MAIN EXPERIMENTS PERFORMED AT THE IPEN/MB-01 RR USING UO2 FUEL RODS CORE

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Abstract. This paper aims to show the main experimental utilization of the IPEN/MB-01 zero power reactor during the last 30 years with 3663 operations cycles. The IPEN/MB-01 reactor it was mainly used to validation of calculation methodology used in nuclear reactor cores design.
Key Words: Nuclear Reaction Rate, Neutron Flux, Noise Analysis, Reactivity

1. INTRODUCTION

The Reactor physics experiments 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 calculation 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 [1-3].

The IPEN/MB-01 reactor (https://www.ipen.br/portal_por/portal/interna.php?secao_id=723) is a zero power reactor (100 watts maximum power level) specially designed for measurements of a wide variety of reactor physics parameters [3].The first core of the IPEN/MB-01 used a total of 680 UO2 fuel rods being two Ag-In-Cd control rods and two B4C safety rods. This core was decommissioned after 30 years (1988-2018) . The experiments made can be divided in two large groups: one group to obtain nuclear parameters of interest to the reactor physics analysis by the measurement of nuclear reaction rates induced in nuclear irradiation of fuel pellets or activation detectors in the neutronic field. The second set of experiments were designed to obtain kinetic parameters of the reactor physics through the response of real time neutron detectors obtained by inserting positive or negative reactivity in the core .1

2. COMMISSIONING EXPERIMENTS

This section describes the experiments to commissioning the first reactor core using UO2 fuel and array 28x26 fuel rods (rectangular standard core). Basically, there were five experiments: Determination of critical mass, initial criticality, calibration of control rods, and calibration of power nuclear channels and measurement of isothermal reactivity coefficient. These experiments were done in 1988 and 1989

2.1. Determination of Critical Mass

The aim here is just to show the main steps of the approach to critical experiments with emphasis on critical mass configuration. The IPEN/MB-01 loading operation standard and its criticality approach [4,5] followed the safety criteria described by IAEA. Several ex-core detectors were strategically positioned around the core at reflector region to monitor the fuel

loading. For each neutron detector a 1/M curve (1/M is the inverse of the neutron multiplication) was constructed from de signal acquired in each loading step (detectors counting) . The loading procedure consisted initially of a sequence of ten steps. Each steps is composed of a number of fuel rods at an specific location inside of the core. The fuel rods were placed in a symmetrical position, given an even number them per step. The eighth step loading corresponds to the critical core configuration. The criticality was reached in the eighth step for a total of (564 ± 2) fuel rods ,(175.7± 0.6) kg of UO_2 and (6.67 ± 0.02) kg of ^{235}U using the criterion that the system is critical when half of detectors more one have indicated criticality (the curve 1/M tends to zero) . The final critical configuration is showed in FIG. 1 .

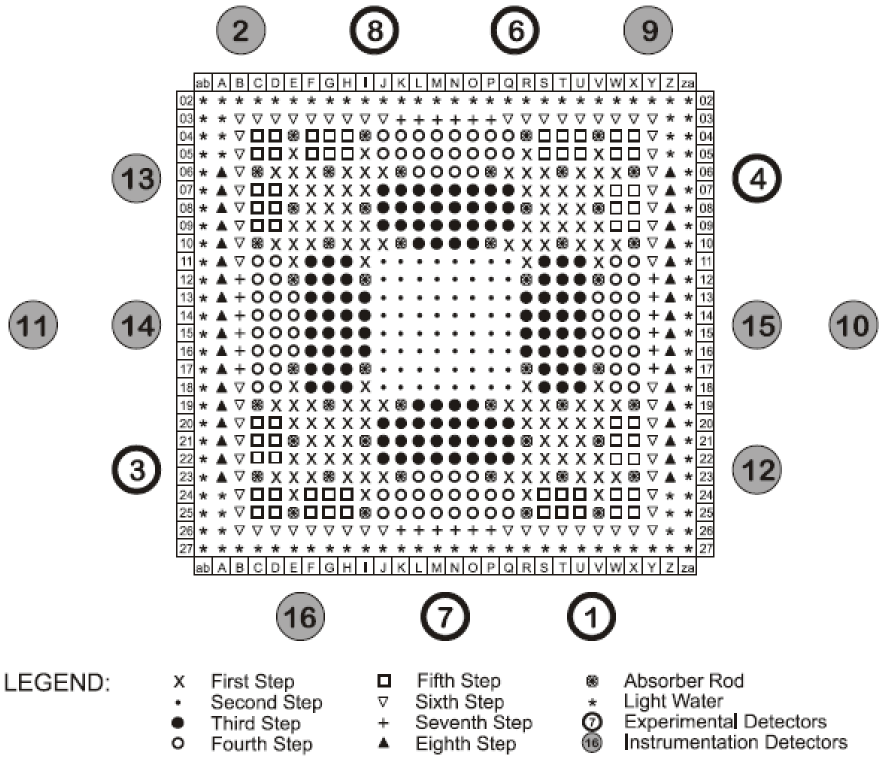

FIG. 1.- Steps of Loading of UO_2 fuel rods of the first core of IPEN/MB-01 reactor.[4,5].

Calculations using the HAMMER-CITATION code showed an underestimation in relation to the experimental value of 5% in the critical mass value, causing an uncertainty in the criticality of 0.7% .

2.2. Initial Criticality: Prevision of Criticality with Control Rods

Initially with 680 fuel rods and the safety and control rods inside in the core it was started the prevision of criticality (initial Criticality) with control rods .The initial criticality was obtained on 9th November 1988 at 15:35 p.m. For this experimental purpose there were made three withdrawn control rods steps. The curve 1/M was used to estimate the preview the critical position, but in this case the multiplication factors M were obtained when a small withdraws of control rods is made and a small positive reactivity is introduced in the system increasing the nuclear channels counting. After 3 steps of control rod BC#2 positions (15, 20 and 25 cm) with the control rod Nº 1 (BC#1) totally withdrawned out the core (54.6 cm) , extrapolating the curve 1/M to zero (M infinite) was obtained the criticality position to control rods Nº 2 (BC#2) outside the core was 18.7 cm (34,3 % withdrawn of the core). The critical control initially with 680 fuel rods and all rods inside in the core it was started the prevision of criticality (initial Criticality) with the control rods. For this purpose 3 withdrawals were made from the control bars. The curve 1/M was used to estimate the preview the critical position, but in this case the multiplication factors M were obtained when a small withdraws of control rods was made and a small positive reactivity was introduced increasing the nuclear channels counting. After 3 steps of control rod BC#2 positions (15, 20 and 25 cm) with the control rod Nº 1 (BC#1) totally withdrawal out the core (54.6 cm) , extrapolating the curve 1/M to zero (M infinite) was obtained the criticality position to control rod Nº 2 (BC#2) of 18.7 cm (34,3 % withdrawn of the core).

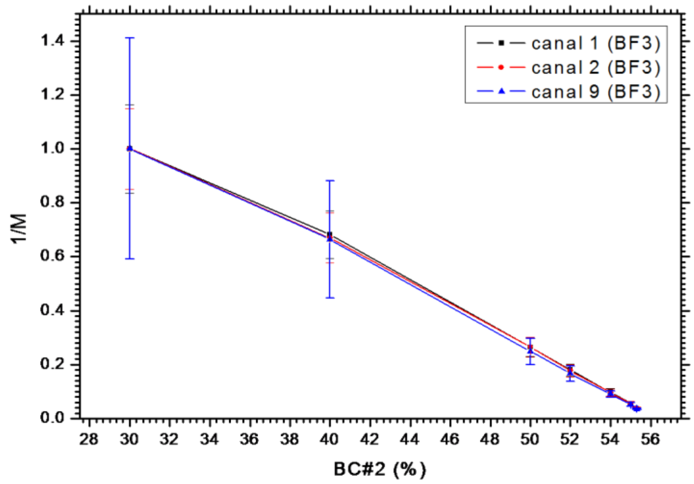

FIG. 2.- Curve 1/M to Prevision of Critical Position of the control rods (BC#1=BC#2) [4,5].

2.3. Control Rods Calibration

The control rods calibration was made to know which reactivity value is introduced in the system when is withdrawn or inserted a small step of control rods in the reactor core [6]. For this purpose were used the experimental methodology by the stable period technique . Thus to measure using stable period a small step of control rods is withdrawn and after wait a time to stabilize de period of increasing of neutron population (decay neutron fluxes harmonics) given by nuclear channels (neutron detectors) are measured the time that neutron population doble (doubled neutron flux). Measured the doubling time then is possible to measure the period of increasing of the neutron flux and consequently to obtain the differential reactivity through inhour equation (The kinetic parameters initially calculated and after some years confirmed experimentally by noise analysis technique) . This way were adjust a Boltzmann curve about the experimental values of differential reactivity versus control rods position obtaining the calibration curve to control rods BC1 and BC2 . Thus is possible to know for each control rods inserted or withdrawn the reactivity introduced in the system and if each differential reactivity value were summed the results will be the integral reactivity of the control rods when them are introduced instantly by gravity inside of the core. These measured confirmed that an unique control rod introduce a negative reactivity value (BC#2:-3231.0 ± 12.1 pcm) enough to shutdown the reactor because introduce more negative reactivity than excess reactivity of the core (2457 pcm).

2.4. Nuclear Power Calibration

The power calibration was made at nuclear channels number 5 and number 6 through gold foils irradiation inside the core of the reactor. Thus were irradiated 210 pure gold foils in the same experimental conditions (power level, control rods in the same positions, etc) with half them with cadmium covered and bare half (without cadmium covered). The induced radioactivity in the irradiated gold foils is directly proportional to the flux of thermal neutrons at the irradiation site. Thus, after an analysis of the spatial distribution of neutron fluxes obtained at each gold foils position inside the core it was possible to obtain the average thermal neutron in the core for a given electric current value given by the nuclear channels Nº 5 and 6 of the reactor. The power generated at the reactor core is directly proportional to the mean Thermal neutron flux. It is these nuclear channels, current-type detectors (ionization chambers) that have their current values correlated to the power of the reactor. The gold foils irradiations were made at several power levels and were obtained various levels of electrical current from the nuclear channels. Thus a power calibration was obtained to nuclear channels. Initially in 1988 the reactor power was unknown thus it was estimated from the calculation performed with the CITATION code that calculated the neutron flux along the active region of the neutron detectors (ionization chambers) that made up the nuclear channels No. 5 and 6. The sensibilities of these detectors were known. Their counts were estimated and their responses correlated with average reactor operating power estimated by the code, this way estimating the reactor's operating power how a first approximation .Thus at 4 watts power estimated by CITATION code were made the gold foils irradiation. After analysis of experimental data was obtained the real operational power level of (2.76 ± 6%) watts in the electrical current level of 0.19.10-7 A and 0.21.10-7 A to nuclear channels Nº 5 and 6, respectively. The mean thermal neutron flux at this power level obtained by gold foils irradiated in the reactor core was of (1.32 ± 0.23).107 n/cm2.s, thus the extrapolated value will be of (4.78± 0.82).108 n/cm2.s at 100 watts (maximum power level). After 20 years the experiment was made again [7] , but now using infinitely diluted gold foils (1% Au-99%Al) that avoid neutron flux perturbation and the calibration equation to Nuclear Channel obtained was given by following equation , P6 (watts) = (1.3917±0.0128).107.I, where I is the electric current level of the linear nuclear channel nº 6 (ionization chamber).

2.5. Measurement of Isothermal Reactivity Coefficient

The isothermal reactivity coefficient [8] is the most important parameter of the reactor physics of the safety analysis because its experimental determination ensures that if there is an uncontrolled power excursion the reactor will be able to auto shutdown without operator action, thus ensuring the not release of fission products in the installation or the environment..

The isothermal reactivity coefficient was obtained in the system temperature range (moderator and fuel) between 20 ºC and 90 ºC. Two techniques were used, the stable period technique and the inverse kinetics technique, using a reactivity meter. The mean values obtained were (-3.75 ± 0.40) pcm / ºc between 20º and 30 ºC and (-15.15 ± 1.35) pcm / ºC between 20 ºC and 90 ºC (mean value between the two experimental techniques).

The experimental procedure consisted of critical the reactor at 0.276 watts and stabilizing it in automatic control with the two control bars equally inserted (58.7%). The next step by removing the automatic control from the BC # 2 control rod was to gradually raise the moderator temperature in steps of 5 ° C through existing electrical resistances for that purpose. Thus, the reactor stayed subcritical at values close to 100 pcm measured after the temperature stabilization indicated by the thermocouple positioned at half height of the core by the two experimental techniques mentioned and the criticality was reached again after the automatic control was turned back on. These measurements were performed from 20º C until 90ºC, obtaining the previously mentioned values of the isothermal reactivity coefficient.

3. MAIN EXPERIMENTS OF THE FIRST 15 YEARS

During the first fifteen years several different kinds of reactor physics parameters were measured [8] besides experiments made for reactor commissioning. Thus for example, measure of neutron flux curvature (Buckling) , spatial neutron flux distribution (thermal and fast neutrons) and neutron spectrum using activation foils and fission chambers, relative power density by gamma scanning of the fuel rods, shielding testing in the maximum power level, power calibration using noise analysis techniques, void reactivity coefficient, inversion point of the isothermal reactivity coefficient α_T (see Figure 3) , effective delayed neutron fraction (β effective), the relative abundance of delayed neutrons using noise analysis techniques , spectral indices using uranium foils and gamma spectrometry of fuel elements, burnable poison with gadolinium, among others. The table 1 show the main experiments performed between the years 1988 until 2003 with containing UO_2 fuel rods core.

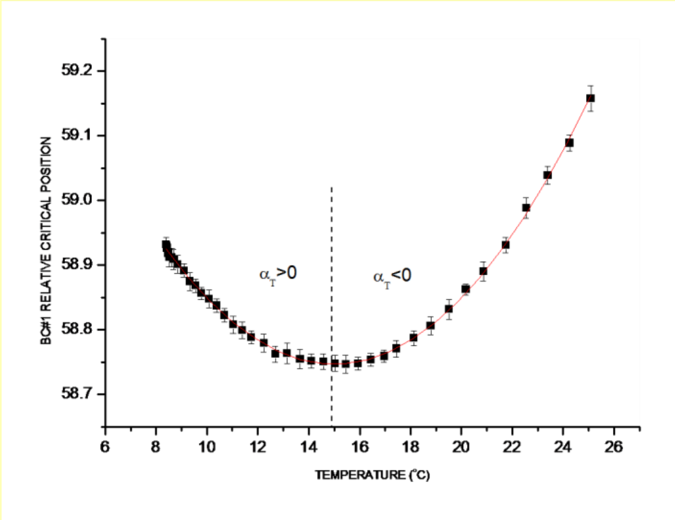

FIG. 3.- Inversion point of the isothermal reactivity coefficient α_T[9]

Experiments	Experimental Techniques
Buckling, Thermal and Fast neutron flux distribution	- Activation Foils (Au and In) and Fission chambers
Relative and Absolute power density	- Gamma Scanning of fuel rods
Spectral indices	- Uranium foils and fuel rods gamma espectrometry
Power calibration	- Activation Foils (Au) - Noise Analysis
Reactivity Coefficient: Void and Isothermal	-Difference between steps rods (Position) without and with void or difference level of temperature (ΔT)
Relative abundance of delay neutrons	- Noise Analysis
Out off-core detector response and burnable poisson	- Neutron Flux distribution (Foils) and Difference between steps control rods without and with perturbation.

Table 1- Main Experiments and its techniques performed at period of 1988 until 2003.

3.6. Main Experiments in the Last 15 years

During the last 15 years several experiments more sophisticated were performed such as determination of the decay constant and relative abundances of delayed neutrons by noise analysis techniques [10] , absolute measurement of $\beta_{effective}$, Λ, $\beta_{effective}/\Lambda$, kinetic parameters using the neutron noise analysis technique [10,11], measurements of kinetic parameters with the reactor in subcritical condition using different subcritical core configurations , measuring the subcritical reactivity using appropriated reactivity meter specially developed for this purpose (https://www.teses.usp.br/teses/disponiveis/85/85133/tde-29012018-104857/publico/2017PintoDesenvolvimento.pdf) , experiments using special reflectors (carbon steel, stainless steel and nickel) to measure critical positions of the control rods and reactivity introduced into the system by each of these reflectors , experimental determination of the main reactor physics parameters using heavy water reflector [12] .

Experiments of measurements of nuclear reaction rates were performed always by irradiation in the core of activation detectors (foil or wires) for several reactor core configurations (cylindrical, rectangular or square) and using neutron flux trap in the core through removing fuel rods to increase the thermal neutron flux inside these regions . An interesting experiments was made using a box with heavy and other with light water positioned in the center of the core and measure the reactivity introduced in the system, spatial neutron flux distribution using gold activation foils positioned inside and around the box with light and heavy water [13]. Too were measures the neutron spectrum using different kinds of activation foils inside the neutron flux traps [14] at several reactor core configurations and appropriated code to unfolding spectrum analysis (Sandbp code). Other important experiments were to measure spectral indices through gamma spectrometry of fuel rods irradiated . Another way is to measure the nuclear fission and radioactive capture reaction rate induced after irradiation of fuel pellets of fuel rods dismountable after their irradiation though gamma spectrometry. The table 2 show the main experiments performed between the years 2003 until 2018 with UO2 fuel rods core. The Fig. 4 show the energetic distribution of neutron energy measured at neutron flux trap created in the center region of the cylindrical core configuration of 26 per 26 fuel rods [14].

Experiments	Experimental Techniques
Decay constants and Relative Abundance of Delayed Neutrons	Neutron Noise Analysis
Neutron Spectrum Measurements and Neutron Flux Distribution	-Activation Foils (Sc, Au , U, In, Ni, Ti, Al, Mg); - Activation Foils (Au- gold Foils)
Measurements of Spectral Indices	-Gamma Spectrometry by Scanning of fuel rods; - Gamma Spectrometry of UO2 Pellets .
Power calibration for different core configuration	-Activation Foils (gold foils); - Noise Analysis .
Absolute Measurement of kinetic parameters β effective , Λ and β effective / Λ	- Noise Analysis.
Thermal neutron flux and Neutron Spectrum inside Neutron Flux Trap and experimental Fuel rods ;	- Activation Foils (gold foils); - Activation Foils (Sc, Au , U, In, Ni, Ti, Al, Mg);
Measurents of Reactivity System with Different kinds of Reflectors	-Critical Position of the rods; -Inverse Kinetics Technique (reactivity meter).
Kinetic Parameters for Different Subcritical Core Configuration	Special Subcritical reactivity Meter ; Neutron Noise Analysis .

Table 2- Main Experiments and its techniques performed at period of 2003 - 2018.

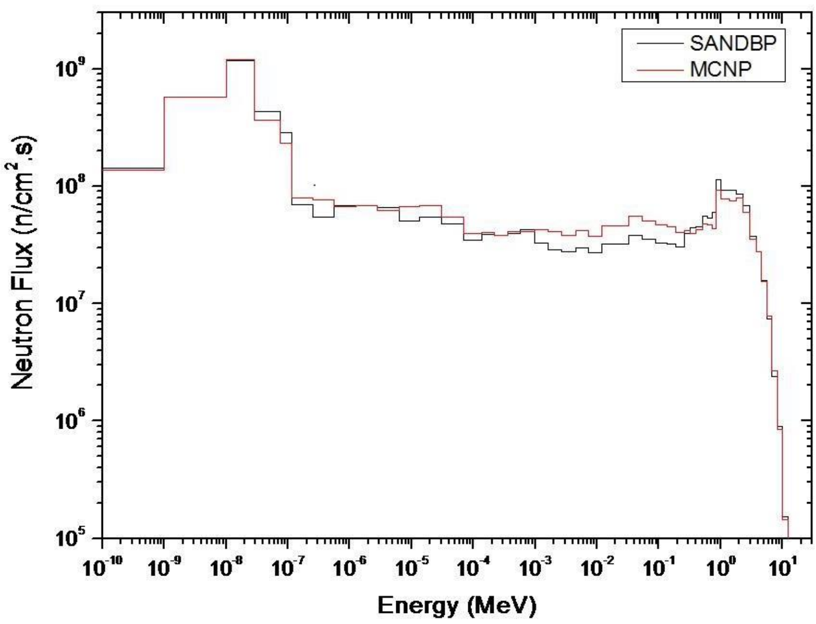

FIG.5 – Neutron spectrum adjusted by the unfolding Sandbp code by irradiation of different activation foils at neutron flux trap assembled in the center of the core cylindrical configuration [14].

The spatial distribution of the thermal neutron flux measured in the center position of the neutral flux trap [15] through irradiation of gold activation foils with and without cadmium cover and the comparison with the main computational codes used by the IPEN reactor physics group is presented in Fig. 6.

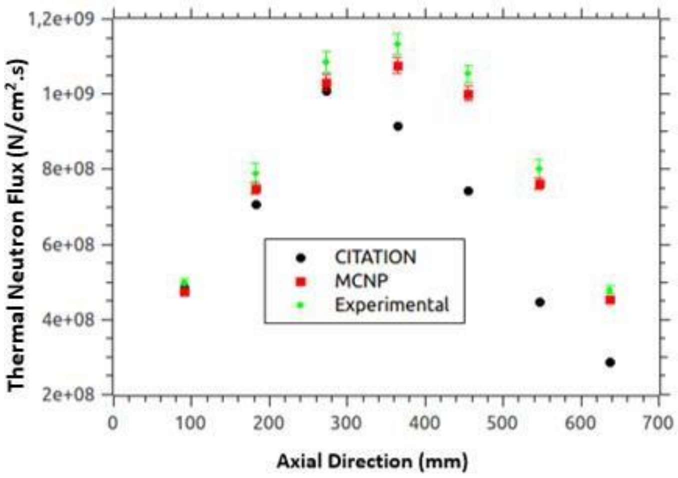

FIG. 6 - Thermal Neutron Flux in the Center position of the UO_2 Fuel Rod Core [15].

4. CONCLUSION

After 30 years the core of the UO_2 fuel rods has been decommissioned (2018) with over 3663 operations, 80% of them dedicated to experiments, 15% to operator training and retraining, graduate and undergraduate courses and 5% to operational adjustments. . The experiments with this core were considered a reference for the NEA / NSC criticality analysis, given the high quality of the experiments performed. Besides it was possible to conduct several courses acting strongly in the formation of students and nuclear researchers. Now begins a new phase with the installation of a new core containing plate-type fuel elements that will allow the accomplishment of several experiments aiming to validate the calculation methodology used in the design of the Brazilian Multipurpose Reactor (https://www.kernd.eu/kernd-wAssets/docs/fachzeitschrift-atw/2015/atw2015_01_perotta_brazilian_research_reactor.pdf).

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