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FINAL RESULTS OF THE CADMIUM AND SPECTRAL RATIOS OBTAINED INSIDE OF THE FUEL ROD POSITIONED IN THE CENTRAL POSITION OF THE IPEN/MB-01 NUCLEAR REACTOR

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ABSTRACT

The spectral ratios are very important to determine some nuclear reactors parameters such as reaction rates, fuel lifetime, etc and some safety operational conditions. This study aims to determine the spectral ratios in 2 (two) spacial positions located inside the core of the Nuclear Reactor IPEN/MB-01. These places are at the central position of the nuclear reactor core in an asymptotic neutron flux region. The experiment consists in inserting different activation foil detectors inside an experimental fuel rod. The experimental rod is assembled at the central position of the reactor core. Activation neutron foil detectors of different elements such as ^{197}Au, ^{238}U, ^{45}Sc, ^{58}Ni, ^{24}Mg, ^{47}Ti and ^{115m}In were used to cover a large range of neutron spectrum. Saturation activity per target nucleus was obtained by gamma spectrometry using a HPGe system. The experimental cadmium ratios compared with values computed by MCNP-4C code show good agreement.

1. INTRODUCTION

It is important determine the spectral ratios in order to get some safety parameters at nuclear plants [1]. In this work, the activation spectrometric technique is used to obtain the reaction rates and the correlated spectral ratios. This technique consists in neutron detection by activation foil (detector) that is submitted to a neutron flux and activated by neutron capture reaction, and then is measured (counting) the radiation emitted by the created radioisotope. These foils are inserted inside an experimental fuel rod that is assembled at the central position of the reactor core [2]. After irradiation the activation foils are counted by a HPGe gamma spectrometry system. Thereafter the saturation activity per target nucleus is obtained from the measurement of the count rate gamma and weighing of the mass in a very high precision scale.

The saturation activity value is mathematically equal to the nuclear reaction rate induced in the activation foil and is related to some nuclear parameters namely: power level, nuclear reactor core configuration, material composition, etc.

To cover a large neutron energy spectrum is necessary to use various neutron detectors (materials) that are activated within different ranges of energy spectrum. Cadmium ratios are

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calculated by experimental data and the results are compared with data computed by the MCNP code [3].

The cadmium ratio for activation foils, disregarding self-shielding effects, given by the following equation (1),

$$R_{cd} = \frac{A_b^{\infty}}{A_{cd}^{\infty}} \frac{m_{cd}}{m_b} \quad (1)$$

Where A^{∞}_b is the saturation activity obtained when the foil is irradiated without cadmium glove; A^{∞}_{cd} is the saturation activity of the material when irradiated with cadmium glove; m_b and m_{cd} are their respective masses. The saturation activity of these detectors is obtained experimentally by gamma spectrometry.

2. EXPERIMENTAL PROCEDURES

The research nuclear reactor IPEN/MB-01 is a zero power reactor specially designed to experimentally demonstrate theoretical methodologies used in the neutronic area, being also a setup for nuclear education for students and technicians. The standard reactor core consists in an array of 680 fuels rods assembled on a rectangular cross section configuration (28 x 26). The fuels are enriched with ^{235}U at a level of 4.3% and the fuel rods use low-swelling stainless steel cladding (304). When the nuclear reactor is operating, the reactor core is maintained immersed into a tank filled with light water that is used as moderator [4].

For this experiment, it is used an experimental fuel rod containing 54 UO_2 fuel pellets and 20 Alumina pellets. Between the UO_2 fuel pellets is possible to place the activation foils. The activation foils are placed inside the experimental rod in two positions shown in Figure 1. Using the bottom of the experimental rod as reference, the first point is far-off 100.5 mm (upper bound) and the second to 347 mm (lower bound) from the bottom. These two detectors positions (lower and upper) are in the asymptotic neutron flux region, where the cadmium ratio is constant and the absolute values of the neutron flux are very close.

The experimental fuel rod is placed at the center position of the reactor core as shown schematically in Figure 2. To obtain the spectral ratios, several activation foils are irradiated, in our case 7 (seven) foils, with 8.49 mm in diameter, the same diameter of the fuel pellets and thickness range between 1.1 and 2.5 mm. The gold activation detectors used are composed by an alloy with 1% ^{197}Au and 99% ^{27}Al, in mass, and are denominated infinitely diluted foils. The others detectors used are very pure activation foils (target nucleus higher than 99.9%). The Table 1 shows the activation foils used and their neutron nuclear reactions. The neutron spectrum distributed into groups of energy is computed by a simulation of the irradiation by the MCNP-4C code (Monte Carlo N - Particle) and it is graphically represented by Figure 3. The total neutron flux at the lower position is ($4.60.10^9$ ± 0.47%) neutrons/(cm^2.s), and the thermal neutron flux is ($6.67.10^8$ ± 0.80%) neutrons/(cm^2.s) [5], both obtained at a reactor power level of (100.0 ± 2.5%) Watts [5].

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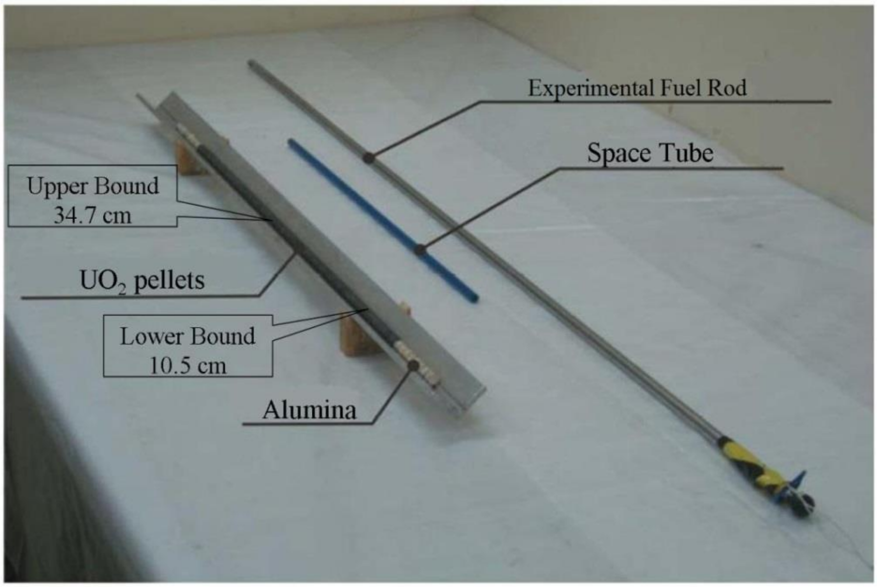

Figure 1: Experimental fuel rod.

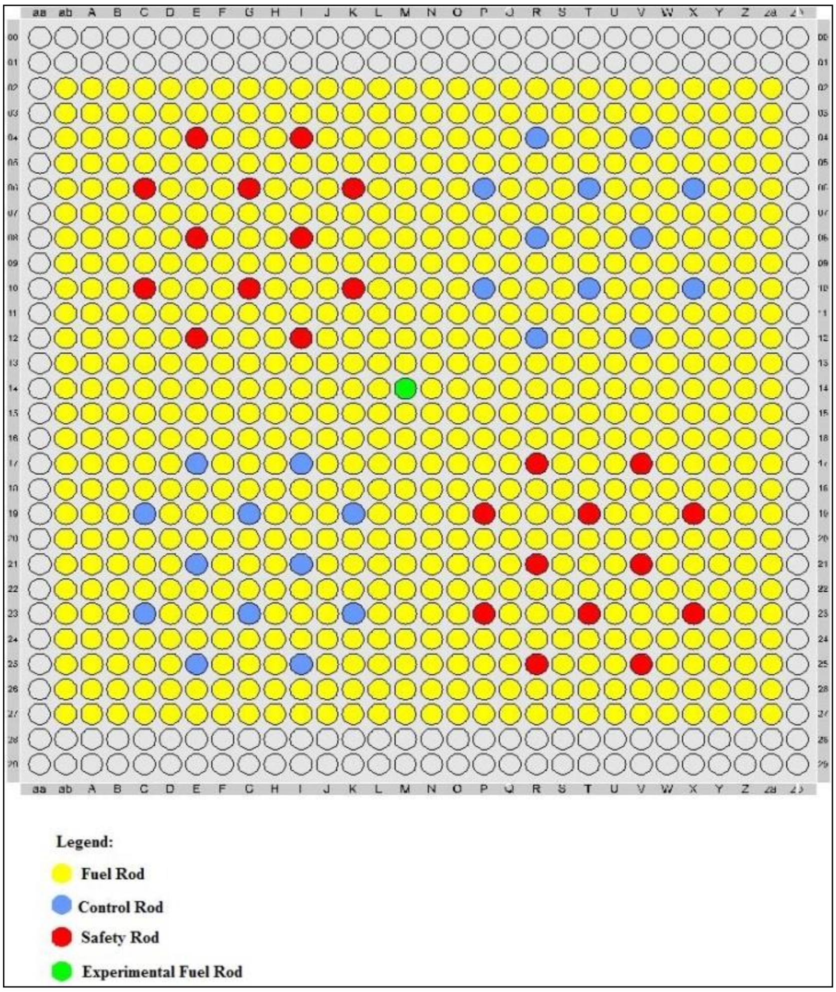

Figure 2: Reactor core configuration used for irradiate the activation foils.

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Table 1: Activation foils and the nuclear reaction of each material.

Activation Foils	Nuclear Reaction
^{197}Au	$^{197}Au(n,\gamma)^{198}Au$
^{238}U	$^{238}U(n,\gamma)^{239}U$
^{45}Sc	$^{45}Sc(n,\gamma)^{46}Sc$
^{58}Ni	$^{58}Ni(n,p)^{58}Co$
^{24}Mg	$^{24}Mg(n,p)^{24}Na$
^{47}Ti	$^{47}Ti(n,p)^{47}Sc$
^{115}In	$^{115}In(n,n')^{115m}In$

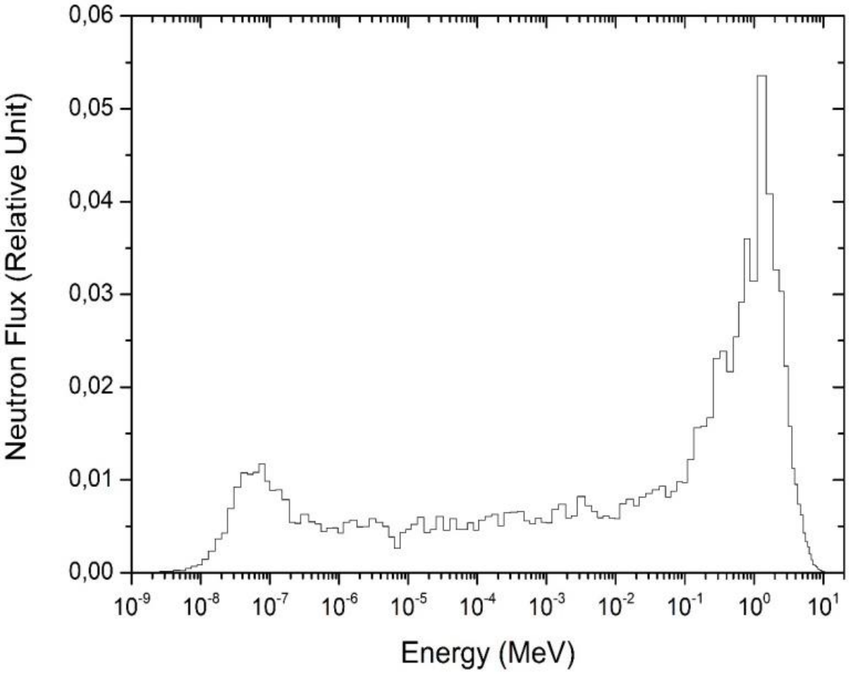

Figure 3: Neutron Spectrum inside Central Fuel Rod of the IPEN/MB-01 Reactor Core at Irradiation lower position Foils (MCNP code to 160 energy values).

A total of 11 (eleven) irradiations were carried out at approximately the same reactor power level (100 ± 6%) Watts and thereafter were normalized. All of the foils received irradiation for at least one hour. The control rods were equally inserted inside the nuclear core to maintain the symmetry of the neutron flux.

Some activation foils were irradiated with cadmium gloves of 0.5 mm thick and 70 mm long. The cadmium glove was placed externally around the experimental fuel rod and its position matched with the position of the activation foils.

The control rods were withdrawn 59.44% when used the cadmium gloves and without the gloves 58.05%. These values are to maintain the criticality of system (k_{eff}=1). During these reactor operations, the temperature of moderator (light water) was maintained at 20ºC. This

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procedure was done to determine the cadmium ratio (R_{cd}). The irradiated foils were analyzed by the HPGe detection system (High Purity Germanium) shown in the Figure 4 [6].

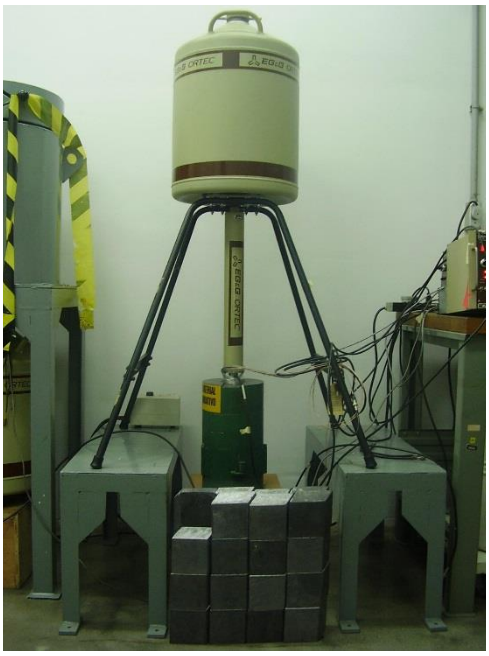

Figure 4: System of high purity Germanium (HPGe) detector.

With the values of the net gamma counting for each foil, the saturation activity (A^{∞}) for every foils was calculated by the following Equation (2) [1,7],

$$A^{\infty} = \frac{Ce^{\lambda t_e}}{\varepsilon I t_c \left(1 - e^{-\lambda t_i}\right)} \cdot \frac{F_r \cdot F_a}{F_n} \tag{2}$$

where λ is the decay constant; t_e is the waiting time to proceed the gamma spectrometry after the irradiation; C is the net counting of the gamma energy; ε is the global efficiency of the gamma spectrometry system; I is the gamma ray branching ratio; t_c is the counting time; t_i is the irradiation time; F_r is the power ramp factor; F_n is the normalization factor to correct the power level fluctuations between irradiations; and F_a is the gamma self-absorption factor.

The Cadmium Ratio (R_{cd}) is calculated by the following Equation (3) [7],

$$R_{cd} = \left[\frac{A_b^{\infty}}{A_{cd}^{\infty}} \frac{G_{epi}}{G_{th}} + F_{cd} \left(1 - \frac{G_{epi}}{G_{th}} \right) \right] \frac{m_{cd}}{m_b} \tag{3}$$

where A^{∞}_b is the saturation activity irradiated without cadmium glove (bare); A^{∞}_{cd} is the saturation activity of the material irradiated with cadmium glove; m_b and m_{cd} are the respective masses; G_{epi} is the epithermal self-shielding factor; G_{th} is the thermal self-shielding factor; and F_{cd} is the cadmium factor [8].

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In order to determine the spectral ratios, it was necessary to obtain the saturation activity per target nucleus (A^{∞}/N_A) by the Equation (4) [1,7],

$$\frac{A^{\infty}}{N_A} = \frac{Ce^{\lambda t_e}}{\varepsilon I t_c \left(1 - e^{-\lambda t_i}\right)} \cdot \frac{F_r \cdot F_a}{F_n} \cdot \frac{W_a}{N_0 m f_{iso}} \tag{4}$$

where N_0 is the Avogadro number; m is the foil mass; f_{iso} is the isotopic abundance of the irradiated material; and W_a is the atomic mass of the material.

The spectral ratio (SR) is the ratio between the saturation activities per target nucleus of two nuclear reactions of different materials irradiated in the same position as the following Equation (5) [5,9].

$$SR = \frac{\left(A^{\infty}/N_A\right)}{\left(A^{\infty}/N_A\right)'} \tag{5}$$

3. EXPERIMENTAL AND CALCULATED RESULTS

3.1. Measured of the Saturation Activities

The Table 2 shows the saturation activities as well as the saturation activities per target nucleus obtained from the irradiated activation foils.

3.2. Cadmium Ratio (R_{cd})

The experimental cadmium ratio is compared with data calculated by MCNP-4C code [3]. To obtain the computed data, the core of the IPEN/MB-01 reactor, assembled with the experimental fuel rod modeled by MCNP-4C code, 2 10^9 histories were performed in the simulation and several hours of computing time were required. The nuclear libraries used in the MCNP code are ENDF-B-VII and dosimetry file ENDF-B-V (indium foils).

The Table 3 shows the cadmium ratios data obtained experimentally and by the MCNP-4C code and shows good agreement between the experimental data and the data computed by MCNP 5 Code.

3.3. Spectral Ratios

The spectral ratios are presented on the Tables 4, 5, 6 and 7. These tables show the activation foils with and without cadmium gloves at lower and upper irradiation positions, regarding the criterion that the value of the spectral ratios should be greater than the unit.

The Tables 6 and 7 present the spectral ratios when using cadmium gloves that have 70 mm length and 0.5 mm thickness.

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Table 2: Saturation activities and saturation activities per target nucleus.

Activation Foils	Irradiation Position	A^{∞} (Bq)	A^{∞}/Na (Bq/atoms)
^{197}Au	Lower	$1.82\ 10^{5}$ ± 0.13%	$2.02\ 10^{-13}$ ± 0.18%
	Upper	$1.81\ 10^{5}$ ± 0.15%	$2.02\ 10^{-13}$ ± 0.20%
^{197}Au*	Lower	$1.26\ 10^{5}$ ± 2.04%	$1.41\ 10^{-13}$ ± 2.03%
	Upper	$1.29\ 10^{5}$ ± 1.88%	$1.44\ 10^{-13}$ ± 1.88%
^{238}U	Lower	$2.17\ 10^{6}$ ± 2.76%	$6.16\ 10^{-15}$ ± 2.77%
	Upper	$2.19\ 10^{6}$ ± 3.08%	$6.43\ 10^{-15}$ ± 3.09%
^{238}U*	Lower	$1.59\ 10^{6}$ ± 2.71%	$4.72\ 10^{-15}$ ± 2.71%
	Upper	$1.64\ 10^{6}$ ± 2.76%	$4.76\ 10^{-15}$ ± 2.76%
^{45}Sc	Lower	$2.90\ 10^{6}$ ± 1.86%	$1.26\ 10^{-14}$ ± 1.86%
	Upper	$2.76\ 10^{6}$ ± 1.87%	$1.24\ 10^{-14}$ ± 1.85%
^{45}Sc*	Lower	$3.04\ 10^{5}$ ± 2.17%	$1.33\ 10^{-15}$ ± 2.17%
	Upper	$3.46\ 10^{5}$ ± 2.12%	$1.49\ 10^{-15}$ ± 2.17%
^{58}Ni	Lower	$1.03\ 10^{5}$ ± 2.02%	$1.20\ 10^{-16}$ ± 2.03%
	Upper	$1.01\ 10^{5}$ ± 2.24%	$1.18\ 10^{-16}$ ± 2.24%
^{24}Mg	Upper	$6.18\ 10^{2}$ ± 4.19%	$1.73\ 10^{-18}$ ± 4.19%
^{24}Mg*	Lower	$4.27\ 10^{2}$ ± 3.77%	$1.32\ 10^{-18}$ ± 3.76%
^{47}Ti*	Lower	$1.15\ 10^{3}$ ± 3.95%	$1.93\ 10^{-17}$ ± 3.94%
	Upper	$1.17\ 10^{3}$ ± 4.03%	$1.96\ 10^{-17}$ ± 4.02%
^{115}In	Lower	$1.02\ 10^{5}$ ± 5.39%	$3.69\ 10^{-16}$ ± 5.37%
	Upper	$1.08\ 10^{5}$ ± 5.00%	$3.96\ 10^{-16}$ ± 5.00%
^{115}In*	Lower	$8.47\ 10^{4}$ ± 5.31%	$3.05\ 10^{-16}$ ± 5.31%
	Upper	$8.38\ 10^{4}$ ± 4.15%	$3.06\ 10^{-16}$ ± 4.16%

* Experimental Fuel rod irradiated with the cadmium glove.
self-shielding effect (G) calculated by MCNP code to uranium (U) and scandium (Sc) foils:.
G (U) = 0.652; G(U)* = 0.571 ; G(Sc)= 0.941 ; G(Sc)*=0.999 [4]

Table 3: Cadmium Ratios Measured (E) and Calculated (C) Using MCNP code.

Activations Foils	R_{cd}		C/E
	Experimental (E)	MCNP Code (C)	
^{197}Au	1.42 ± 1,25%	1.29 ± 0,05%	0.91 ± 1,25%
^{238}U	1.33 ± 0,17%	1.35 ± 1,48%	1.02 ± 1,49%
^{45}Sc	8.90 ± 0,22%	8.44 ± 0,23%	0.95 ± 0,32%
^{24}Mg	1.31 ± 3,99%	1.24 ± 2,51%	0.95 ± 4,71%
^{115}In	1.25 ± 0,42%	1.22 ± 0,05%	0.98 ± 0,42%
		Total Deviation	6.54%

Experimental Fuel rod covered with cadmium Glove (Thickness of 0.0508cm and length of 7 cm).

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Table 4: Spectral Ratios Measured with Activation Foils Irradiated on the Lower Position and Without the Cadmium Gloves.

Activations Foils	Spectral Ratios		C/E
	Experimental (E)	MCNP Code (C)	
Au/U	$5.03x10^1$ ± 2.59%	$4.72x10^1$ ± 1.04%	0.94 ± 2.79%
Au/Sc	$1.70x10^1$ ± 1.68%	$1.74x10^1$ ± 2.06%	1.02 ± 2.66%
Au/Ni	$1.68x10^3$ ± 1.85%	$1.26x10^3$ ± 2.04%	0.75 ± 2.76%
Au/In	$5.47x10^2$ ± 5.19%	$7.07x10^2$ ± 2.02%	1.29 ± 5.57%
Sc/U	$2.96x10^0$ ± 0.91%	$2.71x10^0$ ± 3.10%	0.92 ± 3.23%
Sc/Ni	$9.88x10^2$ ± 0.17%	$7.25x10^1$ ± 0.02%	0.73 ± 0.17%
Sc/In	$3.21x10^1$ ± 3.51%	$4.06x10^1$ ± 0.04%	1.26 ± 3.51%
U/Ni	$3.34x10^1$ ± 0.74%	$2.67x10^1$ ± 3.08%	0.80 ± 3.17%
U/In	$1.09x10^1$ ± 2.60%	$1.50x10^1$ ± 3.06%	1.38 ± 4.01%
In/Ni	$3.08x10^0$ ± 3.34%	$1.78x10^0$ ± 0.03%	0.58 ± 3.34%
		Total Deviation	25.66%

Table 5: Spectral Ratios Measured with Activation Foils Irradiated on the Upper Position and Without the Cadmium Gloves

Activations Foils	Spectral Ratios		C/E
	Experimental (E)	MCNP Code (C)	
Au/U	$4.81x10^1$ ± 2.89%	$4.17x10^1$ ± 4.55%	0.87 ± 5.39%
Au/Sc	$1.73x10^1$ ± 1.65%	$1.67x10^1$ ± 1.57%	0.96 ± 2.28%
Au/Ni	$1.71x10^3$ ± 2.04%	$1.26x10^3$ ± 1.60%	0.74 ± 2.59%
Au/In	$5.10x10^2$ ± 4.80%	$6.93x10^2$ ± 1.79%	1.36 ± 5.12%
Sc/U	$2.79x10^0$ ± 1.24%	$2.49x10^0$ ± 6.12%	0.89 ± 6.24%
Sc/Ni	$9.99x10^1$ ± 0.39%	$7.51x10^1$ ± 0.03%	0.75 ± 0.39%
Sc/In	$2.95x10^1$ ± 3.15%	$4.14x10^1$ ± 0.22%	1.40 ± 3.16%
U/Ni	$3.45x10^1$ ± 0.85%	$3.01x10^1$ ± 6.15%	0.85 ± 6.20%
U/In	$1.06x10^1$ ± 1.91%	$1.66x10^1$ ± 6.34%	1.57 ± 6.62%
In/Ni	$3.36x10^0$ ± 2.76%	$1.82x10^0$ ± 0.19%	0.54 ± 2.77%
		Total Deviation	31.77%

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Table 6: Spectral Ratios Measured with Activation Foils Irradiated on the Lower Position Using the Cadmium Gloves.

Activations Foils	Spectral Ratios with Cadmium Cover		C/E
	Experimental (E)	MCNP Code (C)	
Au/U	$5.24x10^1$ ± 0.68%	$4.47x10^1$ ± 4.00%	0.85 ± 4.05%
Au/Sc	$1.06x10^2$ ± 0.14%	$1.10x10^2$ ± 1.53%	1.04 ± 1.54%
Au/Ti	$7.31x10^3$ ± 1.91%	$7.02x10^3$ ± 1.71%	0.96 ± 2.56%
Au/In	$4.62x10^2$ ± 3.28%	$6.64x10^2$ ± 1.87%	1.44 ± 3.78%
U/Sc	$2.03x10^0$ ± 0.54%	$2.46x10^0$ ± 5.53%	1.21 ± 5.55%
Sc/Ti	6.89x101 ± 1.77%	$6.37x10^1$ ± 0.18%	0.92 ± 1.78%
Sc/In	$4.36x10^0$ ± 3.14%	$6.02x10^0$ ± 0.34%	1.38 ± 3.16%
U/Ti	$1.40x10^2$ ± 1.23%	$1.57x10^2$ ± 5.71%	1.12 ± 5.84%
U/In	$8.88x10^0$ ± 2.60%	$1.48x10^1$ ± 5.87%	1.31 ± 6.42%
In/Ti	$1.58x10^1$ ± 1.37%	$1.06x10^1$ ± 0.16%	0.67 ± 1.38%
		Total Deviation	25.17%

Table 7: Spectral Ratios Measured with Activation Foils Irradiated on the Upper Position Using the Cadmium Gloves.

Activations Foils	Spectral Ratios with Cadmium Cover		C/E
	Experimental (E)	MCNP Code (C)	
Au/U	$5.31x10^1$ ± 0.88%	$4.82x10^1$ ± 3.91%	0.91 ± 4.01%
Au/Sc	$9.66x10^1$ ± 0.29%	$1.14x10^2$ ± 1.60%	1.18 ± 1.63%
Au/Ti	$7.35x10^3$ ± 2.14%	$7.20x10^3$ ± 1.76%	0.98 ± 2.77%
Au/In	$4.71x10^2$ ± 2.28%	$6.67x10^2$ ± 1.67%	1.42 ± 2.83%
U/Sc	$1.82x10^0$ ± 0.59%	$2.37x10^0$ ± 5.51%	1.30 ± 5.55%
Sc/Ti	$7.60x10^1$ ± 1.85%	$6.32x10^1$ ± 0.16%	0.83 ± 1.86%
Sc/In	$4.87x10^0$ ± 1.99%	$5.85x10^0$ ± 0.07%	1.20 ± 1.99%
U/Ti	$1.39x10^2$ ± 1.26%	$1.49x10^2$ ± 5.67%	1.07 ± 5.81%
U/In	$8.90x10^0$ ± 1.40%	$1.38x10^1$ ± 5.58%	1.55 ± 5.76%
In/Ti	$1.56x10^1$ ± 0.14%	$1.08x10^1$ ± 0.09%	0.692 ± 0.16%
		Total Deviation	27.92%

Observing the results in Tables 4, 5,6 and 7 it is noted that the ratios between the calculated and experimental values are somewhat more consistent, ie closer to 1 for the lower position of irradiation of the activation foils (total deviation smaller than compared with upper

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positions). This is farthest position of the reactor control rods. It is also noted that spectral ratios involving activation foils of Au, Sc, U, Ti showed better results than the spectral indices involving the activation foils of In and Ni. However it is noted that the values for the calculated spectral ratios when compared to the experimental values all exhibit the same order of magnitude.

4. CONCLUSION

This work presented the cadmium and spectral ratios obtained by activation foils irradiated inside an experimental fuel rod assembled at the central position of the nuclear reactor IPEN/MB-01. The neutron flux and the correspondent spectral ratios in lower and upper detector positions show close values. This result is expected due the symmetry of the nuclear reactor core and these two positions are in the asymptotic region. The cadmium ratios calculated by the experimental method show very good agreement with results calculated by MCNP code (see Table 3).

The Tables 4, 5, 6 and 7 show the comparison between the data computed by MCNP code and by the experimental method. The spectral ratios between the data computed by MCNP code and by the experimental method (C/E) at Tables 4 , 5, 6 and 7 using activation foils of U, Au, Sc without cadmium gloves show good results, (C/E<10%) and (C/E<13%) to lower and upper positions, respectively. These results show good agreement with MCNP code too to irradiations without cadmium filters (cadmium gloves). The table 6 and 7 shows the results using cadmium filters (gloves). In the last case, the spectral ratios results are good to spectral ratios with capture nuclear reaction with Au, U, Sc activation foils and Ti foil (endothermic nuclear reaction (n,p) .The worst results is to U/Sc with 1.21<C/E< 1.30) to lower and upper positions , respectively.

The spectral ratios using Ni and In foils to endothermic nuclear reaction (n,p) and (n,n´), respectively, do not close the MCNP results (0.54 < C/E > 0.58) to upper r and lower positions, respectively.

All results were calculated by MCNP 5 code with nuclear library ENDF-B-VII to all activation foils, exception to indium foil that was used the ENDF-B-V. The future step will be testing these calculated spectral ratios with experimental data using other nuclear evaluated data files.

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