–GNOMER is designed to provide an independent computational tool that can be used for simple fast calculations (fuel management) as well as for accurate calculations (reloads core design). WIMSD (Askew et al., 1966) is a deterministic lattice code for cell calculations and GNOMER (Trkov, 2008) is the neutron diffusion code developed at the Jožef Stefan Institute used for fuel assembly and core calculations. The unit cell and fuel assembly cross section homogenization method employs the so-called Effective Diffusion Homogenization (EDH) method, which was first elaborated by Trkov and Ravnik, 1994 and is a special case of the Simplified Equivalence Theory (SET) method, developed by Koebke, 1978. It demands conservation of reaction rates as well as surface partial currents in an average sense. Instead of the conventional color-set scheme to treat the radial leakage from a fuel assembly, the critical albedo search is implemented. However, the old WIMSD one-dimensional lattice transport code has limitations. Beside the Serpent-developers group the use of advanced Monte Carlo methods for the generation of group constant for fuel assemblies has been reported by many authors in the literature (Hursin et al., 2013; Ghasabyan, 2013; Hall et al., 2013). The Serpent code (Leppänen et al., 2015) seems to be a convenient tool for such purposes. The main purpose of the present investigation is two-fold (i) identify the magnitude of the errors introduced by the simple 1-D transport models of the WIMSD code and tune WIMSD input parameters to empirically compensate the deficiencies as much as possible, which will allow continued use of the present computational system for routine applications, and (ii) explore the potential of the Monte Carlo method for routine core design calculations in terms of increased accuracy and in view of the computational time penalty. The calculation time is not directly comparable due to the different computer platforms used in Serpent and WIMSD calculations. Usually the difference is at least three orders of magnitude. To achieve these objectives the geometrical models used for WIMSD were not changed. Namely, homogenization of lattice-cell cross sections is done for the central cell in a 3 × 3 array of cells, where the outer cells always represent the fuel. Such a model allows direct comparison with the existing

* Corresponding author.
E-mail address: dusan.calic@ijs.si (D. Ćalić).

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WIMSD–GNOMER scheme and is convenient for studying fuel burnup effects. Extensions to explore homogenization over the entire fuel assembly will be the subject of future research.

The paper is organized as follows: in section two the calculation model is described, section three presents the computer codes overview, section four describes the homogenization method, section five covers the results and in section six the conclusions are presented.

2. Calculationals models

2.1. Unit cell model

In the WIMSD–GNOMER system the geometry model (Fig. 1) is analogous to a 'color-set' scheme to obtain homogenized group constants for the central cell, surrounded by fuel cells. The EDH homogenization preserves the reaction rates as well as partial currents between the central cell and its neighbors. To conserve the whole-core fuel-to moderator volume ratio, a region consisting of water and smeared guide thimble material is added around the 3×3 cluster when calculating the homogenized cross sections of a fuel cell. The fuel unit cell consists of the following cylindrical regions: fuel, gap, cladding, effective (axially-smeared) spacer grids and water.

In the first part of this paper the comparison between Serpent and WIMSD group cross sections using the EDH method are presented for typical fuel used in the Krško nuclear power plant. Three different cases are considered, typical for cycle 1 operation: fuel cell, water cell (empty guide thimble that usually contains control rods and other inserts, like burnable poison rods), and burnable poison rod cell (BPR). The comparison is made for hot zero power (HZP) conditions with all control rods withdrawn (ARO) and fuel enrichment of 2.614%, boron concentration 1445 ppm, fuel temperature 564.8 K and water density 0.7433 g/cm^3. The EDH homogenization is applied on the central cell only; the surrounding cells serve only to determine the radial leakage from the central cell, which is also conserved by the EDH method. In this way the efficiency of the EDH method can be tested on three typical cases encountered in core calculations.

2.2. Fuel assembly model

The cross sections that are calculated in the first step are then used in an array of homogeneous cells that constitute a fuel assembly (Fig. 2). Most of the cells contain fuel, but there are some which contain only guide tubes filled with water or BPR rods.

The results from the fuel assembly calculation are then used on global core power distribution and critical boron concentration

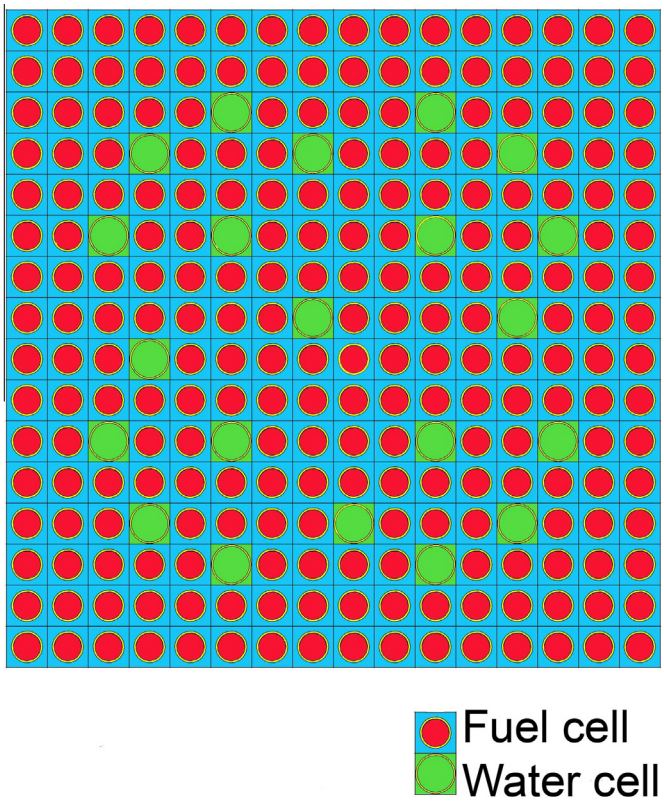

Fig. 2. Fuel assembly model.

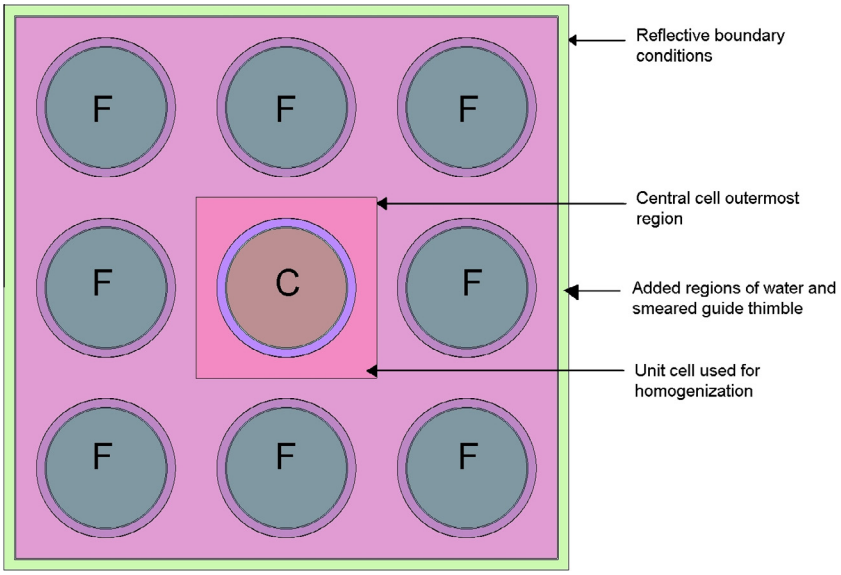

Fig. 1. PWR lattice model with a central cell (C) and surrounding fuel cells (F).