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CALIBRATION OF THE NUCLEAR POWER CHANNELS FOR THE CYLINDRICAL CONFIGURATION OF THE IPEN/MB-01 REACTOR OBTAINED FROM THE MEASUREMENTS OF THE SPATIAL NEUTRON FLUX DISTRIBUTION IN THE REACTOR CORE THROUGH THE IRRADIATION OF GOLD FOILS

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ABSTRACT

The activation foil is one of the most used techniques to obtain and compare nuclear parameters from the nuclear data libraries, given by a gamma spectrometry system. Through the measurements of activity induced in the foils, it is possible to determine the neutron flux profile exactly where it has been irradiated. The power level operation of the reactor is a parameter directly proportional to the average neutron flux in the core. The objective of this work is to obtain, for a cylindrical configuration, the power generation through a spatial thermal neutron flux distribution in the core of IPEN/MB-01 Reactor, by irradiating gold foils positioned symmetrically into the core. They are put in a Lucite plate which will not interfere in the analysis of the neutron flux, because of its low microscopic absorption cross section for the analyzed neutrons. The foils are irradiated with and without cadmium covered small plates, to obtain the thermal and epithermal neutron flux, through specific equations. The correlation between the average power neutron flux, as a result of the foil´s irradiation, and the average power digital neutron flux of the nuclear power channels, allows the calibration of the nuclear channels of the reactor. This same correlation was done in 2008 with the reactor in a rectangular configuration, which resulted in a specific calibration of the power level operation. This calibration cannot be used in the cylindrical configuration, because the nuclear parameters could change, which may lead to a different neutron profile. Furthermore, the precise knowledge of the power neutron flux in the core also validates the mathematics used to calculate the power neutron flux.

1. INTRODUCTION

The activation foil technique developed to determine the neutron flux inside a reactor core, can be done using infinitely dilute gold foils and hyper pure gold foils. In 2007 [1] and 2008 [2] research was developed by these methods, for the rectangular configuration of the reactor, and now, we present here the results for the cylindrical configuration. The main difference between infinitely dilute and hyper pure gold foils is the advantage of simplifying the calculations for the absence of the perturbation factor by the diluted ones. In this paper we used the hyper pure gold foils, which presents the same confidentiality in the results as the diluted ones.

By the use of this technique we obtain the average thermal neutron flux inside the core and as long as this average neutron flux is directly proportional to the power operation of the reactor, we are able to calibrate the nuclear channels of the reactor.

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The equation to determine the power level is [3].

$$P = G\ \overline{\Sigma}_f\ \overline{\phi_{th}} F\ R\ V \qquad (1)$$

where G is the recoverable energy per fission (200 MeV = 3.2 x 10^{-11} joules), Σ_f is the average macroscopic cross section (0.3494 cm^{-1}) [3], Φ_{th} is the average thermal neutron flux and V is the volume of the fuel of the reactor core, which for the IPEN/MB-01 reactor in the cylindrical configuration is 18100 cm3.

The neutron flux was measured only for the thermal neutron flux and not for the entire energy spectrum. These values were obtained from the moderator but nuclear fission reactions occur within the fuel. Therefore, it is necessary to add two correction factors in Equation (1), the factors F and R. The F factor is the ratio of the neutron flux in the fuel to neutron flux in the moderator. The R factor is the fast fission factor (the portion of the reactions that occur with fast neutrons). These factors were estimated in [3].

It is possible to obtain the average thermal neutron flux by three calculation method: by the average of the axial sinusoidal curve and after the average Bessel function; by calculating the weighted average thermal neutron flux, and; directly obtain the power in the core by discrete power sum for each foil.

For this paper we have chosen the discrete power calculation method. We calculated the thermal neutron flux for each foil and obtained the discrete power level for each one in the whole core. This analysis divides the core into small volumes containing the foils and a discrete power for each volume is obtained. These discrete power levels are then summed to obtain the power level inside the core.

To adjust the equation (1) to calculate the discrete power level by foil (2), we need to add the correction factor V_d = 3,5280V (where V is the volume of one fuel rod). This is the exact value obtained by the ratio 568 fuel rods by 161 foils, multiplied by V. This ratio creates the small volumes to determine the discrete power for each foil.

$$P = G\ \overline{\Sigma_f}\ \emptyset_{th} F\ R\ V_d \qquad (2)$$

The electric current of the nuclear power channels 5 and 6, as well as the count in channel 10, were monitored during the irradiation of the gold foils, which were well distributed in the IPEN/MB-01 reactor core by means of a Lucite plate. Thus, we could establish the total correlation between the digital power operation associated with the response of the signals from the electric current and, the real power level obtained through the discrete power summate inside the core.

2. EXPERIMENTAL METHODOLOGY

To obtain the thermal neutron flux by foil in the reactor, we used the technique of irradiating gold foils and then count their decay in an Hyper Pure Germanium Cristal (HPGe), which is a gamma spectrometry system. By irradiating Au-197 we have Au-198 and a (n,γ) reaction, then with the HPGe we obtained the count proportional to the neutron flux. The gold foils

were distributed in 4 planes (positions 14-15, 10-11, 6-7 and 2-3). Only in the position 14-15 we irradiated one centered diluted gold foil (1%Au diluted in 99%Al), and one hyper pure gold foil, to calculate the perturbation factor. The planes were positioned between the fuel rods into the light water, as shown in figure 1.

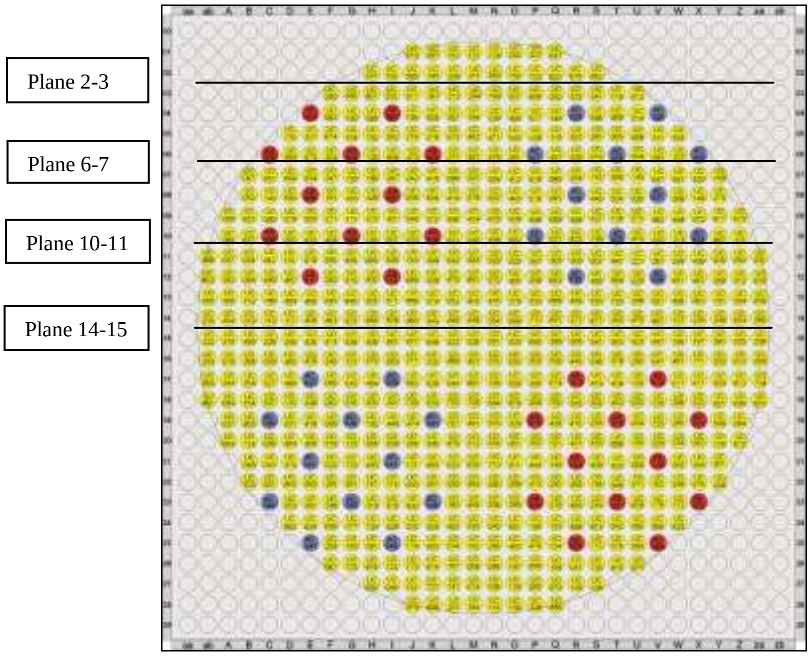

Figure 1: Cylindrical Configuration of IPEN-MB/01 Reactor (28x28 fuel rods) and planes of irradiation - Superior view.

Given the symmetry of the core, we assumed that the values of the neutron flux in each plane at the half which was mapped are of the same magnitude as the values of the half which was not mapped.

To position the gold foils into the reactor we used a lucite (acrylic) plate of 0.4 cm of thickness. This plate has 35 small holes (arrangement of 5 x 7) to fix the foils, as in Figure 2.

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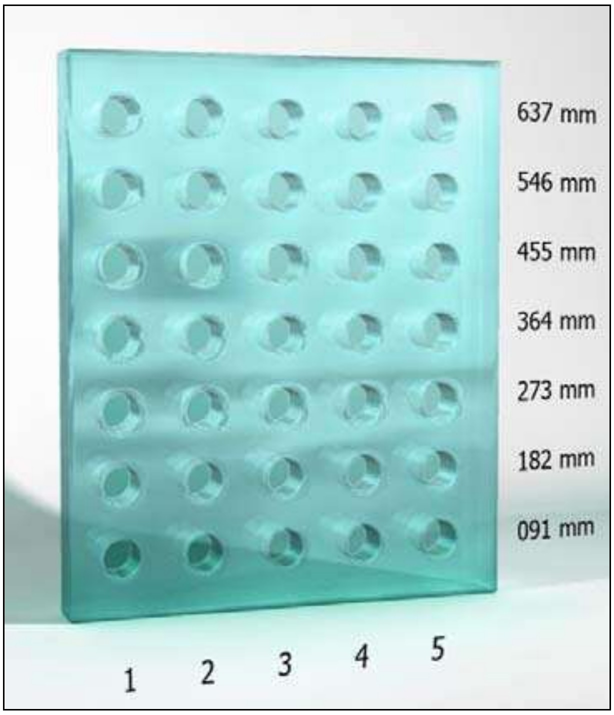

Figure 2: Illustration of the Lucite plate and the positions of the gold foils on it.

The whole process, divided in two parts, involved the saturated activation of 196 gold foils, being 98 bared foils and 98 cadmium covered foils given by expression (3).

$$A^{\infty} = \frac{\lambda\,(C - BG).e^{\lambda\,te}}{\varepsilon.I\,\left(1 - e^{-\lambda\,t}\right)\left(1 - e^{-\lambda\,tc}\right)} \tag{3}$$

where λ is the decay constant, te is the waiting time to gamma spectrometry after the irradiation, ti is the irradiation time, t is the count time (Live Time), C is the net counts of the gamma energy, BG is the background radiation, ε is the global efficiency of the system of the gamma spectrometry, I is the branching ratio to gamma energy.

Considering that the activation by bared foils is the sum of the activation of thermal and epithermal neutrons (4), we used the cadmium cover to give us the quantity of epithermal neutrons that achieved the gold foils placed in the lucite plate.

$$A^{\infty}_{nua} = A^{\infty}_{th} + A^{\infty}_{int} \tag{4}$$

Indeed, the cadmium cover is not an ideal filter to thermal neutrons to obtain epithermal activation, so it was necessary also to obtain the cadmium factor, F_{cd}. The factor F_{cd} takes into account the epithermal neutrons caught in the cadmium, and therefore allows the calculation of the real quantity of epithermal neutrons that induced the reactions in the gold foils. Equation (5) gives the real epithermal activation, calculated by the cadmium factor and the activation of gold foils using cadmium cover.

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$$A_{nua}^{\infty} = F_{cd} \cdot A_{cd}^{\infty} \tag{5}$$

For thermal neutrons we obtained the cadmium factor R_{cd} for hyper pure gold foils, that is the ratio of bared activation and cadmium activation (6).

$$R_{cd} = \left[\frac{A_{nua}^{\infty}}{A_{cd}^{\infty}} \cdot \frac{G_{int}}{G_{th}} + F_{cd} \left(1 - \frac{G_{int}}{G_{th}} \right) \right] \cdot \frac{m_{cd}}{m_{nua}} \tag{6}$$

The m_{cd} and m_{nua} are the weight of the gold foil with cadmium and without cadmium.

Once we used the hyper pure gold foils, we needed to calculate the perturbation factor, herein as, self-shielding, G. The self-shielding gives the probability that neutrons escape from the gold foil. This factor was obtained experimentally. Its values for thermal neutrons (thermal saturation activation ratio for hyper pure and diluted gold foils considering their atoms quantities (7)) and epithermal neutrons (epithermal saturation activation ratio for hyper pure and infinitely dilute gold foils considering their atoms quantities (8)) were G_{th}= 0,827119941 and G_{int}= 0,588038352.

$$G_{th} = \frac{\left(\frac{A_{th}^{\infty}}{N_T} \right)^{Au}}{\left(\frac{A_{th}^{\infty}}{N_T} \right)^{Au-Al}} \tag{7}$$

$$G_{int} = \frac{\left(\frac{A_{ep}^{\infty}}{N_T} \right)^{Au}}{\left(\frac{A_{ep}^{\infty}}{N_T} \right)^{Au-Al}} \tag{8}$$

We considered that epithermal activation has the highest percentage activation in the intermediate region, so epithermal (epit) will be named as intermediate (int).

The thermal neutron flux for each foil was obtained by the expression (9).

$$\phi_{th} = \frac{A_{nua}^{\infty} \left(1 - \frac{F_{cd}}{R_{cd}} \right) \cdot P_a}{N_a \cdot m \cdot \sigma_{atv} \cdot FP} \tag{9}$$

where Pa is the atomic weight of the target nucleus, Na is Avogadro's number, m is the mass of the activation foil, σ_{atv} is the microscopic activation cross section, and FP the factor of perturbation – self-shielding G_{th}.

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The power level obtained in the position 10-11, 6-7 and 2-3 were multiplied by 2, as we just mapped the north half of the reactor. The average was obtained for the power for position 14-15.

3. THEORETICAL METHODOLOGY

To determine the F and R factors, the cadmium factor F_{cd}, and the self-shielding factor G can be used in the computational code MCNP (Monte Carlo N Particles) in its version 4C, by statistical method. In this method the characteristics of the particles are estimated by sampling a large number of individual stories [3].

For the determination of the F factor, the problem is concentrated in the calculation of the neutron flux in the fuel and in the moderator by the following Equation (10).

$$F = \frac{\phi_C}{\phi_M} \tag{10}$$

where Φ_C is the flux in the fuel and Φ_M is the flux in the moderator.

The R factor takes into account the small fraction of the nuclear fissions that occur due to fast neutrons. To determine this factor, it is necessary to obtain the total fission and fast fission rates. In this case the energy range for fast neutrons is above 0.55 eV. According to the Equation (11), we can obtain the R factor.

$$R = \frac{f_{rap}}{f_{total}} \tag{11}$$

where f_{total} is the total fission rate and f_{rap} is the fast fission rate.

The element cadmium is used as a filter for thermal neutrons because of its high absorbing cross section. But cadmium is not an ideal filter, because it absorbs a small part of the epithermal neutrons. The cadmium factor, F_{cd}, restores the contribution due to epithermal neutrons absorbed in the cadmium coverage. In this case it is necessary to obtain the ratio between the reaction rate for neutron above the thermal energy with bared activation detector (R_{epit}) and the reaction rate for a detector covered with cadmium above the cut-off energy (R_{cd}). For this, we have the Equation (12).

$$F_{cd} = \frac{R_{epit}}{R_{cd}} \tag{12}$$

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For the determination of the self-shielding G, the problem is concentrated in the calculation of the average neutron flux in the moderator (here represented by the diluted gold foil neutron flux) and the surface flux in the hyper pure gold foil by the following Equation (13).

$$G = \frac{\bar{\phi}}{\phi s} \tag{13}$$

4. RESULTS

The F and R factors used was [3],

$$F = 0.78735 \pm 0.05\%.$$

$$R = 1.1559 \pm 0.36\%.$$

The value used for F_{cd} in diluted gold foils was [3],

$$F_{cd} = 1.054 \pm 0.44\%$$

The value used for F_{cd} in hyper pure gold foils was [2],

$$F_{cd} = 1.098$$

Then the values inserted in the Equation (2) resulted in the power level of the IPEN/MB-01 reactor,

$$P = (92.08 \pm 0.07) \text{ watts.}$$

The nuclear power channels monitored were the 5 and 6 ones.

The count in nuclear channel number 10 (10B detector), at the east face of the reactor core (40 cm), is the most far detector. Therefore it was used to normalize the small operational difference in power level between each irradiation. Thus each minor power level fluctuation was corrected.

The calibration of the nuclear power channel 5 for rectangular configuration, is shown in the Figure 3.

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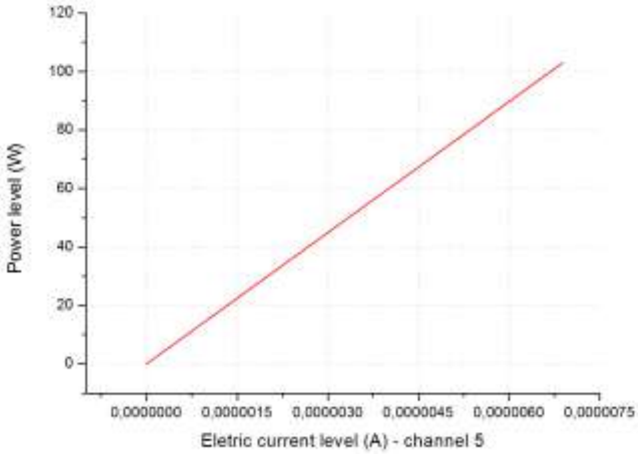

Figure 3 : Calibration straight line to nuclear power channel 5 for rectangular configuration.

The correlation between power level and electric current for the channel 5 (I_5) is expressed in (14).

$$P\ (\text{Channel } 5) = (1.5012 \pm 0.0004) \times 10^7\ I_5 \qquad (14)$$

The calibration of the nuclear power channel 6 for rectangular configuration, can be shown in the Figure 4.

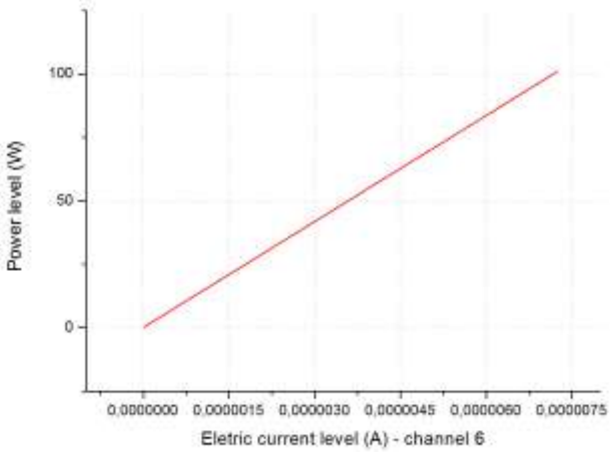

Figure 4 : Calibration straight line to nuclear power channel 6 for rectangular configuration.

The correlation between power level and electric current for the channel 6 (I_6) is expressed in (15).

$$P\ (\text{Channel } 6) = (1.39293 \pm 0.0003) \times 10^7\ I_6 \qquad (15)$$

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These equations for channels 5 and 6 were approximately those found in [3] for obvious reasons.

The calibration of the nuclear power channel 5 for a cylindrical configuration is shown in Figure 5.

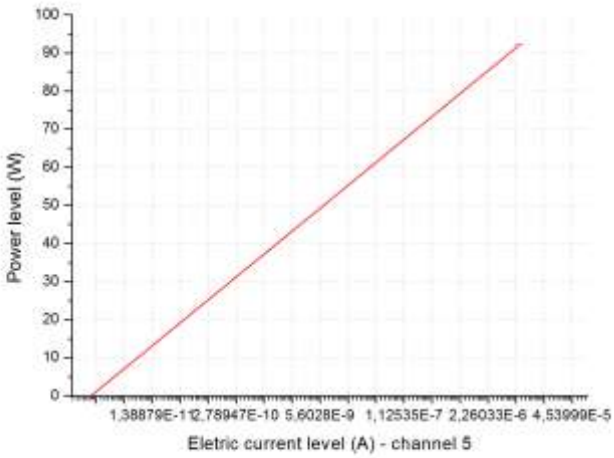

Figure 5 : Calibration straight line to nuclear power channel 5 for cylindrical configuration.

The correlation between power level and electric current for cylindrical configuration in channel 5 (I_{5c}) is expressed in (16).

$$P \text{ (Channel 5)} = (1.3454 \pm 0{,}1943) \times 10^{7} I_{5c} \tag{16}$$

The calibration of the nuclear power channel 6 for a cylindrical configuration, is shown in Figure 6.

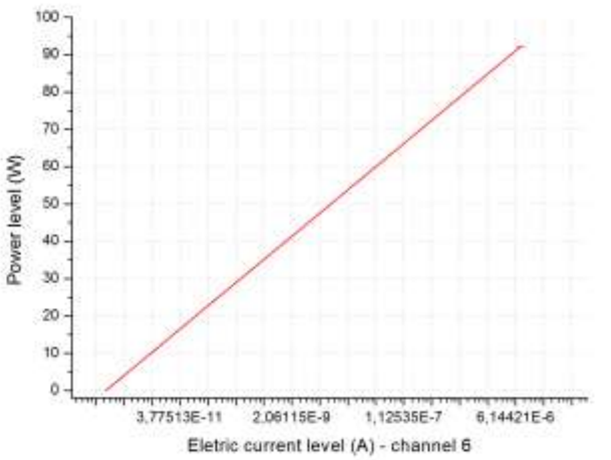

Figure 6 : Calibration straight line to nuclear power channel 6 for cylindrical configuration.

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The correlation between power level and electric current for cylindrical configuration in channel 6 (I_{6c}) is expressed in (17).

$$P\ (\text{Channel } 6) = (1.2700 \pm 0.1904) \times 10^{7}\ I_{6c} \quad (17)$$

Table 1. Power level and electric current of the nuclear power channels 5 and 6, for cylindrical configuration.

Power Level (W)	Electric Current of the Channel 5(A)	Electric Current of the Channel 6 (A)
1.87×10^{-6}	1.56×10^{-12}	2.69×10^{-12}
92.08±0.07	6.89×10^{-6}	7.25×10^{-6}

The calibration of the nuclear power channel 6 versus channel 10 for a cylindrical configuration, is shown in Figure 7.

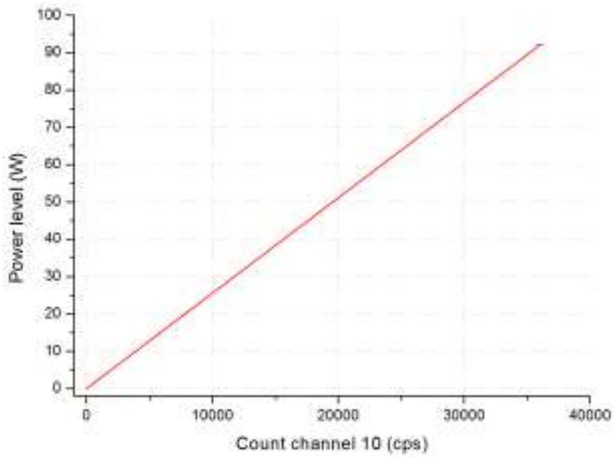

Figure 7 : Calibration straight line to nuclear power channel 6 and count in channel 10 for cylindrical configuration.

The correlation between power level and count for cylindrical configuration in channel 10 (CPS_{c10}) is expressed in (18).

$$P\ (\text{Channel } 6) = (0{,}0025) \times CPS_{c10} \quad (18)$$

5. CONCLUSION

The experiment found a difference between the cylindrical and rectangular configurations of 8.83%, relative to the power indicated in the channel used in the power calibration, which

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was the nuclear channel 6. The current informed by nuclear channel 6 was 0.719 x 10^{-5} A at 100 W, for the rectangular configuration with 28 x 26 fuel rods.

The same way, noise analysis technique indicates a difference of 18.28% (82.53 ± 13.5% W) according to the digital power channel 6 [10, 11].

The difference between the gold foil irradiation experiment and the noise analysis indicates a difference of 10.4%.

All experimental values of the neutron flux used in this work to obtain of the cylindrical configuration power level are given by Bitelli and Arêdes in the reference [12].

It is important to notice that, in the cylindrical configuration (28 x 28) we have 568 fuel rods, 112 less than the rectangular one (26 x 28) which has 680. This is about 16.47% less, however, the power did not decrease at the same rate, by the minor non-scape probability in the cylindrical configuration, what increases the power density when compared to the rectangular configuration at the same power level.

For weighted average thermal neutron flux calculation method, we obtained 4.8322x10^8 ± 8.35 % n/cm^2. s and, for the rectangular configuration the average thermal neutron flux obtained in [3], by the average value of sinusoidal and Bessel functions, was 4.95607x10^8 ± 2.45 % n/cm^2. s, it means a difference of 2.49%.

The weighted average thermal neutron flux has a confidentiality of 95% according to *t of Student.*

The weighted average thermal neutron flux resulted by the equation (1) in the power level of 91.8 ± 0.29 W, which has a difference for the discrete power calculation method of only 0.31%, what represents a very convergent result, validating it.

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