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DETERMINATION OF THE ESPECTRAL RATIOS IN THE FUEL OF THE IPEN/MB-01 REACTOR

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ABSTRACT

This study aims to determine the spectral ratios inside the fuel of IPEN/MB-01 Nuclear Reactor. The spectral ratios are very important to accurately determine spectral physical parameters of nuclear reactors like reaction rates, fuel lifetime and also security parameters such as reactivity. For the experiment, activation detectors in the form of thin metal Foils were introduced in a collapsible fuel rod. Then the rod was placed in the central position of the core which has a rectangular configuration of 26x28 fuel rods. There were used activation detectors from different elements such Au-197, U-238, Sc-45, Ni-58, Mg-24, Ti-47 and In-115 to cover a large range of neutron spectrum. After the irradiation, the activation detectors were submitted to a gamma spectrometry by using a counting system with high purity Germanium, to obtain the saturation activity per target nucleus. The cadmium ratios when compared with calculated values obtained by MCNP-4C code show good agreement.

1. INTRODUCTION

It is important to determine the spectral ratio in order to get security parameters in a reactor [1]. The technique used in this work to obtain the spectral ratio is the activation analysis. This technique consists in submitting metallic foils in a collapsible fuel rod core of the reactor and in obtaining the activation of the nucleus present in the target [2].

After the activation of the nucleus, there is interest in obtaining the counting of the radioactive nucleus formed in the irradiation by the gamma spectrometry. Thus, it is obtained the activity per target nucleus from the target in the point of irradiation of the reactor core.

This work aims to measure the spectral ratio of some materials. It is also measured the nuclear saturated activations in different kinds of materials irradiated inside the fuel rod which remains in the center of the reactor core.

Moreover, cadmium ratios are calculated too, these results are compared using MCNP-4C code [3].

2. EXPERIMENTAL METHODOLOGY

The research reactor IPEN/MB-01 is a zero power reactor specially designed to prove methodologies used in the neutronic area. The standard configuration of the reactor core consists of a rectangular array of 28x26 fuel rods enriched with 4.3% of ^{235}U with a stainless steel (304) encasement, inserted into a tank of light water moderator [4].

This work is possible in the reactor IPEN/MB-01 due to the existence of collapsible fuel rods, which are composed of 54 UO_2 fuel pellets and 20 Alumina pellets. These collapsible fuel rods allow dispose activation foils between the fuel pellets. The foils are placed into the collapsible rod in two positions, 10.5 cm and 34.7 cm axial bounds, both located in the asymptotic neutron flux region of the core (Figure 1).

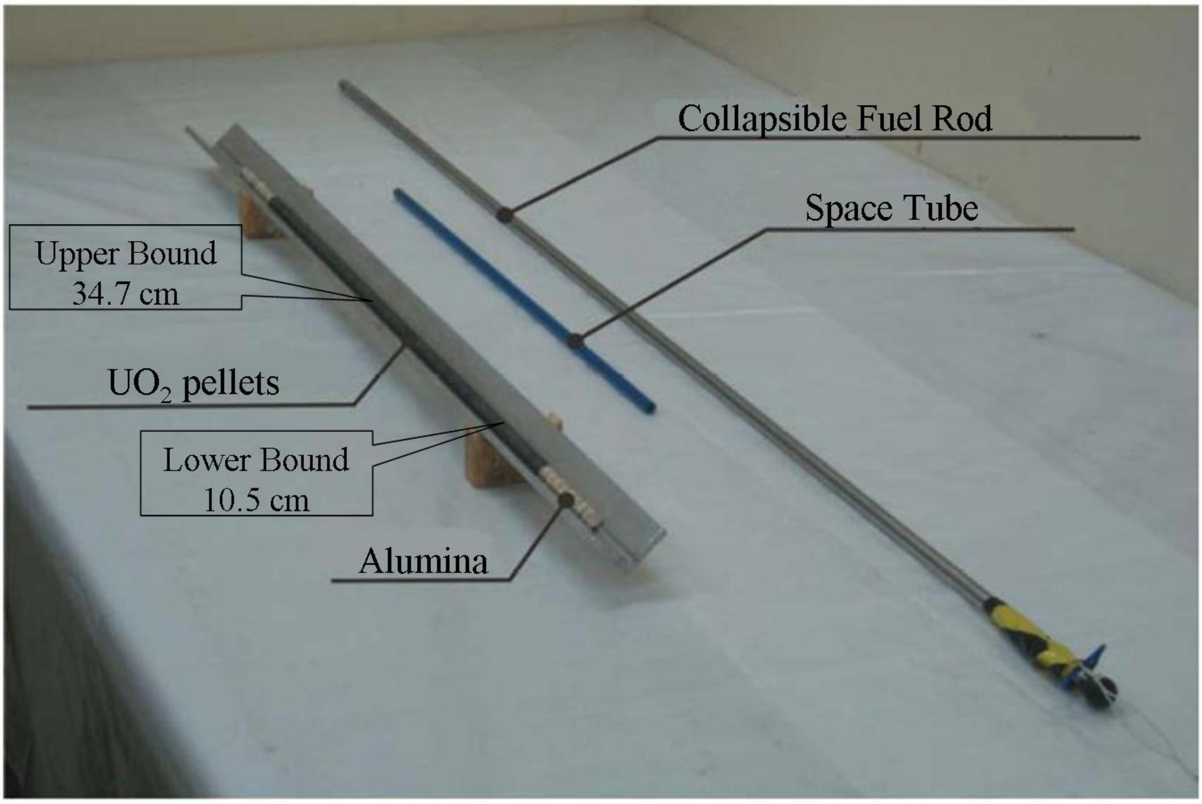

Figure 1. Collapsible fuel rod.

The collapsible fuel rod is placed into the reactor core at the center position as showed in the Figure 2.

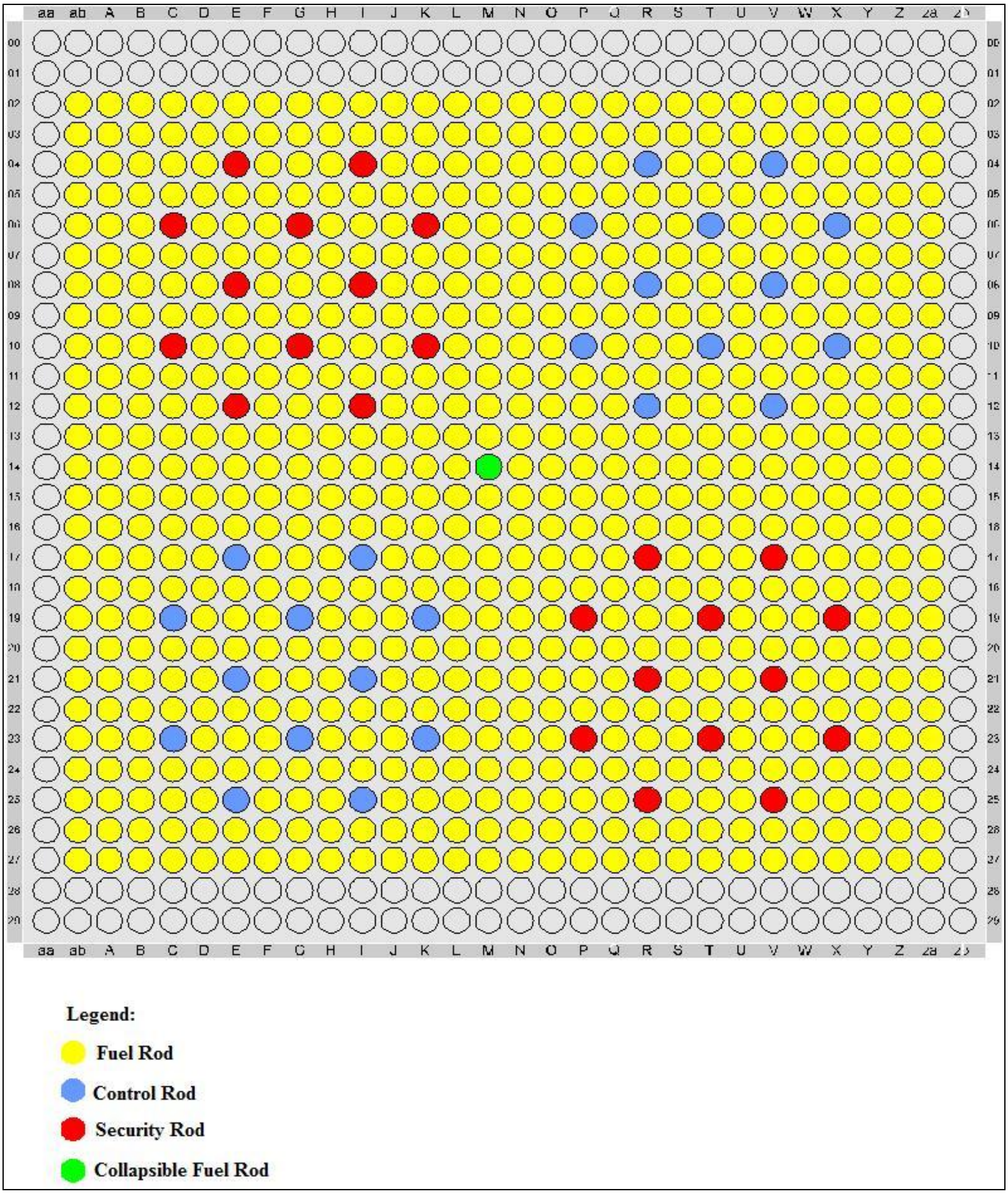

Figure 2. Reactor core configuration used for irradiate the activation foils.

It is irradiated activation foils with 8.49 mm of diameter and thickness that varies between 1.1 and 2.5 mm. Excepted for the gold activation foil, which is an infinitely diluted foil with 1% of ^{197}Au and 99% of ^{26}Al, the activation foils are very high pure materials. The Table 1 shows the activation foils used and their nuclear reaction.

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	$^{115}In(n,n')^{115m}In$
^{58}Fe	$^{58}Fe(n,\gamma)^{59}Fe$

A total of 11 irradiations are realized and each one is done with 100 Watts of power. During irradiations the control rods are equally inserted to keep symmetric conditions on the flux distribution inside the core. Some foils are irradiated with cadmium gloves of 0.5 mm thickness and length of 70 mm. The cadmium glove is placed around the collapsible fuel rod so that the middle of the glove matches with the position of the activation foil. This procedure is adopted to determine the cadmium ratio (Rcd).

After the irradiations, the foils are analyzed in the detection system of high purity Germanium (HPGe), as showed in the Figure 3 [5].

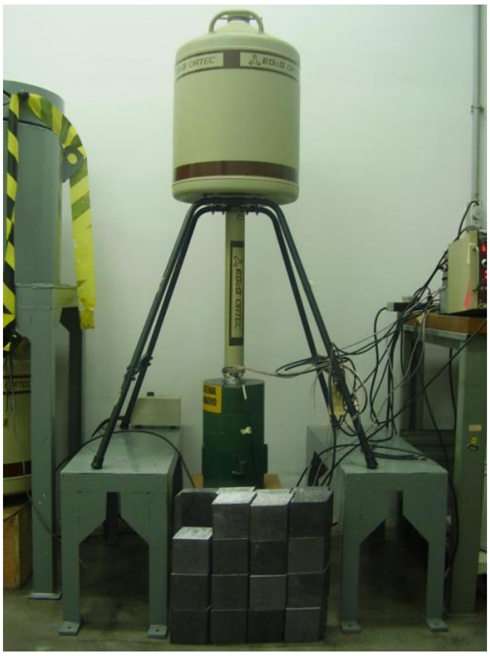

Figure 3. System of high purity Germanium (HPGe) detector.

With the values of the net gamma counting for each foil, the next step is to obtain the saturation activity (A^{∞}) by the following Equation (1) [1,6],

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

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

The Cadmium Ratio (Rcd) is calculated by the following Equation (2) [6],

$$R_{cd} = \left[\frac{A_n^{\infty}}{A_{cd}^{\infty}} \cdot \frac{G_{epi}}{G_{th}} + F_{cd}\left(1 - \frac{G_{epi}}{G_{th}}\right)\right] \frac{m_{cd}}{m_n} \tag{2}$$

where $A^{\infty}{}_n$ is the saturation activity irradiated without cadmium glove, $A^{\infty}{}_{cd}$ is the saturation activity of the material irradiated with cadmium glove, m_n and m_{cd} are the respective weights, G_{epi} is the epithermal self shielding factor, G_{th} is the thermal self shielding factor and F_{cd} is the cadmium factor [7].

In order to determine the spectral ratios it is necessary to obtain the saturation activity per target nucleus (A^{∞}/N_A) as the Equation (3) [1,6],

$$\frac{A^{\infty}}{N_A} = \frac{Ce^{\lambda t_e}}{\varepsilon I t_c \left(1 - e^{-\lambda t_i}\right)} \cdot \frac{F_r \cdot F_a}{F_n} \cdot \frac{W_a}{N_0 m f_{iso}} \tag{3}$$

where N_0 is the Avogadro number, m is the foil weight, f_{iso} is the isotopic abundance from the irradiated material and W_a is the atomic weight from 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 (4) [8].

$$SR = \frac{\left(A^{\infty}/N_A\right)}{\left(A^{\infty}/N_A\right)}, \tag{4}$$

3. RESULTS

3.1. Saturation Activities obtained after Irradiation

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

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

Activation Foils	Irradiation Position	A$^{\infty}$ (Bq)	A$^{\infty}$/Na (Bq/atoms)
^{197}Au	Lower	$2.01x10^{5}$ ± $2.54x10^{2}$	$2.24x10^{-13}$ ± $3.99x10^{-16}$
	Upper	$2.00x10^{5}$ ± $3.05x10^{2}$	$2.24x10^{-13}$ ± $4.56x10^{-16}$
^{197}Au*	Lower	$1.22x10^{5}$ ± $2.47x10^{3}$	$1.35x10^{-13}$ ± $2.75x10^{-15}$
	Upper	$1.24x10^{5}$ ± $2.33x10^{3}$	$1.38x10^{-13}$ ± $2.61x10^{-15}$
^{238}U	Lower	$2.34x10^{6}$ ± $2.35x10^{5}$	$6.64x10^{-15}$ ± $6.68x10^{-16}$
	Upper	$2.35x10^{6}$ ± $2.40x10^{5}$	$6.93x10^{-15}$ ± $7.06x10^{-16}$
^{238}U*	Lower	$1.89x10^{6}$ ± $1.76x10^{5}$	$5.62x10^{-15}$ ± $5.22x10^{-16}$
	Upper	$1.95x10^{6}$ ± $1.82x10^{5}$	$5.66x10^{-15}$ ± $5.28x10^{-16}$
^{45}Sc	Lower	$2.96x10^{6}$ ± $6.20x10^{4}$	$1.08x10^{-14}$ ± $2.26x10^{-16}$
^{45}Sc*	Upper	$9.47x10^{5}$ ± $6.52x10^{4}$	$3.02x10^{-15}$ ± $2.08x10^{-16}$
^{58}Ni	Lower	$9.87x10^{4}$ ± $2.00x10^{3}$	$1.16x10^{-16}$ ± $2.34x10^{-18}$
	Upper	$1.11x10^{5}$ ± $2.50x10^{3}$	$1.30x10^{-16}$ ± $2.92x10^{-18}$
^{24}Mg	Upper	$5.95x10^{2}$ ± $2.49x10^{1}$	$1.67x10^{-18}$ ± $6.99x10^{-20}$
^{24}Mg*	Lower	$4.11x10^{2}$ ± $1.54x10^{1}$	$1.27x10^{-18}$ ± $4.78x10^{-20}$
^{47}Ti*	Lower	$1.10x10^{3}$ ± $4.35x10^{1}$	$1.85x10^{-17}$ ± $7.30x10^{-19}$
	Upper	$1.13x10^{3}$ ± $4.53x10^{1}$	$1.89x10^{-17}$ ± $7.59x10^{-19}$
^{115}In	Lower	$9.81x10^{4}$ ± $5.27x10^{3}$	$3.54x10^{-16}$ ± $1.90x10^{-17}$
	Upper	$1.04x10^{5}$ ± $5.21x10^{3}$	$3.80x10^{-16}$ ± $1.90x10^{-17}$
^{115}In*	Lower	$8.16x10^{4}$ ± $4.33x10^{3}$	$2.94x10^{-16}$ ± $1.56x10^{-17}$
	Upper	$8.03x10^{4}$ ± $3.34x10^{3}$	$2.93x10^{-16}$ ± $1.22x10^{-17}$
^{58}Fe	Lower	$4.07x10^{6}$ ± $2.06x10^{5}$	$2.35x10^{-12}$ ± $1.19x10^{-13}$

* Foils irradiated with cadmium glove.

3.2. Cadmium Ratio

Besides the experimental calculation of cadmium ratio, it is used the MCNP-4C code [3] to compare the experimental results. For this it is modeled a configuration exactly to the core of the IPEN/MB-01 reactor with the collapsible fuel rod and each simulation is calculated with $1x10^9$ histories through almost 5 days. The cadmium ratio obtained by experimental method and by MCNP-4C code and also a comparison between these results is presented on the Table 3.

Table 3. Comparation between cadmium ratios obtained by experimental method and by MCNP-4C code.

Activations Foils	R_{cd}		C/E
	Experimental (E)	MCNP-4C Code (C)	
^{197}Au	1.65 ± 0.03	1.64 ± 0.11	0.994 ± 0.069
^{238}U	1.08 ± 0.24	1.24 ± 0.22	1.148 ± 0.326
^{45}Sc	8.76 ± 0.51	9.61 ± 0.51	1.097 ± 0.086
^{24}Mg	1.31 ± 0.07	1.36 ± 0.10	1.038 ± 0.094
^{115}In	1.20 ± 0.09	1.19 ± 0.01	0.992 ± 0.075

As shown in the third column of the Table 3, the cadmium ratios obtained by experimental method and by MCNP-4C Code show good agreement. The error of the ^{238}U cadmium ratio is high due to the self shielding variance calculated by the MCNP-4C Code, it can be decrease with the increase of histories on the MCNP simulation.

3.3. Spectral Ratios

The spectral ratios are presented on the Tables 4, 5, 6 and 7.

The cadmium gloves used in the irradiations listed on the Tables 6 and 7 have a length of 7 cm and thickness of 0.5 mm of cadmium and are positioned externally to the collapsible fuel rods, centered in relation to the position of the activation foils.

Table 4. Spectral ratios calculated with activation foils irradiated on the lower position and without the cadmium gloves.

Spectral Ratios	Experimental
Au/U	$3.37x10^{1} \pm 3.34x10^{0}$
Au/Ni	$1.94x10^{3} \pm 3.59x10^{1}$
Au/In	$6.33x10^{2} \pm 3.29x10^{1}$
U/Ni	$5.75x10^{1} \pm 4.62x10^{0}$
U/In	$1.87x10^{1} \pm 8.79x10^{-1}$
In/Ni	$3.06x10^{0} \pm 1.02x10^{1}$
Au/Sc	$2.08x10^{1} \pm 3.98x10^{-1}$
Sc/U	$1.63x10^{0} \pm 1.30x10^{-1}$
Sc/Ni	$9.34x10^{1} \pm 6.03x10^{-2}$
Sc/In	$3.05x10^{1} \pm 1.00x10^{0}$
Fe/Au	$1.05x10^{1} \pm 5.12x10^{-1}$
Fe/U	$3.55x10^{2} \pm 1.78x10^{1}$
Fe/Sc	$2.18x10^{2} \pm 6.45x10^{0}$
Fe/Ni	$2.04x10^{4} \pm 6.16x10^{2}$
Fe/In	$6.65x10^{3} \pm 2.14x10^{1}$

Table 5. Spectral ratios calculated with activation foils irradiated on the upper position and without the cadmium gloves.

Spectral Ratios	Experimental
Au/U	$3.23x10^{1} \pm 3.22x10^{0}$
Au/Ni	$1.71x10^{3} \pm 3.49x10^{1}$
Au/In	$5.89x10^{2} \pm 2.82x10^{1}$
U/Ni	$5.31x10^{1} \pm 4.22x10^{0}$
U/In	$1.82x10^{1} \pm 9.46x10^{-1}$
In/Ni	$2.91x10^{0} \pm 8.04x10^{-2}$
Au/Mg	$1.34x10^{5} \pm 5.33x10^{3}$
U/Mg	$4.15x10^{3} \pm 2.49x10^{2}$
Ni/Mg	$7.81x10^{1} \pm 1.52x10^{0}$
In/Mg	$2.27x10^{2} \pm 1.85x10^{0}$

Table 6. Spectral ratios calculated with activation foils irradiated on the lower position using the cadmium gloves.

Spectral Ratios	Experimental
Au/U	$2.41x10^{1}$ ± $1.75x10^{0}$
Au/Ti	$7.32x10^{3}$ ± $1.40x10^{2}$
Au/In	$4.61x10^{2}$ ± $1.51x10^{1}$
U/Ti	$3.03x10^{2}$ ± $1.63x10^{1}$
U/In	$1.91x10^{1}$ ± $7.62x10^{-1}$
In/Ti	$1.59x10^{1}$ ± $2.18x10^{-1}$
Au/Mg	$1.06x10^{5}$ ± $1.84x10^{3}$
U/Mg	$4.42x10^{3}$ ± $2.45x10^{2}$
Ti/Mg	$1.46x10^{1}$ ± $2.63x10^{-2}$
In/Mg	$2.31x10^{2}$ ± $3.59x10^{0}$

Table 7. Spectral ratios calculated with activation foils irradiated on the upper position using the cadmium gloves.

Spectral Ratios	Experimental
Au/U	$2.44x10^{1}$ ± $1.82x10^{0}$
Au/Ti	$7.33x10^{3}$ ± $1.56x10^{2}$
Au/In	$4.72x10^{2}$ ± $1.07x10^{1}$
U/Ti	$3.00x10^{2}$ ± $1.59x10^{1}$
U/In	$1.93x10^{1}$ ± $9.96x10^{-1}$
In/Ti	$1.55x10^{1}$ ± $2.18x10^{-2}$
Au/Sc	$4.58x10^{1}$ ± $2.29x10^{0}$
U/Sc	$1.87x10^{0}$ ± $4.56x10^{-2}$
Sc/Ti	$1.60x10^{2}$ ± $4.58x10^{0}$
Sc/In	$1.03x10^{1}$ ± $2.81x10^{-1}$

4. CONCLUSION

This work aims to measure the spectral ratios using activation foils irradiated inside the fuel of the IPEN/MB-01 Nuclear reactor. The experimental values obtained inside the asymptotic region of the neutron flux show very good agreement when comparing the lower and upper fuel rod position.

The cadmium ratios calculated experimentally reveal good agreement with the computational results calculated by MCNP-4C code.

The future step of this work will be a comparison with the calculation results and MCNP-4C results using different nuclear data libraries.

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