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THE FINAL POWER CALIBRATION OF THE IPEN/MB-01 NUCLEAR REACTOR FOR VARIOUS CONFIGURATIONS OBTAINED FROM THE MEASUREMENTS OF THE ABSOLUT AVERAGE NEUTRON FLUX

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ABSTRACT

The use of neutron activation foils is a widely spread technique applied to obtain nuclear parameters then comparing the results with those calculated using specific methodologies and available nuclear data. By irradiation of activation foils and subsequent measurement of its induced activity, it is possible to determine the neutron flux at the position of irradiation. The power level during operation of the reactor is a parameter which is directly proportional to the average neutron flux throughout the core. The objective of this work is to gather data from irradiation of gold foils symmetrically placed along a cylindrically configured core which presents only a small excess reactivity in order to derive the power generated throughout the spatial thermal and epithermal neutron flux distribution over the core of the IPEN/MB-01 Nuclear Reactor, eventually lending to a proper calibration of its nuclear channels. The foils are fixed in a Lucite plate then irradiated with and without cadmium sheaths so as to obtain the absolute thermal and epithermal neutron flux. The correlation between the average power neutron flux resulting from the gold foils irradiation, and the average power digitally indicated by the nuclear channel number 6, allows for the calibration of the nuclear channels of the reactor.
The reactor power level obtained by thermal neutron flux mapping was (74.65 ± 2.45) watts to a mean counting per seconds of 37881 cps to nuclear channel number 10 a pulse detector, and $0.719.10^{-5}$ ampere to nuclear linear channel number 6 (a non-compensated ionization chamber).

1. INTRODUCTION

The activation foil technique developed to determine the neutron flux inside a reactor core consists in using both infinitely dilute gold foils and hyper pure gold foils. In 2007 [1] and 2008 [2] research was conducted using these methods for the rectangular configuration of the reactor, and now, results for the cylindrical configuration are presented here. The main advantage of using infinitely diluted and hyper pure gold foils lies on simplified calculations due to the absence of the perturbation factor from the diluted ones. In this paper we used the hyper pure gold foils which show similarly reliable results when compared to the diluted ones.

By using this technique an average value for the thermal neutron flux inside of the reactor core can be derived. The average neutron flux is directly proportional to power operation of

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the reactor. Correlating signals from the nuclear channels with the average thermal neutrons flux enables calibration of selected nuclear instruments in terms of power.

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

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

where G is the recoverable energy per fission (200 MeV = 3.2 x 10^{-11} joules), 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 equates 18100cm^3 in the cylindrically configured IPEN/MB-01 reactor.

Power generated by fission reactions is experimentally assessed by the average thermal neutron flux measured at many points throughout the moderator. Those values are subsequently affected by two correction factors shown in Equation (1) above, namely:

F : ratio between neutron fluxes within the fuel and the moderator. Used to evaluate thermal neutron flux inside fuel rods (as neutron flux is measured within the moderator, but nuclear fission reactions actually occur within the fuel);

R : the so called ‘fast fission factor’ – correction for the inclusion of fast fissions (fraction of fission reactions directly initiated by fast neutrons) to the result.

Those factors are estimated in [3].

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 using a Hyper Pure Germanium Cristal (HPGe), which is a gamma spectrometry system. By irradiating Au-197 we get Au-198 and a (n,γ) reaction, then with the HPGe we obtain a count sum which is proportional to the neutron flux. The gold foils were distributed along 4 planes (positions 14-15, 10-11, 6-7 and 2-3). Only at position 14-15 we irradiated one centered diluted gold foil (1%Au diluted in 99%Al), and one hyper pure gold foil, in order to calculate the perturbation factor. The planes were positioned between the fuel rods into the light water, as shown in figure 1.

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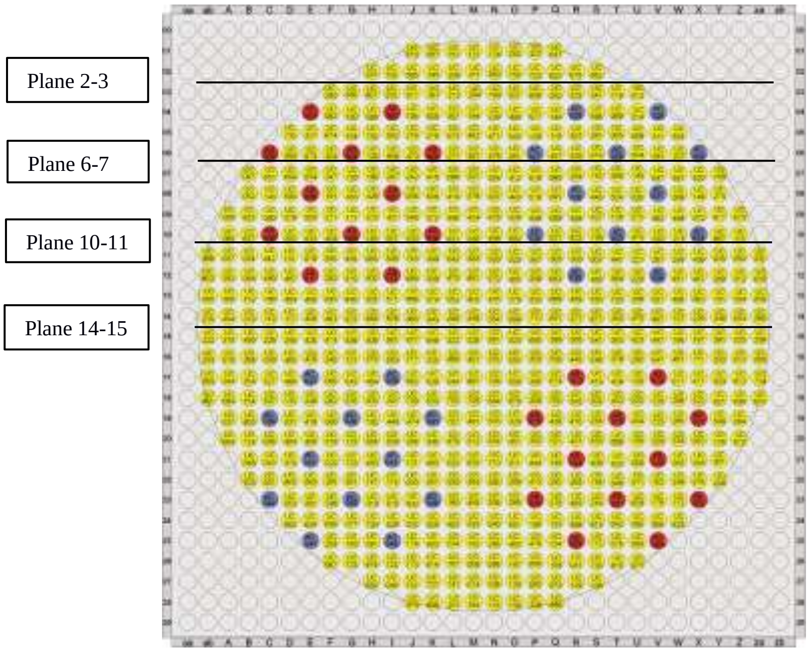

Figure 1: Cylindrical Configuration Core of IPEN-MB/01 Reactor and planes of irradiation - superior view

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

To position the gold foils inside the reactor we used a 0.4 cm thick lucite (acrylic) plate with a 5 x 7 arrangement of 35 tiny circular holes (exaggerated in Figure 2 that follows).

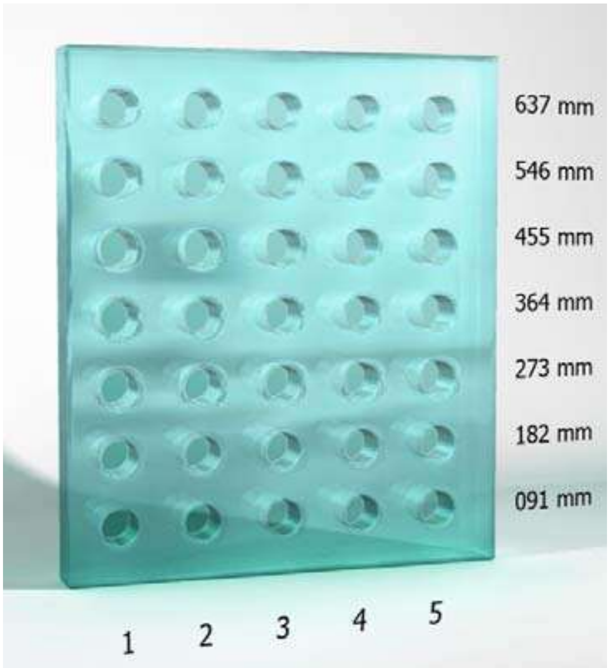

Figure 2: Illustration of the Lucite plate and the positions of the gold foils on it.

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The whole process consisted in measurements of saturated activation (from nuclear reaction rate) of 266 gold foils divided into two parts: 133 bare (without any cadmium), and 133 covered with cadmium foils, respectively, given by expression (3).

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

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

Considering that bare foils activation corresponds to the sum of activation from both thermal and epithermal neutrons (4), the quantity of epithermal neutrons hitting the gold foils placed along the lucite plate can be estimated by using cadmium covers.

$$A^{\infty}_{nua} = A^{\infty}_{th} + A^{\infty}_{int} \qquad (4)$$

Actually, as cadmium covers does not constitute an ideal filter to thermal neutrons to ensure epithermal only activation, a cadmium factor (F_{cd}) is also needed. This factor F_{cd} takes into account the epithermal neutrons absorbed by cadmium, allowing therefore the calculation of the actual quantity of epithermal neutrons that induces reactions in the gold foils. Equation (5) gives the actual epithermal activity, calculated from the cadmium factor and the activity of gold foils with cadmium covers:

$$A^{\infty}_{int} = F_{cd}.A^{\infty}_{cd} \qquad (5)$$

For thermal neutrons we obtained the cadmium factor R_{cd} for hyper pure gold foils, which establishes the ratio between bare activity and cadmium filtered activity (6).

$$R_{cd} = \left[\frac{A^{\infty}_{nua}}{A^{\infty}_{cd}}.\frac{G_{int}}{G_{th}} + F_{cd}\left(1 - \frac{G_{int}}{G_{th}}\right)\right].\frac{m_{cd}}{m_{nua}} \qquad (6)$$

The m_{cd} and m_{nua} are the masses of gold foils with and without cadmium covers, respectively.

When hyper pure gold foils are used, a perturbation factor expressed herein as self-shielding (G) is needed to compensate for the reduction of neutron flux impinged by the layers of gold atoms that compound the molecular structure of the foil. It is an experimentally evaluated factor. Its values for thermal neutrons (ratio between hyper pure and diluted gold foils thermal saturation activities considering their atoms quantities (7)) and epithermal

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neutrons (ratio between hyper pure and infinitely diluted gold foils epithermal saturation activities considering their atoms quantities (8)) are G_{th}= 0.827 and G_{int}= 0.588, respectively.

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

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

It was considered that epithermal activation shows the highest percentual activation in the intermediate region, so epithermal (epit) will be named hereafter as intermediate (int).

The thermal neutron flux for each foil can be obtained from expression (9):

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

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 is the factor of perturbation – self-shielding G_{th}.

The average thermal neutron flux was obtained considering two theoretical assumptions: symmetry of the nucleus and absence of fuel burn as IPEN/MB-01 is a reactor that operates at low power levels (<100 Watts). As flux values of thermal neutrons are the same in the north and south hemisphere core, only half of the core has to be mapped. The average value applies for thermal neutrons using weighted mean and its standard deviation as given below:

ϕ_{th} = $(4.05.10^8 \pm 3.27\%)$ n/cm^2.s

This thermal neutron flux value applies for an average electric current of $7.19 . 10^{-6}$ A at nuclear channel Nº 6 which would correspond to an overall power of 100 watts when using a rectangular standard core configuration (array of 28x26 fuel rods). It will be shown later that such nominal power level no longer applies to the cylindrical configuration (28 fuel rods along diameter) used in this experiment.

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3. THEORETICAL METHODOLOGY

F and R factors, the cadmium factor F_{cd}, and the self-shielding factor G are determined by statistical methods using computational code MCNP5 (Monte Carlo N Particles). By sampling a large number of individual stories, characteristics of particles can be estimated [3].

For the determination of the factor F, the problem focuses around calculation of the neutron flux within the fuel and the moderator according to the following Equation (10):

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

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

Factor R takes into account the small fraction of the nuclear fissions that occur due to fast neutrons. To determine this factor, total fission and fast fission rates have to be evaluated. The considered energy range for fast neutrons lies above 0.55 eV. Factor R derives from Equation (11):

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

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

The element cadmium is chosen as filter for thermal neutrons because of its high thermal absorption cross section. However, it does not constitute an ideal filter as it also absorbs a small fraction of epithermal neutrons. The cadmium factor, F_{cd}, restores the contribution due to epithermal neutrons absorbed by the cadmium covers. The ratio between reaction rates for both bare (R_{epit}) and cadmium-covered (R_{cd} – above the cut-off energy) activation detectors leads to Equation (12) where F_{cd} is the cadmium factor:

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

Determination of self-shielding G involves determining the average neutron flux in the moderator (represented here by diluted gold foils neutron flux) as well as the surface flux over hyper pure gold foils according to Equation (13):

$$G = \frac{\acute{\phi}}{\phi_S} \tag{13}$$

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4. RESULTS

The following values for factors F and R [3] were used:

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

$$R = 1.1556 \pm 0.36\%.$$

Factor F_{cd} for diluted gold foils was [3]:

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

Factor F_{cd} for hyper pure gold foils was [2]:

$$F_{cd} = 1.098$$

Total fuel volume was 18100 cm^2 for a cylindrical configuration with 569 fuel rods.

Inserting values above into Equation (2) resulted in the following power level for the IPEN/MB-01 reactor:

$$P = (74.65 \pm 2.45) \text{ watts.}$$

Previous power calibration of nuclear channels Nº 5 and 6 applies only to the rectangular configuration of the core with 680 fuel rods arranged in a 28x26 array.

Count rate from nuclear channel Nº 10 (a ^{10}B pulse detector placed 40 cm from the east face of the reactor core, the farthest among nuclear channels) is also available. It is commonly used for normalization of small operational differences between irradiations, making it possible to compensate for minor power level fluctuations.

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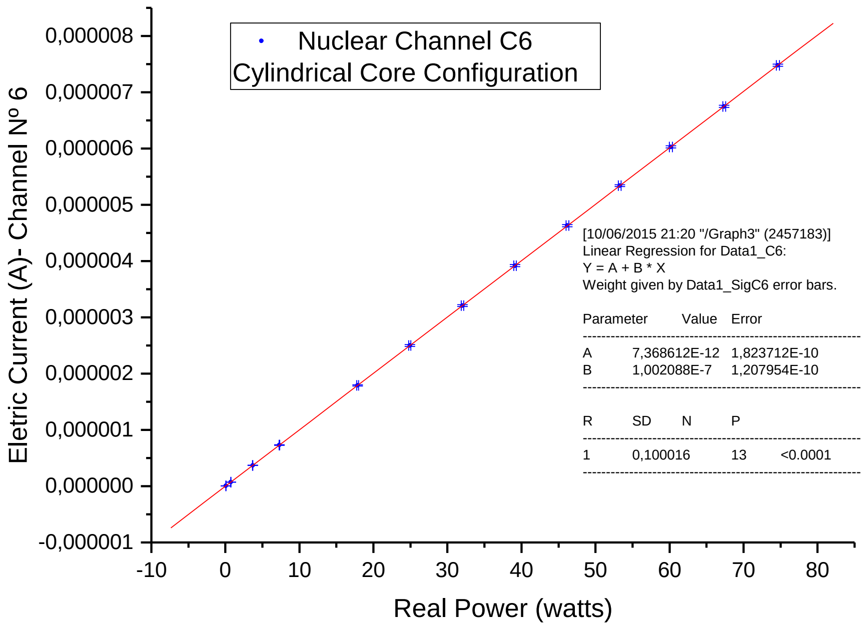

Figure 3 - Calibration straight line to nuclear power channel 6 for cylindrical configuration.

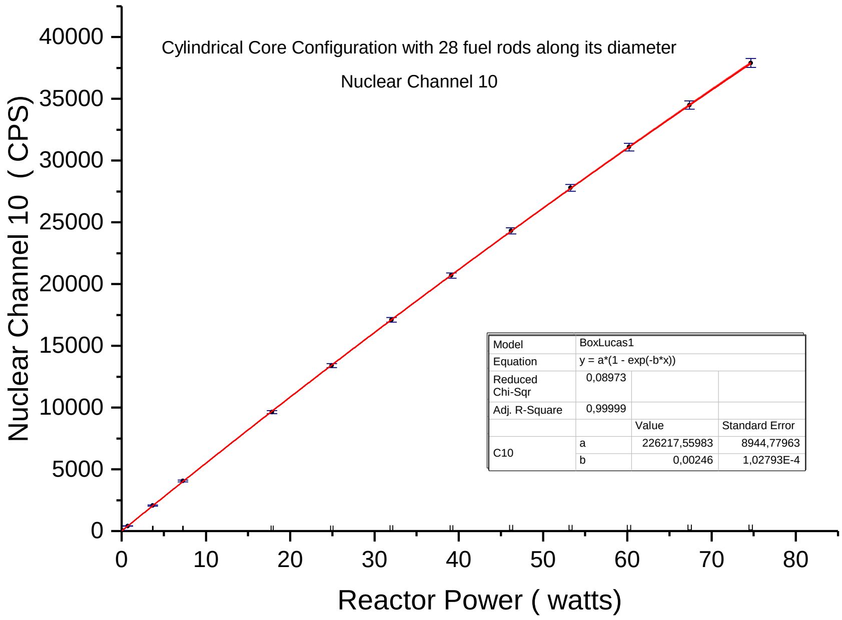

Figure 4 - Calibration straight line to nuclear power channel 10 for cylindrical configuration.

The correlation between power level and electric current and counts per seconds (CPS) for cylindrical configuration in channel 6 (I_{6c}) is expressed in (17) and (18) to Channel 10, respectively.

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$$I\ (\text{Channel } 6) = (1.0021 \pm 0.0001)\ .\ 10^{-7}\ P\ (\text{watts}) \qquad (17)$$

$$CPS\ (\text{ canal } 10) = A.(1 - \exp(-B.P(\text{Watts}))) \qquad (18)$$

Where :

A= 230197 ± 2.3% and B= 0.00241 ± 2.,5% .

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

Real Power Level (W) *	Electric Current of the Channel 6 (A)	CPS of the Channel 10(A)
0.08	7.57E-09 ± 2.51%	4.11E+01 ± 14.4%
0.73	7.28E-08 ± 0.85%	4.05E+02 ± 4.7%
3.70	3,70E-07±0.65%	2.06E+03 ± 2.2%
7.28	7,30E-07±0.55%	4.05E+03 ± 1.7%
17.85	1,79E-06±0.67%	9.63E+03 ± 1.3%
24.92	2,50E-06±0.60%	1.34E+04 ± 1.2%
32.01	3,21E-06±0.53%	1.71E+04 ± 1.1%
39.13	3,92E-06±0.43%	2.07E+04 ±1.0%
46.20	4,63E-06±0.39	2.43E+04 ± 1.0%
53.27	5,34E-06±0.34%	2.78E+04 ± 1.0%
60.20	6,03E-06±0.35%	3.11E+04 ± 1.0%
67.39	6,75E-06±0.30%	3.45E+04 ± 1.0%
74.65	7,48E-06±0.27%	3.79E+04 ± 1.0%

5. CONCLUSION

During this experiment, a difference of 26.05% was found between cylindrical and rectangular configurations regarding indication from power calibrated channel (nuclear channel Nº 6). A current reading of $7.48.10^{-6}$ A at nuclear channel 6 was due to 100.95 watts for the rectangular configuration with 28 x 26 fuel rods, but only 74.65 watts when using the

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cylindrical core configuration. According to extrapolation of calibration curve as seen on Figure3, a current of $1.002.10^{-5}$A on channel Nº 6 would have been required for actual 100 watts operation.

It should be pointed out that in the cylindrical configuration (28 diameter) only 568 fuel rods are used, or 112 less than the 680 used in the rectangular one (26 x 28). While this is about 16% less, the power did not decrease at the same rate, due to the lesser non-scape probability in cylindrical configuration, increasing the power density when compared to the rectangular configuration at the same power level. By operation at 100 watts using the cylindrical configuration it is possible to obtain an average thermal neutron flux of 5.43.108 n/cm^2.s which is 34% over the level attained with the standard (rectangular) configuration core of 28x26 fuel rods.

A precise knowledge of operating power in a zero power reactor is of key importance to keep control of experiments being performed, allowing for an accurate comparison among experimental results and those derived from calculation methodologies and their associated nuclear data libraries. In this sense, this work aims to contribute to a proper power calibration of two nuclear channels when using small excess reactivity core configurations, a situation which lends itself to a small fraction of control rods inserted into the core, favoring an increase of the extent of asymptotic region of the neutron flux with little experimental disturbance from control rods.

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