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INVERSE KINETICS METHOD WITH SOURCE TERM FOR SUBCRITICALITY MEASUREMENTS DURING CRITICALITY APPROACH IN THE IPEN/MB-01 RESEARCH REACTOR

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ABSTRACT

In reactor physics tests which are performed at the startup after refueling the commercial PWRs, it is important to monitor subcriticality continuously during criticality approach. Reactivity measurements by the inverse kinetics method are widely used during the operation of a nuclear reactor and it is possible to perform an online reactivity measurement based on the point reactor kinetics equations. This technique is successful applied at sufficiently high power level or to a core without an external neutron source where the neutron source term in point reactor kinetics equations may be neglected. For operation at low power levels, the contribution of the neutron source must be taken into account and this implies the knowledge of a quantity proportional to the source strength, and then it should be determined. Some experiments have been performed in the IPEN/MB-01 Research Reactor for the determination of the Source Term, using the Least Square Inverse Kinetics Method (LSIKM). A digital reactivity meter which neglects the source term is used to calculate the reactivity and then the source term can be determined by the LSIKM. After determining the source term, its value can be added to the algorithm and the reactivity can be determined again, considering the source term. The new digital reactivity meter can be used now to monitor reactivity during the criticality approach and the measured value for the reactivity is more precise than the meter which neglects the source term.

1. INTRODUCTION

The inverse kinetics is widely used for reactivity measurement during nuclear reactor operations. Since the reactor is been operated in a steady-state condition, the reactivity can be determined using the point kinetics equations and the source term can be neglected in this case. However, when the reactor is at the subcritical state, the external source term must be taken into account.

It was shown that the source term is not so easy to be determined, even using the methods used in the references, and so the procedure is still under development. The first step was to construct the program which is able to calculate the reactivity using the signal from a detector installed inside the core, during an experimental SCRAM, in which all the safety and control rod were dropped. Then, the values where analyzed and the source term was estimated by the Least Square Inverse Kinetics Method, developed by Seiji Tamura [1]. The reactivity is determined again, but now using the source term.

IPEN/MB-01 Reactor was used for performing some rod drop experiments which had the objective to determine the numerical value for the source term. At the same time, a simulation of the experiments was done using Monte Carlo the method of MCNP-4C [2], where the reactor was modelled and simulated. The values of the reactivity determined by the experiments and by the simulations are discussed in the related sections.

2. INVERSE KINETICS WITH SOURCE TERM

The standard point-kinetic equations can be written as [3]:

$$\frac{dn}{dt} = \frac{\rho(t_j) - \beta}{\Lambda} n(t_j) + \sum_{i=1}^{6} \lambda_i C_i(t_j) + S \tag{1}$$

and

$$\frac{dCi}{dt} = -\lambda_i C_i(t_j) + \frac{\mathrm{B}_i}{\Lambda} n(t_j) \tag{2}$$

where $n(t_j)$ is the total number of neutrons in the core, which is directly proportional to the reactor power or to the signal from any neutron detector at time t_j. $C_i(t_j)$ is the total number of precursors of delayed neutrons of group i. S is the total neutron source strength supposed to be constant in time. Λ is the prompt neutron generation time and ρ the reactivity to be determined. The constants β_i and λ_i are the fraction and decay constant of delayed neutron precursor of group i, respectively, and $\beta_{eff} = \sum_{i=1}^{6} \beta_i$ is the effective delayed neutron fraction.

In practice, for discrete time series data, assuming that the reactor power change for the time interval Δt is given by $n(t_j) = n_0 + \frac{n(t_j) - n(t_{j-1})}{\Delta t} t_j$, the inverse kinetics equation can be written as:

$$\rho(t_j) = \frac{\Lambda}{n(t_j)} \frac{dn}{dt} + \beta - \frac{\Lambda}{n(t_j)} \sum_{i=1}^{6} \lambda_i C_i(t_j) - \frac{\Lambda}{n(t_j)} S \tag{3}$$

where,

$$C_i(t_j) = C_i(0) \exp(-\lambda_i t_j) + \frac{\mathrm{B}_i}{\Lambda} \exp(-\lambda_i t_j) \int_0^{t_j} n(t') \exp(\lambda_i t') dt' \tag{4}$$

Equation (3) is suitable for on-line digital reactivity meter provided that the quantity ΛS is known. This term is called source term and its dimension is the same as that of the measured quantity $n(t_j)$. For reactors operating at sufficiently high power the effect of the source term on the calculated reactivity can be neglected. However, at a lower power the source term should be considered, because otherwise zero reactivity will be obtained for a subcritical reactor at constant power.

3. PRELIMINARY RESULTS

3.1 The Rod Drop Experiment

The source term was first determined by the Least Squares Inverse Kinetics Method (LSIKM), as suggested in reference [1]. This method is described below.

Using a digital reactivity meter, the reactivity without the source term ($\rho'(t_j)$) can be determined. For simplicity, the right side of Equation (3) excepting the last term (source term) is going to be called $\rho'(t_j)$. The equation below shows the situation.

$$\rho(t_j) = \rho'(t_j) - \frac{\Lambda}{n(t_j)} S \tag{4}$$

Then the quantities $\rho(t_j)$ and ΛS can be calculated by the Least Squares Method, since the value of $\rho'(t_j)$ is the one given by the digital reactivity meter that neglects the source term. Equation 5 shows the function used for this calculation.

$$\rho'(t_j) = \rho(t_j) + \frac{\Lambda}{n(t_j)} S \tag{5}$$

As mentioned before, this reactivity meter was programmed for acquiring the signal of the neutron detector, and used here.

For the calculation of the quantities $\rho(t_j)$ and ΛS, data of a Rod Drop experiment in the IPEN/MB-01 Research Reactor were used to determine the reactivity without source ($\rho'(t_j)$). On this experiment, the reactor was in a constant power of 100 watts and the rods were at the critical positions. Then, all the rods were dropped and the signal from the neutron detector was taken on a frequency of 1 kHz.

The constants of delayed neutron precursors used in the experiment were measured at IPEN [4] and are given in Table 1. The neutron generation time, Λ, used is 0.000032 s. The time interval Δt, for 1 kHz, is 0.001 s

Table 1. Constants of delayed neutron precursors.

Group i	λ_i (1/s)	β_i
1	0.012456	$(2.679 \pm 0.023)\times10^{-4}$
2	0.0319 ± 0.0032	$(1.463 \pm 0.069)\times10^{-3}$
3	0.1085 ± 0.0054	$(1.34 \pm 0.13)\times10^{-3}$
4	0.3054 ± 0.0055	$(3.10 \pm 0.10)\times10^{-3}$
5	1.085 ± 0.044	$(8.31 \pm 0.62)\times10^{-4}$
6	3.14 ± 0.11	$(4.99 \pm 0.27)\times10^{-4}$

To calculate the quantities $\rho(t_j)$ and ΛS using the least squares method, the reactivity without source and the quantity $1/n(t_j)$ were plotted on a layer, and a fitting was done for the Equation (4). Figure 1 shows this result.

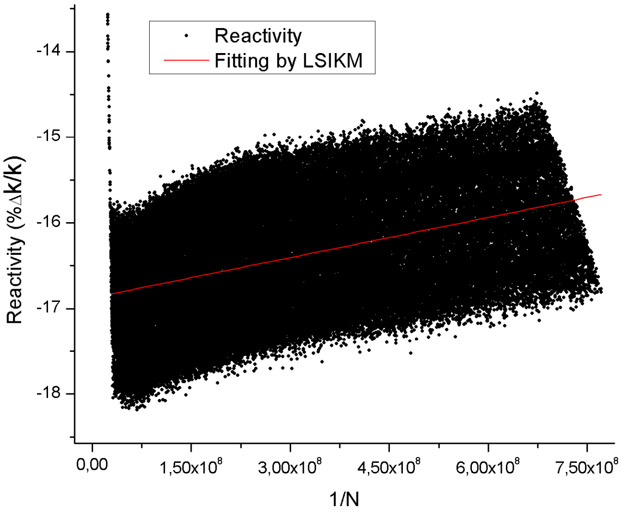

Figure 1- Fitting for the determination of the source.

This plot allowed the calculation of the source term and the reactivity. The values encountered were:

S = 4.87141×10^{-5} ± 3.68958×10^{-7} A/sec
$\rho(t_j)$ = -16.873 ± 0.00441 %Δk/k

When the source was determined, the reactivity was calculated again, but now using the value found for the source term. Reactivity now is a constant value, depending only on the fluctuation of the signal, but not giving zero reactivity, as mentioned before.

After the determination of the new reactivity values, data of the reactivity with source term and without source term were plotted on the same layer, for comparison. Figure 2 shows the comparison.

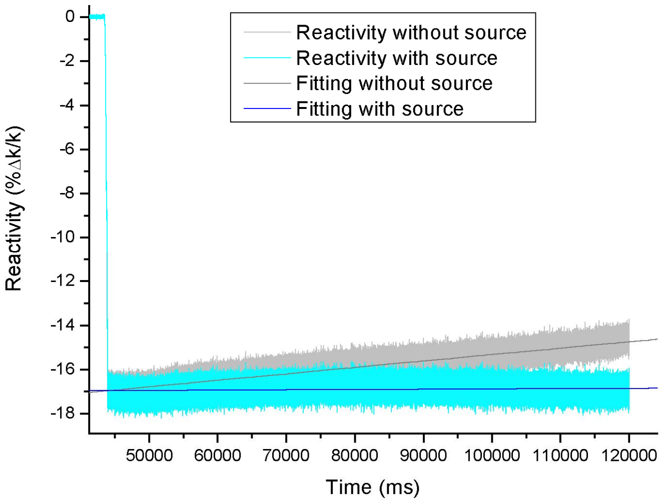

Figure 2- Comparison of the values.

As showed in the Figure 2, the reactivity obtained using the source term calculated by the Least Square Inverse Kinetics Method is constant in time, while the value with the source term neglected shows a tendency to go to zero.

The value found for the constant reactivity is the same as the value determined by the LSIKM for the quantity $\rho(t_j)$. The next step is insert the source term in the algorithm of the on-line reactivity meter, which nowadays neglects this term, and monitor the reactivity during the criticality approach.

3.2 Safety Rod Drop Experiment

It was shown in previous section that the value for S can be determined using the Least Square Inverse Kinetics Method, and it was performed in the IPEN/MB-01 research nuclear reactor facility. The value should be used for the on-line reactivity meter, but before it, another experiment was done, and its results were different.

On this experiment, instead of dropping all the safety and control rods, only the safety rod 1 was dropped, and the reactivity was monitored using the signal from the same detectors as in the first experiment. The period analyzed was larger than the other experiment, and the frequency was reduced to 100 Hz. The objective of this was to monitor the signal from the detector for a larger period and check its effect.

Then, the source term was calculated again, thought the same method, LSIKM. The value found for S was different from the value which was found before, and the conclusion of this is that the External Source S might depend on the operation mode. This case is still under investigation, and some new experiments are been planned for the determination of the right value for the External Source.

The value of the External Source must be determined correctly for the adaptation to the reactivity meter, and this is the reason why these experiments are important, since the reactivity meter must work in any situation, specially during criticality approach.

The analyses of the data collected on the second experiment are related here, and Figure 3 shows the fitting by the LSIKM for this case.

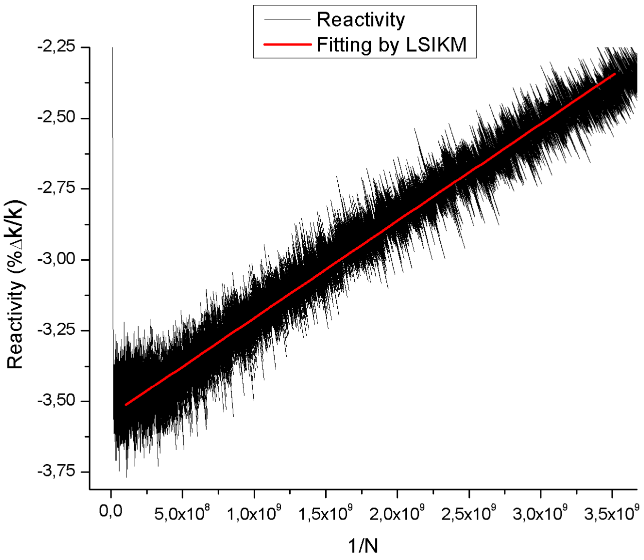

Figure 3. LSIKM for one safety rod drop.

The results for one safety rod drop were:

S	1.07092×10^{-5}	$\pm 1.80255 \times 10^{-8}$	A/sec
$\rho(t_j)$	-3.54771	± 0.000899	%Δk/k

Comparing these results, its possible to see that the source term has a value 4.5 times lower than the first case. Because of this, other experiments are going to be performed, and this data is inconclusive for while.

4. SIMULATION OF THE ROD DROP

4.1. Simulation of Rod Drop

The determination of the reactivity was also made by using MCNP-4C, for comparison with the values found by the inverse kinetics. A schema of the Reactor IPEN/MB-01 was used for the simulation, and the results were compared.

MCNP is a code normally used for statics problems, what is not the case of this problem. Then, to simulate the drop of the rods, twenty cases were considered starting from the critical position of the control rods and with all the safety rods removed. The next case considered was when the control rods were moved 6 cm down, and the safety rods inserted 6 cm. Each other step had the control rods 6 cm more down, and the safety too, until the control rods reach the lower limit. Now, only the safety rods continued dropping, until all of them to be on the lower limit.

The calculation of the k_{eff} was made by the MCNP-4C, and the twenty points of the experiment were plotted, where it is possible to verify the curve of reactivity versus rod positions.

Figure 4 shows the results. The position of the lower limit of the rod is plotted on x axis, and the reactivity calculated by k_{eff} on y axis.

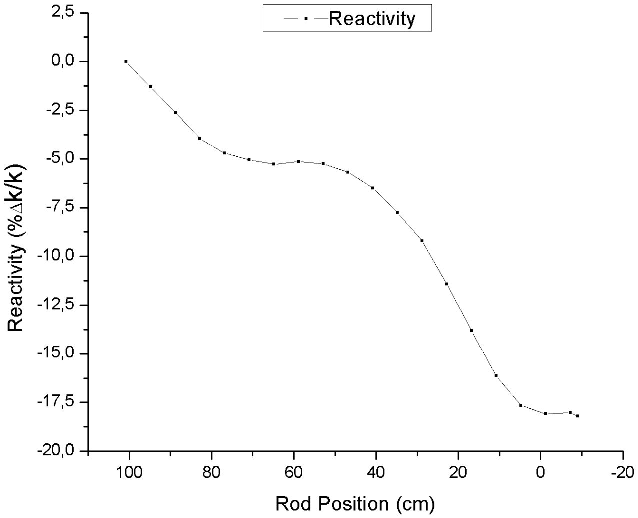

Figure 4. Reactivity x Rod Position.

The lowest value of reactivity, when the rods are all dropped, calculated by MCNP-4C was -18.191 %Δk/k, with an Standard Deviation of 0.00051. This value is lower then the one determined by the reactivity meter, which was -16.873 %Δk/k.

The values for the k_{eff}, considering its standard deviation calculated by MCNP4C are listed in Table 2, where are also listed the values for Reactivity calculated using the value of the k_{eff}.

Table 2. Values for k_{eff} and reactivity, for Rod Drop Simulation

	Value	**Standart Deviation**	**68% confidence**	**95% confidence**	**99% confidence**
K_{eff}	0.84609	0.00051	0.84558 to 0.84659	0.84508 to 0.84709	0.84475 to 0.84742
Reactivity (%Δk/k)	-18.191	0.071	-18.262 to -18.121	-18.331 to -18.051	-18.378 to -18.005

4.2. Calculation of Reactivity for One Safety Rod

For comparison with the values determinate by the reactivity meter, one last simulation was done, using MCNP-4C. The Safety Rod one was left at the lowest position and the k_{eff} was calculated. The value for the reactivity was calculated through the k_{eff} and the value obtained was:

Once again, the values of k_{eff} and reactivity are listed in Table 3.

Table 3. Values for k_{eff} and reactivity, for Safety Rod Drop simulation

	Value	**Standart Deviation**	**68% confidence**	**95% confidence**	**99% confidence**
K_{eff}	0.96387	0.00052	0.96335 to 0.96439	0.96284 to 0.96490	0.96250 to 0.96523
Reactivity (%Δk/k)	-3.7484	0.055	-3.804 to -3.6925	-3.8594 to -3.6377	-3.8961 to -3.6023

Comparing the values for the reactivity obtained by the experiment and by the simulation, there is a difference of approximately 0.2 %Δk/k, or 200 pcm. It’s clear that the difference now is smaller than the one comparison of the values for all rod drops.

5. CONCLUSIONS

After all comparisons of the values found by LSIKM and by MCNP-4C calculations, it is concluded that the simulation for the one safety rod drop is more approximated of the experiment than with the all rod dropped. Then, the difference becomes larger, as the subcriticality is larger.

When checking the values calculated by MCNP4C, considering the 99% confidence, the difference between the calculated and the experimental data becomes smaller. Because of this approximation, the reactivity is going to be calculated again, considering the uncertainties of the parameters β_i and λ_i . So, the experimental determination for the reactivity in the subcritical state is still being studied, and the next experiments will be performed considering this factor.

The External Source was expected to be constant at time, but the fitting by LSIKM showed that it might change when changing the operation mode of the reactor. The term S is very important for reactivity monitoring during criticality approach but its value is still inconclusive for the IPEN/MB-01 Research Reactor Facility . The next experiments might be helpful to determine a consistent value for this monitoring.

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