Experimental Utilization of the IPEN/MB-01 Reactor

Ulysses d´Utra BITELLI, Adimir dos SANTOS, Rogério JEREZ, Ricardo DINIZ,
Leda C.C.B.FANARO, Alfredo Y.ABE**, João M.L. MOREIRA**, Nelson FÉR ** ,
Marino R.GIADA** and Rinaldo FUGA**

IPEN/CNEN-SP- Instituto de Pesquisas Energéticas e Nucleares
Av.Prof. Lineu Prestes,2242 –05508-000 - São Paulo – Brasil

** CTMSP- Centro Tecnológico da Marinha em São Paulo
Av.Prof. Lineu Prestes,2468 – 05508-000 -São Paulo-Brasil

This paper aims to show the experimental utilization of the IPEN/MB-01 nuclear reactor during the last fourteen years. The IPEN/MB-01 is a zero-power critical assembly specially designed to measure integral and differential reactor physics parameters to validate calculational methodologies and related nuclear data libraries. Experiments involving determination of spectral indices, critical mass, relative abundance of delayed neutrons, the inversion point of the isothermal reactivity coefficient and burnable poison are considered the most important experiments. Current experiments at IPEN/MB-01 reactor are also commented.

KEYWORDS: spectral indices,* effective delayed neutron fraction*, isothermal reactivity coefficient, critical mass, Burnable Poisson, power density,* relative abundance of delayed neutrons, m*ethodology testing, nuclear data testing.

1. Introduction

Reactor physics experiments[1-4] have enjoyed a long history in the nuclear science and technology areas and constitute an essential tool for the reactor physicists in their task to validate calculational methodologies and related nuclear data libraries. For a long time, reactor physics experiments have been carried out worldwide and very valuable experimental data have been published to serve as benchmarks. The main type of reactor physics experiments belongs to the category of critical mass experiments and related spectral indices even though some very important reactor physics parameters such as the effective delayed neutron fraction (β_{eff}) and the relative abundance of delayed neutrons (β_i/β_{eff}) have been measured by specific experimental approaches. The basic principles of the reactor physics experiments are generally accepted, but minor differences in the detailed procedures are encountered in the various facilities. Probably, the most famous reactor physics experiments are the ones chosen by the CSEWG[1]. Numerous researchers[5] have assessed the adequacy of several nuclear data libraries by simulating the CSEWG benchmarks and several other experiments in a wide variety of situations.

During the last fourteen years several different kinds of reactor physics parameters were measured. For example, Buckling, spatial neutron flux distribution (thermal and fast) using activation foils and fission chambers, relative power density by gamma scanning of the fuel rods, shielding testing in the maximum power level, loading core with determination of mass critical and control rods criticality prevision, power calibration using gold foils, power calibration using noise analysis techniques, integral and differential reactivity of control rods, void reactivity coefficient, inversion point of the isothermal reactivity coefficient, effective delayed neutron fraction (β_{eff}), the relative abundance of delayed using noise analysis techniques , spectral indices using uranium foils and gamma spectrometry of fuel elements, out-of-core detector response experiment, burnable poison with gadolinium, among others.

2. Facility Description

The IPEN/MB-01 reactor is a zero power critical facility specially designed for measurement of a wide variety of reactor physics parameters to be used as benchmark experimental data for checking the calculational methodologies used to design a nuclear reactor and related nuclear data libraries commonly used in the field of reactor physics. The IPEN/MB-01 reactor reached its first criticality on November 9, 1988 and since then it has been utilized for basic reactor physics research and as an instructor laboratory system. This facility consists of a 28x26 rectangular array of UO_2 fuel rods 4.3% enriched and cladded by stainless steel (SS-304) inside a light water tank. The control banks are composed by 12 Ag-In-Cd rods and the safety banks by 12 B_4C rods. The pitch of the IPEN/MB-01 reactor was chosen to be close to the optimum moderator ratio (maximum k-∞). This feature favors the neutron thermal energy region events and at the same time provides the isothermal reactivity coefficient of the IPEN/MB-01 reactor core with an inversion point.

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* Ulysses d´Utra BITELLI, Tel. +55-11-3816-9430,
Researcher and Reactor Manager
Fax. +55-11-3816-9428, E-mail: ubitelli@ipen.br

Figure 1 shows the axial view of the IPEN/MB-01 reactor core with details of the fuel and control rods while Figure 2 shows its cross section view.

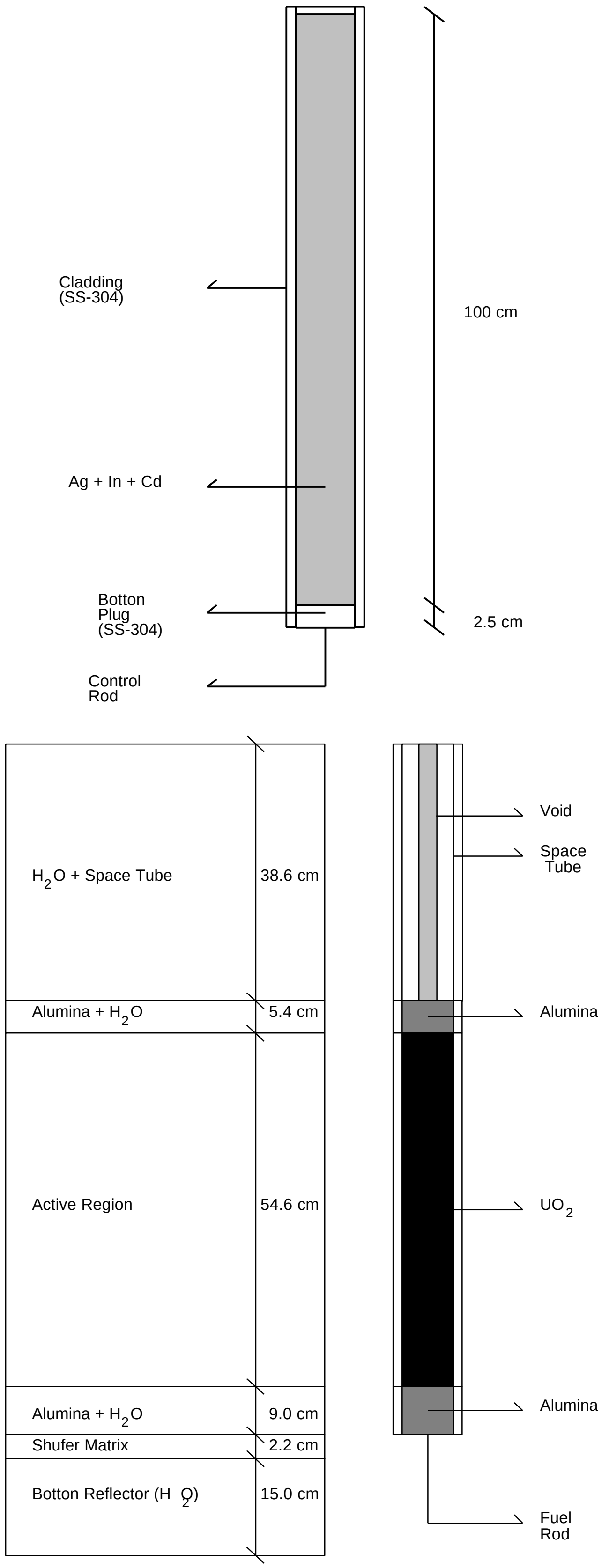

Fig. 1 Axial view of the IPEN/MB-01 core and details of the fuel and control rods.

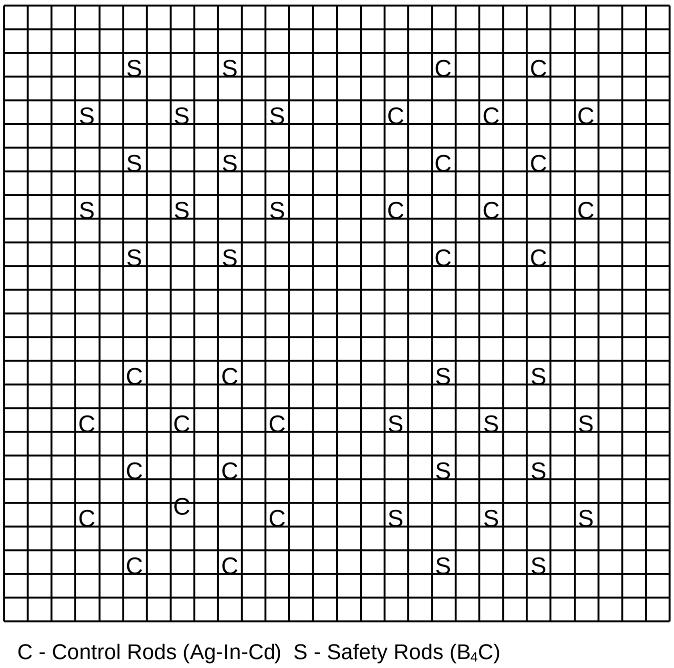

Fig. 2 Cross section of the IPEN/MB-01 core and details of the fuel and control rods.

The geometric data and the isotopic composition for the fuel and control rods are presented in Table I and Table II respectively.

Table I - Geometric Data for the Fuel and Control Rods

Active Region	
Fuel	UO_2
Pellet Diameter	0.849 cm
Cladding Outer Diameter	0.980 cm
Cladding Thickness	0.060 cm
Pitch (Square)	1.500 cm
Alumina Region	
Pellet Diameter	0.849 cm
Cladding Outer Diameter	0.980 cm
Cladding Thickness	0.060 cm
Spacer Tube Region	
Inner Diameter	0.730 cm
Outer Diameter	0.849 cm
Control Rod Data	
Absorber Material	Ag-In-Cd
Absorber Diameter	0.832 cm
Outer Cladding Diameter	0.980 cm
Cladding Thickness	0.060 cm
Guide Tube Outer Diameter*	1.200 cm
Guide Tube Thickness*	0.035 cm

(*) Also for the safety rod

The control bank at the upper right corner (see Figure 2) is named BC1 while the one at lower left corner is named BC2. The control/safety bank position is given in % withdrawn. The reference level or zero for the withdrawn position occurs when the bottom of the active absorber length (excluding the bottom plugs) is aligned with the bottom of the fuel region. The uppermost position (100 % withdrawn) is the top of the fuel region. During the reactor operation both of the safety banks are kept far away from the 135 % withdrawn position (35% above of the fuel region) and the control banks can both be withdrawn from the bottom of the fuel region but the fine criticality control is made with just one of them.

Table II- Isotopic Composition of the Fuel and Control Rods

Fuel Rod	**Concentration (atoms/barn-cm)**
U^{235}	1.00349E-03
U^{238}	2.17938E-02
O^{16}	4.55138E-02
Cladding, Guide Tube and Bottom Plug	
Fe	5.67582E-02
Ni	8.64435E-03
Cr	1.72649E-02
Mn^{55}	1.59898E-03
Si	3.34513E-04
Alumina Pellet	
Al	4.30049E-02
O^{16}	6.45074E-02
Control Rod	
Ag^{107}	2.35462E-02
Ag^{109}	2.18835E-02
In^{113}	3.42506E-04
In^{115}	7.65996E-03
Cd	2.72492E-03

3. Experimental Reactor Physics Parameters

This paper presents some of the most important reactor physics parameters measured at the IPEN/MB-01 reactor core such as critical mass, spectral indices, effective delayed neutron fraction, isothermal reactivity coefficient and burnable poison.

3.1 Determination of Critical Mass

The first criticality of the IPEN/MB-01 reactor occurred on November 9, 1988. The aim here is just to show the main steps of the approach [6] to critical experiments with emphasis on critical mass configuration. The IPEN/MB-01 loading pattern operation and its criticality approach[6] followed the safety criteria described by International Atomic Energy Agency. Several ex-core detectors were strategically positioned at the reflector region of the reactor to monitor the fuel loadind. For each them, a 1/M curve (M is the multiplication counts) was constructed from the sign acquired in each loading step. The loading procedure consisted initially of a sequence of ten steps. Each step is composed of a number of fuel rods, each with a specific location and always placed in a symmetrical position, given an even number of fuel rods per step. The eighth step corresponds to the critical configuration. Criticality was reached in the eighth step for a total of 564 ± 2 fuel rods (175,7± 0,6 Kg – UO_2), using the criterion that the system is critical when half of detectors plus one have indicated criticality. The final critical configuration is show in Fig. 3. Originally the eighth step consisted of 48 fuel rods with a total of 576 fuel rods in the core, but experimentally it was verified that criticality would be reached in this step.

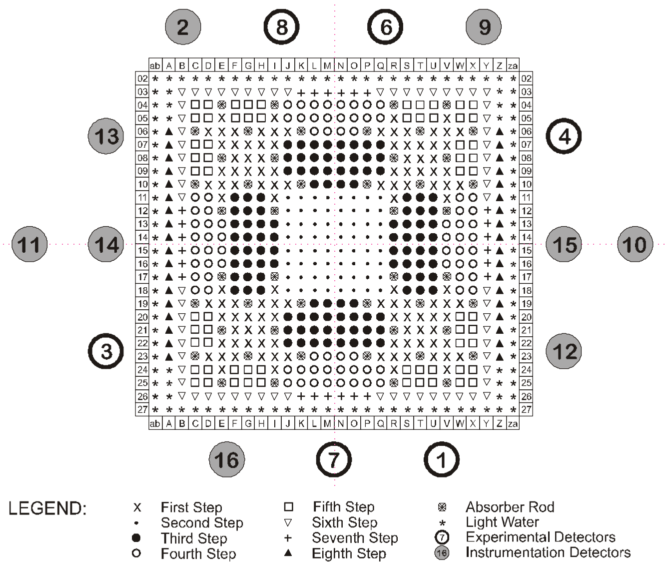

Fig. 3 IPEN/MB-01 Loading-pattern steps.

Therefore, this step was divided into sub steps with smaller number of fuel rods to attempt to determine the exact number of fuel rods in the core configuration for the critical mass.

The fig. 4 show the curve 1/M, where the multiplication factor M is a ratio between final counts and initial counts (M=Ci/C0) of the i-th step (i=1,2,…8). For each step loading the M is given by simple expression M = 1/ (1 - keff), where keff is the effective multiplication factor and when keff tends a unitary value the 1/M tends to zero. Thus 1/M zero means k_{eff}=1.0 and that the system will be critical.

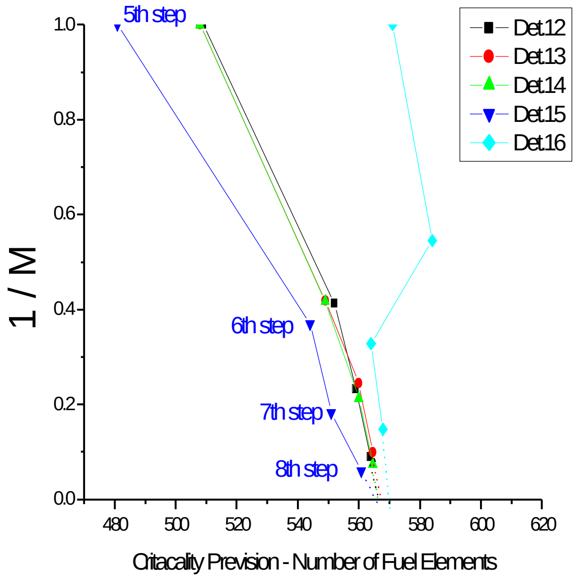

Fig. 4 Prevision of criticality – control rods withdrawn.

3.2 Determination of Spectral Indices

Experiments involving determination of the reaction rates in the fuel pellets are of fundamental importance to correlate theory and experiment mainly concerning calculation methods and related nuclear data libraries. These experiments are normally performed through the irradiation of bare and cadmium covered fertile and/or fissile foils. Typical examples are the spectral indices $^{28}\rho$ and $^{25}\delta$? , which provide the ratio of the epithermal to thermal neutron captures in ^{238}U and the ratio of the epithermal to thermal fission in ^{235}U respectively. For a long time, experiments involving reaction rate measurements have been carried out worldwide. The most famous spectral indices measurements are the ones performed in the TRX and BAPL critical facilities selected by the CSEWG [1] (Cross Section Evaluation Working Group) as benchmarks. Historically, there has been a long-standing problem related to the over prediction of the $^{28}\rho$ predicted by several nuclear data libraries[5]. Nowadays there has been a great progress in the calculation schemes so that the main uncertainty of the calculated reactor responses are mostly credited to the nuclear data used in the process. However, the effort placed in these areas has to be followed in the same level by experiments that have uncertainties lower than that inherent in the calculation methodologies. The available experimental support for $^{28}\rho$ possesses high uncertainties and makes use of approximated methods to take into account the cadmium perturbations. Aiming to contribute in these previous aspects.

The spectral indices $^{28}\rho$ and $^{25}\delta$ were determinate [7] using two different experimental techniques: gamma gamma spectrometry method employing a fuel rod scanning equipment with a collimator opening size of 1 cm.

This methodology for the measurements of spectral indices was compared to the commonly one used based on the uranium foils irradiations. It was considered depleted uranium foils (400 ppm) for the determination of $^{28}\rho$ (epithermal-to-thermal capture ratio) and enriched uranium foils (93.18%) for $^{25}\delta$ (epithermal-to-thermal fission rates).

For this purpose, bare and cadmium covered uranium foils were irradiated at the central region of the core using a dismountable fuel element. The uranium foils were also covered with aluminum foils to prevent the transference of the fission products from the surrounding fuel. A cadmium sleeve of 5 cm length was used to cover the dismountable fuel rods at thee uranium foil position. The procedure basically follows the same procedure as in case of the gamma spectrometry of fuel rods. The cadmium rate R_{cd} is obtained by determination of C8 (absolute reaction capture rate) and F5 (absolute fission at ^{235}U nuclide) that are given by [8]:

$$C8 = \frac{l_{Np} C_{Np} \exp(l_{.Np} t_e)}{f_{g\,Np} I_{Np} h_{Np} \left[1 - \exp(-l_{Np} t_i)\right]\left[(1 - \exp(-l_{Np} t_c)\right]} \qquad (1)$$

$$F = \frac{l_{Ce} C_{Ce} \exp(l_{Ce} t_e)}{Y_{Ce} f_{g\,Ce} ICeh_{Ce} \left[1 - \exp(-l_{Ce} t_i)\right]\left[(1 - \exp(-l_{Ce} t_c)\right]} \qquad (2)$$

$$F5 = F.F_{25} \qquad (3)$$

where λ_{Np} is the ^{239}Np decay constant; C_{Np}, $f_{\gamma Np}$, $I_{Np,}$ and η_{Np} are respectively the integral counts at the end of the irradiation, the fuel rod self-shielding factor, the gamma emission probability, the global counting efficiency, all for the ^{239}Np (product of capture reaction) photo peak located at 277.6 keV; t_e is the counting waiting time, t_i is the irradiation time; t_c is the counting time; λ_{Ce} is the ^{143}Ce decay constant; C_{Ce}, $f_{\gamma Ce}$,I_{Ce}, η_{Ce} are respectively the integral counts at the end of the irradiation; the self-shielding factor, the gamma emission probability; the global efficiency all for the ^{143}Ce (fission product) photo peak located at 293.3 keV; F_{25} is the ^{235}U relative fission density and Y_{Ce} is the effective fission yield of ^{143}Ce. Thus the spectral indices will be given by:

Finally the perturbed values of $^{28}\rho$ and $^{25}\delta$? are given by:

$$^{28}r = \frac{1}{^{28}R_{Cd} - 1} \qquad (4)$$

$$^{25}d = \frac{1}{^{25}R_{Cd} - 1} \qquad (5)$$

where $^{28}R_{Cd}$ and $^{25}R_{Cd}$ are given by:

$$^{28}R_{Cd} = \frac{(C8_{Np} / f_g)_{bar\,e}}{(C8_{Np} / f_g)_{Cd}} \qquad (6)$$

and

$$^{25}R_{Cd} = \frac{(F5_{Ce} / f_g)_{bar\,e}}{(F5_{Ce} / f_g)_{Cd}} \frac{Y_{cd}}{Y_{bar\,e}} \qquad (7)$$

The same way the spectral indices C8/F5 (Modified Conversion Factor), C8/F and $(C8/F)_{epith}$. were determined using the uranium foils (depleted and enriched) and fuel elements by gamma spectrometry using the expressions (1) and (2) . The cadmium perturbation was estimated by Monte Carlo code and depends of cadmium sleeves length and cadmium thickness and show that is minimum, when the cadmium length tends to zero and cadmium length to infinite to $^{28}\rho$ and $^{25}\delta$, respectively.

The table 3 shows the spectral indices measured at the rectangular core of the IPEN/MB-01 reactor.

These measurements introduces a novice approach for the determination of spectral indices $^{28}\rho$ and $^{25}\delta$ by means of a fuel rod gamma spectroscopy irradiated with and without cadmium sleeves. The results are consistent with traditional methodology based on irradiation of uranium foils. The methodology used to obtain the cadmium correction factor by the Monte Carlo MCNP-4B code is original and showed better agreement when the

ENDF/B-VI.5 library was used for the spectral index $^{28}\rho$. The same does not occur for the spectral index $^{25}\delta$, which shows very similar results for ENDF/B-V or ENDF/B-VI.5. The spectral indices C8/F5, C8/F and (C8/F)$_{epith.}$ could be measured with a high level of accuracy and in a general sense the ENDF/B-VI.5 shows better performance for all spectral indices of this work.

Table III Spectral indices measured at the rectangular core of the IPEN/MB-01 reactor

Spectral Index	Experimental Value	C/E (1)	C/E (2)
$^{28}\rho$	2.358±0.008	1.039±0.008	1.023±0.009
$^{25}\delta$	0.1215±0.001	1.064±0.007	1.035±0.008
$^{28}\rho^F$	2.358±0.025	1.039±0.013	1.023±0.013
$^{25}\delta^F$	0.1241±0.002	1.041±0.018	1.013±0.019
C8/F5	0.3206±0.003	1.030±0.010	1.024±0.012
C8/F	0.3124±0.003	1.015±0.008	1.009±0.011
(C8/F)$_{epith.}$	1.5520±0.005	*	0.977±0.014

(1) Calculated by MCNP-4 B using ENDF/B-V ;
(2) Calculated by MCNP-4B using ENDF/B-VI.5;
F – Using uranium foils;
* - Not calculated.

3.3 The inversion point of Isothermal Reactivity Coefficient

The inversion point [9] is by definition, the temperature where the isothermal reactivity coefficient becomes positive. Instead of heating the reactor system as usual in experiments considering temperature variations, the reactor system is cooled to $t_0 \approx 8.5$ °C. By means of a heating and cooling system, the temperature is allowed to increase slowly in a stepwise manner. For each step, the control bank critical position is recorded and by analysing its behaviour as a function of the temperature, the inversion is inferred. The final results experimental results are shown in Figure 5.

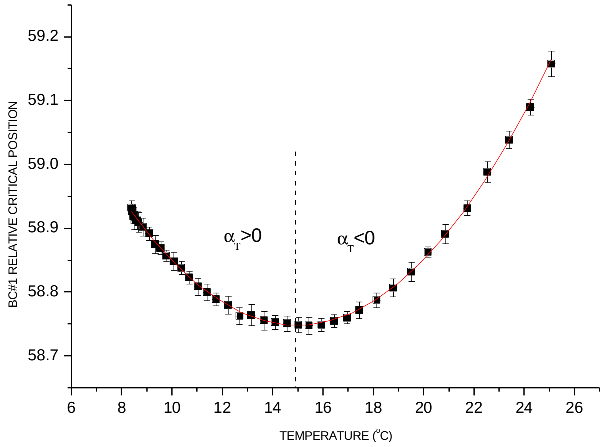

Fig. 5 The BC1 Control Bank Critical position as a function of temperature.

The excellent level of accuracy due mainly to the very precise characteristics of the control bank system of the IPEN/MB-01 reactor. Since the BC1 control bank critical position is considered of the most important parameters for the determination of the inversion point, a special system has been developed to acquire this experimental data. The true control rod critical position is rarely achieved. The automatic control system keeps continuously positioning the control bank around the true value. The Figure 6 shows the control bank position acquisition system used in the experiment.

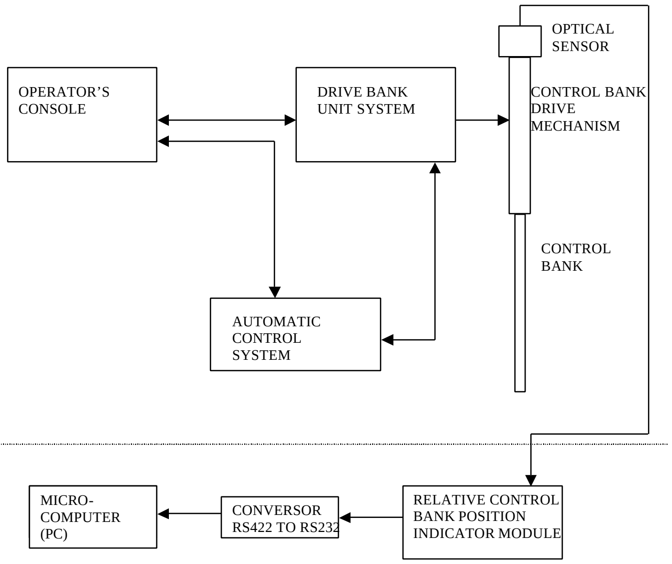

Fig. 6 Control Bank System.

The control bank system of the IPEN/MB-01 reactor is composed of an automatic control system, a driver bank unit system, a control bank drive mechanism, and a relative control bank position indicator module. The automatic control system achieves a fine control on the power level and on the criticality of the reactor by continuously monitoring the signals of a set of out-of-core detectors that are strategically positioned around the reactor core.

The automatic control system performs both of these tasks by continuously adjusting position of the control bank. The drive mechanisms are composed of a stepping motor with a mechanical reduction, which allows a very accuracy control bank position indicator. The relative control bank position indicator is constituted by an incremental optical encoder sensor coupled to the control bank drive mechanism and an intelligent module, with four digits of accuracy (in units of percent withdrawn). The module is connected to a micro-computer PC by means of an RS232 serial interface. Considering a specific critical state, the control bank position can be written in a computer file at a rate of one acquisition every 1 ms, making it possible to perform statistical analyses on this variable.

The control rod system of the IPEN/MB-01 reactor can be considered a high-resolution system, and its linearity has been demonstrated since the reactor start-up. Its response is the relative control bank position, which in conjunction with the reference level (bottom of fuel region) can constitute a very accuracy control rods position indicator. The zero of the relative control banks system occurs when the bottom of absorber rods (excluding the bottom plugs) is aligned with the bottom of the fuel region. This reference level or zero was calibrated by a mechanical pattern that allows an accuracy of 0.1 mm. In conclusion, the experiment has been successfully accomplished. The final value for the inversion point is 14.99 ± 0.15 °C and moreover, the control bank position during the reactor operation can be acquired with an excellent level of accuracy, what explain the excellent level of accuracy obtained in this experiment.

3.4 A Noise Analysis Approach for Measuring the Relative abundance of Delayed Neutrons.

There are several experimental ways to determine these delayed neutrons parameters and they are generally classified as “in-pile” and “out-of-pile” experiments [10]. The purpose here is to introduce a new in-pile experiment based on the measurement of the fluctuations of the neutron population. In this technique the Cross Power Spectral Density (CPSD) between the signals of two neutron detectors is measured in a very low frequency range and the result is least-square fitted assuming a point kinetic model. The parameters of the fit are β_i or λ_i.

This technique is interesting because it does not disturb the reactor, which is always maintained in a critical state, there is neither contamination of the results due to the harmonic excitation or residual multiplication and nor dependence on the efficiency and positioning of the detectors. The experiments were realized in the IPEN/MB-01 reactor [11] using a square configuration core.

The global dynamic behavior of a nuclear reactor can be described adequately using the point reactor model through the well known point kinetic equations.

Considering six groups of delayed neutrons and assuming that the neutron flux and the delayed neutron precursor concentration are composed of a steady part and a fluctuating part, the zero-power transfer function H can be obtained as :

$$H(f) = \frac{\Lambda}{i\omega\Lambda - \rho + \sum_{j=1}^{6} \frac{i\omega\beta_j}{i\omega + \lambda_j}} \qquad (8)$$

where $\omega = 2\pi f$ is the angular frequency and $i = \sqrt{-1}$.

Now a generic CPSD, which depends upon the electronics transfer functions, the detector currents and the reactor parameters, can be written as[11]:

$$\Phi_{nk} = 2D\frac{\gamma I_n I_k}{P\Lambda^2}\left|W(f)\right|^2\left|H(f)\right|^2 \qquad (9)$$

Where D = 0.795 is the Diven factor; γ = 3.2E-11 is the energy released per fission (in Joules); I_j is the current from detector j (n or k) in Amperes; P is the reactor power in Watts; W(f) is the transfer function of the associated electronics.

In order to obtain the experimental CPSD, the experimental setup was assembled as follow: two compensated ionization chambers CC54A from Merlin-Gerin operating in current mode, two Keitthley 614 electrometers to read and convert the currents from the CC54A chambers into voltage signals and two filter-amplifiers IPEN 036.ZZ (low frequency cut-off of 1.0 mHz) to cut off the DC component of the voltage signals and to amplify the AC component which is composed of the correlated and uncorrelated noise. The AC signals are then sent to the HP3562A dynamic signal analyzer (DSA) which has 800 frequency lines to perform the CPSD between the two signals. In making the CPSD the uncorrelated noise is eliminated or, at least, well minimized.

The transfer function of the electronic equipments can now be obtained. The electrometers do not alter the frequency of the signals from the ionization chambers since they just convert current into voltage. Thus, the transfer function of the electrometers is a constant given by:

$$E = \frac{2}{\text{electrometer scale}} \quad \frac{[\text{Volts}]}{[\text{Ampere}]} \qquad (10)$$

The number 2 above is the output voltage when the current reading is at the full scale of the electrometer.

On the other hand, the filter-amplifiers change the frequency composition of the signal since they cut off the DC component. However this occurs in a very low frequency (around 1.0 mHz) and for our purposes the transfer function of the filters can also be considered a constant given by the gain G of the filter-amplifiers. For the IPEN 036.ZZ, G = 1, 10, 30, 100, 300, 1000, 3000 and 10000.

With the transfer functions of the electronic equipment as given above the theoretical CPSD for the system reactor-detectors-electronics is:

$$\Phi_{nk} = 2D\frac{\gamma I_n I_k}{P\Lambda^2} E_n E_k \cdot G_n G_k \cdot \left|H(f)\right|^2 \qquad (11)$$

The experimental CPSD was obtained with the reactor as close to critical as possible and at a thermal power of 20 W. At this power level the average currents from the ionization chambers were $262\text{x}10^{-9}$A and $280\text{x}10^{-9}$A for the CC54A1 and CC54A2 respectively. With the electrometers scales in $2000\text{x}10^{-9}$ A their respective transfer functions are E_n=E_k= $2/2000\text{x}10^{-9}$ = $1.0\text{x}10^{6}$ V/A. The gain of the filter-amplifiers was set to 30 so G_n=G_k=30. The HP3562A DSA was set as follow: differential input mode, DC coupling, Hanning windowing, linear average and linear resolution.

In the course of the data acquisition, the control rods were “frozen” in order to avoid the interference of its movement in the low frequency region. Eventually the power level may begin to change and in this case, the data acquisition is stopped and the power is restored either manually or with one of the control rods returning to the automatic mode. The core configuration of the IPEN/MB-01 reactor has also been changed to get a lower reactivity (26x26 square array) and consequently a better manual control over the rod that correct the power. Two neutron detectors have been located out-of-core at reflectors region in front of north and south face of the core.

The data acquisition by the dynamic signal analyzer was done in 5 frequency intervals in order to obtain the entire CPSD including the plateau. In the plateau region ($\omega >> \lambda_i$) one can obtain the absolute power of the reactor but it is not the interest of this work. The signals have been acquired up to the plateau and beyond that only for illustration purposes. The five steps of data acquisition were: 0 to 0.640 Hz ,.0 to 2.0 Hz , 0.640 to 16.64 Hz , 16.64 to 32.64 Hz , and 16.64 to 56.64 Hz . In all acquisitions the experimental conditions were identical and it was performed 200 averages.

Figure 7 shows that the plateau is in the interval 1.0 to 10 Hz approximately and the region of interest for the present work is about 0.0048 to 5.0 Hz because it is the region where the delayed neutrons dominate the CPSD; i.e , $\omega << \lambda_i$. This experimental CPSD was fitted assuming the theoretical CPSD given by Equation (5). The fitting parameters are β_i and λ_i .

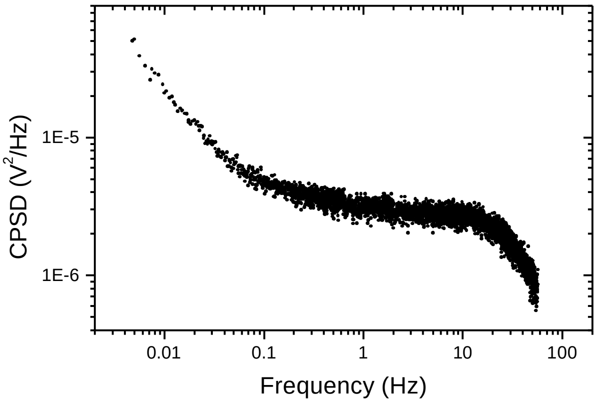

Fig. 7 Experimental CPSD containing 4442 data points and 200 averages obtained with all the five frequency interval .

This experimental work introduces a novice approach for the determination of the decay constants and the relative abundance of the delayed neutrons. The experimental procedure consists in obtaining the CPSD from the signals of two compensated ionization chambers in the frequency range from 0.005 to 5.0 Hz approximately. Assuming the point kinetic model, the theoretical expression for the CPSD can be written and the experimental CPSD can be fitted employing a least-square approach. The fitting parameters are β_i and λ_i. The least-square approach was able to fit all the betas for a six group model. However, it was not possible to fit the first decay constant (the group of longest half-live) accurately although the other five were achieved. The analysis reveals that the relative abundances of ENDF/B-IV and –VI are in a fair good agreement (see Table IV and V) and that it is not only possible to perform successfully such measurements but also the decay constants and the relative abundance can be measured with a very good level of accuracy. ENDF/B-VI heavily underestimates the reactivity for small negative periods because its first decay constant is overestimated.

Table IV Results of Least-Squares Fit.

Exp-1 (λ's from ENDF/B-VI)	Exp-2 (λ's from ENDF/B-IV)
0.0333 ±0.0007	0.0365 ±0.0006
0.1993 ±0.0045	0.1880 ±0.0036
0.2357 ±0.0091	0.2320 ±0.0077
0.3490 ±0.0142	0.3528 ±0.0106
0.0022 ±0.0116	0.0492 ±0.0092
0.1806 ±0.0073	0.1415 ±0.0066

Table V Comparisons of the calculated relative abundances with the in-pile experiments.

ENDF/B-VI C/Exp-1	ENDF/B-IV C/Exp-2
0.9969	0.9890
0.8886	1.0760
0.7344	0.8038
1.1031	1.1544
74.7727	2.7886
0.3709	0.2155

3.5 Burnable Poison Experiments

Most of the PWR reactors are loaded with some burnable poison pins in the fresh fuel assembly. The effectivity of burnable poison in terms of reactivity is an important parameter to be considered in a fuel design among others. A burnable poison experiment at IPEN/MB-01 reactor [12] was conducted in order to check the loss of reactivity due to the burnup. Several pins with different burnable poison concentrations were fabricated to simulate the depletion of burnable nuclide. The Al_2O_3-B_4C burnable poison with five different ^{10}B concentrations was selected to be the first set of measurement. The concentrations of ^{10}B in the Al_2O_3-B_4C pellets were 11.20, 10.30, 7.40, 5.01 and 2.54 g/cm^3. Initially, the burnable poison pins were inserted at two different regions of the reactor core, one at center of the reactor core and other around of control rod. At the central region, five burnable poison pins were symmetrically positioned and nine burnable poison pins positioned close to the control rods.

A different core parameters were measured for these two configurations: control rods worth, reactivity, radial and axial flux profile for thermal and fast neutron, void and temperature reactivity coefficients. The measured and calculated reactivity of Al_2O_3-B_4C with 5.01g/cm^3 of ^{10}B is shown in the Table VI.

Table VI Measured and Calculated Reactivity per Burnable Poison Pin.

Case	Calculated reactivity per pin (pcm)	Measured reactivity per pin (pcm)	Difference (%)
Nine pins around	175	179±11	-0,2

control rod			
five pins at center	324	339±5	-4,4

As can be seem in Table VI, the calculated and measured values are in good agreement. The presence of burnable poison around the control rod will reduce the effectiveness, an effect knowing as shadowing. Figure 8 shows a differential control rod worth with and without burnable poison. The shadowing effect can significantly reduce the control rod worth.

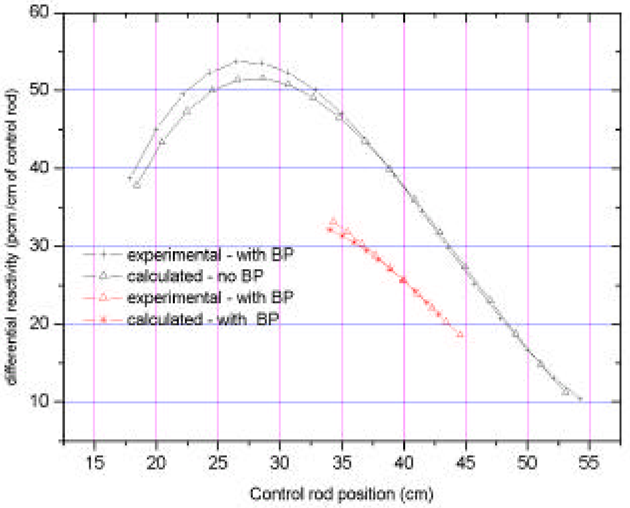

Fig. 8 Shadowing of control rod due to the presence of burnable poison pins around the control rod

4. Current Experiments

Actually there are four different kinds of experiments at IPEN/MB-01 reactor: Absolute power density, Relative abundance of delayed neutrons by a Multiple Transient technique[10], Burnable Poison (different gadolinium enrichment) and spectral indices using uranium foils with diameter smaller than that of fuel pellets.

The absolute power density of the IPEN/MB-01 is measured by irradiation of fuel rods and the counts of ^{143}Ce (fission product) by a high pure germanium detector. The total number of fission in the fuel elements is obtained by irradiation of enriched uranium foil inside the fuel element and subsequent determination of its absolute activity. Since the yield of fission to ^{143}Ce is about 6%, then is possible to obtain the absolute fission rate at foil and to correlate this parameter with absolute fission at the same fuel rod position.

The spectral indices measurements using uranium depleted foils with diameter smaller than uranium fuel pellet is very interesting experiment and very important to available uranium-238 spatial shelf shielding effect.

Finally the experiment to determine the relative abundances of delayed neutrons using a different technique than noise analysis is the multiple transient[10] technique. This experimental methodology consists to remove a small cadmium target very quickly of the core reactor introducing a small step of positive reactivity. The measurements of relative abundances of the delayed neutrons by multiple transient technique is based on a least-square fitting technique that simultaneously fits a series of transients produces by small reactivity perturbation to a reactor operating at critical condition. The function that is least-squares fits is the analytic solution as obtained by the point kinetic model for the reactor response following a step change in positive reactivity.

5. CONCLUSIONS

The IPEN/MB-01 reactor has been utilized since 1988 for measurement of a variety of reactor physics parameters to be used as benchmark experimental data for checking the calculational methodologies and related nuclear data libraries used to design nuclear reactors. The results are very useful, thus for example the critical mass prevision that was different in 700 pcm initially (the difference of reactivity between experimental and calculational results), with the experiment was possible decrease to 180 pcm only, using appropriated nuclear data library and calculational methodology. The isothermal reactivity experiment [9] is now under compilation to be sent to NEA Data Bank under the IRPhE (International Reactor Physics Experiment Project).

That will be a very good opportunity to share our experimental results to the international community.

There are a lot of studies and ideas about future experimental utilization of the facility, how a new core of smaller distance (pitch) between fuel rods (hardest spectrum neutron) and utilization like an ADS (Accelerated Driven System) using a neutron accelerator (reactivity source) near of the core.

The IPEN/MB-01 reactor is disposable to international cooperation among experimental groups interested to obtain a wide variety of reactor physics parameters to be used as benchmark experimental data .

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