ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN
2019 International Nuclear Atlantic Conference - INAC 2019
Santos, SP, Brazil, October 21-25, 2019

Agência Brasileira do ISBN
ISBN 978-85-99141-08-3

IPEN/MB-01 REACTOR EXPERIMENTS WITH NICKEL REFLECTORS

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ABSTRACT

In the validation and verification processes of calculation methodologies and associated nuclear data libraries, the existence of experiments that can be considered benchmarks is of fundamental importance. For this purpose, a set of experiments with heavy material nuclear reflector was performed in the IPEN/MB-01 reactor using nickel plates properly inserted in the west face of the reactor core. A total of 32 plates around 3 mm thick were used in the experiment. The axial width and length were sufficient to cover the entire active reactor core. For each plate placement step, reactivity measurements were made due to their insertion in the core; as well as of the critical position of the equally removed BC1 and BC2 control rods. It could be observed that the increase of neutron absorption and consequent decrease of neutron moderation dominated the whole physics of the problem when few plates of reflective material were inserted (about 3 plates). Thereafter, neutron reflection became important overcoming neutron absorption; the reactivity increased until it surpassed the situation without plate (excess reactivity zero) obtaining an increase (net gain) of reactivity with the 32 plates inserted (about 295 pcm). Therefore, it was observed that the reflected nucleus became more reactive than the nucleus without reflective material. The theoretical analysis using MCNP-5 and ENDF/B-VII.0 nuclear data library showed the physical aspects of neutron absorption and reflection in the heavy reflector considered; however, it presented a discrepancy when fast neutron reflection dominates the physical phenomenon of neutron transport. In order to verify the impact of other models of thermal scattering of hydrogen in water for the computational simulations of the experiments, three models were considered, besides the one used by the ENDF/B-VII.0 library: ENDF/B-VI.0 scattering law; new evaluation of the S(α,β) for hydrogen bound in water performed in Bariloche Atomic Center, Argentina; and the calculated with new released evaluations for ^{235}U, ^{238}U and ^{16}O.

1. INTRODUCTION

Using a suitable reflective material, which has an important position between the components of a nuclear power plant, helps to reduce the reactor core size; not only by reducing the flow of neutrons escaping from the reactor core, but also by reducing the consumption of fissile material. In addition, a good reflector reduces the incidence of neutrons in the pressure vessel by increasing reactor life. In particular, choosing a suitable heavy reflector requires the development of validations of new calculation methodologies to take into account the amount of material and its neutronics effects.

For this purpose, a set of benchmarks with heavy reflector was performed in the IPEN/MB-01 reactor using nickel plates, in a total of 32 plates, adequately juxtaposed on the west face of the reactor core. The plates were about 3 mm thick and their width and axial length were large enough to cover the whole active core of the reactor. Competition between the effect of thermal neutron capture in the heavy reflector and the effect of fast neutrons back scattering to the core is highlighted by varying the reflector thickness. The neutron capture is predominant for small thicknesses (about 1 or 2 cm), whereas scattering effect increases with the reflector thickness.

The theoretical analysis was performed employing MCNP-5 [1] computer code using the ENDF/B-VII.0 [2] nuclear data library. Besides the ENDF/B-VII.0 scattering law, more three thermal scattering law were considered to verify the impact of other models of thermal scattering of hydrogen in water: ENDF/B-VI.0 scattering law, thermal scattering law generated by the Bariloche Atomic Center (CAB) and the calculated with new nuclear data for ^{235}U [3], ^{238}U [4, 5] and ^{16}O [6] (recently completed and made available to the reactors physics community).

2. THE NICKEL REFLECTOR EXPERIMENT

The nickel heavy reflector experiments performed in the IPEN/MB-01 research reactor facility comprise a set of critical configurations employing the standard 28x26 4.3% enriched UO2 fuel-rod array configuration. The nickel plates were placed at the west the face of the IPEN/MB-01 reactor as shown in Fig. 1. Two banks of control rods control the IPEN/MB-01 reactor. They are located diagonally opposite each other in the core. Criticality is achieved by inserting the control banks BC1 and BC2 to the critical position. The safety-rod banks were always kept at their fully withdrawn position during the whole set of experiments; consequently they do not interfere with the measurements performed for this evaluation. The reactor power was maintained at 1 W to ensure adequate detector signal/noise ratio. Up to 32 plates, approximately 3.0-mm-thick each, were used in the experiment. The chosen distance between the last fuel rod row and the first plate was 5.5 ± 1.0 mm.

A mechanism was specially designed and mounted at the west face of the IPEN/MB-01 core to hold and fix the heavy reflector plates in the reflector region. Fig. 2a is a mock-up made of wood specially built with the purpose to show the details of the supports of the whole set up and the location of the plates relative to the core. The supports are made of stainless steel and they are fixed in the frames of the facility. A maximum weight of 300 kg was allowed in the experiment. This is the reason why a maximum of 32 plates were used. The distance between the active core (last row of fuel rods in the real case) and the plates is controlled by the screws shown in Fig. 2a. There are four of them: two in the face shown in Fig. 2a, and two on the back side. Fig. 2a also shows a polyethylene disk. This disk is connected to two wheels designed to compress the plates tightly together. The innermost wheel compresses the plates and the second rotates in the opposite direction to tighten everything together. Fig. 2b shows a front view of the plates with the core location and several other details.

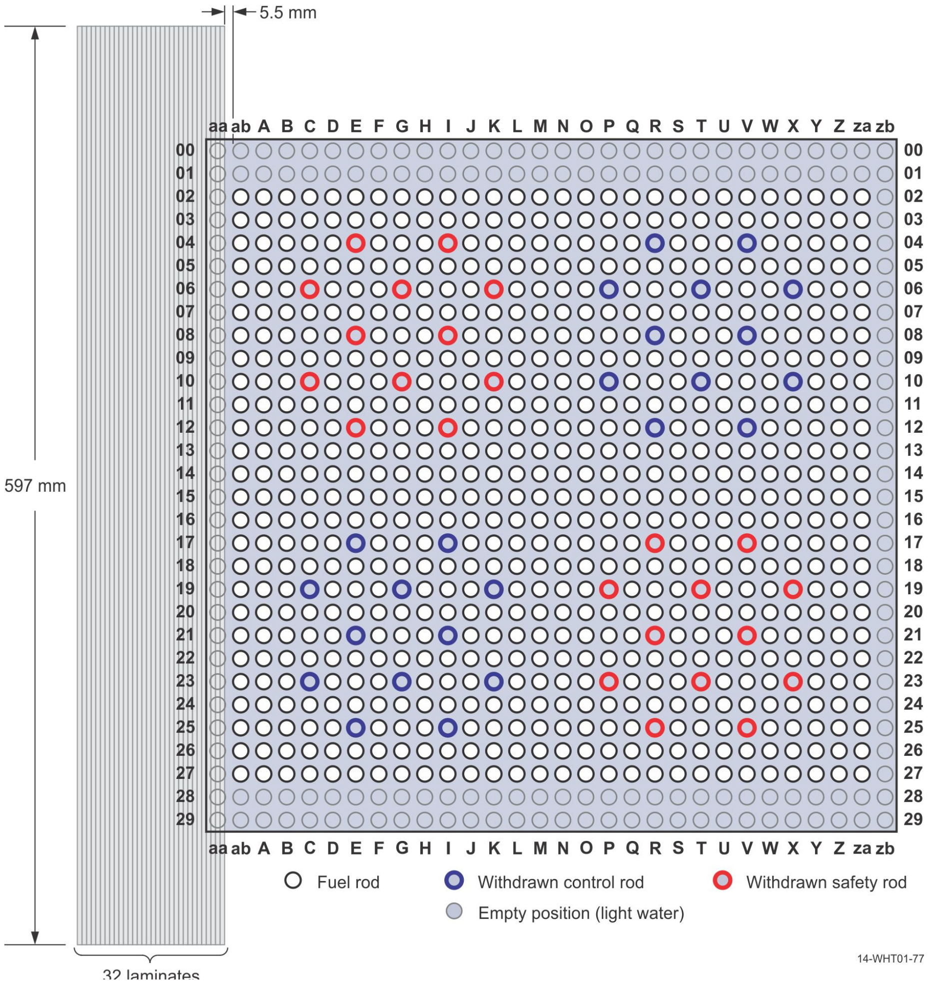
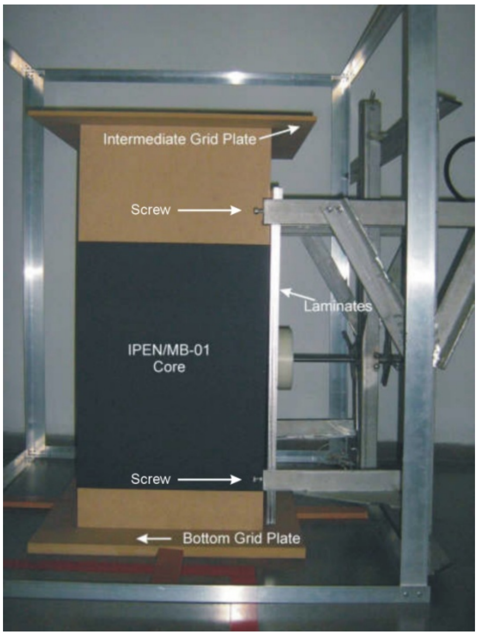


Figure 1: Experimental core configuration for the case of 32 nickel plates.



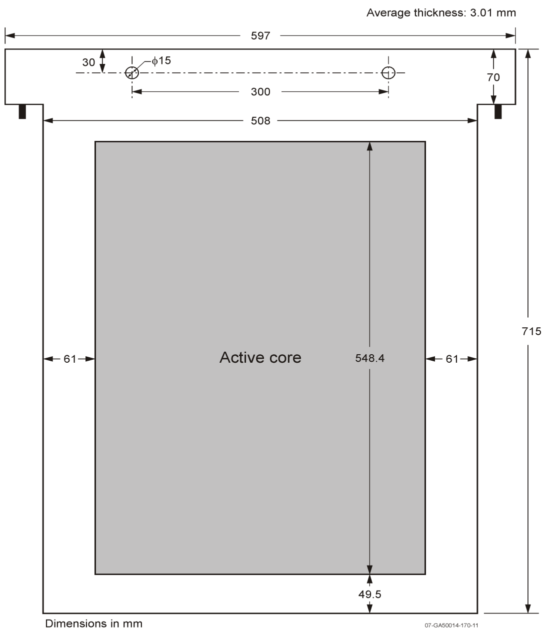


Figure 2a: Heavy reflector experiment.

Figure 2b: Front view of the experiment.

mock-up. **set up.**

2.1. Experimental Procedure

For each experimental configuration, the water temperature distribution in the core and reflector was adjusted to the mean value 21.00 ± 0.04 ºC. The temperature in the fuel region was monitored by the 12 thermocouples strategically located in the reactor core. Extreme care was taken to homogenize the temperature in the reactor core in order to guarantee that uncertainties in the final average temperature were small.

The nickel plates were positioned in the west face of the reactor core. Criticality is reached following the standard procedure by raising the control rods (BC1 and BC2) to the critical position.

Initially the plates were added one at a time up to ninth plate, thereafter two plates were added at a time up to the fifteenth plate, then three plates at a time up to the twenty-fourth plate, and finally, four plates were introduced at a time up to the thirty -second or last plate.

The reactivity was measured by the reactivity meter in the following way. Initially, for a specific number of nickel plates the reactor was made critical (reactivity nearly zero) maintaining the positions of the control rods BC1 and BC2 at the same withdrawn level. Subsequently, both rods are moved to the critical control bank of the previous configuration. The reactivity difference ($\Delta\rho$) between these two successive configurations is then measured by the reactivity meter. Finally, after this step, the control rods are brought to the criticality position corresponding to the case without plates (reference) and the total reactivity inserted (ρ), for the considered situation, is measured.

Another quantity that was part of the experimental data was the water gap between plates. The total thickness (plate plus water gap) of the plate set was measured for every configuration of the experiment. The measurements were made with the laminates assembled inside the reactor tank. The chosen points to measure the total thickness are shown in Fig. 3. A total of seven points were strategically chosen to cope with this task. Table 1 shows the final set of measurements of the total thickness for the nickel cases. The accuracy of the equipment that performs the measurements was 0.01 mm. The average value in the last column is the mean value of the seven measurements and its uncertainty is the standard deviation of the mean of these seven measurements.

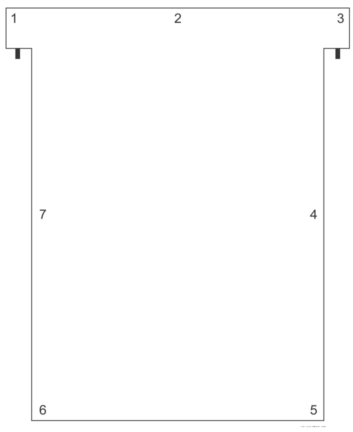


Figure 3: Positions chosen for the total thickness measurements.

Table 1: Total nickel thickness (in units of mm) in the experiment assembly

Number of Plates	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Average
1	-	-	-	-	-	-	-	
2	6.60	6.60	6.75	7.80	6.80	6.60	6.80	6.85±0.16
3	9.85	9.90	10.25	9.90	9.90	10.10	10.00	9.99±0.05
4	13.20	13.45	14.05	13.35	13.40	13.85	13.40	13.53±0.11
5	16.45	16.90	17.45	16.70	16.95	16.90	16.90	16.89±0.11
6	19.80	20.00	20.50	20.10	20.00	20.45	20.25	20.16±0.10
7	26.10	26.90	26.40	23.30	24.00	24.60	23.50	24.97±0.56
8	28.00	29.45	28.10	26.40	26.80	27.60	26.60	27.56±0.41
9	30.80	32.20	31.55	30.50	30.15	31.70	30.20	31.01±0.30
11	37.20	38.00	37.80	36.60	37.00	37.80	36.70	37.30±0.21
13	43.55	44.10	44.00	43.20	43.20	43.70	43.30	43.58±0.14
15	50.30	51.45	50.50	49.35	49.80	50.50	49.60	50.21±0.27
18	61.50	61.80	60.40	59.80	59.85	62.10	59.55	60.71±0.40
21	71.20	72.05	71.60	69.90	70.50	72.20	69.25	70.96±0.42
24	82.45	82.80	81.50	79.60	80.15	81.20	79.40	81.01±0.51
28	95.60	95.85	95.30	92.95	93.10	94.10	92.50	94.20±0.52
32	108.55	109.40	109.80	107.10	106.20	107.10	106.00	107.74±0.57

2.1. Experimental Results

Table 2 shows the measured reactivity and the critical control rod position as a function of the number of nickel plates. The first column represents the number of plates; the second one is the critical position for both control banks at the same withdrawn position; the third one is the critical position for previous case; the fourth one is the reactivity variation to the previous case; the fifth one is the reference critical control rod position (without plates); and finally the sixth column is the total reactivity inserted relative to the case without plates (reference).

According to the data shown in Table 2, the total reactivity (ρ) decreases up to the third plate and after that it increases, becomes nearly zero (which was equivalent to initial zero excess reactivity with zero plates) for the 13 plates case and reaches a value of 294.13 pcm when the whole set of 32 plates are inserted in the reflector. This is a very striking result because it demonstrates that when all 32 plates are inserted in the reflector there is a net gain of reactivity. The reactivity behavior demonstrates all the physics events already mentioned in this work. When the number of plates are small (around 3), the neutron absorption in the plates is more important than the neutron reflection and the reactivity decreases. This condition holds up to a point where the neutron reflection becomes more important than the neutron absorption in the plates and the reactivity increases. The neutronic importance of a thermal neutron scattered back to the core by a water reflector is larger (in term of ability for fuel fission) than a fast neutron. However, a lot of fast and epithermal neutrons are also scattered back through the nickel plates, and this compensates their small neutron importance.

It can even explain why a positive reactivity effect is observed for a number of plates greater than 13.

Table 2: Inserted reactivity and critical control rod position as a function of the number of nickel plates

Number of Nickel Plates	Critical Position BC1=BC2 (% withdrawn)	Critical Position Previous Case BC1 = BC2 (% withdrawn)	$\Delta\rho$ (pcm)	Critical Position Reference Case BC1 = BC2 (% withdrawn)	ρ (pcm)
0	58.00		-	-	-
1	61.62	58.00	-339.38 ± 11.83	58.00	-339.38 ± 11.83
2	62.40	61.62	-70.49 ± 0.69	58.00	-409.11 ± 15.03
3	62.43	62.40	-2.36 ± 0.53	58.00	-409.14 ± 14.64
4	62.06	62.43	32.14 ± 0.53	58.00	-379.54 ± 13.05
5	61.69	62.06	33.44 ± 0.53	58.00	-343.73 ± 10.55
6	61.21	61.69	43.53 ± 0.52	58.00	-300.08 ± 8.76
7	60.89	61.21	28.56 ± 0.53	58.00	-272.88 ± 8.04
8	60.33	60.89	52.15 ± 0.54	58.00	-220.34 ± 7.18
9	59.80	60.33	49.40 ± 0.55	58.00	-173.71 ± 6.40
11	58.97	59.80	79.03 ± 0.62	58.00	-93.08 ± 5.80
13	58.26	58.97	68.58 ± 0.53	58.00	-25.31 ± 5.70
15	57.71	58.26	54.37 ± 0.52	58.00	28.79 ± 5.71
18	56.88	57.71	81.80 ± 0.58	58.00	110.59 ± 5.70
21	56.28	56.88	59.35 ± 0.53	58.00	169.94 ± 5.70
24	55.77	56.28	50.06 ± 0.51	58.00	220.00 ± 5.70
28	55.36	55.77	42.36 ± 0.51	58.00	262.36 ± 5.71
32	55.05	55.36	31.77 ± 0.52	58.00	294.13 ± 5.71

The critical control rod positions shown in Table 2 also show the same features as already discussed for the reactivity behavior. When the number of plates is small (less than 3) the neutron absorption in the plates dominates the neutron balance and the control rods are withdrawn in order to compensate the loss of reactivity. After that, the neutron reflection in the plates starts to dominate the neutron balance and the control banks are inserted to compensate the reactivity gain.

3. THEORY – EXPERIMENT COMPARISONS

The nickel reflector experiment was explicitly modeled with the geometric features of the MCNP-5 code. All details inherent to the IPEN/MB-01 reactor core and reflector have been taken into account. MCNP-5 cross section library utilized in the analysis was ENDF/B-VII.0.

The geometric model for all experiments comprises a set of critical configurations employing a square array of 28x26 positions, and everything is immersed in a 100 cm radius water cylinder. The water in the core is located in the region between the rods, between the rods and the guide tubes, between the nickel plates, and inside the guide tubes. The nickel plates were placed at the west the face of the IPEN/MB-01

Fig. 4 and Fig 5 show the geometric data for the fuel, control rods and nickel heavy for the radial and axial representations; respectively. It should be added that throughout the experiment HBC1 = HBC2 (Fig. 5).

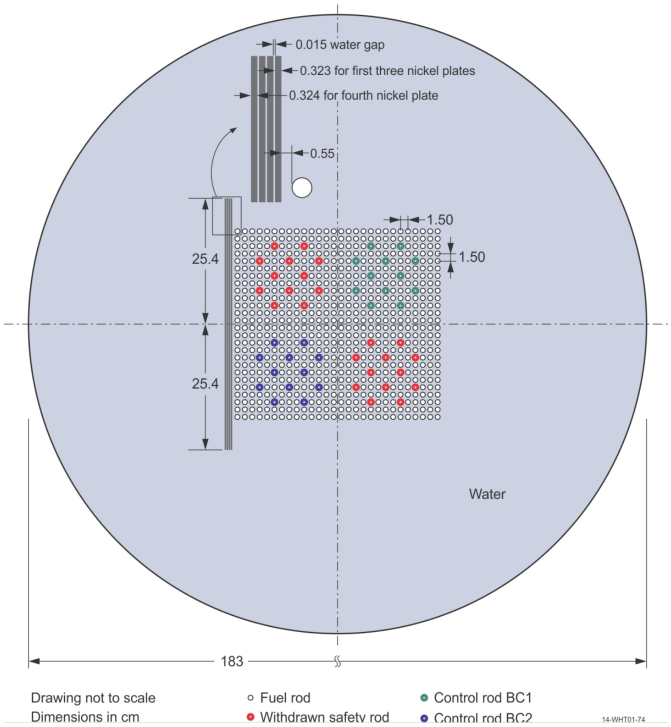


Figure 4: Radial representation (midway plane) of the IPEN/MB-01 core for 4 nickel plates inserted.

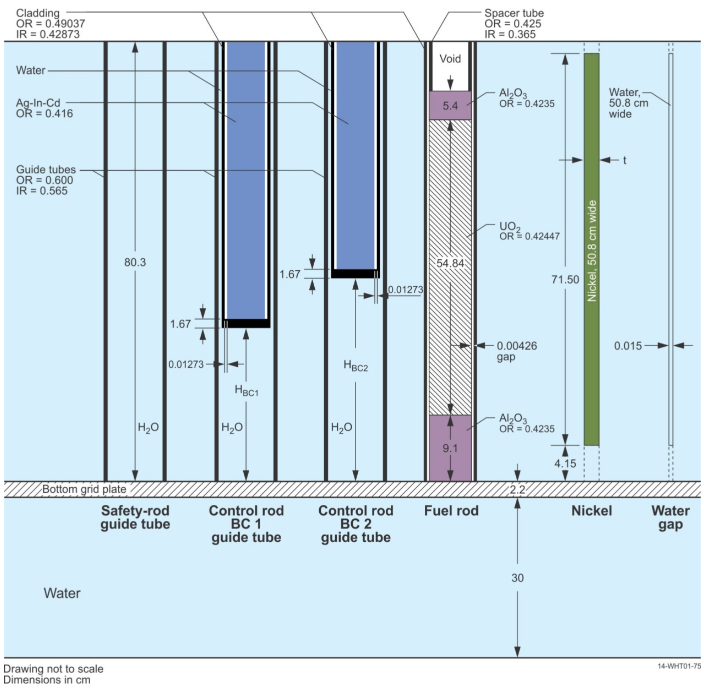


Figure 5: Representation of the fuel rod, the control rods inside their guide tubes, the safety-rod guide tube, and the nickel plates in the geometric model.

Nickel plates were represented by rectangular parallelepipeds 50.8 cm wide, 71.50 cm high and thick according to Table 3. The corners and the holes in the laminates were omitted. The cone shape of the bottom of the control rod was replaced by a cylinder of stainless steel of 1.67 cm height. The thermocouples and the tubes for the control and experiment detectors were replaced by water in the model.

Table 3: Thickness of the nickel plates

Plate Identification	Thickness (mm)	Mass (g)
01F	3.23±0.01	10,605.0±0.1
02F	3.23±0.01	10,605.0±0.1
03F	3.23±0.01	10,610.0±0.1
04F	3.24±0.01	10,605.0±0.1
05F	3.24±0.01	10,600.0±0.1
06F	3.21±0.01	10,530.0±0.1
07F	3.23±0.01	10,605.0±0.1
08F	3.23±0.01	10,605.0±0.1
09F	3.24±0.01	10,600.0±0.1
10F	3.24±0.01	10,600.0±0.1
11F	3.24±0.01	10,620.0±0.1
12F	3.22±0.01	10,570.0±0.1
13F	3.22±0.01	10,560.0±0.1
14F	3.22±0.01	10,565.0±0.1
15F	3.23±0.01	10,610.0±0.1
16F	3.22±0.01	10,560.0±0.1
17F	3.20±0.01	10,530.0±0.1
18F	3.24±0.01	10,630.0±0.1
19F	3.24±0.01	10,635.0±0.1
20F	3.24±0.01	10,625.0±0.1
21F	3.21±0.01	10,550.0±0.1
22F	3.20±0.01	10,540.0±0.1
23F	3.19±0.01	10,510.0±0.1
24F	3.19±0.01	10,510.0±0.1
25F	3.20±0.01	10,520.0±0.1
26F	3.21±0.01	10,560.0±0.1
27F	3.20±0.01	10,520.0±0.1
28F	3.20±0.01	10,520.0±0.1
29F	3.21±0.01	10,500.0±0.1
30F	3.21±0.01	10,515.0±0.1
31F	3.24±0.01	10,620.0±0.1
32F	3.23±0.01	10,585.0±0.1

Others details that were not included in the computer simulation were: the upper part of the fuel rod, the safety rod (completely removed during the whole experiment) and the support and fixation devices of the plates. In addition, impurities present in water and alumina have also been omitted. The reactivity effect of the support and fixing plate system was measured and was equal to -5.5 pcm. [7], this was considered as a bias.

Additional information regarding the IPEN/MB-01 reactor and facility, like geometric and material data, is available in benchmark reports LEU-COMP-THERM-077 [7] and LEU-COMP-THERM-088 [8].

The quantity calculated by MCNP-5 was the effective multiplication factor (k_{eff}) and the reactivity inserted by the nickel plates was calculated using the equation 1.

$$\rho = \frac{(k_j - k_i)}{(k_j \cdot k_i)}, \tag{1}$$

where ρ is the reactivity, k is the effective multiplication factor, sub index i refers to the case in question and sub index j to the case without plates or previous case.

To this end, the code was executed in the criticality calculation module "KCODE" which provides the effective multiplication factor. The standard deviation of the MCNP-5 was 1 pcm, which required 4050 cycles of 800,000 stories.

Three calculation methodologies were adopted for computer simulations, namely:

- Homogeneous - the first plate was treated explicitly and from the second plate was considered a homogenized region of thickness "t" that depended on the number of plates. The homogenization transformed the water gap and the heavy metal into a single region of uniform composition.

- Explicit 1 - All plates were treated explicitly considering the same average water gap between them.

- Explicit 2 - each plate was considered explicitly, but for each insertion the average water gap for the arrangement in question was calculated.

Fig. 6 shows the measured and calculated inserted reactivity as a function of the number of the nickel plates introduced in the west face of the IPEN/MB-01 core reactor. It was observed that the three methodologies used show the same qualitative behavior, showing that the physical aspects of neutron absorption and reflection were taken into consideration. From the quantitative point of view, the explicit methodologies were better than the homogeneous methodology. For the two ways of considering the plates explicitly, they were found to be similar.

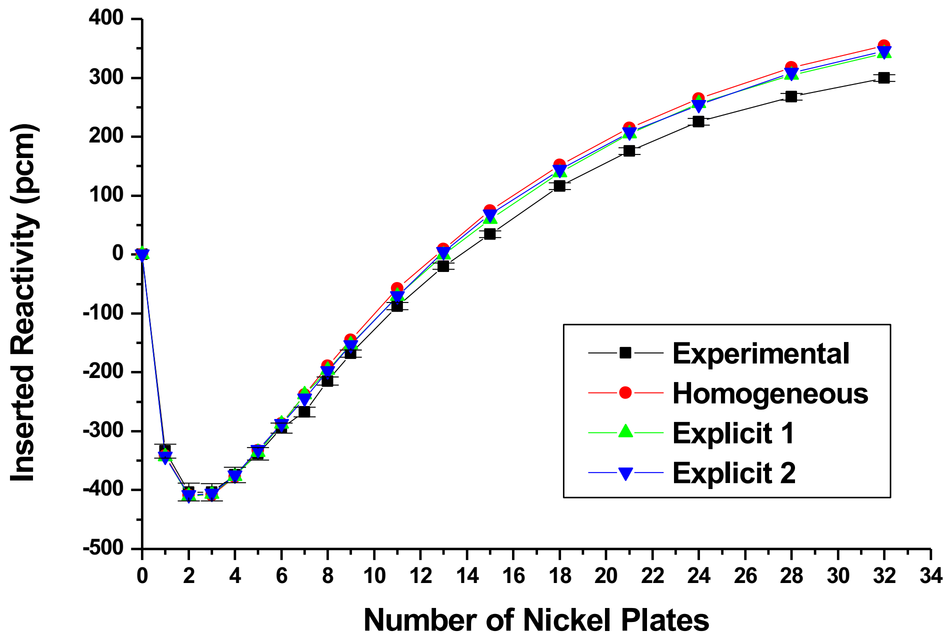


Figure 6: Theory-Experiment comparison for the reactivity as function of the number of nickel plates (in relation to the case without plates).

Fig. 7 shows the experimental comparisons considering more three S(α,β) models for hydrogen bound in water: from evaluated data library ENDF/B-VI.0; the performed in CAB; and the new nuclear data for ^{235}U, ^{238}U and ^{16}O, recently completed and made available to the reactor physics community. Explicit 1 methodology was utilized for this computational simulation.

In this case, both measured and calculated values show the competition between the effect of thermal neutron capture and fast neuron scattering as nickel plate thickness increases. It was also observed that the calculated values performed with S(α,β) from ENDF/B-VI.0 library showed a greater discrepancy, with relation the experimental values, than the others scattering laws used. The calculated values with the scattering law from CAB showed a better agreement with the experimental values.

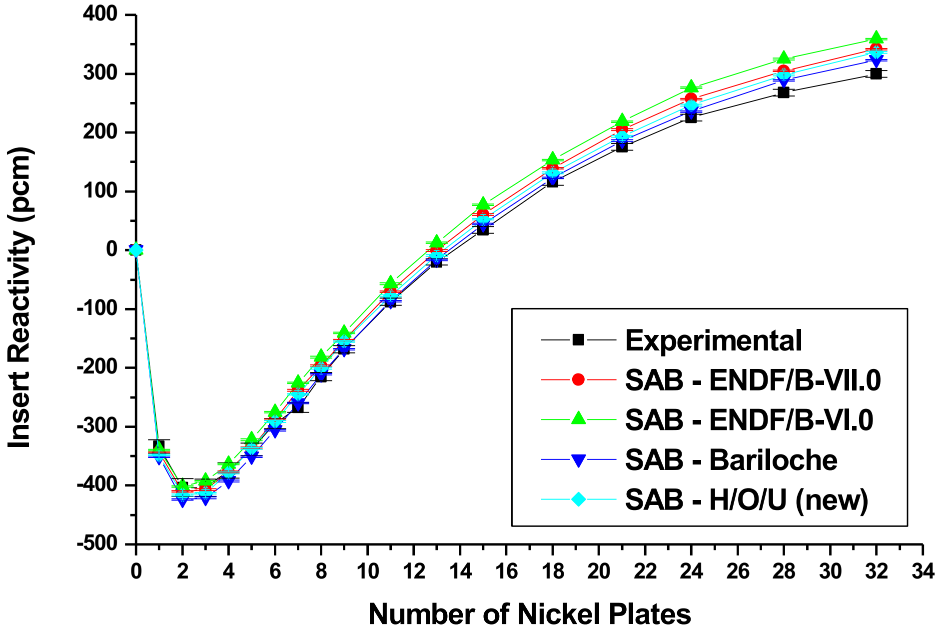


Figure 7: Theory-Experiment comparison for the reactivity as function of the number of nickel plates (in relation to the case without plates) - MCNP-5 /ENDF/B-VII.0 / Several S(α,β) / Explicit 1 Methodology.

4. CONCLUSIONS

The IPEN/MB-01 reactor experiments with nickel reflectors was successfully completed and analyzed. The reported experimental data are of high quality and can be very valuable to validate methodology and nuclear data libraries currently employed in LWR designs with heavy reflector. The competition between thermal neutron absorption and fast neutron reflection in the nickels plates was demonstrated experimentally. All calculation methodologies demonstrate their capability to describe the physics involved in such a heavy reflector system. The theoretical analysis employing MCNP5 and ENDF/B-VII.0 show that the calculated results have a good results up to fifteen plates and after that a systematic overprediction.

ACKNOWLEDGMENTS

The authors are grateful to Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for providing computational resources and material for the research project No. 2011/50516-8. The authors would also like to thank the operational staff of the IPEN/MB-01 reactor for their patience and efficient operation during the course of the experiment.

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