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THE FINAL CALIBRATION OF THE NUCLEAR POWER CHANNELS OF THE IPEN/MB-01 REACTOR BY THE USE OF THE ACTIVATION FOILS AND THE MONTE CARLO METHOD

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ABSTRACT

This work aims the final calibration of the nuclear power channels of the IPEN/MB-01 reactor using infinitely dilute gold foils (1% Au - 99% Al), this is, metallic alloy in the concentration levels such that the phenomena of flux disturbance, as the self-shielding factors become worthless. During the irradiations were monitored the nuclear power channels of the reactor used to obtain the neutron flux and consequently the power operation of the reactor. The current values were digitally acquired during each second of operation. Once the foils were irradiated for the analysis of its induced activity it was used a detection system of hyper-pure germanium. Ally to this experimental procedure it was used the computational code MCNP-4C as a tool for theoretical modeling of the core of the IPEN/MB-01 reactor. Thus it was possible to determine the parameters necessary to obtain the power operation of the reactor, such as the inverse of the thermal disadvantage factor and fast fission factor. Thus, using the correlation between average thermal neutron flux, proportional to a power operation and the average of the digital values of current of the nuclear channels, during the irradiations of the foils, it was obtained the calibration of the nuclear power channels, the ionization chambers number 5 and 6 of the IPEN/MB-01 reactor.

1. INTRODUCTION

The knowledge of the neutron flux in the reactor's core is very important to know the lifetime of a particular configuration of core, the power operation, safety conditions, etc.

The objective of this work is finalize the calibration of the nuclear channels of the IPEN/MB-01 reactor started in 2007 [1] and re-did 19 years after its inauguration. The average neutron flux is a factor directly proportional to the power operation. For this new calibration of the nuclear power channels it was used activation detectors to determine the neutron flux. These detectors had a form of infinitely dilute foils. Allied to the experimental apparatus was used the computer code MCNP-4C for the determination of factors related to the power operation.

The Equation for obtaining the power level is [2]

$$P = G\ \overline{\Sigma}_f\, \overline{\phi_{th}} F\ R\ V\ , \tag{1}$$

where G is the recoverable energy per fission (200 MeV = 3.2 x 10^{-11} joules), $\overline{\Sigma}_f$ is the average macroscopic cross section (0.3494 cm^{-1}) [3], $\overline{\Phi_{th}}$ is the average thermal neutron flux and V is the volume of the fuel of the reactor core and the value to the IPEN/MB-01 reactor is 21019 cm^3.

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The neutron flux was not measured all over the energy spectrum, but only for the average thermal neutron flux. These values were obtained in the moderator and the nuclear fission reactions occur where the fuel is, so it is necessary the addition of two corrections factors in the Equation (1), the factors *F* and *R*.

The *F* factor relates the ratio of the neutron flux in the fuel to neutron flux in the moderator and the *R* fast fission factor (the portion the reactions that occur with fast neutrons). These factors were estimate by calculation methodology using the computational code MCNP-4C.

During the operations of the IPEN/MB-01 reactor, the electric currents of the nuclear power channels were monitored, and we could establish the total correlation between average neutron flux and power operation with the responses of the signals from the electric current.

2. EXPERIMENTAL METHODOLOGY

The experimental methodology used for determining the average thermal neutron flux was the irradiation of the infinitely dilute gold foils distributed in 4 planes of irradiation (plane 2-3, plane 6-7, plane 10-11 and plane 14-15). These planes are positioned between the fuel rods and located in the moderator (light water), as shown in the Figure 1.

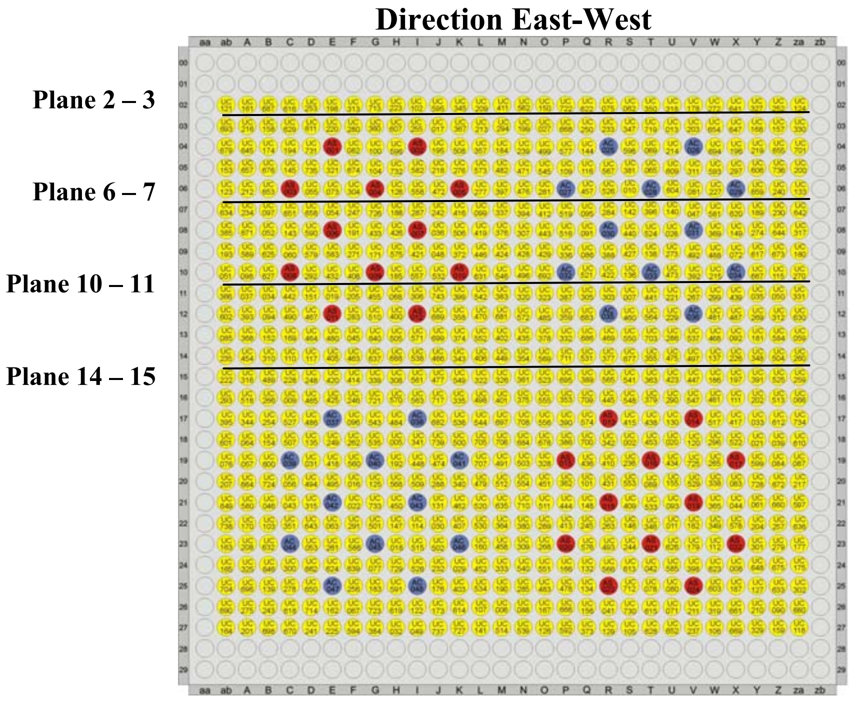

Figure 1. Configuration of the IPEN/MB-01 reactor and the planes of irradiation.

At each plane of irradiation 35 infinitely dilute gold foils were distributed in a 5x7 arrangement. These activation foils were distributed in an acrylic plate of 0.4 cm of thickness (material that has properties similar to those used in the moderator of the IPEN/MB-01 reactor), as Figure 2 shows.

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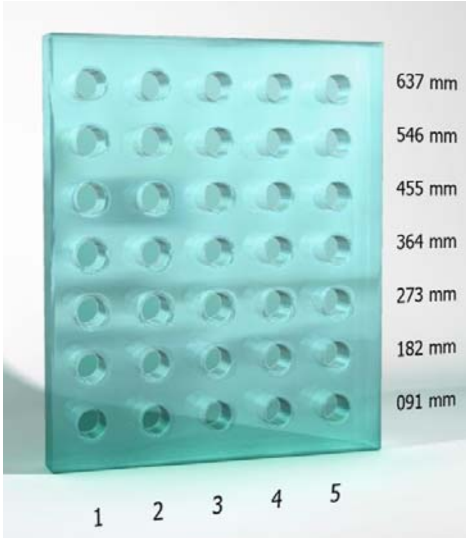

Figure 2. Illustration of acrylic plate and the positions of the infinitely dilute gold foils.

In total 280 infinitely dilute gold foils were irradiated (140 bared foils and 140 covered with cadmium plate). Given the symmetry of the core we assumed that the values of the average neutron flux in each plane at the half mapped are of the same magnitude as the values of that half not mapped.

The infinitely dilute gold foils used were made by Institute of Material and Measurements [4] and each foils had 0.2 mm of thickness and 7.5 mm of diameter.

After the irradiations the gamma spectrometry was done for each foil irradiated to determine the saturate activity by the following Equation (2),

$$A^{\infty} = \frac{e^{\lambda\, t_e} C}{\varepsilon\ I\ LT(1-e^{-\lambda\, t_i})} \frac{F_r F_a}{F_n}, \tag{2}$$

where λ is the decay constant, t_e is the waiting time to gamma spectrometry after the irradiation, C is the net counts of the gamma energy, ε is the global efficiency of the system of the gamma spectrometry, I is the branching ratio to gamma energy, LT is the counting time during the gamma spectrometry discount the background, t_i is the irradiation time, F_r is the ramp factor, F_n is the factor that consider the little fluctuation power level between the several irradiations and F_a is the self-absorption factor.

It was used the Equation (2) to obtain the saturate activity for both cases, bared foils and covered with cadmium foils. This methodology was adopted for determining the cadmium ratio, R_{cd}.

Thus, the thermal neutron flux has been obtained by the following Equation (3),

$$\phi_{th} = \frac{A^{\infty}_{nua}\left(1-\frac{F_{cd}}{R_{cd}}\right)P_a}{N_a m \sigma_{atv}} \tag{3}$$

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where P_a is the atomic weight of the target nucleus, N_a is the Avogadro's number, m is the mass of the activation foil, σ_{atv} is the microscopic activation cross section and F_{cd} is the factor cadmium. In this work the factor cadmium also was estimated using the computational code MCNP-4C.

To study the linearity of the responses of nuclear power channels five operations with hyper-pure gold foils (99.9%) were used. Due to its high concentration of gold atoms high activation can be obtained even at low power levels.

3. THEORETICAL METHODOLOGY

To determine the F and R factors and the cadmium factor, the computational code MCNP (Monte Carlo N Particles) in its version 4C [5] by statistical method was used. In this method the characteristics of the particles are estimated by sampling a large number of individual stories.

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 (4),

$$F = \frac{\phi_C}{\phi_M} \tag{4}$$

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 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 (5), we can obtain the R factor,

$$R = \frac{f_{rap}}{f_{total}} \tag{5}$$

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

The element cadmium is used as filter to thermal neutron because of its high absorbing cross section. But the cadmium is not an ideal filter, because it absorbs a small part of the epithermic neutrons. The cadmium factor, F_{cd}, restores the contribution due to epithermic 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 following Equation (6),

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$$F_{cd} = \frac{R_{epit}}{R_{cd}} . \tag{6}$$

4. RESULTS

The value of the average thermal neutron flux in the core obtained through the irradiation of the 140 infinitely dilute gold foils was

$$\overline{\Phi}_{th} = 4.95607 \text{ x } 10^8 \text{ n/cm}^2 \text{ s} \pm 2.45\%.$$

For the calculation to obtain the cadmium factor a square arrangement 4x4 fuel rods was modeled instead of the original arrangement 26x28 fuel rods. This procedure was adopted because the dimensions of the foil simulated were very small. The simulated foil had the same dimensions as the foils used in the experiment.

The calculation was done in two steps. In the first time the R_{epit} was calculated in 1085 minutes of processing time and the R_{cd} in 1589 minutes of processing time. The nuclear data used for this problem were the ENDF/B-VI and the NJOY. The value of the cadmium factor was

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

The result obtained for the *F* factor was

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

For this value the whole core of the IPEN/MB-01 reactor was modeled. In the same problem we obtained the flux in the fuel rod and in the moderator, and in this case the processing time was 1221 minutes. The nuclear data used were the ENDF/B-VI.

To the *R* factor, the value obtained was

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

and for this calculation the processing time was 1346 minutes and the nuclear data used was the ENDF/B-VI.

In all cases that we used the MCNP-4C, we adopted 300 cycles of process in a total of 90 million of stories

These values inserted in the Equation (1) give the power level of the IPEN/MB-01 reactor,

$$P = (106.00 \pm 2.60) \text{ watts}.$$

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The nuclear power channels monitored were the channels 5 and 6. The values of the irradiation with the hyper-pure gold foils are showed in the Table (1):

Table 1. Power level and electric current of the nuclear power channels 5 and 6.

Power Level (W)	Electric Current of the Channel 5 (A)	Electric Current of the Channel 6 (A)
0.090 ± 0.002	7.04×10^{-9} ± 1.46%	7.66×10^{-9} ± 1.46%
1.470 ± 0.036	1.01×10^{-7} ± 0.84%	1.03×10^{-7} ± 0.48%
10.810 ± 0.265	7.14×10^{-7} ± 0.39%	8.03×10^{-7} ± 0.09%
54.831 ± 1.343	3.65×10^{-6} ± 0.14%	3.80×10^{-6} ± 0.54%
106.001 ± 2.601	7.06×10^{-6} ± 0.02%	7.68×10^{-6} ± 0.02%

The calibration of the nuclear power channel 5 can be shown in the Figure 3:

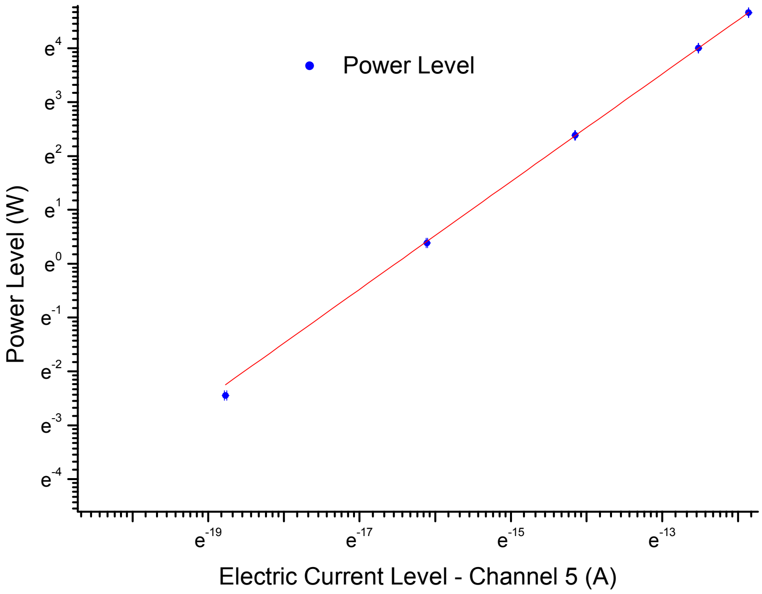

Figure 3. Calibration straight line to nuclear power channel 5.

The total correlation between power level and electric current of the channel 5 (I_5) is expressed in the Equation (7),

$$P\ (\text{Channel } 5) = (1.5018 \pm 0.0009) \times 10^{7}\ I_5. \quad (7)$$

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The calibration of the nuclear power channel 6 can be shown in the Figure 4:

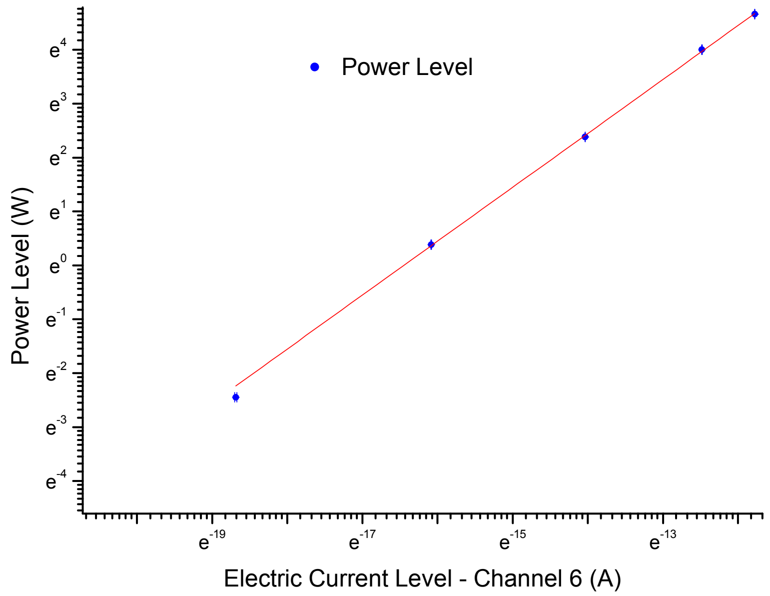

Figure 4. Calibration straight line to nuclear power channel 6.

The total correlation between power level and electric current of the channel 6 (I_6) is expressed in the Equation (8),

$$P\ (\text{Channel 6}) = (1.3917 \pm 0.0128) \times 10^7\ I_6. \quad (8)$$

5. CONCLUSION

The results obtained in this work show an error of 50% less than those obtained in the first calibration in 1982 [3]. This high precision can be credited to the utilization of infinitely dilute foils. Therefore not causing perturbation of the neutron flux, thus the self-shielding factor is very small.

Another point that helped to obtain a smaller error were the readings of the values of the electric currents of the channels 5 and 6. The readings were done in each second of the reactor operation. Thus, we had a rich statistics.

The differences found between the calibrations, 100 watts in the last calibration and 106 watts in the new calibration can also be credited to the aging of the nuclear instruments of the IPEN/MB-01 reactor.

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