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HEAVY REFLECTOR EXPERIMENTS COMPOSED OF CARBON STEEL AND NICKEL IN THE IPEN/MB-01 REACTOR

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ABSTRACT

The heavy reflector experiments performed in the IPEN/MB-01 research reactor facility comprise a set of critical configurations employing the standard 28x26-fuel-rod configuration. The heavy reflector either, carbon steel or nickel plates was placed at one of the faces of the IPEN/MB-01 reactor. Criticality is achieved by inserting the control banks BC1 and BC2 to the critical position. 32 plates around 0.3 mm thick were used in all the experiment. The chosen distance between last fuel rod row and the first laminate for all types of laminates was 5.5 mm. Considering initially the carbon steel case, the experimental data reveal that the reactivity decreases up to the fifth plate and after that it increases, becomes nearly zero (which was equivalent to initial zero excess reactivity with zero plates) for the 28 plates case and reaches a value of 42.73 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 5), 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 experimental data for the nickel case shows the main features of the carbon steel case, but for the carbon steel case the reactivity gain is small, thus demonstrating that carbon steel or essentially iron has not the reflector capability as the nickel laminates do. The measured data of nickel plates show a higher reactivity gain, thus demonstrating that nickel is a better reflector than iron. The theoretical analysis employing MCNP5 and ENDF/B-VII.0 show that the calculated results have good results up to fifteen plates and after that a systematic overprediction.

1. INTRODUCTION

Water reflector and Stainless Steel (SS) baffle reflector (about 1 or 2-cm thick) are commonly used in (experimental and industrial) Light Water Reactors. However, they do not present the best neutron's characteristics in terms of neutron savings, i.e. economy of fissile material, contrary to SS heavy reflector (about 10cm thick) that enables to limit the radial leakage, in particular by back scattering the fast neutrons to the core. The major awaited improvements of such a reflector are: a better reflector savings, i.e., an economy in fissile material, an optimized radial power distribution, and the reduction of fast fluence to the vessel, leading to a plant life extension.

The purposes of this work are to present the effect of two types of heavy reflector on several configurations of the IPEN/MB-01 core. The experiments consider carbon steel and nickel reflectors with a varying thickness at the west face of the IPEN/MB-01 core. The experiments were performed with each type of heavy reflector individually. Carbon steel, which is composed mainly of iron, and nickel experiments were performed to provide a consistent and an interpretative check for the SS-304 reflector experiment [1]. Several plates (around 3 mm thick) of each type of reflector were introduced in the west face of this reactor and the quantities such as critical control bank configuration and reactivities were measured as a function of the number of plates. A total of 32 plates for each type of reflector were used in the experiment which gave a total thickness of around 10 cm. 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 preponderant for small thicknesses (about 1 or 2 cm), whereas scattering effect increases with the thickness.

The theoretical analysis will be performed employing MCNP-5 [2] computer code using the ENDF/B-VII.0 [3] nuclear data library.

2. THE HEAVY REFLECTOR EXPERIMENT

The reactor core setup for this experiment employs the standard 28x26 4.3% enriched UO2 fuel rod array configuration and it is shown in Figure 1. A complete core description of the IPEN/MB-01 core can be found in [4]. The control bank (BC) at the upper right corner is named BC1 while the one at lower left corner is named BC2. The columns of the IPEN/MB-01 core configuration are identified by numbers ranging from 00 to 29 while the lines are identified by letters as shown in Figure 1. This is an important aspect in order to identify the fuel rod location in the core.

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. Figure 2 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 Figure 2. There are four of them: two in the face shown in Figure 2, and two on the back side. Figure 2 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. Figure 3 shows a front view of the plates with the core location and several other details.

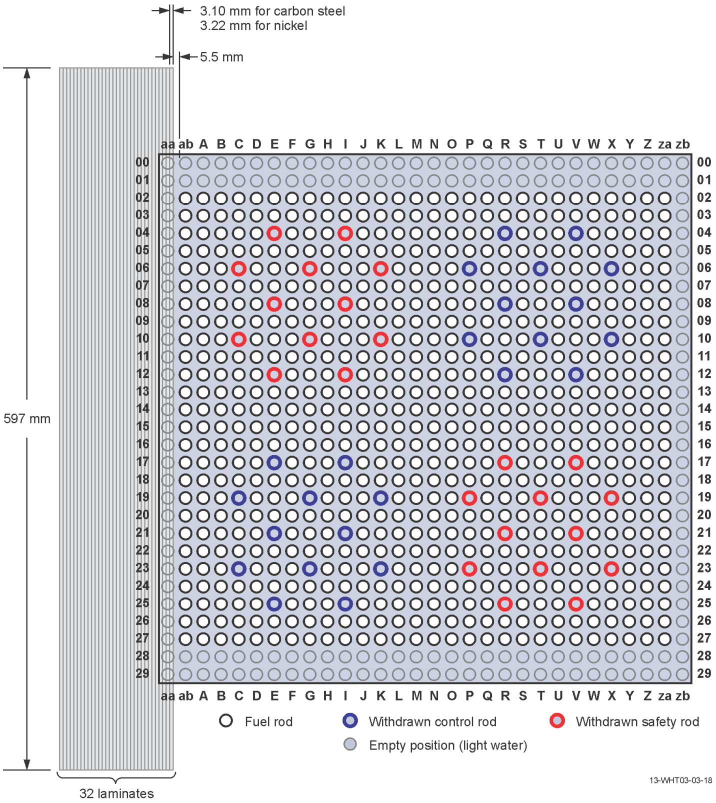

Figure 1: Experimental core configuration.

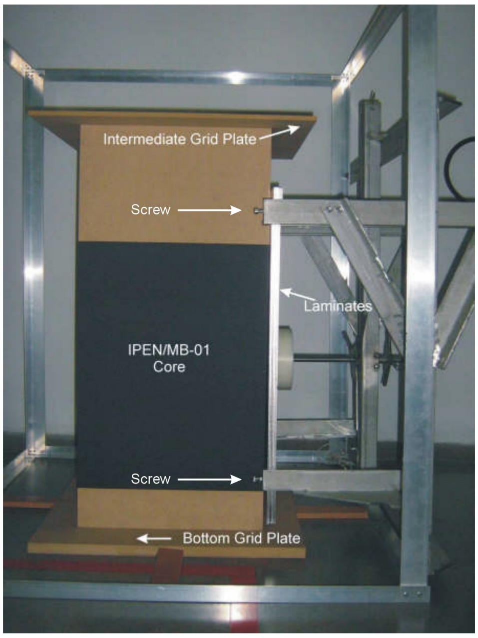

Figure 2: Heavy reflector experiment mock-up.

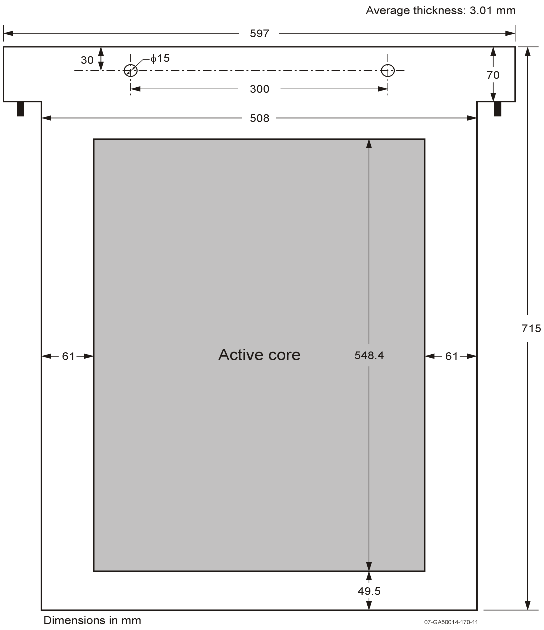

Figure 3: Front view of the experiment set up.

The chosen distance between last fuel rod row and the first plate was 5.5 ± 1.0 mm. The reactivity inserted by the compress disk and the plate support were measured and were equal to 5.5 pcm; a small effect that may be neglected in the theoretical analysis.

2.1. Experimental Procedure

Thirty five critical experiment configurations are considered in this work, including the reference case.

The reactivity was measured by the reactivity meter in the following way. Initially, for a specific number of plates (either nickel or carbon steel), the reactor was made critical maintaining the positions of the control banks BC1 and BC2 at the same withdrawn level. Subsequently, both banks are moved to the critical control bank of the previous configuration. The reactivity difference between these two successive configurations is then measured by the reactivity meter. The total reactivity induced for a specific number of plates is then the sum of the partial reactivity measurements starting from the configuration of one plate up to that point under consideration.

All the previous evaluations of the critical configurations of the IPEN/MB-01 reactor considered the control banks completely withdrawn. The experiments of this evaluation consider a set of heavy reflector plates (either carbon steel or nickel) placed at the west face of the reactor core. The purpose here was to get critical configurations as a function of the number of plates. The number of plates and the control bank positions are the changing variables to get criticality of the reactor.

The procedure adopted for the experimental approach was the following: The water temperature is initially kept at around 21.0 °C. The heavy reflector plates are positioned in the west face of the reactor core. Criticality is reached following the standard procedure by raising the control banks (BC1 and BC2) to the critical position. 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. For each experiment, the reactor system was allowed to reach thermal equilibrium, and the experimental data (temperature from all thermocouples, detector current and reactivities) were analyzed on line to verify the acceptable conditions of the experiment.

Another quantity that was part of the experimental data was the water gap between plates. The total thickness of the plate set was measured for every configuration of the experiment. The measurements were made with the laminates assembled inside the reactor tank. A total of seven points were strategically chosen to cope with this task. The accuracy of the equipment that performs the measurements was 0.01 mm.

The final compiled data are presented in Table 1. The fractions of heavy metal, ink, and water are average values for the case of 32 plates. The fraction of heavy metal, ink, and water refers to the homogenization of all these materials in the total measured thickness of 32 plates. The largest water fraction in the carbon steel laminates is due to the ink used to protect this sort of material. This does not occur for the nickel plates since there was no need for any sort of corrosion protection and consequently its fraction of water is smaller than that of carbon steel.

Table 1: Determination of the water gap thickness for the carbon steel and nickel experiments

Quantity	**Carbon Steel**	**Nickel**
Total Thickness (32 plates) (mm)	99.056 ± 0.128	103.098 ± 0.32
Total Thickness (32 plates) in the Experiment Set-up (mm)	107.486 ± 0.636	107.736 ± 0.575
Average Gap Thickness Between Plates (mm)	0.272 ± 0.021	0.150 ± 0.020
Volume Fraction of Heavy Metal (32 plates) (%)	90.830 % ± 0.01	95.695 ± 0.006
Volume Fraction of Heavy Metal (31 plates) (%)	91.915 ± 0.01	95.560 ± 0.006
Volume Fraction of Ink (first plate) (%):	0.613 ± 0.56	-
Volume Fraction of Ink (31 plates) (%):	1.450 ± 0.56	-
Volume Fraction of water (32 plates) (%):	7.84 ± 0.56	4.440 ± 0.006.
Volume Fraction of water (31 plates) (%):	8.085 ± 0.56	4.305 ± 0.006.

2.2. Experimental Results

Table 2 shows the measured reactivity and the critical control bank position as a function of the number of plates for the carbon steel and nickel case. These measurements considered both BC1 and BC2 at the same withdrawn level. The unit of the control bank position is % withdrawn with the zero level at the beginning of the active length of the fuel stack, while the condition of 100% withdrawn is at the top of the fuel stack. In Table 2, 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 total reactivity inserted by the plates relative to the case without plates; and the fourth one is the reactivity variation between successive cases for the carbon steel. The same pattern is repeated for the nickel cases.

The complete description and uncertainty analysis of the experiments reported here are described in the IRPhE handbook [5].

Table 2: Inserted reactivity and critical control bank position as a function of the number of carbon steel and nickel plates – experimental results

NºPlates	**Carbon Steel**			**Nickel**		
	Critical Position	**ρ (pcm)**	**Δρ (pcm)**	**Critical Position**	**ρ (pcm)**	**Δρ (pcm)**
0	58.00	0	---	58,00o	0	
1	60.44	-226.31 ±0.41	-226.31 ±0.41	61.62	-333.40±0.52	-338.90±0.52
2	61.57	-329.37±1.04	-103.03±0.30	62.40	-403.91±0.73	-70.57±0.27
3	61.90	-357.86±0.49	-29.99±0.24	62.43	-401.54±0.63	-2.34±0.16
4	62.05	-373.56±0.82	-14.02±0.23	62.06	-373.51±0.46	32.08±0.19
5	62.03	-372.65±0.59	1.70±0.16	61.69	-338.31±0.58	33.35±0.15
6	62.06	-370.95±0.85	-3.30±0.22	61.21	-294.27±0.35	43.49±0.14
7	61.71	-343.37±0.59	31.11±0.14	60.89	-267.01±0.45	28.48±0.17
8	61.54	-325.86±0.53	15.13±0.11	60.33	-214.60±0.32	52.16±0.13
9	61.21	-296.44±0.32	31.04±0.14	59.80	-167.99±0.23	49.37±0.15
11	60.79	-259.46±0.43	39.55±0.12	58.97	-87.24±0.15	78.95±0.12
13	60.28	-211.25±0.25	46.69±0.12	58.26	-19.80±0.07	68.63±0.12
15	59.82	-169.08±0.21	43.21±0.10	57.71	34.27±0.11	54.31±0.19
18	59.30	-118.58±0.45	49.41±0.15	56.88	116.07±0.11	81.80±0.11
21	58.77	-69.59±0.15	50.51±0.12	56.28	178.07±0.11	62.00±0.11
24	58.34	-28.19±0.11	41.95±0.12	55.77	228.08±0.11	50.01±0.10
28	58.00	5.14±0.10	66.03±0.15	55.36	270.46±0.11	42.38±0.11
32	57.61	42.73±0.11	37.23±0.11	55.05	302.15±0.11	31.70±0.12

Referring to the carbon steel cases, Table 2 shows that the reactivity decreases up to the fifth plate and after that it increases and becomes nearly zero (condition of zero plates) for the 24 plates case and reaches a value of 42.73 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 5), 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 carbon steel plates, and this compensates their small neutron importance. It can even explain why a positive reactivity effect is observed for a number of plates more than 28.

Table 2 shows also the competition for neutron absorption and neutron reflection in the nickel plates. For the case of nickel plates the absorption in these plates dominates the neutron balance up to around third plates and the reactivity decreases or in another way of seeing the phenomenon, the control banks BC1 and BC2 are withdrawn. After that, the neutron reflection in the plates becomes more important and the reactivity increases and the control banks BC1 and BC2 are inserted.

The carbon steel and nickel cases show identical behavior, however nickel has the highest reactivity gain when all the 32 plates are inserted in the reflector. This is partly due to its higher scattering cross section and partly to its higher material density (higher atoms/cc).

Figure 4 shows the experiment comparisons for the critical control bank positions for both BC1 and BC2 at the same withdrawn for all kinds of heavy reflector performed in this work.

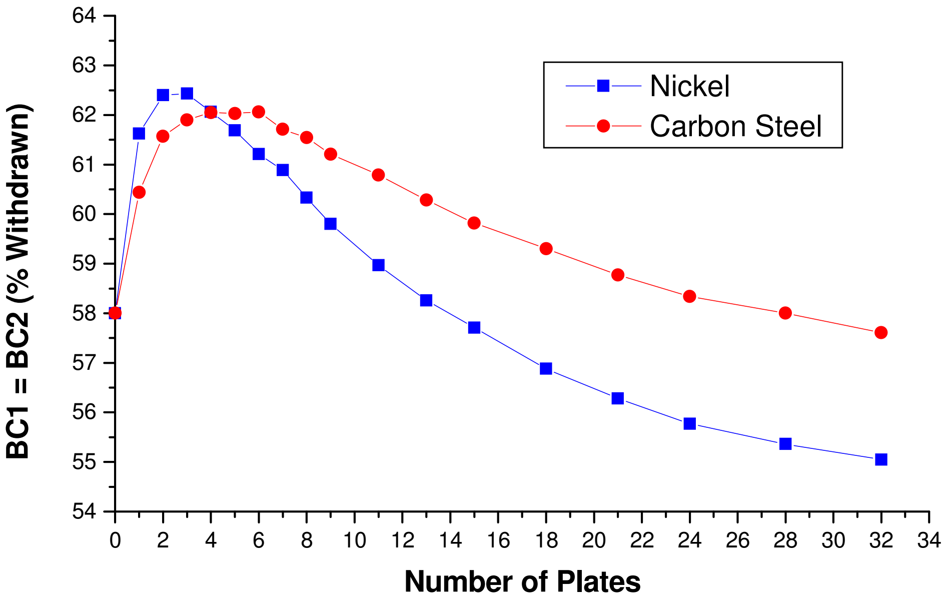

Figure 4: Critical Control Bank Positions.

3. THEORY-EXPERIMENT COMPARISONS

MCNP-5 was employed for the analyses of the heavy reflector experiment. It is considered a very well detailed geometric model of the IPEN/MB-01 and the heavy reflector region. MCNP-5 cross section library utilized in the analysis was ENDF/B-VII.0 [3].

The geometric model for the IPEN/MB-01 configurations is shown in Figures 5 and 6 for the radial and axial representations. The radial model comprises a square array of 30 x 30 positions, and everything is immersed in a cylinder of water of 91.5 cm radius. The water in the core is located in the region between the rods, between the rods and the guide tubes, and inside the guide tubes.

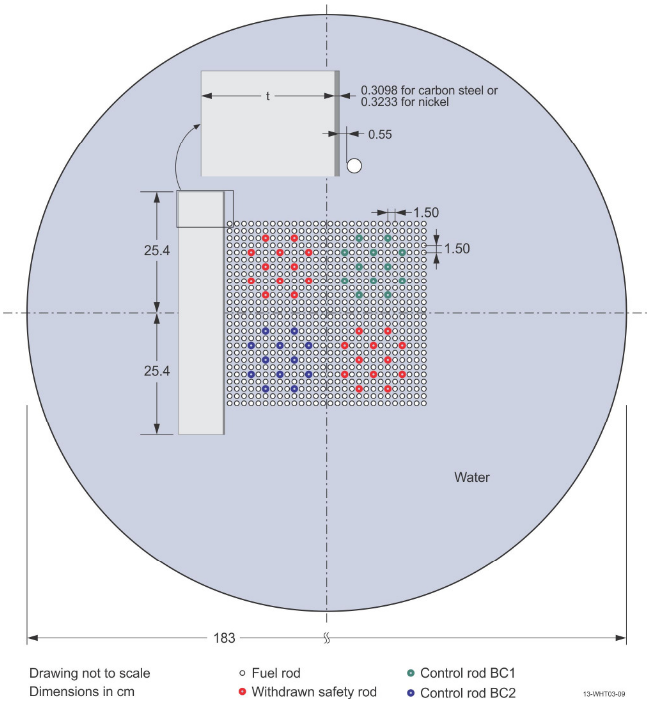

Figure 5: Radial representation (midway plane) of the IPEN/MB-01 core.

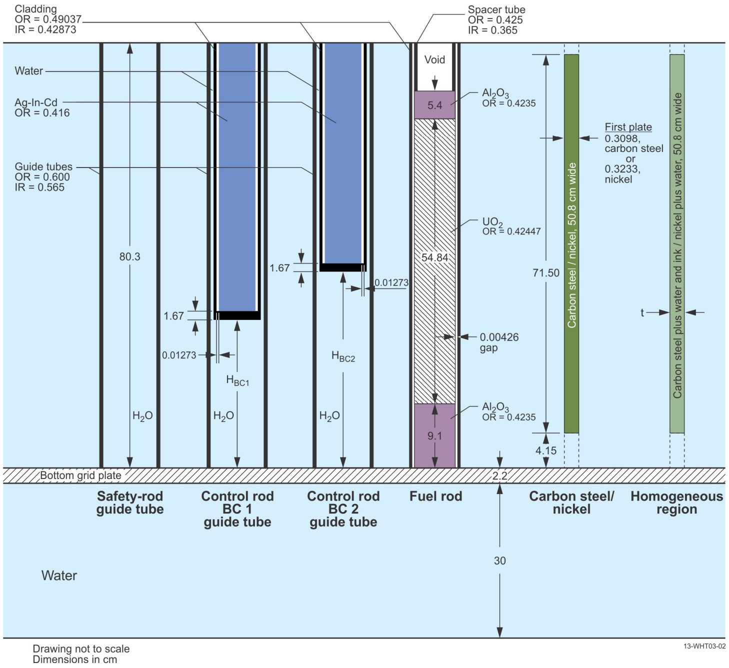

Figure 6: Representation of the fuel rod, the control rod inside its guide tubes, and the safety-rod guide tube in the benchmark model.

The geometrical model treats the laminates in the following way. The first laminate is treated explicitly and the second and higher laminates are treated as a homogenized region of thickness “t” that depends on the number of laminates as well as its type (either carbon steel or nickel). The homogenization transforms the water in the gaps, the heavy metal and where appropriate the ink used for corrosion protection into a single region of uniform composition. The specific case of carbon steel, the ink used for corrosion protection is homogenized with the heavy metal into a single region. The volume fractions for each of the regions are given in Table 1 taking into consideration that only 31 plates are being homogenized.

All geometric and material data are described in [4].

Figure 7 shows the measured and calculated inserted reactivity as a function of the number of the plates for both heavy reflectors used.

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.

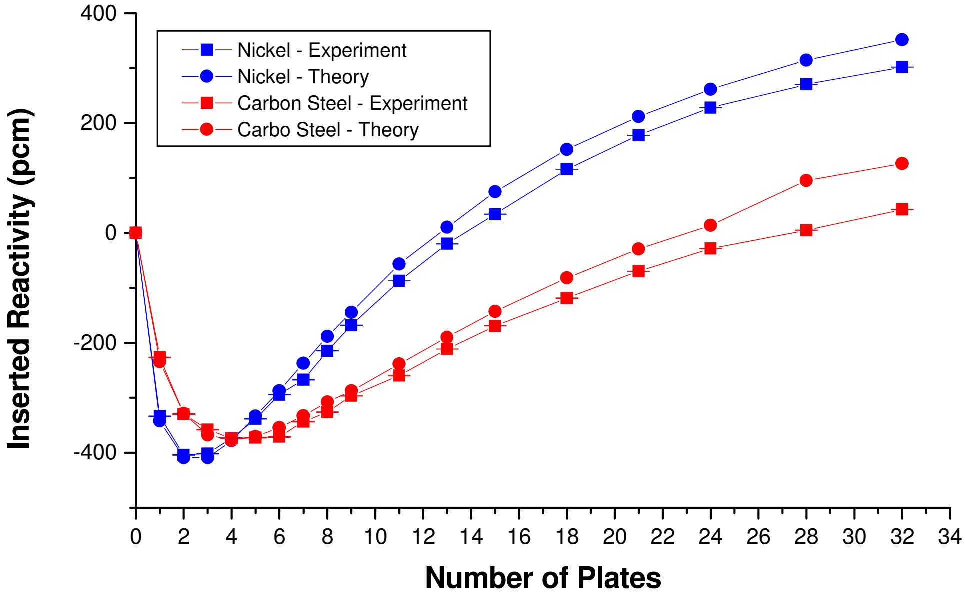

Figure 7: Theory-Experiment comparison for the reactivity (in relation to the case without plates).

4. CONCLUSIONS

The heavy reflector experiments in the IPEN/MB-01 research reactor facility have been successfully performed. The uncertainties are well understood and suitable for a benchmark problem. All the experiment results show clearly the competition between neutron absorption and neutron reflection in the heavy reflector. The analyses reveal that the MCNP5 calculated values together with ENDF/B-VII.0 library agree well to the experiment up to thirteen plates and after that the calculated results are overestimated. These trends were found independently of the type of the heavy reflector (Carbon Steel or Nickel) employed in the experiments.

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REFERENCES

1. Dos Santos, A. et al., "Heavy reflector experiment in the IPEN/MB-01 reactor," *International Conference on the Physics of Reactors. "Nuclear Power: A Sustainable Resource" – PHYSOR'08*, Interlaken, Switzerland, September 14-19 (2008).
2. X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N- Particle Transport Code, Version 5, Volume I: Overview and Theory," LA-UR-03-1987, Los Alamos National Laboratory (2003).
3. Chadwick, M.B. et al., "ENDF/B-VII.0 next generation evaluated nuclear data library for nuclear science and technology," *Nucl. Data Sheets*, **107**, 2931–3060 (2006).
4. Dos Santos. A., et al., "LEU-COMP-THERM-0077 Critical Loading Configurations of the IPEN/MB-01 Reactor," *International Handbook Experiments*, Nuclear Energy Agency (NEA/NSC/DOC (95)03/I), J. Blair Briggs (Ed.), Paris (September Edition – 2004).
5. Dos Santos A., et al., "IPEN (MB01)-LWR- CRIT-SPEC-REAC-COEF-KIN-RRATE-POWDIS-001: Reactor Physics experiments in the IPEN/MB-01 Research Reactor Facility," *International Handbook of Evaluated Reactor Physics Benchmark Experiment,* ed. Paris: Nuclear Energy Agency (NEA DATA BANK), pp. 1-142 (2012).