2011 International Nuclear Atlantic Conference - INAC 2011
Belo Horizonte,MG, Brazil, October 24-28, 2011
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
***ISBN:* 978-85-99141-04-5**

IPEN/MB-01 Heavy Reflector Benchmark Calculations using Serpent Code

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ABSTRACT

A series of critical experiments with water-moderated square-pitched lattices with low-enriched uranium fuel rods was conducted at the IPEN/MB-01 research reactor facility, in 2005. Later, this data become some benchmarks. In one of these experiments the west face of the reactor core was covered with a set of thin SS-304 plates to simulate a heavy reflector as used in the EPR reactor (LEU-COMP-HERM-043). The plates are 3 mm thick and their width and axial length were large enough to cover one whole side of the active core of the reactor. The critical configurations were found as a function of the number of plates. Fuel rods containing UO_2 with uranium enriched to 4.3% ^{235}U were arranged in specific geometric configurations to be as close as possible to the critical state.

In this work, these benchmark configurations with heavy reflectors were modeled using the Serpent Monte Carlo Code. Serpent uses a universe-based geometry model, which allows the description of practically any three-dimensional fuel or reactor configuration. Neutron transport is based on a combination of surface-to-surface ray-tracing and the Woodcock delta-tracking method. Woodcock method is many times faster than ray-tracing, so compared to MCNP code, Serpend code can bring huge gains in processing time of reactor calculations and reaction rate calculations.

The results of these calculations were compared with experimental data and calculations with codes MCNP5 and SCALE6 (KENO-VI) using ENDF/B-VII.0 as cross-section input data. The codes performances are compared in terms of CPU calculation time and agreement with experimental data. Additionaly, sensitivity on keff of Serpent woodcock threshold parameter was analyzed.

1. INTRODUCTION

In order to produce some benchmarks in the field of reactor physics, a series of experiments were conducted at the research reactor IPEN/MB-01 in 2005 [1]. In one of these experiments

ISBN: **978-85-99141-04-5**

the west face of the reactor core was covered with a set of stainless-steel thin plates to simulate a heavy reflector, as used in the EPR reactor (LEU-COMP-THERM-043) [2].

Nine critical configurations were evaluated and they were accepted as benchmark experiments. These configurations consist of essentially square, uniform lattices of stainless-steel-clad cylindrical fuel rods immersed in light water with the west side covered with a changeable number of 3 mm thick SS-304 plates . The pitch of the rods is 15.0 mm, which is close to the optimal pitch (maximum $k\infty$).

The configurations included the presence of a specified number of stainless steel (SS-304) and Gd_2O_3 (gadolinia) rods to compensate the withdrawal of control rods of the active region of the core. The fuel rods, stainless steel rods, and Gd_2O_3 rods were appropriately distributed in the core such that criticality could be established. Thirty-two (32) plates were used in the experiment, so the critical configurations were found as a function of the number of plates.

In these benchmarks, the code MCNP-4C with continuous energy data library ENDF/B-VI was used to compare experimental data with calculations resulting in differences of approximately 300 pcm or 3σ.

In this work, these benchmark configurations with heavy reflectors were modeled using the Serpent Monte Carlo Code [3] in order to estimate neutrons multiplication factors and flux distribution. Serpent uses a universe-based geometry model, which allows the description of practically any three-dimensional fuel or reactor configuration. Neutron transport is based on a combination of surface-to-surface ray-tracing and the Woodcock delta-tracking method [4]. Woodcock method is many times faster than ray-tracing, so compared to MCNP code (which uses surface-to-surface), Serpent can bring huge speedup in processing time of reactor calculations.

2. THE SERPENT CODE

Serpent is a three-dimensional continuous-energy Monte Carlo (MC) reactor physics code which has a built-in burnup calculation capability. It has been developed at VTT Technical Research Centre of Finland since 2004 and has been publicly distributed by OECD/NEA Data Bank and RSICC since 2009. Recently, the code is gaining the international community attention being already used by 43 organizations in 20 countries around the world.

From geometrical point of view, Serpent is similar to other MC codes (e.g. MCNP and KENO) as it uses a universe-based geometry model that allows the description of complicated three-dimensional reactor geometries (e.g. ATR reactor [4, 5, 6]).

One of the main advantages of Serpent, however, is the option to combine Woodcock delta-tracking with ray-tracing for neutron transport. In traditional ray-tracing MC, the collision distance has to be adjusted each time the neutron enters a new region with higher or lower interaction probability so the distance to the nearest boundary surface has to be calculated each time the next collision site is sampled. The calculation of the surface distances demands

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a major part of the computational time especially if the neutron mean free path is long compared to the characteristic dimensions of the geometry.

The key idea in the delta-tracking method is to add an appropriate virtual collision cross-section to each material total cross-section in such a way that the modified total cross section has the same value in all materials. The result is that the total interaction probability, in this case the sum of real and virtual collision probabilities, is the same in all materials. This eliminates the need to calculate the free path length each time the neutron enters a new material, and eventually, the need to calculate the surface distances. The problem of calculating the shortest optical surface distance is reduced to the calculation of in which cell the collision point is located. Consequently, the neutron flight direction plays no role and the maximum number of free variables is reduced from six to three.

The combination of surface-to-surface ray-tracing and the Woodcock delta-tracking method can speedup the simulation up to 20 times for PWR calculations without losing accuracy [4]. This overcomes the efficiency problems normally encountered with delta-tracking in the presence of localized heavy absorbers. On the other hand, the main drawback of delta-tracking is that the track-length estimate of neutron flux is not available and reaction rates have to be calculated using the potentially less-efficient collision estimator.

The selection between the two methods is made by comparing the neutron mean-free-path produced by the majorant to the physical value given by the material total cross section.

$$\frac{l_{\mathrm{maj}}(E)}{l_m(E)} = \frac{\Sigma_{\mathrm{tot},m}(E)}{\Sigma_{\mathrm{maj}}(E)} > 1 - c\,,$$

If the path length is sampled using the majorant and the rejection sampling is carried out at the collision point (delta-tracking). In the opposite case, when the ratio between the physical cross section and the majorant is less than (1-c), the geometry routine calculates the distance to the nearest material boundary, samples the path length using the physical total cross section, and stops the neutron at the surface if the boundary is crossed (surface-to-surface). Constant *c* is the pre-defined cut-off criterion with value between 0 (no delta-tracking) and 1 (full delta-tracking mode).

From the physical interaction point of view, Serpent reads continuous-energy cross sections from MCNP ACE format data libraries. The interaction physics is based on classical collision kinematics and ENDF reaction laws and unresolved resonance cross sections can be sampled from probability tables.

Serpent also uses a unionized reconstruct energy grid for all reaction modes. This approach speed-up the calculation at the cost of large memory consumption, that may be a problem in burnup calculations and in parallel processing with Message Passing Information (MPI). In Serpent, parallelization is implemented by dividing the neutron histories to several tasks and combining the results after the transport cycle.

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Serpent has been extensively validated in LWR lattice calculations [5,6]. Effective multiplication factors are within the statistical accuracy from reference MCNP results, when the same ACE libraries are used in the calculations. Differences to other Monte Carlo codes (Keno-VI) are small, but statistically significant discrepancies can be observed in some cases due mainly to differences in SCALE/AMPX cross section processing [7, 8].

For real 3D reactors, however, the Serpent validation is scarcer. In this context, this work aims to perform the validation of Serpent by simulating the LEU-COMP-THERM-043 benchmark of the International Criticality Safety Benchmark Evaluation Project.

3. METHODOLOGY

3.1. The IPEN/MB-01 Research Reactor

The IPEN/MB-01 reactor is a zero power critical facility specially designed for measurement of a wide variety of reactor physics parameters to be used as benchmark experimental data or checking the calculation methodologies used to design a nuclear reactor and related nuclear data libraries commonly used in the field of reactor physics. The IPEN/MB-01 reactor reached its first criticality on November 9, 1988 and since then it has been utilized for basic reactor physics research and as an instructor laboratory system. This facility consists of a 30x30 rectangular array inside a light water tank. The UO_2 fuel rods 4.3% enriched and cladded by stainless steel (SS-304) are distributed in this array to study the possible critical configurations. The control banks are composed by 12 Ag-In-Cd rods and the safety banks by 12 B_4C rods (see Figures 1 and 2). The pitch of the IPEN/MB-01 reactor was chosen to be close to the optimum moderator ratio (maximum k_∞). This feature favors the neutron thermal energy region events and at the same time provides the isothermal reactivity coefficient of the IPEN/MB-01 reactor core with an inversion point (approximately 14°C).

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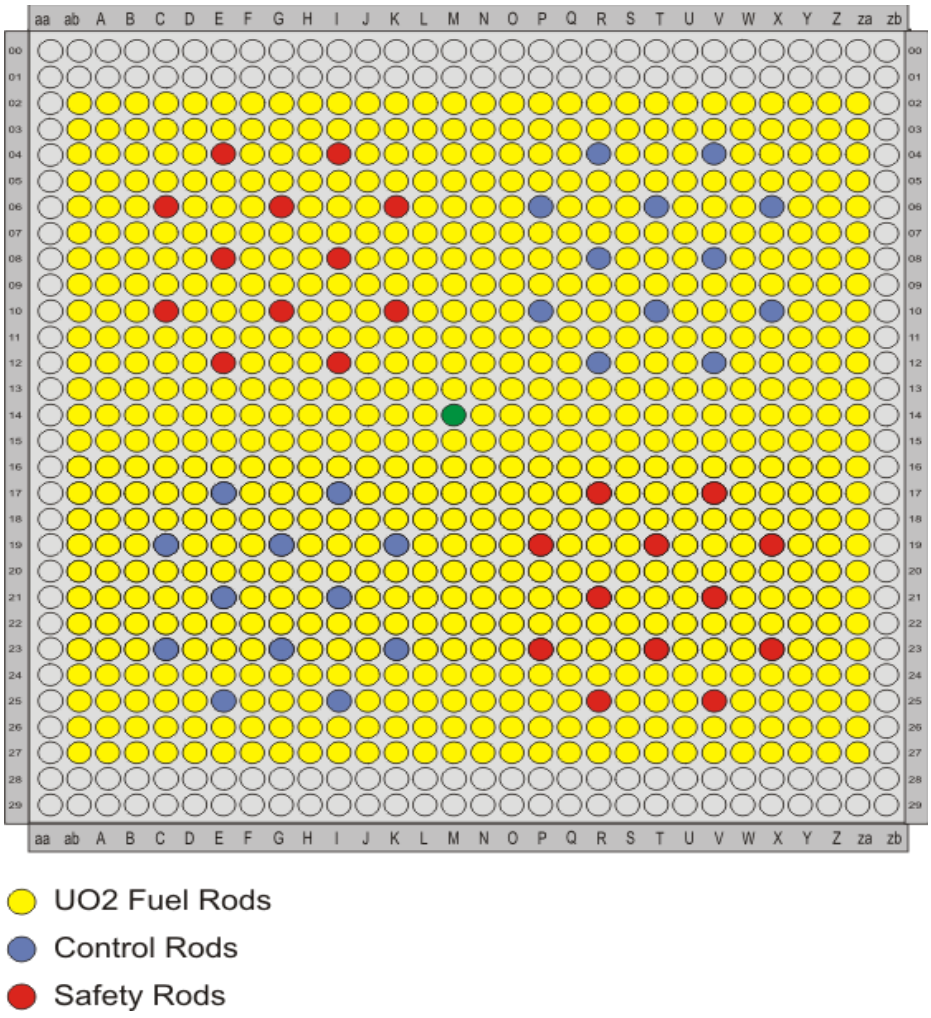

Figure 1. Upper side view of IPEN/MB-01 reactor

The control bank at the upper right corner is named BC1 while the one at lower left corner is named BC2. The control/safety bank position is given in % withdrawn. The reference level or zero for the withdrawn position occurs when the bottom of the active absorber length (excluding the bottom plugs) is aligned with the bottom of the fuel region. The uppermost position (100 % withdrawn) is the top of the fuel region. During the reactor operation both of the safety banks are kept far away from the 135 % withdrawn position (35% above of the fuel region) and the control banks can both be withdrawn from the bottom of the fuel region but the fine criticality control is made with just one of them.

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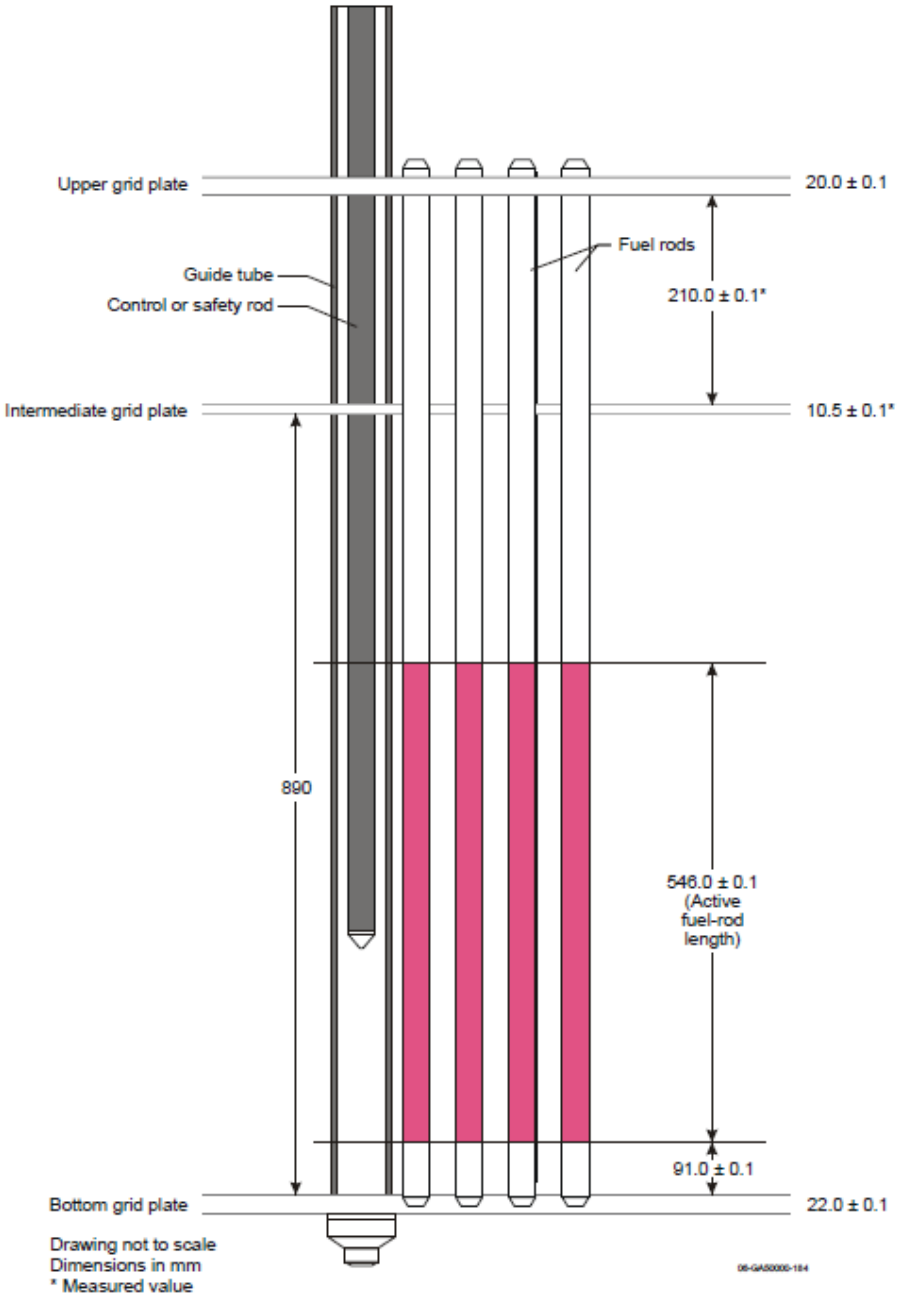

Figure 2. Schematic Side View of the Rods.

3.1.2 The SS-304 Plates

The SS-304 plates were specially designed to simulate a heavy stainless steel reflector. The SS-304 plates were cut in a special laser machine in order to achieve a very precise geometric definition and dimensions. The mean value of the plate thickness along with its standard deviation is 3.01375 ± 0.00907 mm. Figure 3 shows details of its geometric design.

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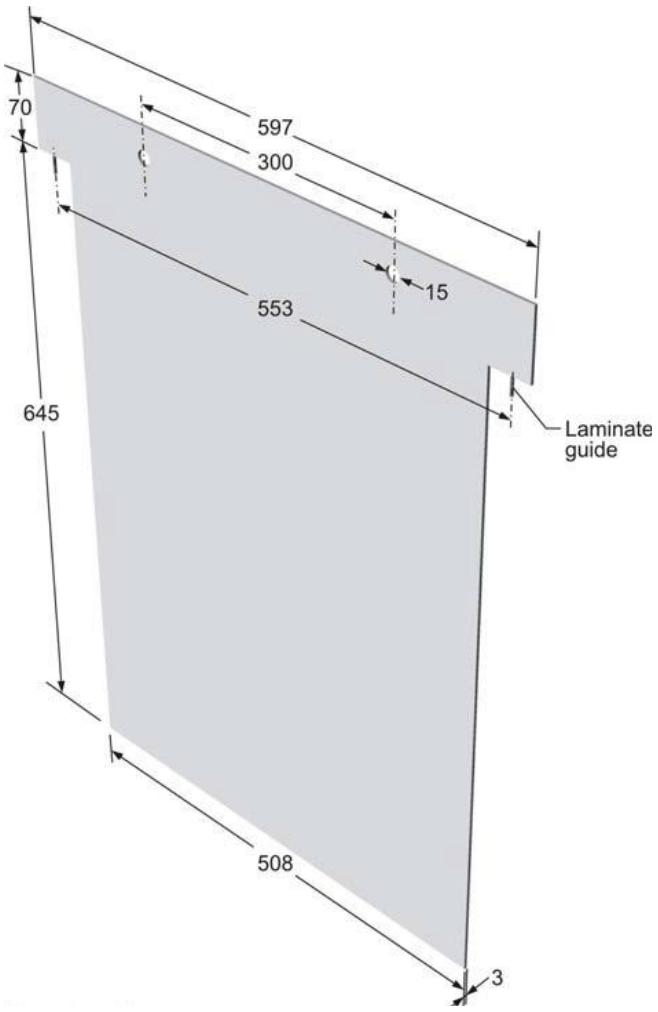

Figure 3. Schematic View of the Geometric Details of the Plates.

3.2 Critical Configurations for Calculation

Nine critical experiment configurations are considered in the benchmark evaluation. The experiment was designed to fulfill a specific need where neutron reflection is important for the criticality of the system. A reactivity meter was utilized for the accurate determination of the reactivity. This equipment was set up for a dual mode of operation, picking up the signals from two compensated ionization chambers (CIC).

All configurations were based on the 30 x 30 array of available positions in the grid plates. For all the configurations considered, the control and safety rods were kept totally removed from the core. By the design criteria, the safety rods are kept in a removal position 35 % (~19 cm) above the active core. The control rods are also totally removed, but, as mentioned previously, when the control rods are at their uppermost position the bottom surface of the absorber coincides with the top of the active core. The bottom plug remains inside the active core. To compensate the excess of reactivity in the core due to the removal of the control rods Stainless Steel rods and Gd_2O_3 rods were inserted in the core and in some cases UO_2 rods

ISBN: 978-85-99141-04-5

were removed from the ends of the active region. Table 1 shows some aspects of the 9 critical configurations. Figures 4 and 5 show cases 1 and 9 of critical configurations that were modeled with Serpent Code and SCALE 6. Cases 2 to 8 can be viewed at LEU-COMP-THERM-043.

Table 1. Characteristics of the nine critical configurations

Case	Fuel Rods	Gd_2O_3	Stainless Steel Rods	Empty Positions (a)	Number of Plates
1	654	4	0	194	32
2	674	6	0	172	32
3	674	6	0	172	24
4	664	4	0	184	24
5	672	4	0	176	18
6	674	4	2	172	18
7	676	4	0	172	9
8	676	4	0	172	5
9	674	4	2	172	1

a. Each configuration is based on a 30 x 30 array. The empty positions are those positions that are not occupied by a fuel, control, safety, or stainless steel rod. The empty positions are filled with water, except the 30 positions covered by the SS reflector plates.

In all cases, the temperature of the system is in the range 21.0 ± 0.4 °C and with the absolute value of the reactivity less than 15 pcm.

3.3 Calculation Features

The calculation with Serpent and SCALE (KENO) were performed using ENDF\B-VII.0 as cross-section input data with probability tables for unresolved resonances processed at 300K, which are very close to the experimental temperature.

Calculations with Serpent were performed in a parallelized SGI Cluster with 21 Intel Xeon CPU E5520 2.27GHz cores. In all cases the number of cycles was set up to 1900 with 2 x 10^6 histories generating an approximated error of 2 pcm in K_{eff}. The probability threshold for delta-tracking [4] was tested and analyzed. Delta-tracking threshold was set to 0.9 in cases 1 to 9. The approximated time for each of nine cases was 16.5 hours.

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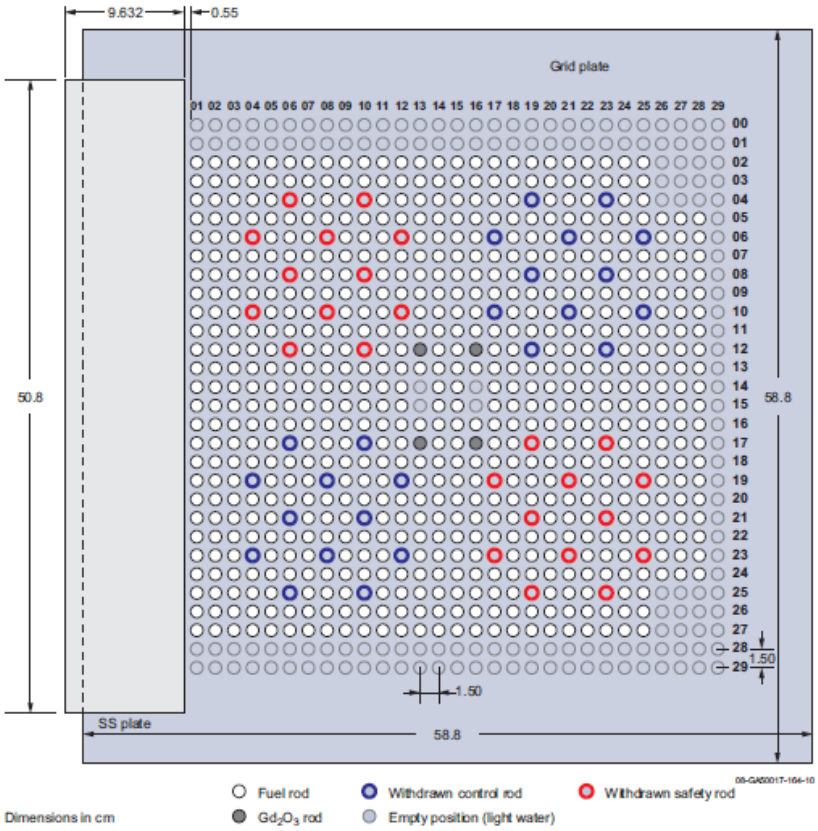

Figure 4. Critical configuration of Case 1.

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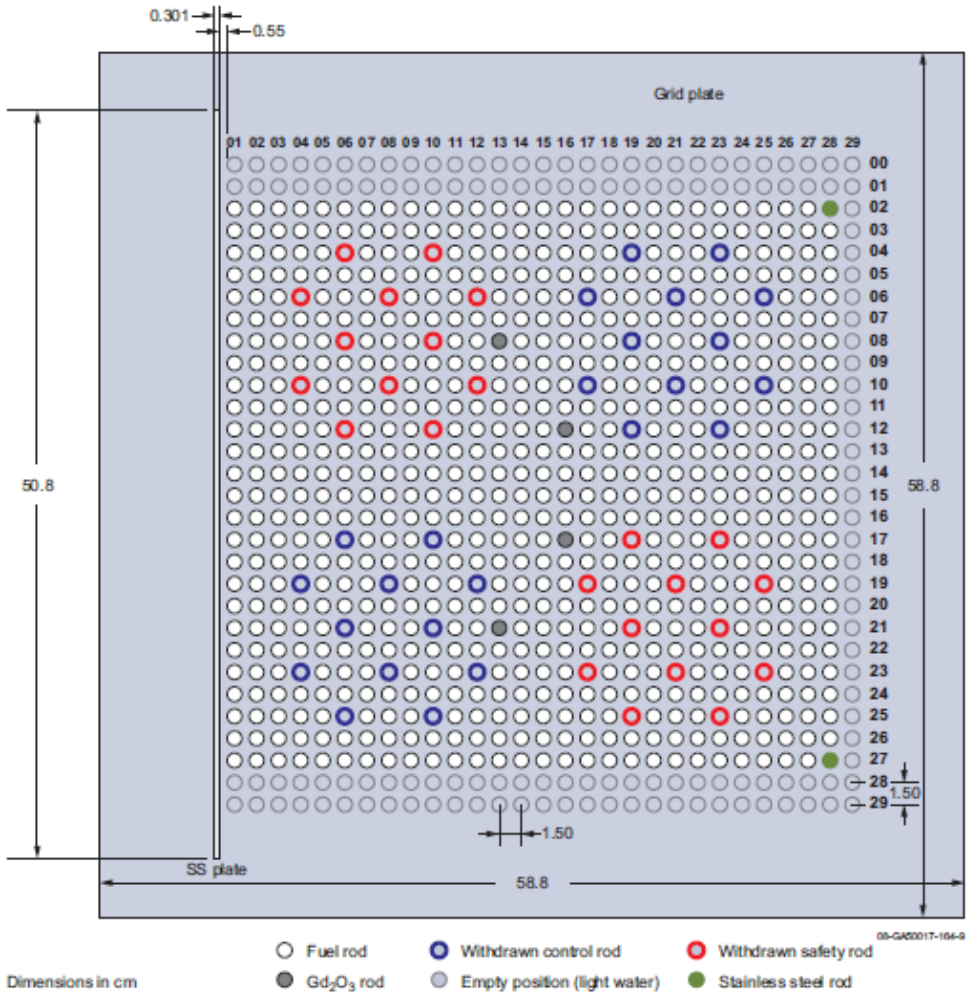

Figure 5. Critical configuration of Case 9.

4. DISCUSSIONS AND RESULTS

The main objective of this work is to verify the efficiency of Serpent Code in calculations of K_{eff} in core configurations that have heavy reflectors. Results obtained in Serpent are presented in the following table.

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Table 2. K_{eff} Values obtained with SERPENT

Case	Number of plates	K_{eff}	σK_{eff}	Total CPU Time (s)
1	32	1.00176	0.00002	2.04×10^4
2	32	1.00207	0.00002	2.00×10^4
3	24	1.00071	0.00002	2.01×10^4
4	24	1.00186	0.00002	2.03×10^4
5	18	1.00207	0.00002	2.03×10^4
6	18	1.00212	0.00002	2.05×10^4
7	9	1.00179	0.00002	2.03×10^4
8	5	1.00158	0.00002	2.05×10^4
9	1	1.00172	0.00002	2.05×10^4

The results of the calculations with Serpent and SCALE are compared with experimental and calculated results (MCNP with ENDF/B-VI). The following table shows the comparative results of all calculated and experimental results.

Table 3. Comparison between calculated and experimental K_{eff}

Case	Serpent Analogic K_{eff}	SCALE/KENO K_{eff}	MCNP-4C K_{eff} (a)	Experimental Benchmark Model
1	1.00176 ± 0.00002	1.00074 ± 0.00009	0.9977 ± 0.0001	1.0004 ± 0.0001
2	1.00207 ± 0.00002	1.00066 ± 0.00009	0.9977 ± 0.0001	1.0004 ± 0.0001
3	1.00071 ± 0.00002	1.00142 ± 0.00009	0.9974 ± 0.0001	1.0004 ± 0.0001
4	1.00186 ± 0.00002	1.00142 ± 0.00008	0.9976 ± 0.0001	1.0006 ± 0.0001
5	1.00207 ± 0.00002	1.00198 ± 0.00009	0.9977 ± 0.0001	1.0004 ± 0.0001
6	1.00212 ± 0.00002	1.00220 ± 0.00008	0.9978 ± 0.0001	1.0005 ± 0.0001
7	1.00179 ± 0.00002	1.00360 ± 0.00008	0.9978 ± 0.0001	1.0006 ± 0.0001
8	1.00158 ± 0.00002	1.00403 ± 0.00008	0.9978 ± 0.0001	1.0004 ± 0.0001
9	1.00172 ± 0.00002	1.00290 ± 0.00009	0.9984 ± 0.0001	1.0006 ± 0.0001

a. Calculated data with ENDF/B-VI presented in LEU-COMP-THERM-043.

The values presented in table 3 are displayed in Figure 6 in format of a graph to better visualize the results.

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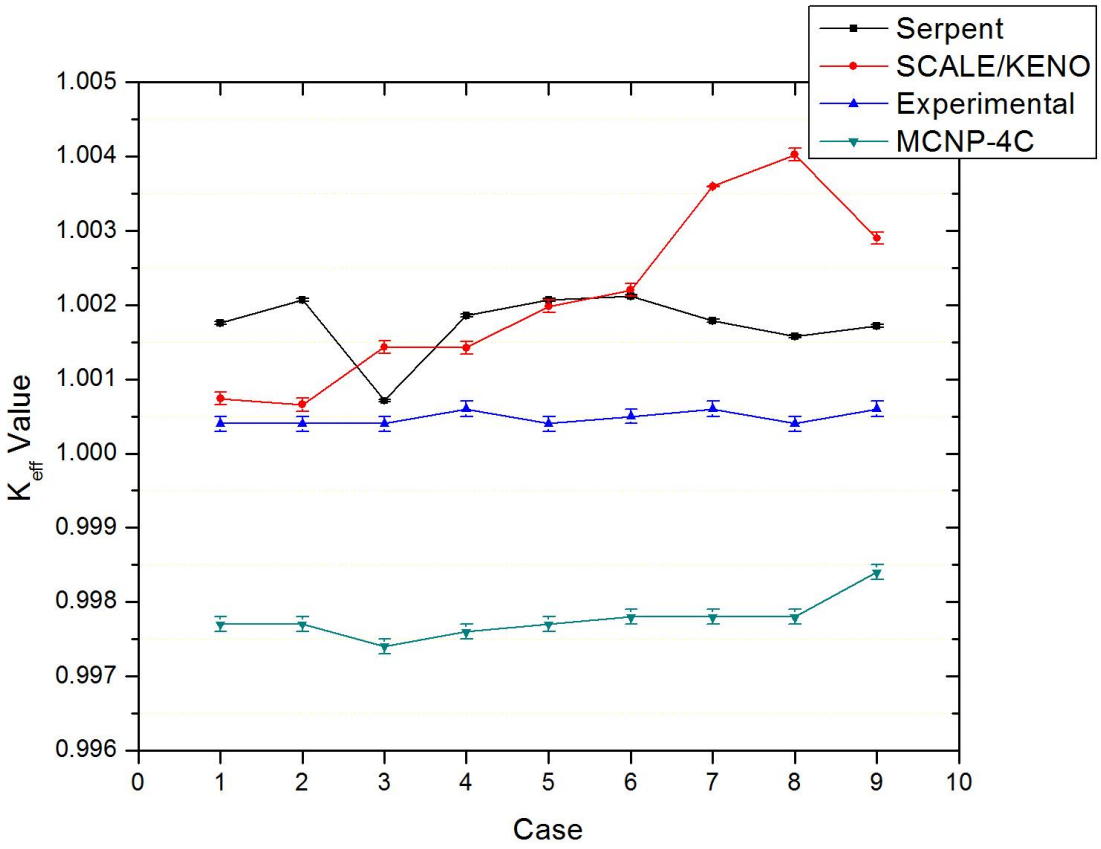

Figure 6. Graphic comparison between K_{eff}.

The results obtained by SERPENT shows good agreement with experimental results, producing result as good as SCALE/KENO. In average, Serpent overestimates K_{eff} by 127 pcm, while KENO overestimates in 163 pcm. Comparing to the MCNP-4C which uses ENDF\B-VI libray, both codes using ENDF\B-VII are closer to experimental results. However MCNP results are shifted below experimental results, the behavior of Keff is closer to the experimental ones, if we apply a bias of 217 pcm in MCNP results, this corrected values the root-mean square difference is only 15 pcm. The results obtained are preliminary and we should better investigate the SERPENT and KENO results.

We analyzed the effect of varying the probability threshold for delta-tracking on the computer simulation time and in the results. We cannot note any difference statistically significant using different delta tracking threshold, but the simulation time shows the expected behavior reported in [4], with the optimum delta-tracking threshold between 0.8 and 0.9 (Figure 7).

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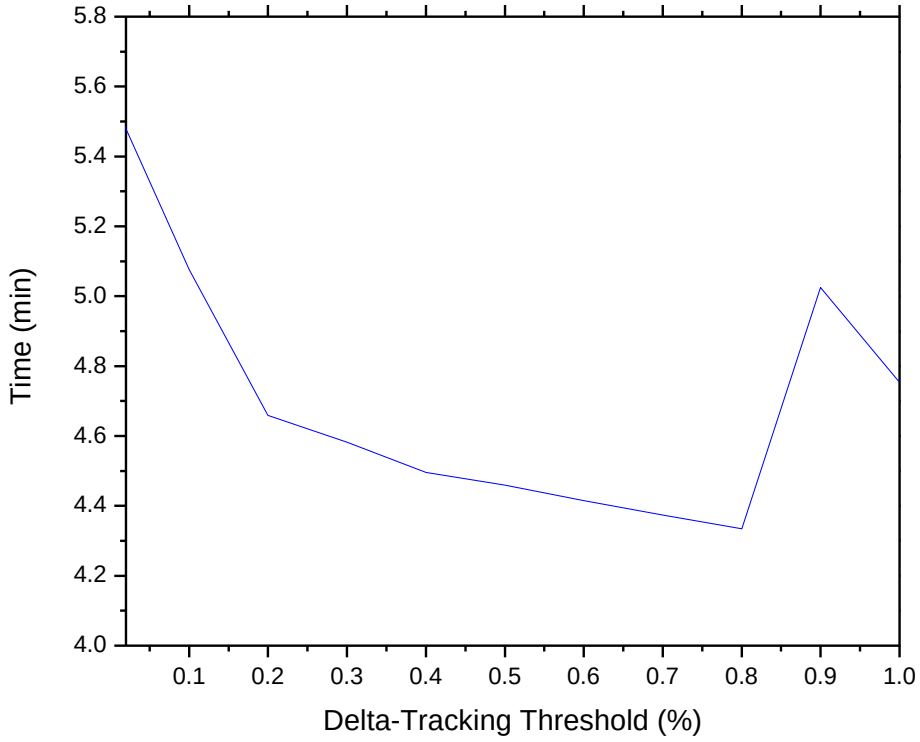

Figure 7. Variation of the computer simulation time as function of the probability threshold for delta-tracking.

5. CONCLUSIONS

The set of benchmarks using heavy reflector in IPEN/MB-01 was performed using SERPENT MC code and KENO/SCALE. The preliminary results show better agreement in the results comparing with the reference MCNP/ENDF\B-VI results. However the results obtained by SERPENT and KENO should be better investigated.

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