ABSTRACT

The Serpent-GNOMER code sequence was validated for Krško NPP using first fuel cycle in 2015. This is a three step sequence where we applied the Monte Carlo method to obtain the cell homogenized cross sections and to use them in fuel assembly calculations. The results showed good agreement between the Serpent-GNOMER simulation and the reference WIMSD-GNOMER calculation. This study also showed that the difference in computational time is about 3 orders of magnitude so for routine calculations the computational time must be shorter.

Shorter calculational time can be achieved using a new approach that will be developed in the following years. In this new approach we will obtain the cell homogenized cross sections in fuel assembly calculations and to use them in full core nodal diffusion calculation. In recent years we have learned that it is very important to have a really good reference results. We will compare the results with the MIT BEAVRS benchmark, which provides a detailed description of a commercial PWR with a lot of experimental measurements.

In this paper the results of 3D heterogeneous model of the full core using a Monte Carlo code Serpent 2 will be presented using zero power conditions and fresh core configuration.

1 INTRODUCTION

Full core calculation has been performed using the WIMSD-GNOMER (WG) system to ensure safe and reliable operation of the Krško Nuclear Power Plant within the limits of the technical specifications since its operation. The WIMSD-GNOMER was 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). The WIMSD [1] is a deterministic lattice code for cell calculations and GNOMER [2] 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 homogenisation method employs the so-called Effective Diffusion Homogenization (EDH) method, which was first elaborated by Trkov and Ravnik [3].

Advances in computer capabilities enable us to use more sophisticated methods and models to improve and validate the existent models. Therefore new approach was developed where the existent WIMSD code for lattice cell calculations was replaced with sophisticated Monte Carlo code Serpent 2 [4]. The homogenization procedure was developed using the effective diffusion homogenization method (EDH), to obtain the cell homogenized cross sections to use them in fuel assembly model.
The first results of the Serpent-GNOMER (SG) code coupling was investigated for Krško NPP fuel cycle [4]. Three-step procedure using Serpent-GNOMER calculations were compared to results obtained from established deterministic WIMSD-GNOMER calculation. The results turned out to be in good agreement at HZP and HFP conditions. The accuracy of the power distribution results at HZP using SG simulation was close to the accuracy of the WG simulation with an average difference being around 0.5 %. At HFP and burnup conditions the differences in critical boron concentration were mostly less than 50 ppm, compared to the measurements and WG simulation. It was shown that the difference in computational time is about 3 orders of magnitude. Replacing the present transport solver with a Monte Carlo solver and using conventional three step procedure is still out of the question for routine calculations.

The next step is to develop the sequence that is commonly used by other research institutes. The most extensive work has been carried out with the Serpent-DYN3D [5] code sequence. In these studies, assembly group constants are generated using Serpent code to use them in DYN3D nodal diffusion code. The sequence is used for modeling the hot zero power (HZP) conditions of various PWR and SFR cores. Other similar comparisons include full-scale calculations with Serpent-PARCS [6] and assembly-level comparisons to CASMO-5 [6] and DRAGON codes [7].

The best available reference solution for the homogenized full-core calculation is the modeling of the 3D heterogeneous problem by using Monte Carlo method. This approach has one disadvantage. Due to the limitation of the computational resources it is not sufficient for performing the coupling between neutronics and thermal hydraulics calculations, therefore the validation is limited to the analyses of zero-power conditions and initial cores.

This paper is the first publication in a study involving the validation of the Serpent-GNOMER code sequence for PWR fuel cycle simulations, including comparison to experimental data provided in the MIT BEAVERS benchmark [8] problem by performing homogenization on fuel assembly level. In this paper, the HZP condition of the initial core reference calculations using 3D Monte Carlo model are presented.

2 BEAVERS BENCHMARK

The benchmark for evaluation and validation of reactor simulations (BEAVRS) was initiated by the research group at the Massachusetts Institute of Technology (MIT). The goal was to provide a test case for the validation of 3D Monte Carlo methods. The benchmark test case provides a detailed description of a commercial 1000 MW Westinghouse PWR reactor core. Operating history for the first two cycles, together with experimentally power distributions and control rod bank worths are given.

Reactor core is loaded with 193 fuel assemblies with pin lattice configuration \(17 \times 17\) and three fuel regions enrichments: 1.6, 2.4 and 3.1 wt.% U-235. The active fuel height is 365.76 cm and 264 fuel rods inserted in the core. In cycle 1 the burnable poisons in the form of borosilicate glass burnable absorber pins containing 12.5 % \(B_2O_3\) was used for partial control of excess reactivity. There were a total of 1266 burnable poison rods inserted in the guide tubes of fuel assemblies in 5 configurations. Also Ag-In-Cd control rods clusters are divided in 4 control and 5 shutdown banks. Axial flux profiles are measured at 58 assembly positions. The fuel loading pattern for cycle 1 is shown in Figure 1.
Figure 1: Core loading pattern and burnable absorber positions for cycle 1.

3 SERPENT CODE

Serpent is a Monte Carlo reactor physics code [9]. Development started at VTT Technical Research Centre of Finland nine years ago, and since its public release in 2009, the code has gathered an active user community of more than 250 users in 100 organizations in 28 countries around the world. The Serpent code is used in different nuclear fields: group constant generation and fuel cycle studies, full Monte Carlo research reactor modeling and in coupling multi-physics calculations.

Serpent 2 is still in a beta-testing phase, and available to licensed users of Serpent 1. Development of Serpent 2 started due to the difficulties in memory handling in Serpent 1. In Serpent 2 the unionized energy grid approach in lattice physics calculations was made optional, and different optimization modes were introduced for large and small burnup calculation problems. Parallelization is based on the combination of MPI and OpenMP, which is a shared-memory parallelization technique that allows dividing the calculation into multiple threads within the same computational unit, without increasing the overall memory demand. Test calculations on a modern PC workstation with 96 GB of memory have shown that Serpent 2 can handle 200,000 depletion zones in burnup calculation, without limitations in parallelization [10].
4 CALCULATIONS

In order to successfully model BEAVRS experiment a detailed 3-D Serpent model was constructed where the core configuration is changed and adjusted to the experimental configuration. 3-D Serpent model is presented in Figures 2 and 3 where the core is surrounded with baffle, barrel, neutron shields, pressure vessel and container.

In the axial assembly model, a fuel assembly is divided into several axial zones to represent the fuel rod elements and assembly support structures such as the spacer grids, upper plenum, fuel end plug, bottom supporting plate and upper nozzle. Axial configuration was modeled in detail, total of 35 axial planes with a very heterogeneous plane structure was included.

![Figure 2: Geometrical model (xy view) of the BEAVRS reactor using Serpent code.](image-url)
Figure 3: Geometrical model (xz view) of the BEAVRS reactor using Serpent code.

4.1 HZP Core Calculations

The benchmark specification provides various measured data such as critical boron concentration, control rod bank worth, isothermal temperature coefficients, and in-core detector signals. In this paper only the criticality comparison is made for the first cycle data. The analyses was performed with 50 inactive and 250 active cycles of $10^5$ neutrons using 2.67GHz Intel Xeon CPU.

The core reactivity was calculated for the given measured boron concentration (Cb), 975 ppm, and for the all rod out (ARO) case. Inlet coolant temperature was 566.5 K. Table shows the results of the criticality calculations.

Table 1: Comparison of criticality calculation at 1st cycle HZP with the measurement.

<table>
<thead>
<tr>
<th>Measured Cb [ppm]</th>
<th>Serpent</th>
<th>$\Delta k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARO 975</td>
<td>1.00016 ± 0.00014</td>
<td>16 ppm</td>
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For the all rod out case, three dimensional Serpent model gives an excellent prediction of criticality with only 16 ± 14 pcm difference. From the given results, we could conclude the the Serpent Monte Carlo modeling was made properly and that the code can estimate the core reactivity of the BEAVRS benchmark accurately for the given HZP condition.
5 CONCLUSION

In this paper the first phase of the study, involving the development of Serpent-GNOMER code sequence is presented by calculating the reference solution using Monte Carlo method of 3-D BEAVRS benchmark. Only the HZP conditions with all rods out was calculated. The comparison of the Serpent results with the measurement data proved the solution accuracy in criticality is less than 50 pcm for a given criticality core configuration.

REFERENCES


