Commissioning Experiments of the New Core of the IPEN/MB-01 Research Reactor with Plate-Type Fuel Elements

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Abstract. This work aims to show the main experimental use of the zero power IPEN/MB-01 reactor during the commissioning of the new core containing plate-type fuel elements. The IPEN/MB-01 reactor is mainly used to validate the calculation methodology used in the design of nuclear reactor cores and the new core to specifically validate the methodology used in the design of the future core of the RMB research reactor (Brazilian Multipurpose Reactor).

Key Words: Commissioning, Critical Mass, Control Rods Calibration, Critical Position, Isothermal Reactivity Coefficient

1. Introduction

The reactor physics experiments have joined a long history in the nuclear science and technology areas and constitute an essential tool for the reactor physicists in their task to validate calculation methodologies and related nuclear data libraries. For a long time reactor physics experiments have been carried out worldwide and very valuable experimental data has been published to serve as benchmarks [1-3].

The IPEN/MB-01 reactor (https://www.ipen.br/portal_por/portal/interna.php?secao_id=723) is a zero power reactor (100 watts maximum power level) specially designed to measure a wide variety reactor physics parameters [3]. The first core of the IPEN/MB-01 used a total of 680 UO_2 fuel rods, being two Ag-In-Cd control rods and two B_4C safety rods and fuel enrichment of 4.3%. The new core consists of 19 Plate-Type fuel elements and one massive aluminum element assembled in a 4 per 5 arrangements. Each fuel element contains 21 fuel plates, the fuel being of U_3Si_2 enriched to 19.75%, and the criticality is maintained by the insertion of four hafnium control rods into the core.

2.1. Determination of the Critical Mass

The aim is to present the main steps and experimental methodology of the approach to critical experiments with emphasis on critical mass configuration. The IPEN/MB-01 loading operation standard and its criticality approach [4,5] followed the safety criteria described by IAEA. Five ex-core detectors were strategically positioned around the core at reflector region to monitor the fuel loading. For each neutron detector a 1/M curve (1/M is the inverse of the neutron multiplication) was constructed from de signal acquired in each loading step (detectors counting) . The loading procedure consisted initially of a sequence of thirteen steps. Each step is composed by the insertion of a number of fuel elements (two for each step) at a symmetric specific location inside the core. The fuel elements were placed in a symmetrical position of the reactor core. Exactly on the 13th step of loading it was possible to estimate the critical core configuration with a good accuracy and precision. The prediction of criticality was reached on the 13th step for a total of (4626.33 ± 3.82) grams of ^{235}U or (16.34 ± 0.02) fuel elements. This value was obtained from the data in table 1 using the curve of the multiplication of neutrons ($1/M=C_0/C$) obtained through counting C of experimental neutron detectors number 11,12,13,14 and 15 positioned around the reactor core (see figure 1) in relation to the same reference counts (C0) with the core at the initial stage of fuel loading. The final configuration is shown

in FIG. 1 together with the position of neutrons experimental detectors used to predict the critical mass
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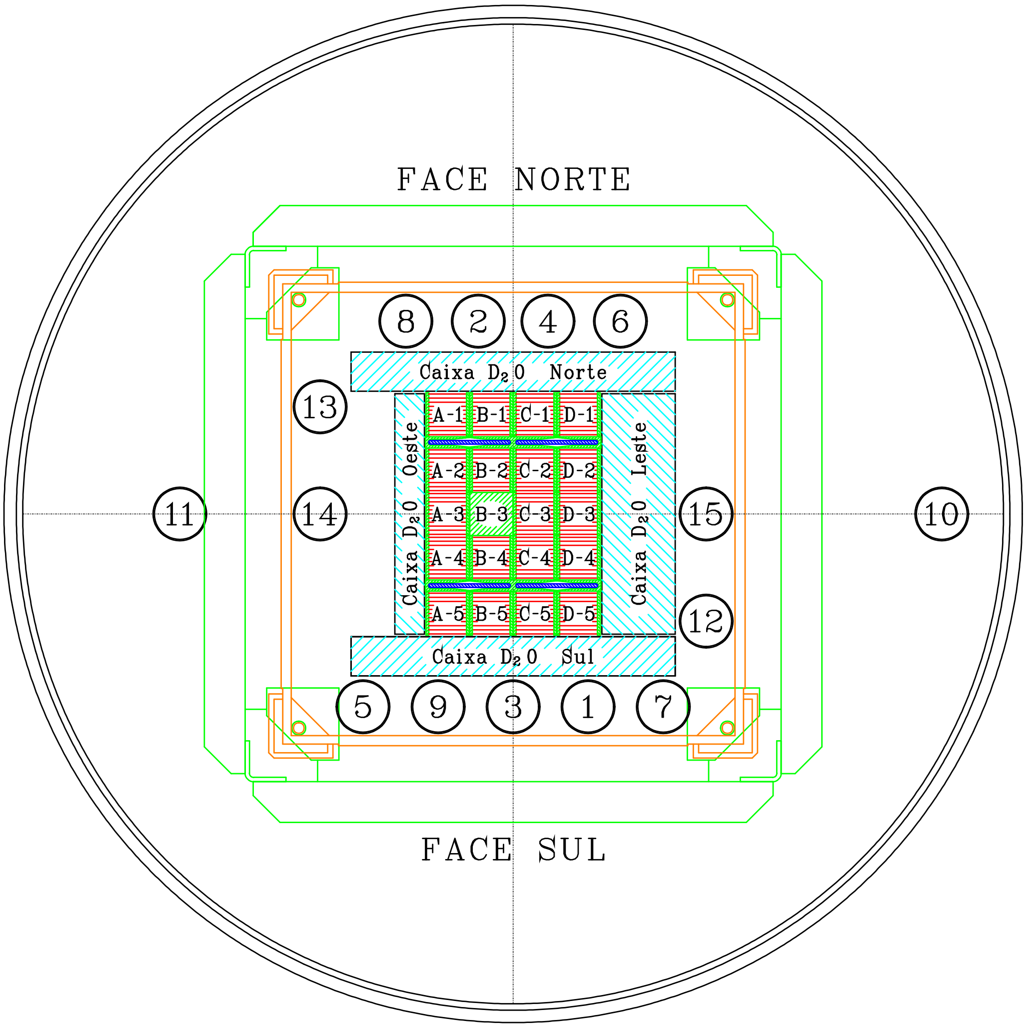


FIG. 1.- Experimental Neutron Detectors Around the Core of IPEN/MB-01 Reactor Used in Critical Mass Prediction (Nº 11 until N° 15).

Initially, up to the 8th step, 15 standard fuel elements with 21 fuel plates were inserted in the core (two for each step). Subsequently, aiming a finer and safer approximation of criticality, special fuel elements with different amounts of fuel plates were introduced into the core and consequently different ^{235}U mass, as it can be seen in figure 2 from de 9th to the 13th step.

At each stage of fuel loading, a criticality prediction is made through the inverse graph of multiplication of neutrons (1/M) by the amount of mass of ^{235}U present in the core. The multiplication of neutrons M is given from one step loading to the other by ratio of counts in neutron detectors positioned around the core ($M=C_0/C$, where C_0 is an initial reference count and C is the step counts). When M tends to infinity, we know that 1/M tends to zero ($1/M=C_0/C$). Thus, extrapolating the straight line adjusted to two values of 1/M (current step in relation to the previous step) up to the zero value, we obtain on the abscissa axis the predicted value of critical mass for each of the detectors.

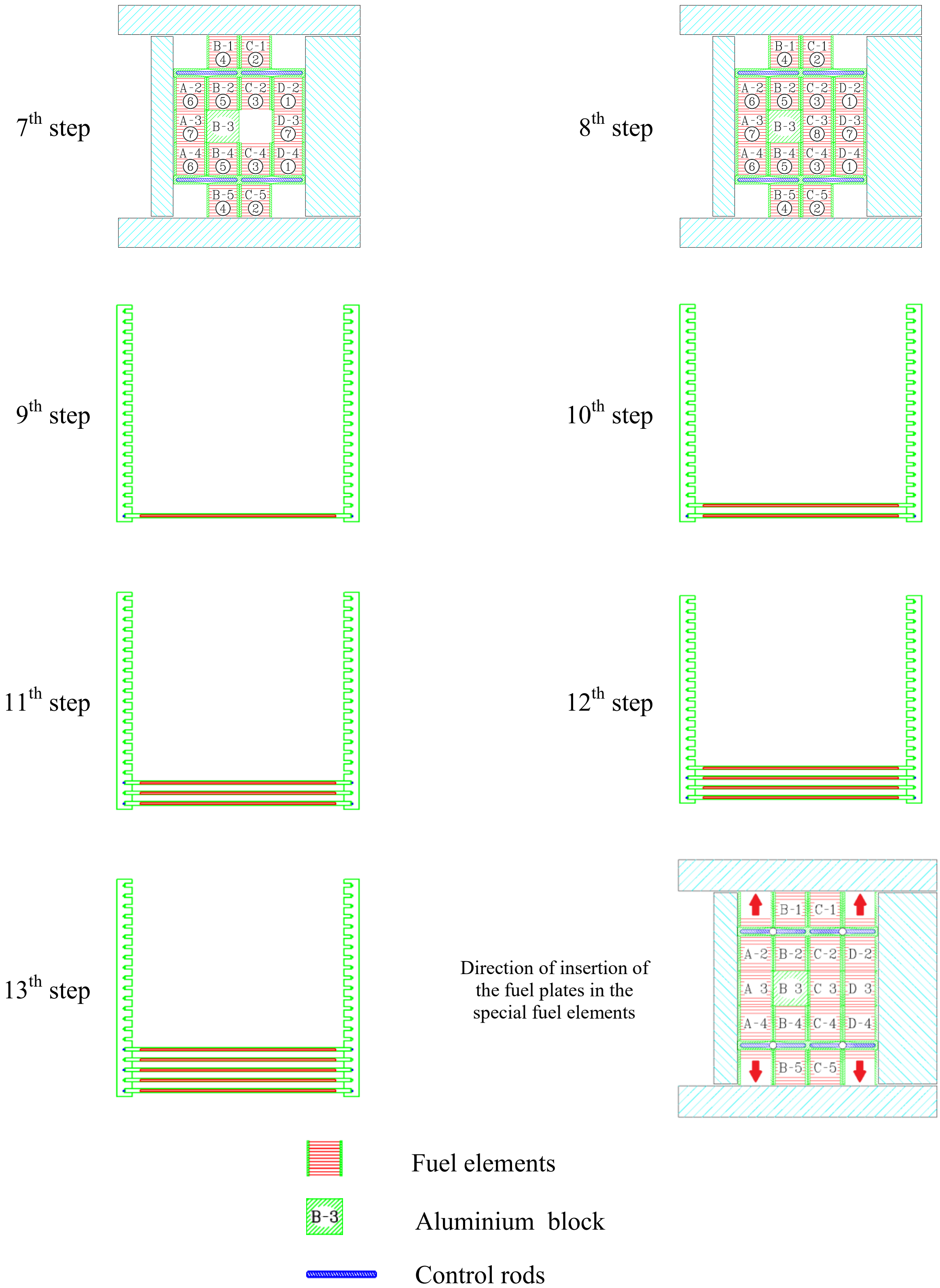


Figure 2 – Fuel Loading Steps with Standard Fuel Elements (up to 8th step) and with Special Fuel Elements Containing Different Amounts of Fuel Plates (9th to 13th steps).

The calculated value is (4623,00 ± 80) grams, then the calculation using the MCNP-5 code showed a critical mass value underestimated in relation to the experimental value of 0.1 % .

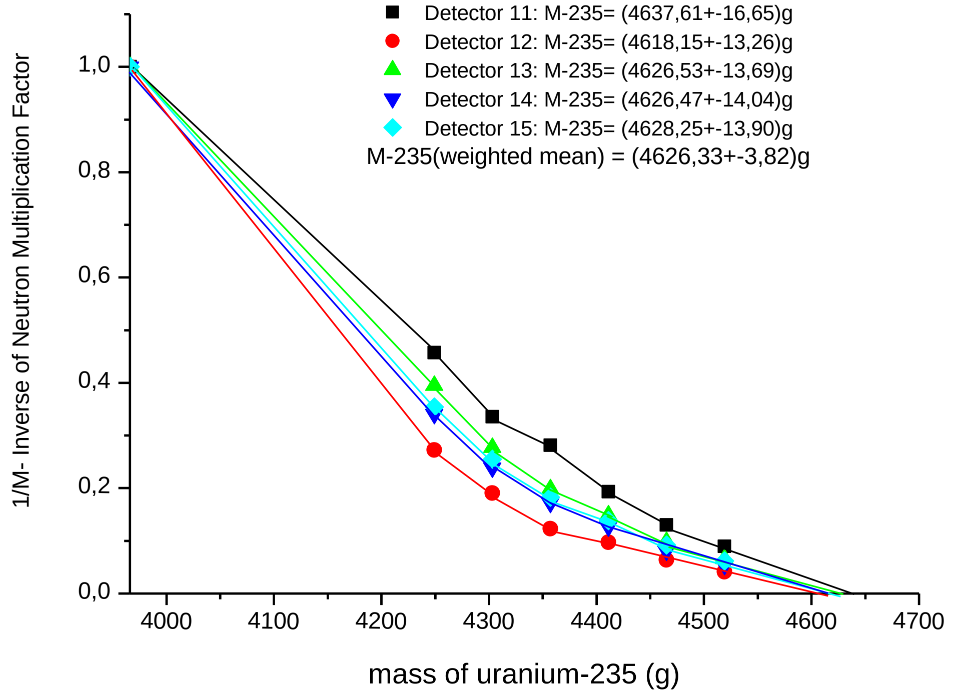


Figure 3 – Curve 1/M versus mass of de uranium-235 (M-235) grams.

2.2. Initial Criticality: Prediction of Criticality with Control Rods

Initially with 19 fuel elements and the four control rods inside the core, the prediction of criticality (initial Criticality) with the four control rods inside the reactor core could have been estimated. The initial criticality was obtained on March 3rd, 2020 at 11:11 a.m. For this experimental purpose several steps at control rod nº 3 (BC#3) were withdrawn from the core.

The experimental procedure consisted in removing the three control rods BC#1, BC#2 and BC#4 from the height active core, all of them kept in the critical position of the rods estimated by the calculation (64.23% by MCNP-5 code) for the four control rods equally inserted in the reactor core. After the removal of the three control rods (BC#1, BC#2 and BC#4), the BC#3 control rod was removed from the core in many steps, starting from 0%, where the reference counts (C_0) were performed in the starting nuclear channels Nº 1, 2 and 9 (neutron detectors type B-10). At each BC#3 control rod removal step, counts were acquired in the initial nuclear channels 1,2 and 9 and it has calculated the neutron multiplication factor (1/M=C0/C) and the critical position of control rod BC#3 was estimated. In Table 1, we see the various movement steps carried out until the final criticality prediction for BC#3. The other control rods BC#1, BC#2 and BC#4 were kept fixed at 64.23% position out of the core (fuel active height).

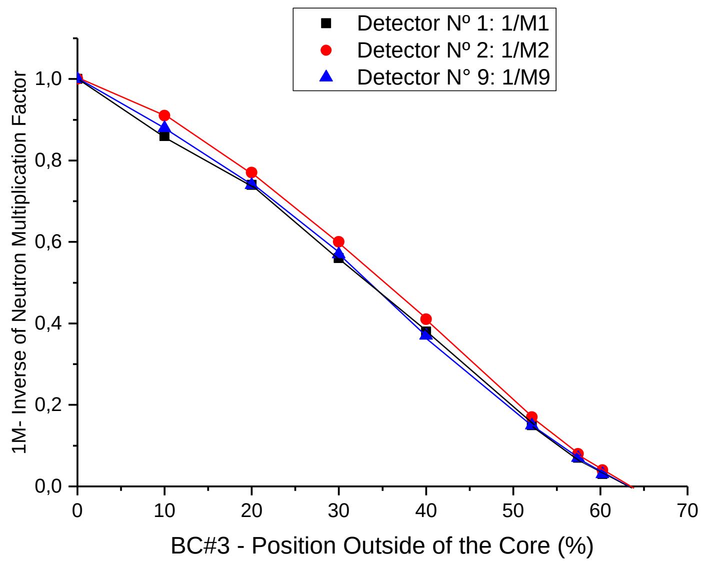
In this experiment, as in all the other ones, an attempt is always made to maintain the temperature of the moderator at (20.5± 0.5) ºC using, when necessary, a heater to heat or chiller-type refrigerating machines to cool the moderator.

Table 1- Data obtained by the removed percentage of control rod BC#3 (steps) with BC#1, BC#2 and BC#4 fixed at 64.23% (critical position calculated by the four control rod equally removed from the core).

STEP	BC#3 (%)	C_1	C_2	C_9	$(1/M_1)$	$(1/M_2)$	$(1/M_9)$	Moderator Temperature (ºC)
1	0.00	3340	8710	5481	1	1	1	20.19 ± 0.11
2	10.00	3873	9587	6312	0.86	0.91	0.88	20.18 ± 0.09
3	20.00	4491	11365	73805	0.74	0.77	0.74	20.16 ± 0.09
4	30.00	5939	14476	9615	0.56	0.60	0.57	20.15 ± 0.10
5	40.00	8889	21061	14883	0.38	0.41	0.37	20.18 ± 0.11
6	52.16	22032	49874	37753	0.15	0.17	0.15	20.17 ± 0.11
7	57.44	47721	106896	83597	0.07	0.08	0.07	20.14 ± 0.08
8	60.34	109846	240114	192430	0.03	0.04	0.03	20.16 ± 0.10
Critical Prevision	**62.60 ± 0.10**[1]	↑∞	↑∞	↑∞	↓0	↓0	↓0	**20.16 ± 0.07**[2]

1-Mean value of the critical prevision of the three nuclear start channels 1,2 and 9 with uncertainty with the confidence statistical level of 95% ;2-Mean value of temperature of all steps with uncertainty with confidence statistical level of 95% .

FIG. 4.- Curve 1/M to Prevision of Critical Position of the control rod BC#3 with BC#1, BC#2 and BC#4 fixes in percentage of 64.23% of active height outside of the core [4,5].



The critical position of the control rod experimentally predicted through the 1/M curve (Table 1) for BC#3 is 62.60%. When compared to the calculated value of 64.23%, a difference between the estimated value and the calculation of 2.60% is obtained. Regarding the real value obtained from the critical reactor, the critical position value of BC#3 is 62.52%. So there is a difference of only

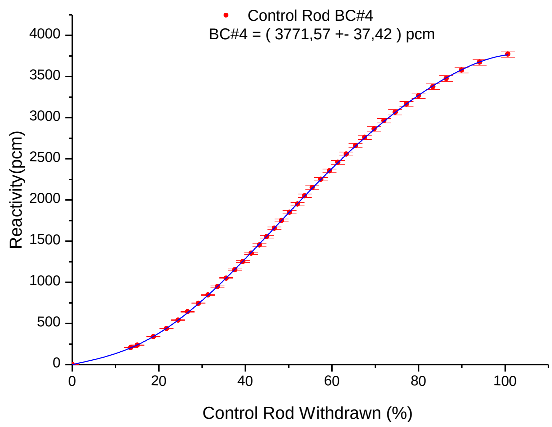
0.13% . The estimated value presents a difference of only 1 to 2 pcm of reactivity when compared with the real criticality value and of 73 pcm with the calculated value, if that reactivity difference is estimated from the control rod calibration equation BC#3 which will be following presented.

2.3 Control Rods Calibration

The four control rods are made of hafnium and are calibrated to know which reactivity value is introduced in the system when a small step of control rods in the reactor core is totally withdrawn or inserted. For this purpose a experimental methodology was used by the use of reatimeter. The reatimeter consists of a software that uses Kinetic punctual equation and Kinetics parameters obtained by JEND 3.3 code [5]. The reatimeter receives the counting signal of nuclear power Channels nº 3 and nº 4 (see Figure 1) positioned around the reactor core. Then one step of control rod is withdrawn from the core and there is the insertion of positive reactivity that is recorded by reatimeter and used by kinetic punctual equation to calculate the reactivity inserted in the system. At this point the reactor is supercritical with a specific period ($T \leq 100$ s) and several values of reactivity are collected by the reatimeter what will enable the calculus of the mean value of reactivity for each step of control rod withdrawn. After this acquisition of values is finished, the reactor returns to its critical condition by inserting another control rod in the core. The process is resumed again with the removal of a new step from the control rod and it ends when the entire control rod is measured by the reatimeter that assigns differential reactivity values along all the scanned steps of the control rod. The summation of the differential reactivity values of all the removed control rod steps of the active core gives the integral reactivity value of the control rods. In this situation we say that the control rods are calibrated. This way a Boltzmann equation curve is adjusted to the experimental values of differential reactivity versus control rods position withdrawn from the reactor core. This way the calibration curve to all control rods (BC#1, BC#2 , BC#3 and BC#4) is obtained. Thus it is possible to know that for each control rod withdrawn from the core a positive reactivity in the system is inserted. Then if each differential reactivity value is summed, the results will be the integral reactivity of the control rod that is exactly its reactivity value when totally inserted inside the reactor core.

These measures confirmed that a unique control rod introduces a negative reactivity value (BC#4 = -3772.08 ± 37,52 pcm) more than enough to shutdown the reactor because it is introduced more negative reactivity than the excess reactivity of the core (3511 pcm). The values obtained for the other control rods are BC#1 = (3371.99 ± 34.38) pcm, BC#2 = (3780.89 ± 39.41) pcm and BC#3= (3309.78 ± 37,52) pcm .

Figure 5 - Integral Reactivity curve of the control rod BC#4, the most reactive control rod in the IPEN/MB-01 reactor core.



2.4 Measurement of Isothermal Reactivity Coefficient

The isothermal reactivity coefficient ($\alpha_{iso}(T) = \Delta\rho/\Delta T$) is the most important parameter of the reactor physics from the point of view of the safety analysis because its experimental determination ensures that if there is an uncontrolled power excursion, the reactor will be able to auto shutdown without the operator action.

The isothermal reactivity coefficient is obtained in the system temperature range between 20 ºC and 80 ºC. The technique used is the inverse kinetics technique [ ], using a reactivity meter (reatimeter) previously described in 2.3. The mean values obtained were (-17.38 ± 0.12) pcm/ºC between 20ºC and 50ºC and (-25.70 ± 0.06) pcm/ºC between 20ºC and 80ºC. The experimental procedure consisted of the reactor criticalization at 1 watt of power and stabilizing it in automatic control with the four control rods equally inserted. The next step was to gradually increase the temperature of the moderator in steps of 5°C using existing electrical resistances for this purpose. Thus, without the automatic control acting on BC#3 (off) the reactor becomes subcritical with the moderator temperature increase of 5 °C and the negative reactivity values introduced in the system are acquired in the reatimeter. The reactivity measurement is carried out after the stabilization of the mean temperature of the moderator indicated by three temperature values of three thermocouples positioned at different heights of the active core (initial, middle and final). After the reactivity measurements, the BC#3 control rod is removed from the core so that the reactor returns to its criticality condition through the control of the BC#3 position performed by the automatic control, returning the reactor to a power of 1 watt again. After criticality at 1 watt is reached, the moderator is heated again and the reactivity measurement process continues nonstop through several steps of increasing the temperature by 5°C until the aimed final temperature is reached. All reactivity measurements were carried out from 20º C to 50º C and subsequently from 50 to 80º C, obtaining the negative values of the isothermal reactivity coefficient.

Table 2 - Isothermal reactivity coefficients measurements in each step of the temperature starting 20ºC until obtaining the final temperature of 50° C.

Steps	Mean Temperature (T °C)	Critical Position of BC#3 (%)	Withdrawn (%)	Mean Reactivity (Δρ pcm)	$\alpha_{iso}(T)$ (pcm/°C)
1	20,02 ± 0,04	9,00	0	0	---
2	25,57 ± 0,02	13,15	4,15	-74,77 ± 3,76	-13,47 ± 0,54
3	30,57 ± 0,20	16,29	3,14	-76,29 ± 3,20	-15,26 ± 0,45
4	36,77 ± 0, 20	20,00	3,71	-99,44 ± 3,60	-16,04 ± 1,75
5	40,27 ± 0,28	22,60	2,60	-72,44 ± 3,56	-20,70 ± 3,06
6	45,64 ± 0,14	25,20	2,60	-91,24 ± 3,26	-16,99 ± 1,869
7	50,46 ± 0,12	28,20	3,00	-114,33 ± 2,78	-23,72 ± 0,50
ΔT_m	**30,44 ± 0,44**		Σ	**-528,95 ± 7,46**	**-17,38 ± 0,12**

Conclusion

After 30 years using the core of the UO_2 rods, it was deactivated in 2018 with more than 3,663 operations, most of them dedicated to experiments [5-12] , training and recycling of operators, undergraduate and graduate courses. Several experiments with this core were considered a reference for the NEA/NSC criticality analysis [5], given the high quality of the carried out experiments. In addition, it was possible to carry out several courses acting strongly in the training of students and nuclear researchers. A new phase is now beginning with the installation of a new core containing plate-type fuel elements that will allow the performance of several experiments aimed at validating the calculation methodology used in the project of the RMB reactor - Brazilian Multipurpose Reactor [13]. The initial step was taken with the completion of the commissioning experiments for the new core presented for analysis by the Brazilian Licensing Authority. Such experiments served to validate the entire calculation methodology used in the project, as well as the future RMB nuclear reactor through the supply of experimental results that demonstrate that such calculations are accurate and precise and with values being very close to the experimental ones.

Appendix 1: References

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