# STEADY STATE SIMULATION OF RMB MULTIPURPOSE BRAZILIAN REACTOR WITH SERPENT NUCLEAR CODE

G.A.M. VIDAL, A.A.C. Santos, V.V. ARAÚJO SILVA, D. CAMPOLINA
*Serviço de Tecnologia de Reatores,CDTN/CNEN*
*Av. Antônio Carlos 6627, Campus da UFMG, CEP 31270-901, Belo Horizonte, MG - Brasil*

T.A.S. Vieira
*Departamento de Engenharia Mecânica, UFMG*
*Av. Antônio Carlos 6627, CEP 31270-901, Belo Horizonte, MG - Brasil*

## ABSTRACT

The Multipurpose Brazilian Reactor (RMB) plays a fundamental role in the nuclear technology program in Brazil, mainly because of radioisotopes production. The conclusion of the RMB project will make Brazil autonomous in this field. RMB is designed as an open pool research reactor with a maximum power of 30 MWth. Besides radioisotopes production, the reactor project is a priority in Brazilian Nuclear Program for research and development of nuclear fuel and materials testing. It is worth to note that the RMB is still in the detailed project phase and its expected conclusion is in 2021. Neutronic models of the reactor are being improved in order to build up knowledge of its operational parameters. In the present work, a full core simulation of the RMB simplified model is shown. Neutronic parameters such as effective multiplication factor and neutron flux distribution have been computed through Monte Carlo transport code Serpent, chosen due to its fast and reliable calculations. This work presents a steady state simulation and is seen as an initial step of a greater plan which aims to perform multi-physics simulations using thermal-hydraulics open source Computational Fluid Dynamics (CFD) tool called OpenFOAM. The results obtained in this study were compared with other simulations using MCNP under the same parameters and show good agreement.

## 1. Introduction

The Multipurpose Brazilian Reactor (RMB) is under development and its project started in 2011 [1]. This project is extremely important for the future of nuclear research and energy in Brazil because of several reasons, such as:

1. Radioisotopes production;
2. Development of nuclear fuel;
3. Testing materials with neutron beams;
4. Production of neutron beams for research and applications in all areas [2].

RMB initial project and design was planned by Brazilian Nuclear Energy Commission (CNEN). A partnership with National Atomic Energy Commission of Argentina (CNEA) added the basic design of the reactor core and neutron beams. This partnership aims to use the same basic design for Argentinian (RA-10) and Brazilian multipurpose research reactors.
The RMB project was created for an open pool research reactor with a maximum power of 30 MWth and was inspired on the Australian nuclear reactor OPAL (20 MWth), designed by the Argentinian company INVAP [3].
As provided in the Safety Analysis Report of nuclear installations, it's essential to know and predict the behaviour of the reactor in all particular situations that can occur. For that purpose, neutronics and thermo-hydraulics simulations must be done to evaluate the reactor operation parameters. For the basic design, preliminary neutronics simulations were performed [2], as well as thermo-hydraulics experiments and numerical simulations [4, 5], but none of them in a multi-physics coupled scheme. Besides, just a few simulations [9] were conducted using Serpent nuclear code [6], which is a strong, reliable and relatively new nuclear code.

Serpent is a stochastic (Monte Carlo method) code that solves criticality problems such as the goal of this work. Previous studies showed that it is possible to run a simulation faster than others nuclear codes, such as MCNP [10]. That is possible because some factors, but especially due to delta tracking mechanism used to calculate the path of neutrons [6].
In order to obtain trustable and verified values to represent the neutronic behaviour of RMB, simulations using Serpent, MCNP and other software must be done, compared with each other for a future verification and validation. Moreover, it is of the most importance to estimate parameters such as the effective multiplication factor and neutron flux distribution. They are used in the safety analysis to anticipate eventual problems and also to build up expertise for the reactor design.
Neutronic calculations with Serpent of the reactor core have been carried out in order to present the power distribution and the effective multiplication factor of RMB in steady state. A comparison with the effective multiplication factor between the Serpent simulation presented in this work and another model using MCNP has also been performed.
This work is the first part of a bigger project which aims to perform multi-physics and thermal-hydraulics simulations using Serpent and an open source Computational Fluid Dynamics (CDF) tool called OpenFOAM, the simulation will run coupled based on an under development methodology [7].

## 2. Multipurpose Brazilian Reactor (RMB)

The RMB is an open pool material testing reactor (MTR) with 30 MWth of maximum power, moderated and cooled by light water and reflected by heavy water and beryllium. The reactor core is circumscribed of a heavy water reflector cylinder that also contains irradiation spots for radioisotopes production and neutron detection. A general design of RMB is shown in Fig. 1 [2].

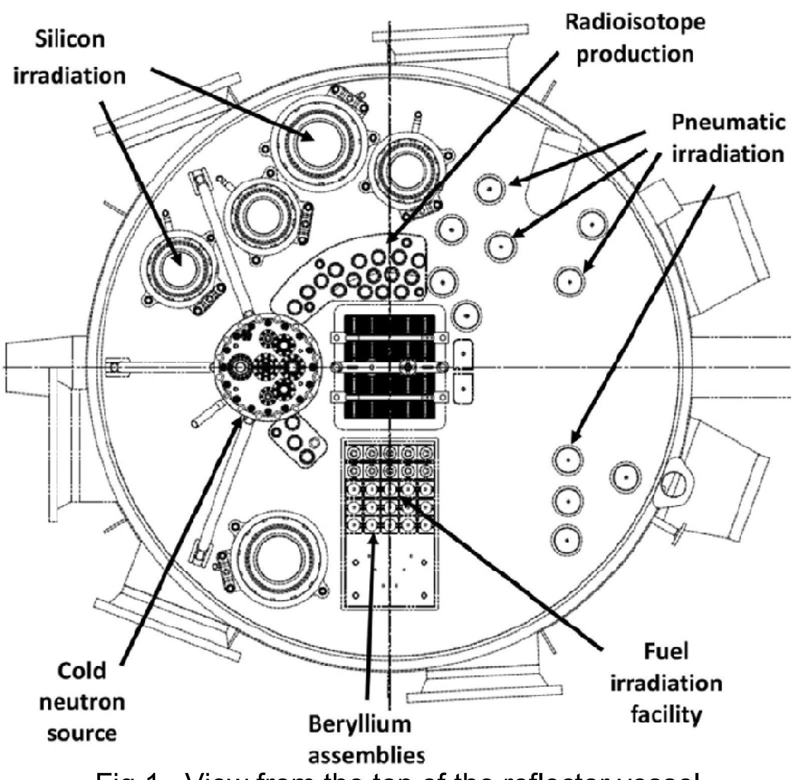



Fig 1. View from the top of the reflector vessel

The core of the reactor is a 5 x 5 matrix which can be filled with 23 fuel assemblies. The other 2 positions in that matrix are for materials irradiation tests, which are shown in Fig. 2 [3]. Also in Fig. 2, a scheme of the OPAL core allows a comparison with the RMB core, where RMB hold more fuel assemblies. Both reactor have the same level of fuel enrichment, however control plates in OPAL are in a symmetric position that provide a more homogeneous neutron flux.

Fuel assemblies in the RMB core are an aggregate of 21 rectangular aluminium fuel plates. The fuel plates are confined inside an aluminium cladding plates. The fuel meat is a mix of enriched uranium silicide with aluminium. The core is cooled by force light water flow from the main cooling system and the pool surrounding the core is cooled by natural convective flow [4]. The pool also has a hot water layer system that actuates to provide radiation protection based on the formation of a thermally stratified layer of purified water at the top of the pool [4].

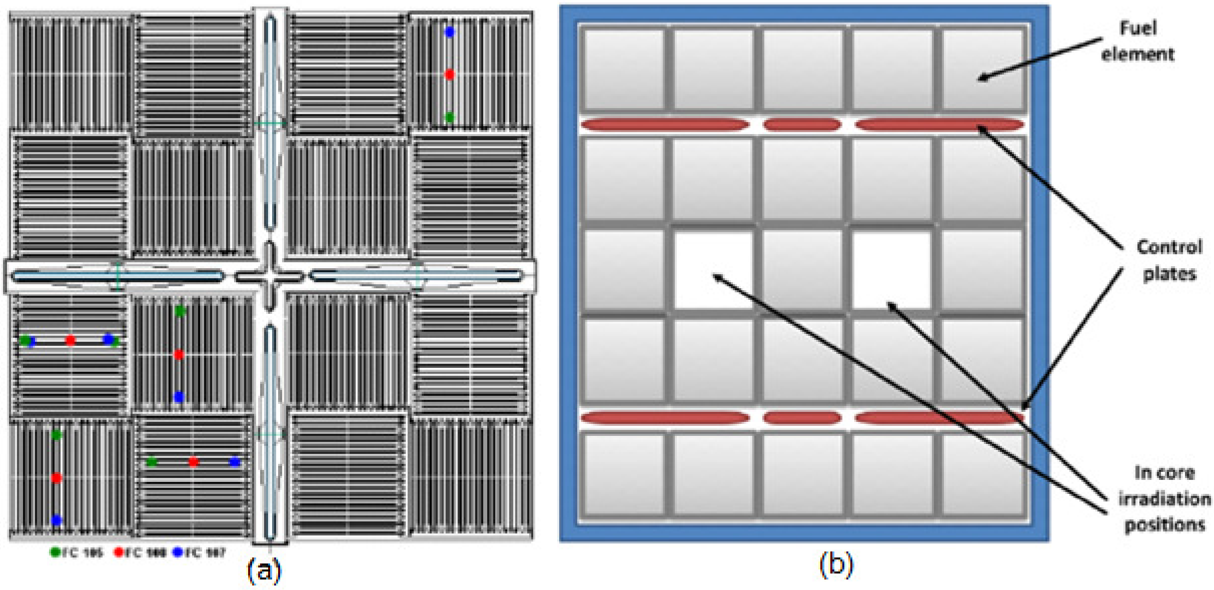



Fig 2. OPAL (a) and RMB (b) cores [2, 3]

There are forty two cadmium wires alongside the fuel plates, to be depleted with the fuel assemblies. For the control system, there are two sets of three independent hafnium control plates, which can move parallel to the fuel plates. There is also a removable beryllium reflector on the fuel irradiation facility, occupying one side of the reactor core (Fig. 1). The reflector vessel is a Zircaloy cylinder filled with heavy water surrounding the reactor core. The general dimensions, configuration and materials are shown in Tab. 1 [2].

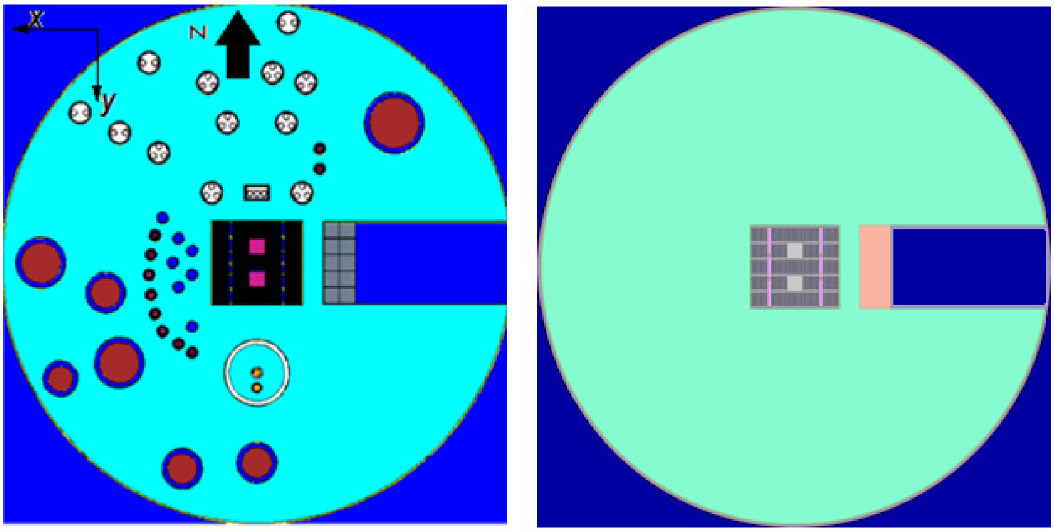
| | |
|---|---|
| Core total power | 30 MWth |
| Fuel locations | 23 |
| Experimental locations in core | 2 |
| Radial reflector and moderator | $D_2O$ and Be |
| Active height | 61,5 cm |
| Fuel dimensions | (8,05 x 8,05 x 104,5) cm |
| Meat dimensions | (0,061 x 6,5 x 61,5) cm |
| Fuel (19,75% $U_{235}$) | $U_3Si_2$ |
| Cladding material | Al alloy |
| Safety plates | Hafnium |
| Coolant and moderator pool | $H_2O$ |

Tab 1: RMB general dimensions, configuration and materials [2]

## 3. Methodology

### 3.1 Simulated geometry and materials

The geometry was based on the RMB documentation and its nominal dimensions. It consists of 6 control plates, 23 fuel assemblies, 2 in-core irradiation boxes. And, inside every assembly, 21 coated uranium plates take place. The core is surrounded by a moderator / reflector heavy water pool, a beryllium reflector for an irradiation device and a cooling light water pool (Fig. 3). Figure 3.a shows the model used on MCNP simulations.




(a) (b)

Fig 3. Top view of the reflector vessel for the simulated geometry with MCNP (a) and present work (b)

This work presents a model with several simplifications for a first assessment of Serpent code. The development of the model was done step by step. Firstly, it was made in one universe a uranium plate inside a cladding and two cladding supports, each one on one side of the plate and inside every support has a Cadmium wire. Then, this universe was multiplicated by 21 plates using lattice structure, in order to build one fuel assembly as shown in Fig. 4. After the first assembly was created, one in-core irradiation box with the same dimension of the fuel assembly was created. Next, another lattice was used to create the middle band of the core (5 lines and 3 columns), with the 2 in-core irradiation boxes between 13 fuel assemblies (Fig. 5).

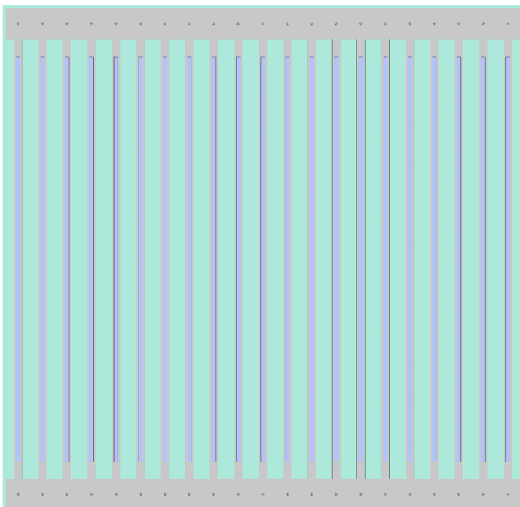
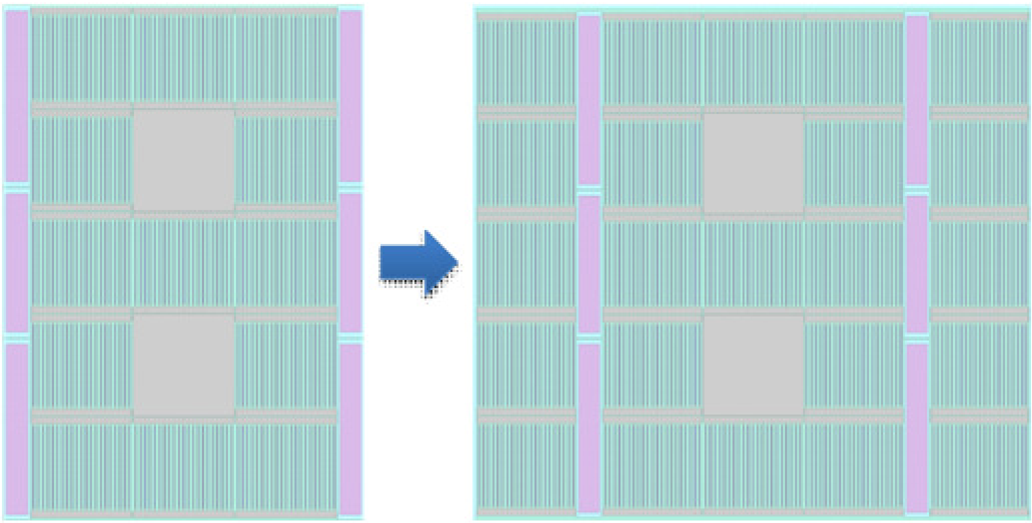


Fig 4. Fuel assembly

The 6 control plates were made one by one with its respective dimensions and coordinates to fit on the geometry as shown in the Fig 5. Due to its different sizes, a lattice structure was not used.



(a) (b)

Fig 5. Middle band of the core (a) and complete core geometry (b)

In order to complete the 5x5 fuel core, another universe was created to put 10 more assemblies in the geometry, 5 on each side of the middle band and control rods set. For that another lattice was created (Fig. 5).
After the core was modelled, the moderator / reflector heavy water pool, the beryllium reflector and the cooling pool were made around the core, its walls were also made according to the dimensions in the project. It is a 3D geometry using cuboids and cylinders as surfaces with a total of 9 universes with 78 zones. For a simplest geometry, the X-Y plane was extruded in the Z-axis, and the extrusion has the same size of the fuel plates. Further simulations will contemplate an improvement in this 3D model.
The materials used in this simulation are presented in the Tab. 2. They were similar to the materials used in simulations on MCNP.

| Material | Place |
|---|---|
| $U_3Si_2$ (19,75% $U_{235}$) | Fuel plate |
| Aluminium | Cladding, $D_2O$ wall |
| Cadmium | Wire |
| Hafnium | Control rods |
| Zircadyne | Control rods guide wall |
| Zircaloy | Control rods guide |
| Beryllium | Reflector on irradiation device |
| Stainless Steel | External wall |
| $D_2O$ | Reflector / Moderator pool |
| $H_2O$ | Coolant pool |

Tab 2: Materials and its respective locations

### 3.2 Simulation configuration

The Monte Carlo simulations performed by Serpent nuclear code was made by sampling 8E05 neutrons, with 10 inactive cycles and 1E03 active cycles. This numbers were a result of

adjustments for a desire standard deviation around 10 pcm. The results were compared with simulations using MCNP.
The boundary conditions used in the external surfaces were black in all directions, which mean that when a neutron escapes the geometry, it doesn't return, it is killed.
The nuclear data library used for the cross section of the materials was ENDF/B-VII.1, the same used in the MCNP simulations.
For this simulation it was used Serpent 2.1.29 running in parallel with 8 processors. The computer used was a Dell processor Intel Xeon(R) CPU E5520 2.25 GHz with 24 GB of memory and Linux SentiOS based system. It took place at the Thermo-hydraulics laboratory of CDTN. With this computer and Serpent configuration, the simulation lasted less than two hours.

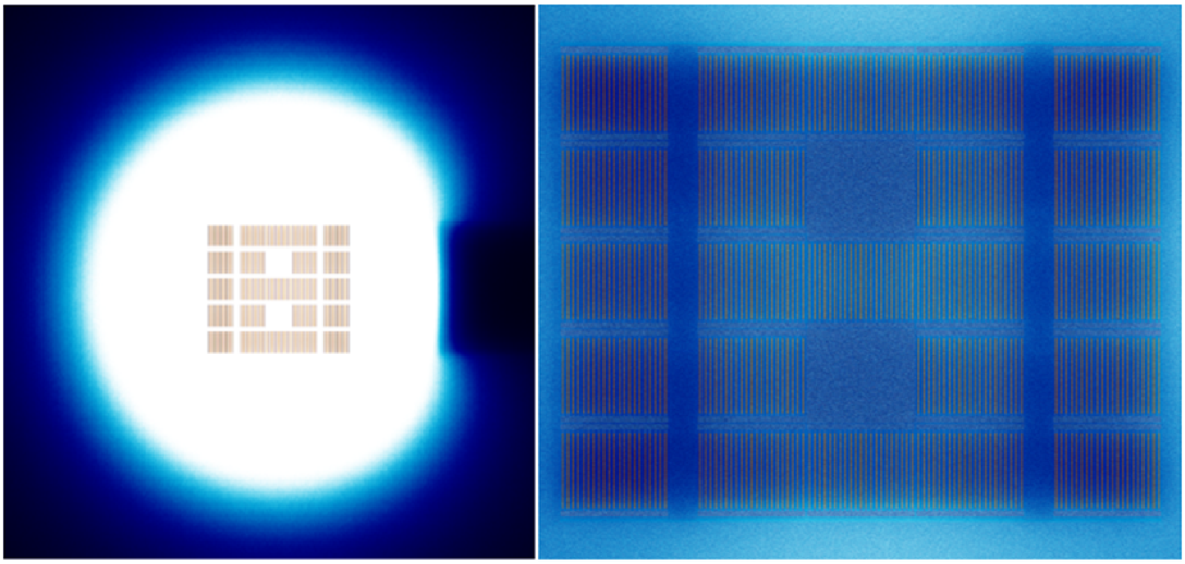
## 4. Results

The results were only evaluated in terms of reactivity. Standard deviation on Serpent results were adjusted to the same order of magnitude of the simulations performed using MCNP, which was less than 10 pcm. The results were shown in Tab 3.
The difference for the reactivity on simulations can be explained by the models dissemblance. While MCNP used more detailed geometries, Serpent was fed with a preliminary simplified model. Nevertheless, the model presented in this work show encouraging results, and thereat improvements in this model will take place in future works.

| Fuel State | Operational State | Control Rod Position | Nuclear Code | Reactivity [pcm] | Standard deviation [pcm] |
|---|---|---|---|---|---|
| Fresh | Hot | Not inserted | MCNP | 6880 | less than 10 |
| Fresh | Hot | Not inserted | SERPENT | 8782 | 9,2 |
| Fresh | Hot | Inserted | SERPENT | -8184 | 33 |

Tab 3: Comparison between results with MCNP and Serpent

In Tab. 3 it's also possible to see the result for a simulation with the control plates inserted and, as expected, the reactor became sub-critical. The results for the neutron distribution on Serpent simulation without the control plates are shown in Fig 6.a and Fig.6.b.



(a) (b)

Fig 6. Top view of the RMB neutron distribution for the simulated geometry (a) and zoom in the core (b)

## 5. Conclusions

The resulted value of reactivity using Serpent was higher than the simulations in MCNP by 1902 pcm. Although it was higher than expected, this reactivity value is consistent with a real core reactor. When simulated with the control rods, the reactor became subcritical, which is expect to occur.
Since this is a simplified model, it doesn´t consider all the components inside the reactor, that, when acting as an absorber, insert negative reactivity. Furthermore, the extrusion was only the height of the core. Those factors allied with the neutron multiplication factor a little bit higher and sub criticality response according to control rods inclusion, shows this is a promising model.

## 6. References


[1] Perrotta, J.A., Soares, A.J., (2015). “RMB. The New Brazilian Multipurpose Research Reactor”, Atw. Int. Z. fuer Kernenerg. 60 (1), 30e34.

[2] Campolina, D., et al., (2017). “Neutronic Analysis of the Fuel Loaded Irradiation Loop Device of the RMB Multipurpose Brazilian Reactor”, Progress in Nuclear Energy, (2017) 1-8.

[3] Barbot, L., et al., (2013). On Line Neutron Flux Mapping in Fuel Coolant Channels of a Research Reactor. IEEE Transactions on Nuclear Science.62.10.1109/ANIMMA.2013.6727951.

[4] Santos, A.A.C., et al., “Verification and Validation of CFD Simulations Applied to Thermal-hydraulic Systems Present in Nuclear Reactors: Thermal Stratification in Nuclear Piping Systems”, In: SIMMEC, 2012, Belo Horizonte. SIMMEC, 2012.

[5] Tomaz, G.C.Q., “Estudo experimental da camada de água quente em um modelo em escala do Reator Multipropósito Brasileiro (RMB)”, Master dissertation. Universidade Federal de Minas Gerais, Belo Horizonte, MG, 2017. (Portuguese).

[6] Leppänen, J., et al. (2015) *"The Serpent Monte Carlo code: Status, development and applications in 2013",* Ann. Nucl. Energy, 82 (2015) 142-150.

[7] Araújo Silva, V.V., Santos, A.A.C., Theler, G., Pereira, C. (2016). “Open Software One-Step Coupled Neutronics and CFD Thermohydraulics Calculation”, INTERNATIONAL JOURNAL OF EMERGING TECHNOLOGY AND ADVANCED ENGINEERING , 6 (2016) 174-179.

[8] Dalle, H. M., “Simulação do Reator TRIGA IPR-R1 Utilizando Métodos de Transporte por Monte Carlo”, Ph.D thesis. Faculdade de Engenharia Química da Universidade Estadual de Campinas, Campinas, SP, 2005. (Portuguese).

[9] Domingos, D.B., “Análises Neutrônica e Termo-hidráulica de Dispositivos para Irradiação de Alvos Tipo LEU de UAlx-Al e U-Ni para Produção de Mo-99 nos Reatores IEA-R1 e RMB”, Diss. Universidade de São Paulo, 2014. (Portuguese)

[10] Meireles, S.P., et al., “Influence of Geometry in TRIGA Reactor Criticality Calculation and Reactivity Determination Using Serpent 2 and MCNPX Codes”, International Journal of Nuclear Energy Science and Technology 11.2 (2017): 146-162.

[11] CNEN – Comissão Nacional de Energia Nuclear., “RMB e a Produção de Radiofármacos”, Avaliable at: <http://www.cnen.gov.br/radiofarmacos> Last accessed : 30 Jan. 2018 (Portuguese).