Monte Carlo Simulation of Critical Mass Experiment in the IPEN/MB-01 Reactor

Hélio Yoriyaz, Adimir dos Santos, Roberto Cabezas Solorzano
*Instituto de Pesquisas Energéticas e Nucleares – **IPEN/CNEN-SP***
Travessa R-400 Cidade Universitária, São Paulo Brazil
yoriyaz@net.ipen.br; asantos@net.ipen.br; rjsolor@net.ipen.br

Abstract

A Monte Carlo analysis has been employed to calculate the 1/M curve of the critical mass configuration of the IPEN/MB-01 reactor. For this purpose, MCNP-4B code has been used to simulate the several steps of the experiment. The proposed approach will not consider any kind of reaction rate in the detectors. The basic calculated parameter is the volume integrated neutron flux at the detector's location considering the volume occupied by the detectors filled with water. The nuclear data library needed for the MCNP-4B analysis came from ENDF/B-IV for all nuclides but ^{238}U which was obtained from JENDL-2.2. The NJOY 94.61 was assumed to provide all the nuclear data needed for MCNP-4B. Generally speaking, the 1/M curves obtained with MCNP-4B considering the proposed approach are in a rather good agreement with the experimental points and let us to obtain a good prediction of the critical mass of the system.

1 Introduction

The procedure of the start-up of a reactor relies mainly on the signals of a set of out-of-core detectors strategically positioned at the shielding zone of the facility. During the design of the reactor the information about the best out-of-core detector positions are obtained by calculational methodologies which may receive eventual support of experimental benchmarks. Among the several methods (Rhoades, 1991; Briesmeister, 1993; Crump, 1982) that could be used for this purpose, the Monte Carlo method is the one that offers the best solution for neutron transport problem in the system mainly if one considers the recent computer technology development.

The purposes of this work are twofold: a) To calculate the 1/M value as a ratio of the volume integrated neutron flux in the volume occupied by each out-of-core detector of the IPEN/MB-01 reactor using the MCNP-4B code (Briesmeister, 1997) and; b) to compare the MCNP-4B results with the available experimental results for the first criticality of the IPEN/MB-01 reactor. This reactor is a critical facility located at the Instituto de Pesquisas Energéticas e Nucleares in São Paulo and it has been used for basic reactor physics research and also for student training and instruction. Its core consists of a rectangular array of 28 x 26 positions with a total of 680 fuel rods, moderated and reflected by light water and controlled by two sets of control banks diagonally placed. The complete description of the core configuration, fuel rods, control rods and so forth can be found on reference (Santos, 1998).

The MCNP-4B calculations consider a very detailed description of the fuel rods, the neutron source, the reflector regions, and the guided tubes for the several steps of the IPEN/MB-01 approach to critical configuration.

2 Fuel Loading Pattern

The first criticality of the IPEN/MB-01 reactor occurred in November 9, 1988. Its loading pattern operation and the criticality approach followed the safety criteria described by IAEA (Cox, 1971). The loading procedure consisted initially of a sequence of 10 steps. Figure 1 shows steps one through eight. Each step is constituted by a number of fuel rods, each of which with specific location and always placed in symmetrical position given an even number of fuel rods for step. The eighth step corresponds to the critical configuration.

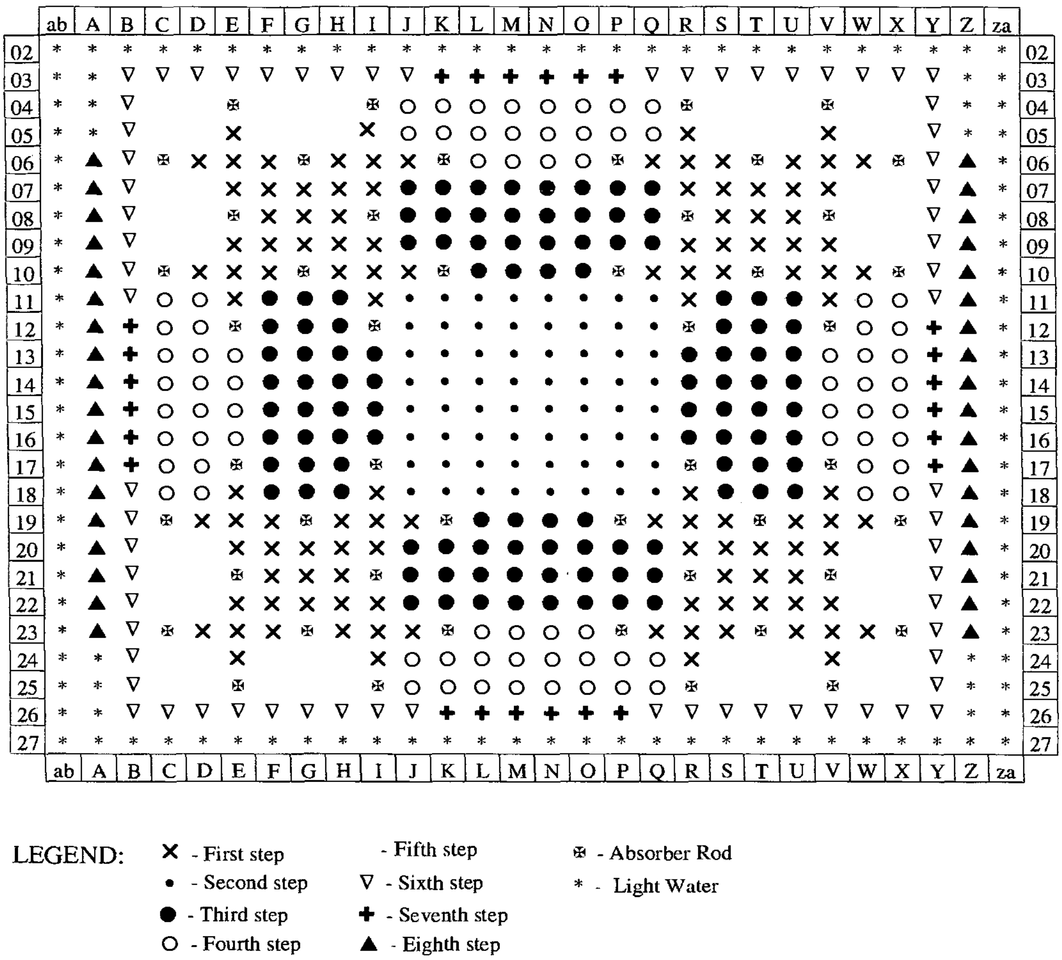

Figure 1. Loading Pattern Steps

The fuel rod locations are also strategically set adding a small amount of reactivity in the system and at the same time allowing the control and safety rods to be effective as much as possible. During the loading operation, all the absorber rods (control and safety) are introduced into the core with the moderator tank empty. At the end of the loading step the safety rods are removed and the moderator tank is filled with light water followed by the control rods withdrawn for the criticality approximation. The control rods withdrawn were made in a stepsize manner. The subcriticality during all the experiment was guaranteed by constructing a 1/M curve taking the control rod withdrawn position as the independent variable. For every withdrawn step an interpolation was performed to find any possible critical condition. The detector countings are obtained for a specified interval of time (200 sec.). At the end of this procedure all control and safety rods are inserted again and the water removed from the moderator tank. The entire procedure is repeated for each loading step. The experimental data considered for this work was taken when all the absorber rods were completely withdrawn. Table 1 shows the corresponding number of fuel rods in each loading step of the experiment. The neutron source is a ^{241}Am-Be with a average intensity of 2.5 x 10^6 neutrons/sec and is located at the central axial line and 2 cm below the active core.

Table 1. Number of Fuel Rods for the Loading Steps

Loading Step	Number of fuel rods added in the step	Total number of fuel rods in the step
1	116	116
2	64	180
3	112	292
4	80	372
5	64	436
6	68	504
7	24	528
8	36 (48)	564 (576)

Five BF_3 out-of-core detectors from Centronic, 31EB70/25G model, were used in the experiment to predict the critical mass. Their locations are strategically set around the core in the reflector region. The axial and radial detector's positions are shown respectively in Figures 2 and 3. The experimental results were obtained as the ratio of the detector's counting of the first to the i th step at the end of each criticality approximation (moderator tank filled with water and safety/control rods completely withdrawn) for each detector as follow:

$$\left(\frac{1}{M_i}\right)_{\exp} = \frac{N_{i1}}{N_{ij}} \qquad (1)$$

where N_{i1} and N_{ij} are the counting of the first and i-th detector respectively in the j-th step, and its corresponding uncertainties were estimated by the formula:

$$\left(\sigma^2_{1/M_i}\right)_{\exp} = \frac{N_{i1}}{N^2_{ij}}\left(1+\frac{N_{i1}}{N_{ij}}\right) \qquad (2)$$

The criticality was reached in the eighth step with 36 fuel rods given a total of 564±2 fuel rods assuming the criteria that the system is critical when half number of detectors plus one have indicated the criticality. Originally, the eighth step consisted of 48 fuel rods with a total of 576 fuel rods in the core, but experimentally this step was divided into sub-steps with smaller amount of fuel rods due to the close proximity to criticality and to attempt to determine the "exact" number of rods in the core configuration for the critical mass. In each sub-step the same experimental procedure as described was adopted.

3 Methodology

The general-purpose Monte Carlo MCNP-4B code has been utilized to the simulation of the fuel loading experiment. Each fuel rod was geometrically modeled explicitly with its components and the whole core geometry for each loading step was constructed using the repeated structure option in MCNP. With this procedure it is possible to calculate the spatial neutron flux distribution in a great deal of details. For each fuel loading step it was created a specific MCNP input model representing the fuel rod array of that specific step configuration with a corresponding number of fuel rods and location, according to the experiment step. The five BF_3 detectors were not modeled explicitly. The approach adopted in this work is to calculate the volume integrated neutron flux at the detector position considering the presence of the water instead of the detector. This approximation was taken to simplify the geometry model with the assumption that the detector's counting is proportional to the integrated neutron flux at their position when filled with water. Therefore, the ratio of the detector countings between two loading steps should be the same as the ratio of the integrated neutron flux in water at their positions, since the loading procedure does not introduce any perturbation on the detector sensitivities.

A source fixed problem with 10 millions particles histories was specified for the MCNP simulation in each step. In each fuel loading step MCNP simulation, the volume integrated neutron flux has been calculated in the whole volume of water equivalent to the detector's volume. The ^{241}Am-Be neutron source in MCNP was modeled as a point source placed 20 mm bellow the active core as shown in the Figure 2 with an energy spectra taken from reference (Griffith, 1990). The source energy spectra and its probability density were introduced in the MCNP code using the SDEF card. Throughout the calculations, it was not considered any kind of variance reduction technique. The 1/M value at the i-th detector in the j^{th} step is obtained as a ratio of the integrated neutron flux of the first step to that of the j^{th} step, as stated in the equation (3):

$$\frac{1}{M_{ij}} = \frac{\phi_{i1}}{\phi_{ij}} \qquad (3)$$

where:

ϕ_{1i} is the integrated neutron flux at the i-th detector's position in the first step and;

ϕ_{ij} is the integrated neutron flux at the i-th detector's position in the j^{th} step

The errors in the calculation were computed using the formula:

$$\left(\sigma^2_{1/M_i}\right)_{calc} = \frac{1}{\phi^2_{ij}}\sigma^2_{i1} + \frac{\phi^2_{i1}}{\phi^4_{ij}}\sigma^2_{i1} \qquad (4)$$

where σ_{i1} and σ_{ij} are the standard deviation of the integrated neutron flux at the i-th detector in the first and j-th steps respectively, and

$$\left(\sigma^2_{1/M_i}\right)_{calc}$$

is the square of the standard deviation of the ratio 1/M calculated for the i-th detector.

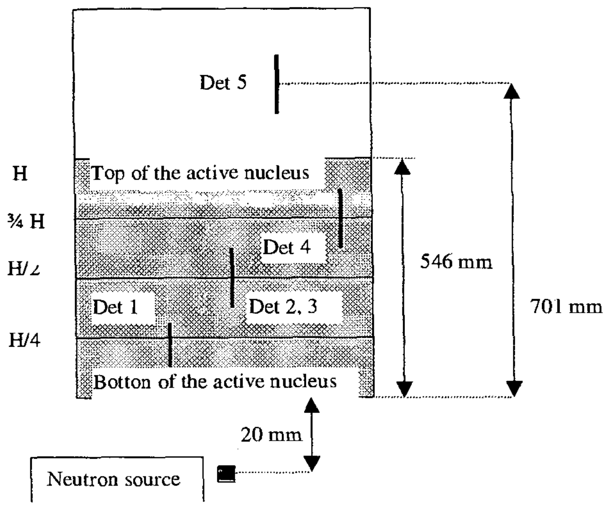

Figure 2: Position of the detectors and the neutron source (axial section view)

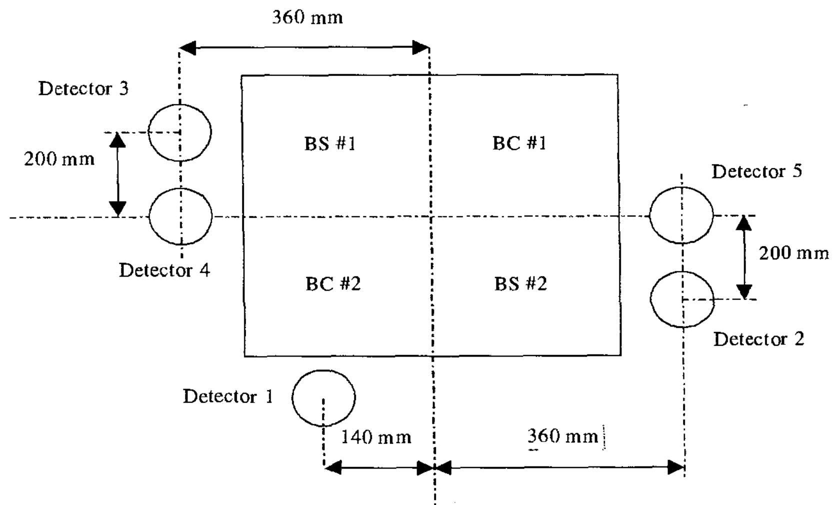

Figure 3: Position of the detectors. Cross section view (BC- control rods; BS -safety rods).

The cross section libraries considered for this work were obtained by NJOY 94.61 (MacFarlane, 1994), using the data from ENDF/B-IV but ^{238}U which came from JENDL 2.2. The thermal scattering law $S(\alpha,\beta)$ was obtained from LEAPR module of NJOY considering hydrogen bound in water at 293 °K. The calculational scheme is shown in Figure 4. The RECONR and BROADR modules of NJOY for cross section linearization and reconstruction and Doppler broadening were run with 0.5% and 0.2% interpolation tolerance respectively for all nuclides. The final MCNP-4B library is performed by the ACER module of NJOY.

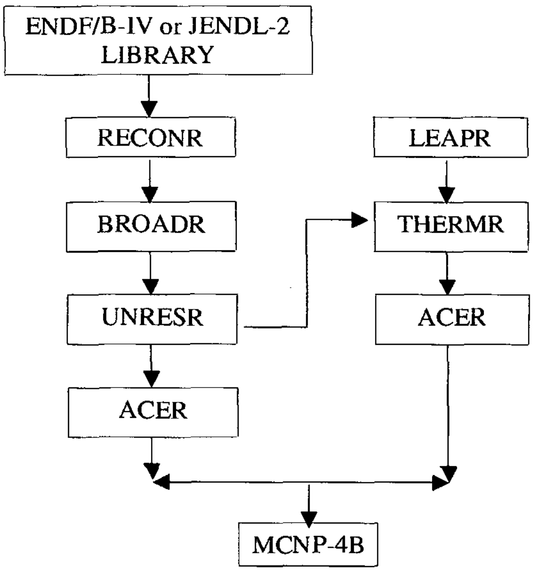

Figure 4: Calculational Scheme

4 Comparison of Calculational and Experimental Results

The comparisons between calculated and experimental data are shown in Figure 6 and in Table II. All uncertainties considered in this work are 1σ values. As expected, both large calculated and experimental uncertainties have been found in the first steps of the loading sequence due to the small amount of fuel rods and consequently lower neutron multiplication. Particularly, the reflex of that can be seen in the second step where we found the largest errors for all detectors. For those steps it was simulated 10 millions neutron histories to obtain a standard deviation of about 6 % in the 1/M value (except for detector 5). For the others steps the standard deviation decreases but the effect of the first step is still carried out in the uncertainty analysis (see Eqs. 1-4). The considerable discrepancies obtained between the experimental and calculated value in the second step, as evidenced in the Figure 6, is mainly due to the difficulties to obtain an accurate value both experimentally and in the simulation. In the experiment, the statistical uncertainties in the detectors response are larger in the earlier steps and also in the Monte Carlo simulation the convergence to a desirable standard deviation become more difficult to reach. Even increasing the number of neutron histories to obtain a desirable standard deviation the problem per se is more complicated geometrically and the nature of neutron interactions, i.e., more scattering for instance. Generally speaking, a good agreement between theory and experiment has been achieved for detectors 1, 3 and 4. The calculated values for detector 5 (the farthest one from the core), show the largest errors compared to the experimental values. This detector shows a systematic error after the third step which evidences a probable normalization problem due to the very low statistics reached in the first step.

However, a consistent critical number of fuel rods prediction has been achieved with all detectors as shown in Table III. The simulation went up to the seventh step due to a slight overestimation of reactivity produced by the cross-section libraries.

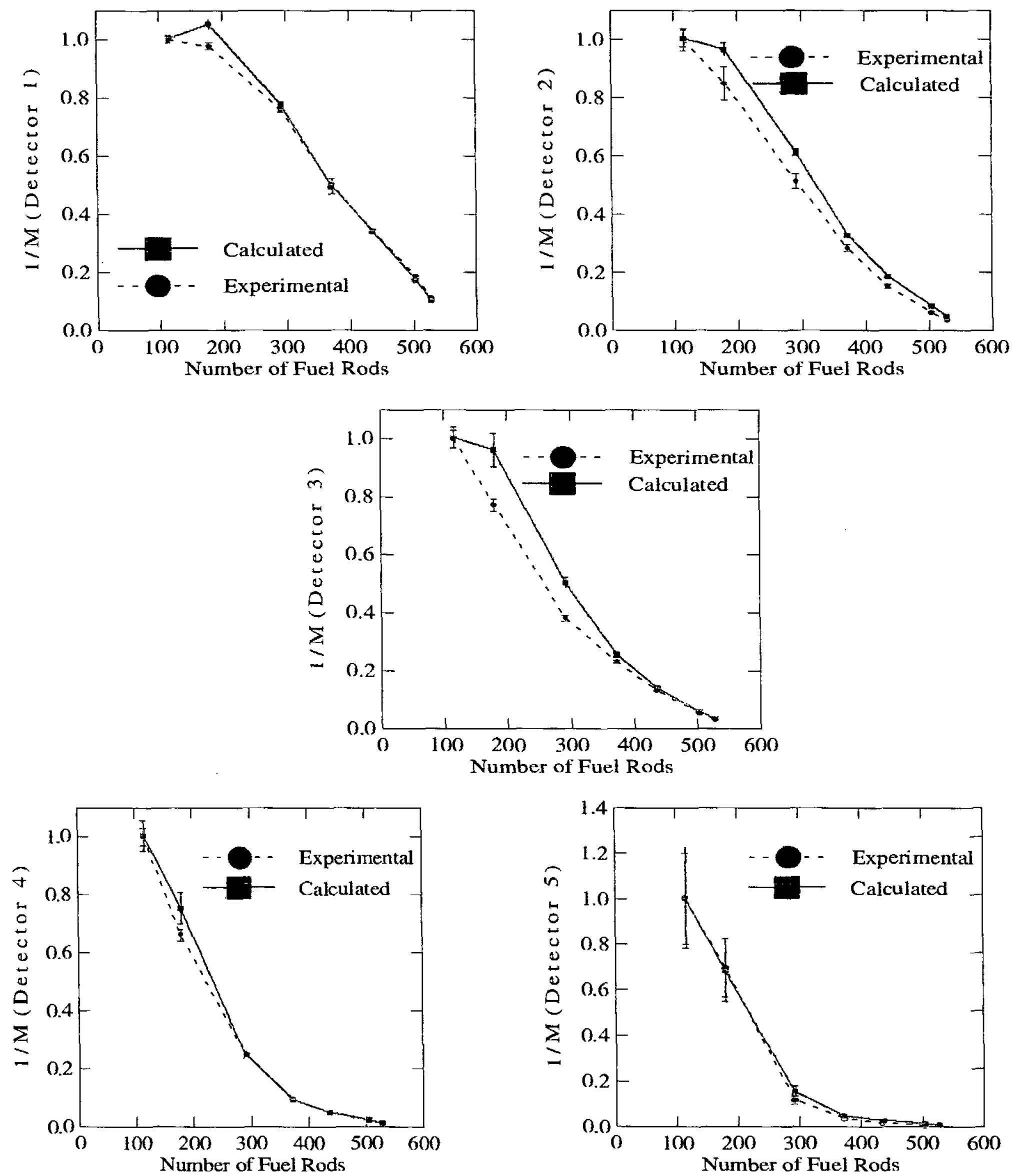

Figure 6. 1/M curve for the detectors.

Table II: MCNP calculation for the different steps. The zones here are referred to the place ocuppied by the corresponding detector in the water.

Step	Zone	1/M		
		Calculated	Experimental	Calc./Exp.
1	1	1 ± 0.0115	1.0000 ± 0.0128	1.00
	2	1 ± 0.0385	1.0000 ± 0.0286	1.00
	3	1 ± 0.0376	1.0000 ± 0.0293	1.00
	4	1 ± 0.0518	1.0000 ± 0.0295	1.00
	5	1 ± 0.2227	1.0000 ± 0.2000	1.00
2	1	1.0492 ± 0.0169	0.9767 ± 0.0125	1.07
	2	0.9612 ± 0.0567	0.8484 ± 0.0233	1.13
	3	0.9586 ± 0.0569	0.7734 ± 0.0213	1.24
	4	0.7499 ± 0.0546	0.6604 ± 0.0195	1.14
	5	0.6775 ± 0.1350	0.6944 ± 0.1278	0.98
3	1	0.7717 ± 0.0107	0.7574 ± 0.0091	1.02
	2	0.6070 ± 0.0257	0.5133 ± 0.0128	1.18
	3	0.4928 ± 0.0193	0.3817 ± 0.0093	1.29
	4	0.2451 ± 0.0114	0.2447 ± 0.0072	1.00
	5	0.1490 ± 0.0249	0.1163 ± 0.0174	1.28
4	1	0.4921 ± 0.0063	0.4998 ± 0.0056	0.98
	2	0.3247 ± 0.0123	0.2840 ± 0.0065	1.14
	3	0.2507 ± 0.0087	0.2301 ± 0.0053	1.09
	4	0.0886 ± 0.0037	0.0942 ± 0.0028	0.94
	5	0.0412 ± 0.0066	0.0375 ± 0.0054	1.10
5	1	0.3354 ± 0.0037	0.3433 ± 0.0036	0.98
	2	0.1829 ± 0.0059	0.1515 ± 0.0033	1.21
	3	0.1368 ± 0.0042	0.1313 ± 0.0029	1.04
	4	0.0468 ± 0.0018	0.0472 ± 0.0014	0.99
	5	0.0210 ± 0.0034	0.0165 ± 0.0024	1.27
6	1	0.1707 ± 0.0025	0.1872 ± 0.0019	0.91
	2	0.0800 ± 0.0028	0.0626 ± 0.0013	1.28
	3	0.0555 ± 0.0018	0.0550 ± 0.0012	1.01
	4	0.0190 ± 0.0008	0.0194 ± 0.0006	0.98
	5	0.0080 ± 0.0013	0.0061 ± 0.0009	1.31
7	1	0.1012 ± 0.0018	0.1127 ± 0.0011	0.90
	2	0.0446 ± 0.0016	0.0352 ± 0.0007	1.27
	3	0.0310 ± 0.0011	0.0322 ± 0.0007	0.96
	4	0.0093 ± 0.0004	0.0099 ± 0.0003	0.94
	5	0.0036 ± 0.0006	0.0030 ± 0.0004	1.21

Table III: Number of fuel rods obtained at critical mass

Detector Number	Number of fuel rods at criticality
1	564 ± 2
2	562 ± 2
3	559 ± 2
4	564 ± 2
5	555 ± 5
Mean value	561 ± 3
Experimental value	564 ± 2

Table III shows the extrapolated values of fuel rods obtained from the 1/M curves calculations for each detector. In all cases it is observed a rather good convergence of the theoretical curves towards a mean value of 561 ± 3 fuel rods. This result is in a good agreement with the experimental data.

5 Conclusion

In general, the proposed method to calculate the 1/M curve of the IPEN/MB [illegible] [illegible] adopted including the utilization of the [illegible] [illegible] simulates adequately the critical mass approach experiment. Also the volume integral neutron flux in the volume of water at the detector's position are an appropriate quantity to estimate the critical mass. The CPU time for each case was about 20 hours in an ALPHA Workstation which is a reasonable amount of time for such calculation and almost impossible to perform in the time period when the first criticality of the reactor was reached in 1988. The [illegible] integrated neutron flux at the detector's location.

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Helio Yoriyaz, Adimir dos Santos, Roberto Cabezas.

LOTAÇÃO: RAF   RAMAL: 7406

TIPO DE REGISTRO:

art. / periód.:	☐	Publ. IPEN	☐	. resumo	☐
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TITULO DO TRABALHO:

Monte Carlo Simulation of Critical Mass Experiment in the IPEN/MB-01 Reactor.

APRESENTADO EM: (informar os dados completos - no caso de artigos de conf., informar o título da conferência, local, data, organizador, etc..)

Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications, M&C 99 Madrid, ESpanha, Setembro, 1999.

PALAVRAS CHAVES PARA IDENTIFICAR O TRABALHO:

Monte Carlo Simulation, reactor physics, experiment

INIS:

ANS International Conference on Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications. Madrid (Spain) 27-30 Sep. 1999

ASSINATURA: [signature]

DATA: 18/02/2000.

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