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MONTE CARLO MODELING OF THE NEW PLATE-TYPE CORE FOR THE BRAZILIAN IPEN/MB-01 RESEARCH REACTOR

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ABSTRACT

After 30 years of operation, the IPEN/MB-01 research reactor is about to receive a new plate-type core. This replacement is due to the Brazilian Multipurpose Reactor (RMB) needs, the largest project in nuclear engineering taking place in Brazil. The RMB will be a 30MW open pool-type research reactor, keeping the core in a 5x5 configuration (23 fuel elements, made of U_3Si_2-Al fuel plates, with 3.7 gU/cm^3, 19.75% enriched in U-235 and two extra positions available for materials irradiation). The radioisotopes production, material irradiation, nuclear fuels structural testing and the development of scientific and technological research using neutron beams are the main targets of the RMB enterprise. In this way, in order to verify, experimentally, the calculation methods and data libraries used for the Brazilian Multipurpose Reactor design, reactor cell and mesh structures, control rods effectiveness, isothermal reactivity coefficients and core dynamics due to reactivity insertions, the IPEN/MB-01 new plate-type core is being implemented at the Nuclear and Energy Research Institute (IPEN/CNEN-SP), SP-Brazil. It´s a tank-type research reactor. The core has a 4×5 configuration, with 19 fuel elements (U_3Si_2-Al, 2.8gU/cm^3 and 19.75% enriched in U-235), plus one aluminum block (internal irradiation position). As burnable poison, cadmium wires were used, once they are also employed at the RMB project to control the power density and the excess of reactivity during its operation. The core is reflected by four boxes of heavy water (D_2O) and its maximum nominal power is 100W. Thereby, a Monte Carlo modeling was developed using the Monte Carlo N-Particle code (MCNP), along with NJOY, for processing the materials nuclear cross sections. This modeling for the IPEN/MB-01 new plate-type core is presented and some neutronic calculations were also depicted in this paper.

1. INTRODUCTION

In any nuclear engineering project, all the calculation methodology applied must be verified and validated through experimental analysis before being implemented. Zero power reactors, as IPEN/MB-01, play an important role in this context. Theses reactors are usually used to validate neutronic results predicted by computational simulations (i.e., light water moderated reactor cell and mesh structures, control rods effectiveness, isothermal reactivity coefficients and core dynamics due to reactivity insertions). The IPEN/MB-01 research reactor facility achieved international level for experiments comparison and validation (benchmarks) and its versatility allows building many different core configurations, such as rectangular, square and cylindrical as well. Today, it´s running, nowadays, in Brazil, the Brazilian Multipurpose Reactor (RMB) project, focused on the production of radioisotopes, silicon doping, neutron activation analysis, nuclear fuels and structural materials testing and the development of scientific and technological research using neutron beams.

Therefore, in order to validate, experimentally, this new project, a new critical configuration for the IPEN/MB-01 was designed, changing the rod-type to the plate-type fuels, as will be presented in the next subsections. This work presents the Monte Carlo modeling used during the project and some neutronic calculations for the IPEN/MB-01 new plate-type core.

1.1. IPEN/MB-01 Research Reactor Facility

The IPEN/MB-01 achieved its first criticality in the year of 1988 (November 9), in which also started its operation. As mentioned before, due to a high level of versatility, this research reactor core allows setting up different configurations. Its first core was a rectangular-type (parallelepiped), with 39 x 45 x 54.6 as active dimensions, being an assembly of 28 x 26 fuel rods, 48 guide tubes for the control and safety rods using demineralized D_2O as moderator in this facility. In this configuration, there are a total of 680 fuel rods and an excess of reactivity of, approximately, 2415 pcm [1]. Figure 1 shows one of the IPEN/MB-01 rod-type core configuration. Aiming to accommodate new core configurations, the matrix plate has 900 roles (30 x 30) equally spaced by 15mm. The Fuel rods are made of UO_2, enriched 4.3% in U-235 and, as cladding, stainless steel AISI-304. The control rods are made up of Ag-In-Cd and the safety ones, B4C (the safety rods are completely withdrawn during normal operation).

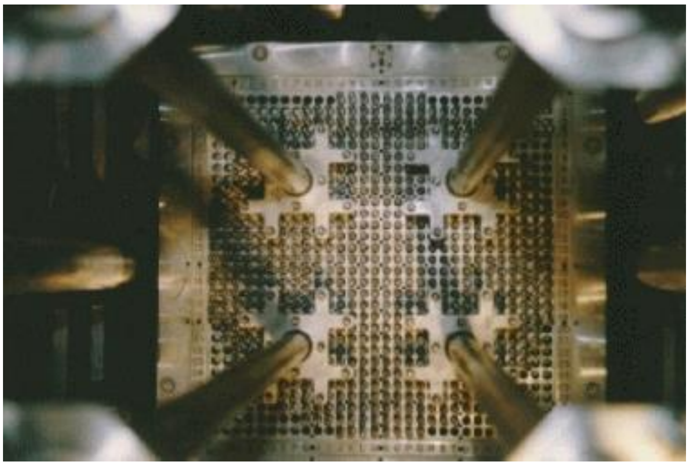

Figure 1: IPEN/MB-01 research reactor core top view.

The associated nuclear instrumentation used for safety and control consists of 10 nuclear channels, being 2 startup channels (BF3 detectors), 2 power channels (compensate ionization chamber - CIC), 2 linear channels (non-compensate ionization chamber - CINC), 3 safety channels in the power range (2 CINC + 1 B-10 detector) and 1 safety channel in the startup range (BF3 detector). All of them are placed around the reactor core, within the moderator tank, in many axial positions, protected by aluminum tubes [1]. The IPEN/MB-01 nuclear facility is able to simulate real power plants without having to build a complex system for heat removal and, because of these many features, in the next subsection it´s presented its usage within the RMB project, the largest nuclear engineering enterprise running in Brazil for the time being.

1.2. IPEN/MB-01 and the RMB Project

The Brazilian Multipurpose Reactor (RMB) project is being developed in Brazil (current in the detailed engineering project stage) and has, as main targets, the following items:

- Radioisotopes production;
- Material irradiation;
- Nuclear fuels structural testing;
- Development of scientific and technological research using neutron beams.

This research reactor will be placed at Iperó/SP, being a 30MW open pool-type reactor, keeping the core in a 5x5 configuration (23 plate-type fuel elements, each one with 21 fuel plates made of U_3Si_2-Al and Al 6061 as Cladding, 3.7 gU/cm^3, 19.75% enriched in U-235 and two extra positions available for materials irradiation). As control elements, 6 plates made of Hafnium are presented in the core. Figure 2 depicts the RMB research reactor core, showing the fuel assembly configuration, along with the Al blocks (positions for in core material irradiation) and the control plates.

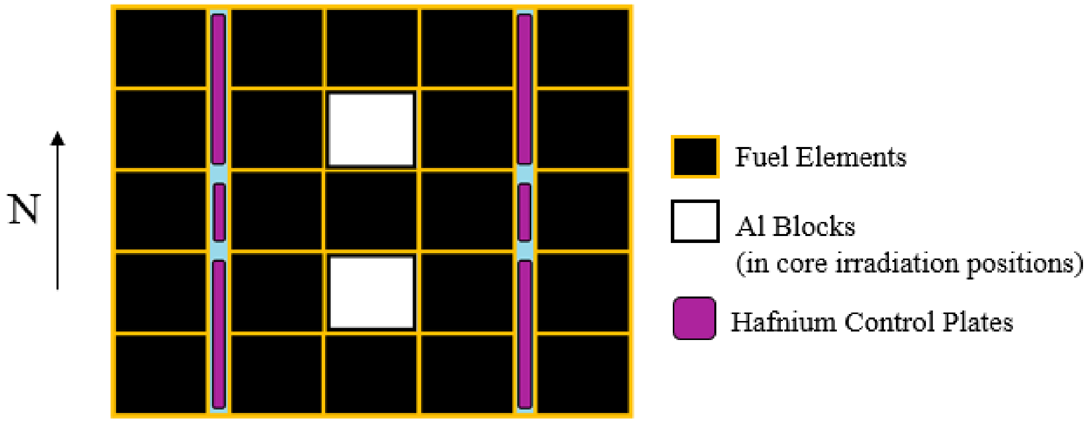

Figure 2: Top view of RMB research reactor core.

Once the RMB has a plate-type core, in order to validate and to provide support for the neutronic calculation methodology used during its project, it was designed a new critical assembly, named new plate-type core, for the IPEN/MB-01 research reactor facility, replacing the old rod-type one, after 30 years of operation. The new critical configuration will be operated by the National Nuclear Energy Commission (CNEN) and it´s placed at the Nuclear and Energy Research Institute (IPEN/CNEN-SP) in Sao Paulo, Brazil.

The next subsection presents the IPEN/MB-01 new plate-type core and the main parameters used for the Monte Carlo modeling (as designed) presented in the following sections.

1.3. IPEN/MB-01 New Plate-Type Core

The new IPEN/MB-01 plate-type core is a tank-type research reactor. The core configuration is disposed in a 4×5 configuration (Figure 3), with 19 fuel elements (U_3Si_2-Al, 2.8gU/cm³ and 19.75% enriched in U-235), plus one aluminum block (internal irradiation position). As burnable poison, cadmium wires were used, once they are also employed at the RMB project to control the power density and the excess of reactivity during its operation. The core is reflected by four boxes of heavy water (D_2O), having Hafnium control plates (4) and its maximum nominal power is 100W. Table 1 presents the general description of the IPEN/MB-01 plate-type core fuel assembly and Table 2, other relevant information.

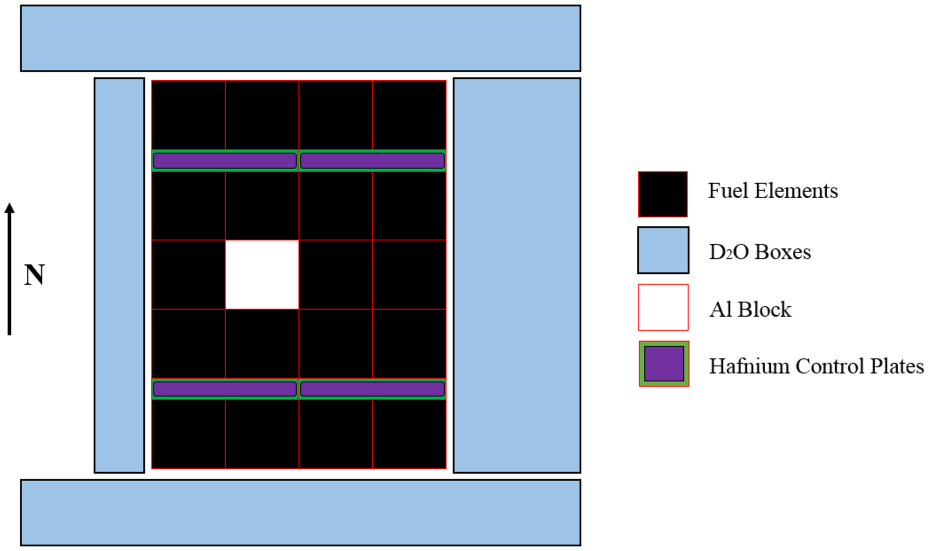

Figure 3: Top view of IPEN/MB-01 new plate-type core and D_2O boxes.

Table 1: General description of the IPEN/MB-01 plate-type core fuel assembly

Fuel assembly type	MTR - U_3Si_2-Al	
Enrichment in U-235	19.75 %	
Uranium density (meat)	2.8 gU/cm³	
U-235 mass per fuel assembly	283.08 g	
Amount of plates	21	
Plates array	Parallel	
Fuel plates dimensions	Inner plates	Outer plates
	1.35 x 75 x 655 mm³	1.50 x 75 x 825 mm³
Meat dimensions	0.61 x 65 x 615 mm³	
Coolant channel dimensions	2.45 x 70.5 mm²	
Fuel assembly dimensions	80.5 x 80.5 x 1045 mm³	
Cladding material	Al 6061 (2.7 g/cm³)	
Burnable poison	Cadmium (8.636 gU/cm³)	
Burnable poison dimensions	Diameter	Length
	0.4215 mm	400 mm

Table 2: Other dimensions and data

Al block dimensions	80.5 x 80.5 x 835 mm³
Hafnium plates dimensions	7 x 152 x 635 mm³
North/South D2O box dimensions	76.25 x 608 x 715 mm³
East D2O box dimensions	140 x 452.5 x 715 mm³
West D2O box dimensions	58 x 452.5 x 715 mm³
Startup source	Am-Be (1Ci, ANM-9022)

2. IPEN/MB-01 NEW PLATE-TYPE CORE MONTE CARLO MODELING

The new core was modeled using the Monte Carlo N-Particle code (MCNP) [2, 3], along with NJOY [4] (coupled system NJOY/MCNP, where NJOY (99.90) was used to generate the nuclear material data used in MCNP). In all neutronic calculations, the version 5 [2] of MCNP was used, except during the kinetic parameters evaluation, where it was applied the version 6 [3]. The MCNP solves the neutron transport equation through the Monte Carlo method and has a very powerful way to build 3D geometries using Boolean logic.

2.1. Coupled System NJOY/MCNP

The methodology followed when modeling with NJOY and MCNP is depicted in Figure 4. The Nuclear data library ENDF/B-VII.0 [5] was used to feed NJOY and generate a new set of nuclear material data accounting the Doppler effect (BROADR), unresolved resonance region (UNRESR), $S(\alpha,\beta)$ (LEAPR) and thermal neutron treatment (THERMR). The NJOY´s modules RECONR and ACER are used to prepare the ENDF/B-VII.0 library and to create an ACE file to be used in MCNP, respectively. The continuous energy cross sections (70c) and the thermal cross sections for the light water, heavy water, beryllium and polyethylene (10t) were used in the model. When using the MCNP 6 for the kinetic parameters calculations, the JENDL 3.3 [6] nuclear data library was used for the tallies and ENDF/B-VII.0 for the nuclear reactor materials.

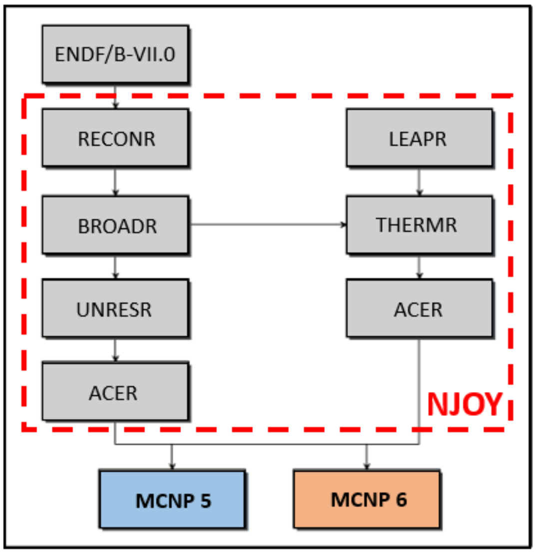

Figure 4: Calculation methodology.

2.2. MCNP 3D Model

The Figure 5 shows the MCNP top view model of the IPEN/MB-01 new core used during its project (Figures 6 and 7 show, in more details, the 3D model from different views). On the left (a), it´s the real core, without yet the fuel elements and, on the right (b), a top view (x-y, z = 50 cm) of the MCNP model. The circles near the D_2O boxes and the one far to the right are the out of core detectors, mentioned in the section 1.1. Other gray elements are related to the reactor structure. The arrow number 1 means that the model was created to project the new core, while the arrow 2 wants to point out that the *as built* data are also being used to feedback the Monte Carlo model (i.e., *as built* dimensions, material densities, and so on).

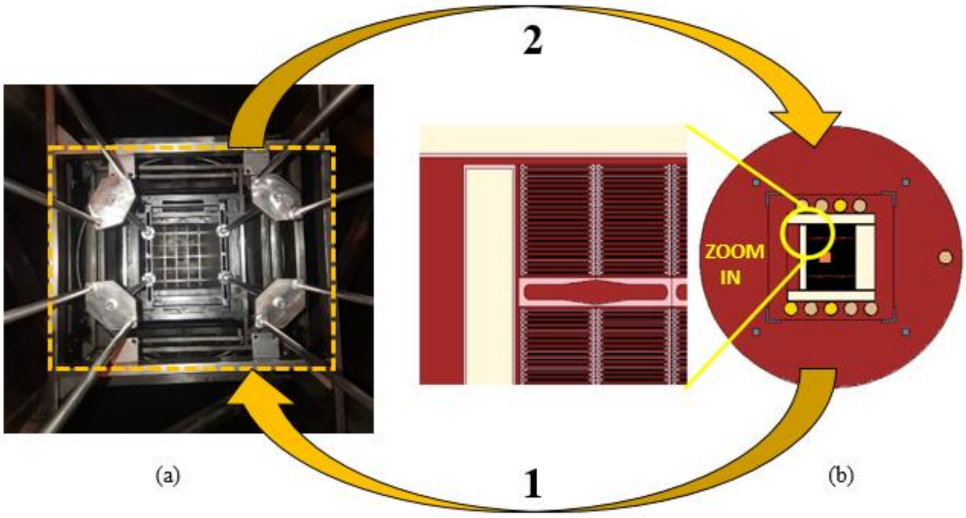

Figure 5: Real IPEN/MB-01 new core under development (a) and the MCNP model (b).

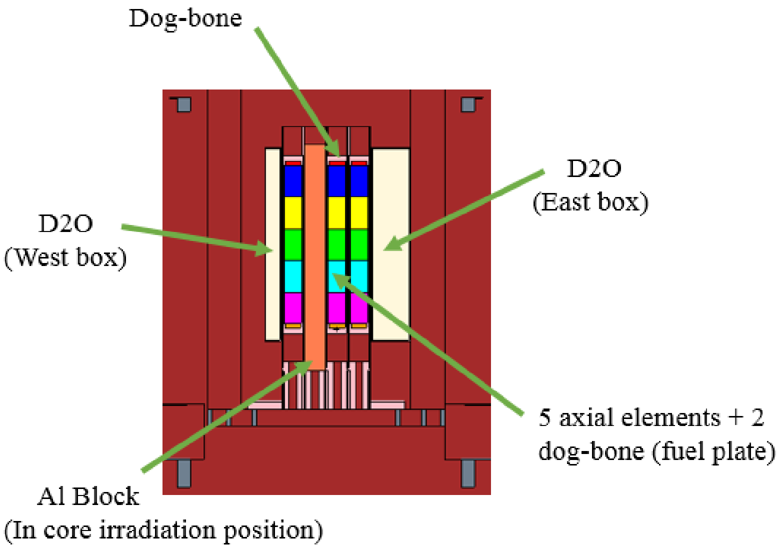

Figure 6: MCNP axial view (x-z, y=2.66 cm)

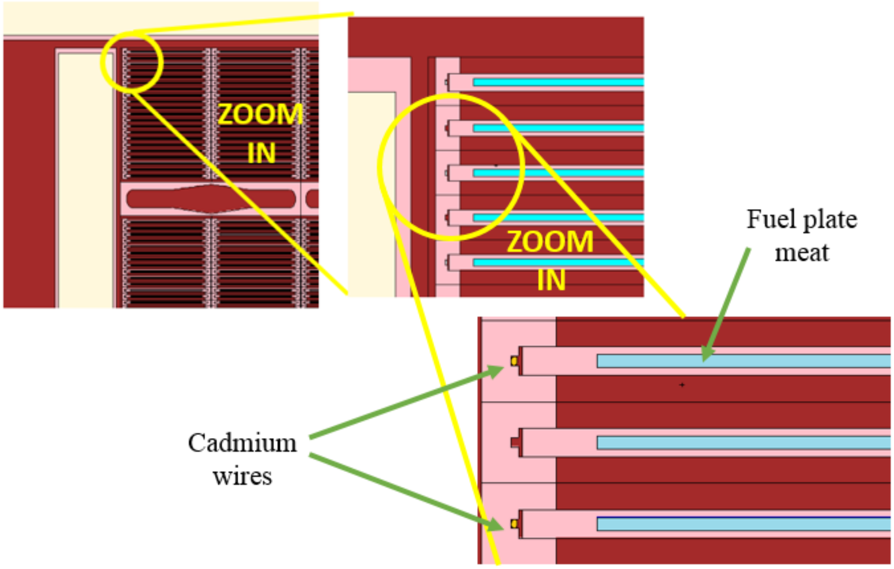

Figure 7: MCNP (x-y, z=80) radial view: cadmium wires and fuel plate meat.

3. NEW CORE NEUTRONIC ANALYSIS

In this section some neutronic calculations are presented for the IPEN/MB-01 new plate-type core (considering all data adopted *as designed*), such as isothermal reactivity coefficient (α_{ISO}), effective kinetic parameters, average neutron flux per material/component per neutron energy group, power densities and neutron flux distribution passing through the power peaking factor spot and the total control plates worth.

3.1. Isothermal Reactivity Coefficient (α_{ISO})

Table 3 shows the isothermal reactivity coefficient, α_{ISO}, calculated considering two different average temperatures, 20 ºC and 50 ºC.

Table 3: Isothermal reactivity coefficient (α_{ISO})

T (ºC)	k_{eff}	$\Delta\rho$ (pcm)	α_{ISO} (pcm/ºC)
20	0.99905 ± 0.00001	-547 ± 3	-18.23 ± 0.11
50	0.99362 ± 0.00003		

3.2. Effective Kinetic Parameters

Table 4 presents the effective kinetic parameters, effective delay neutron fraction (β_{eff}) and prompt neutron generation time (Λ). All of them were calculated with MCNP 6, setting the control plates to the critical position (63.41% withdrawn) and using JENDL3.3 and ENDF/B-VII.0 as nuclear data libraries.

Table 4: Effective kinetic parameters

Precursors	β_i	β_i/β_{eff}	λ_i
1	0.00023 ± 0.00001	0.0314 ± 0.0014	0.01249 ± 0.0000
2	0.00122 ± 0.00002	0.1664 ± 0.0029	0.03181 ± 0.0000
3	0.00121 ± 0.00002	0.1651 ± 0.0029	0.10944 ± 0.0000
4	0.00337 ± 0.00003	0.460 ± 0.005	0.31730 ± 0.0001
5	0.00097 ± 0.00002	0.1323 ± 0.0029	1.35320 ± 0.0002
6	0.00033 ± 0.00001	0.0450 ± 0.0014	8.65810 ± 0.0010
β_{eff}	0.00733 ± 0.00005		
Λ (μs)	65.44 ± 0.08		

3.3. Average Neutron Flux per Reactor Core Component

Table 5 shows the average neutron flux, normalized by the reactor power (100W), in each nuclear reactor component (Al block, D_2O boxes and control plates). The components are named in Table 5 according to orientation proposed in Figure 3. The neutron energy groups are divided as depicted bellow:

- Group 1: 0.825 MeV to 10 MeV;
- Group 2: 5.533 keV to 0.825 MeV;
- Group 3: 0.625 eV to 5.53 keV;
- Group 4: 0 to 0.625 eV.

Table 5: Average neutron flux per nuclear reactor component

Component	Group 1 (n/cm^2-s)	Group 2 (n/cm^2-s)	Group 3 (n/cm^2-s)	Group 4 (n/cm^2-s)
Aluminum Block	$5.39E+08 \pm 0.02\%$	$7.25E+08 \pm 0.02\%$	$6.21E+08 \pm 0.02\%$	$5.70E+08 \pm 0.02\%$
North D2O box	$7.57E+07 \pm 0.02\%$	$1.83E+08 \pm 0.02\%$	$2.18E+08 \pm 0.02\%$	$6.43E+08 \pm 0.02\%$
South D2O box	$7.60E+07 \pm 0.02\%$	$1.84E+08 \pm 0.01\%$	$2.19E+08 \pm 0.02\%$	$6.48E+08 \pm 0.02\%$
East D2O box	$9.06E+07 \pm 0.02\%$	$2.48E+08 \pm 0.01\%$	$3.44E+08 \pm 0.01\%$	$9.41E+08 \pm 0.01\%$
West D2O box	$1.34E+08 \pm 0.05\%$	$2.95E+08 \pm 0.01\%$	$3.07E+08 \pm 0.02\%$	$7.07E+08 \pm 0.02\%$
Control Plate 1 (bottom left)	$1.05E+08 \pm 0.05\%$	$1.45E+08 \pm 0.05\%$	$8.29E+07 \pm 0.05\%$	$1.85E+07 \pm 0.06\%$
Control Plate 2 (upper left)	$1.05E+08 \pm 0.05\%$	$1.44E+08 \pm 0.05\%$	$8.29E+07 \pm 0.05\%$	$1.85E+07 \pm 0.06\%$
Control Plate 3 (upper right)	$1.15E+08 \pm 0.05\%$	$1.59E+08 \pm 0.04\%$	$9.20E+07 \pm 0.05\%$	$2.10E+07 \pm 0.05\%$
Control Plate 4 (bottom right)	$1.16E+08 \pm 0.05\%$	$1.59E+08 \pm 0.04\%$	$9.23E+07 \pm 0.05\%$	$2.10E+07 \pm 0.05\%$

3.4. Power Densities and Neutron Flux Distribution

The following Figures (8-14) show the radial and axial power densities and neutron flux distribution at the position where it´s found the peaking factor (~2.2). This value results from the rate between the maximum power density (3.276 mW/cm^3) and the average one in the core (1.489 mW/cm^3). The maximum power density occurred at the position [6.00, -14.50, 52.55], within the third fuel element situated, from the left to the right, on the bottom close to the south D_2O box. The maximum neutron flux found within the Al block were at the position [-4.00, 0.00, 52.05]. The system origin for the 3D model is located at the medium point of the nuclear reactor matrix plate.

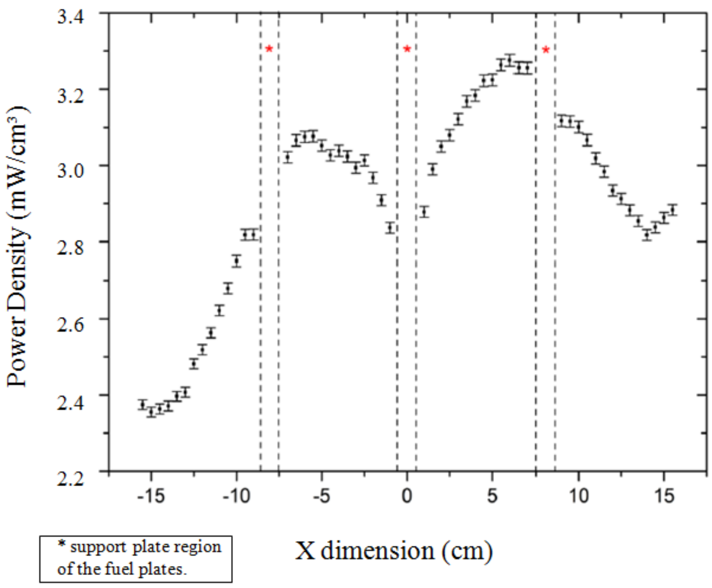

Figure 8: Radial power density distribution at the power peaking factor [X,-14.5,52.55].

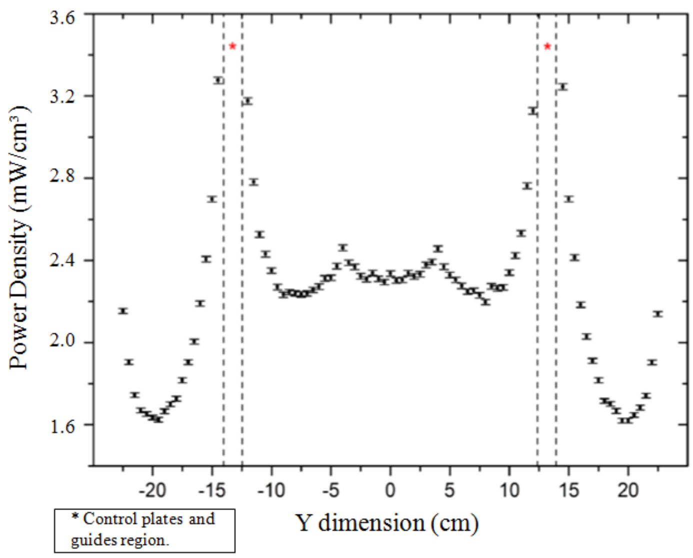

Figure 9: Radial power density distribution at the power peaking factor [6,Y,52.55].

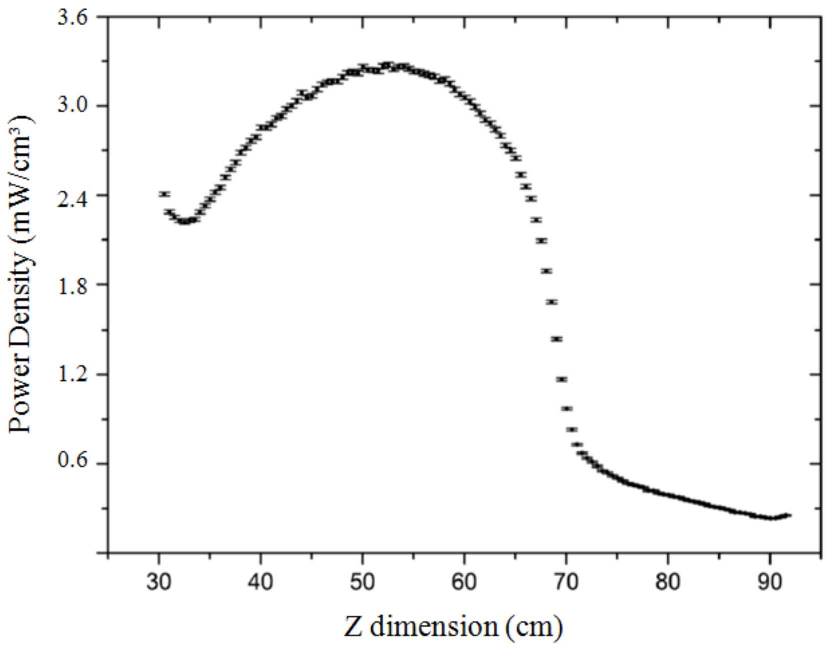

Figure 10: Axial power density distribution at the power peaking factor [6,-14.5,Z].

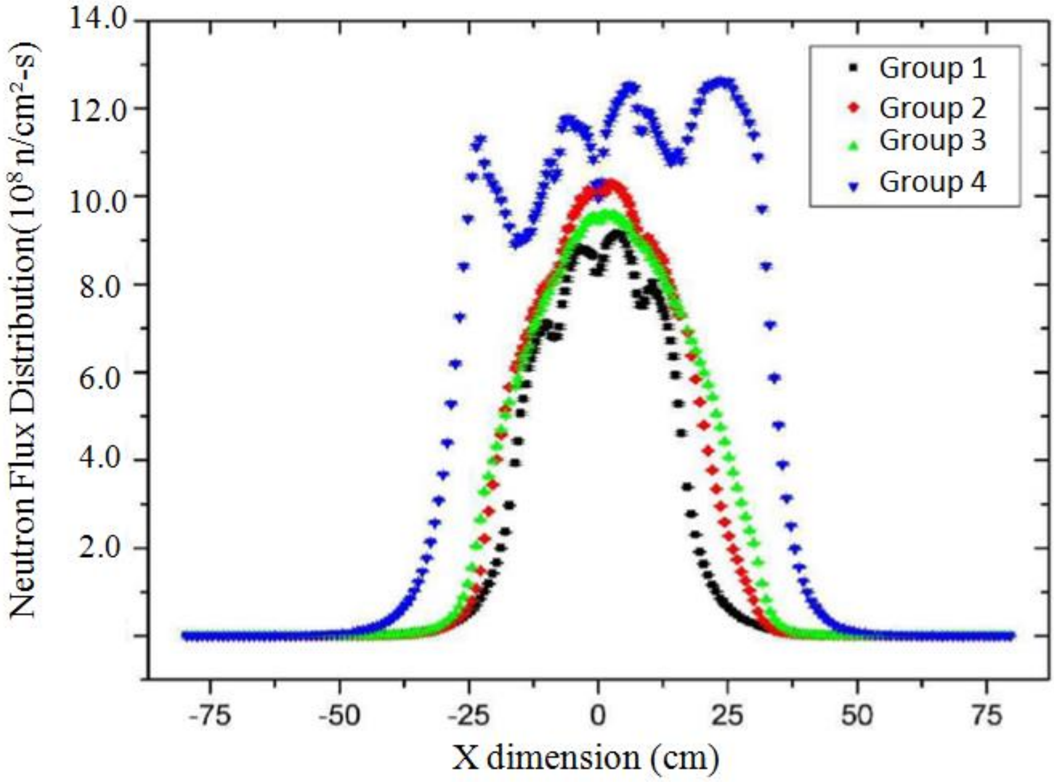

Figure 11: Radial neutron flux distribution at the power peaking factor [X,-14.5,52.55].

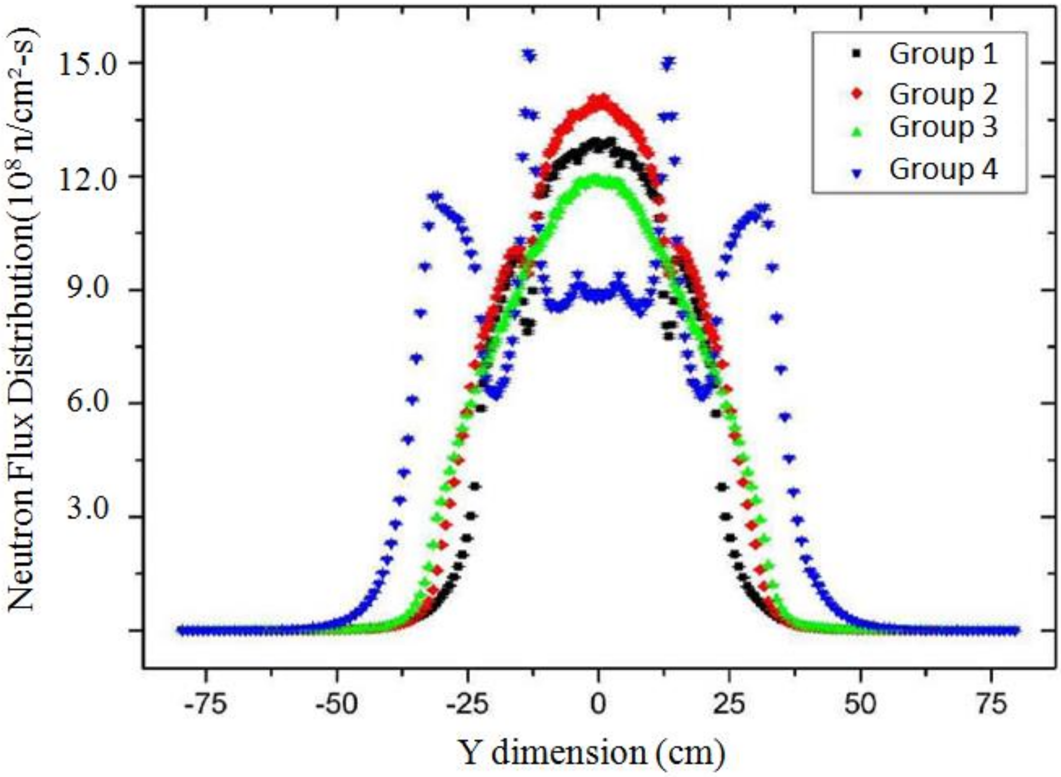

Figure 12: Radial neutron flux distribution at the power peaking factor [6,Y,52.55].

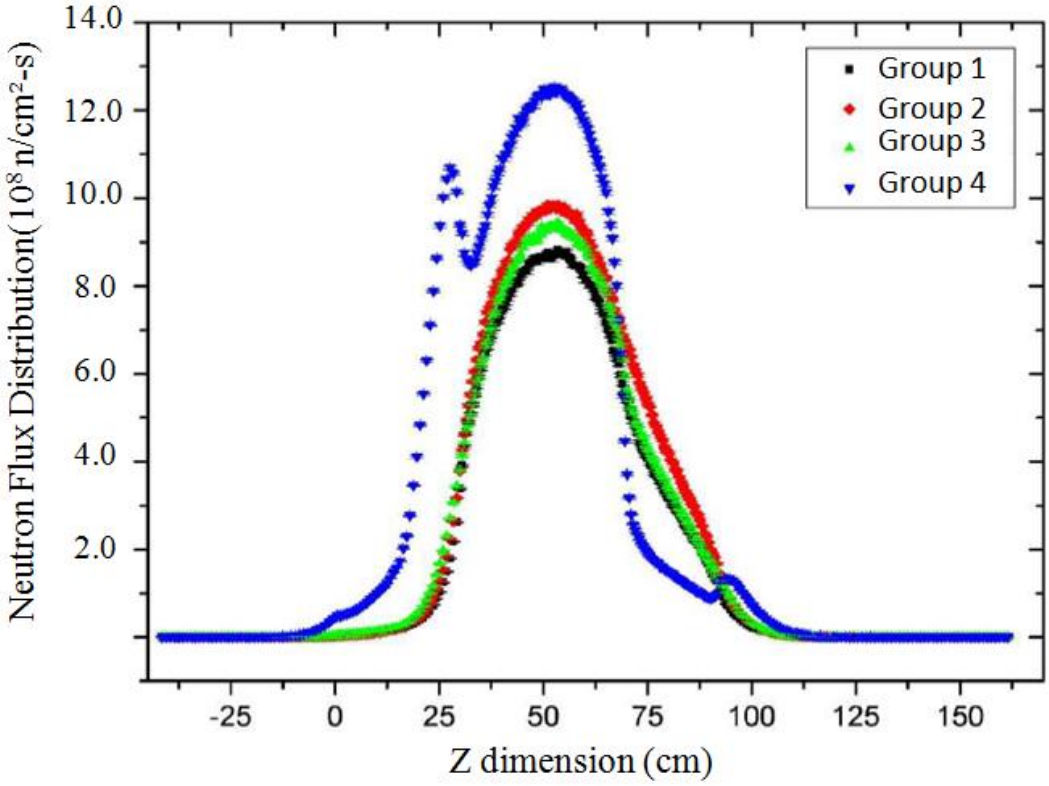

Figure 13: Axial neutron flux distribution at the power peaking factor [6,-14.5,Z].

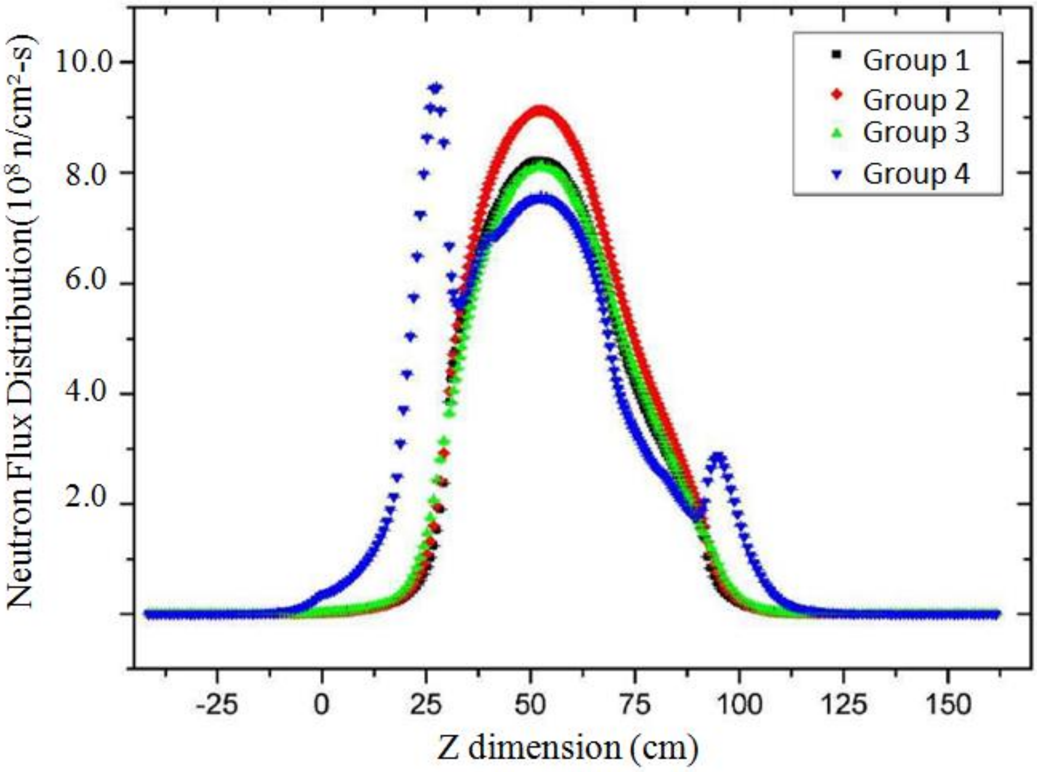

Figure 14: Axial average neutron flux distribution at the fuel element with the peaking factor.

3.5. Total control plates worth

Table 6 presents the core reactivity with all control plates withdrawn (core excess of reactivity), the total control plates worth and the partial control plates worth (1 control plate stuck, the one with the highest worth).

Table 6: Core excess of reactivity, total and partial control plates worth

State	Reactivity (pcm)	Calculated Shutdown Margin	Shutdown Margin (Design Criteria)
Excess of Reactivity	3511 ± 2	Reference	-
Total Control Plates Worth	-16576 ± 4	372%	100%
Partial Control Plate Worth (Control Plate Stuck)	-10622 ± 3	203%	50%

3. CONCLUSIONS

The IPEN/MB-01 research reactor, located at IPEN/CNEN-SP, is passing through a new transformation aiming the Brazilian Multipurpose Reactor project. The old rod-type core is being replaced by a plate-type one, in order to, experimentally, validate the neutronic methodology used in the RMB enterprise. Some details about the 3D Monte Carlo Modeling were presented in this paper for this new core configuration, along with preliminary neutronic calculations with a coupled system NJOY/MCNP. Considering future works, besides presenting more neutronic calculations for this reactor, the data used for modeling will be updated by the ones presented in the IPEN/MB-01 data book (*as built* modeling). A comparison between the results from the modeling and the real ones (through experiments), when the new reactor core starts its operation, will also be presented in prospective works.

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