KINETIC PARAMETERS ESTIMATION IN A MTR RESEARCH AND PRODUCTION REACTOR IN SUBCRITICAL STATES

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Abstract

Subcritical measurements were performed for the first time at the RA-3 research and production reactor in order to obtain relevant kinetic parameters for the safe operation of the reactor. Measurements were made during the shut-down period in presence of high background gamma radiation (greater than 10^6 R/h) and xenon. At each stationary subcritical state, the neutron source was assumed to come from photoneutron precursors produced during the normal operation of the reactor. Kinetic parameters were estimated using both neutron noise and inverse kinetics techniques. It was possible to estimate the photoneutron effectiveness of the RA-3 reactor, giving a value of $(1.11 \pm 0.05)\ 10^{-4}$. Using the least squares inverse kinetics method the neutron source strength was estimated and then used in the inverse kinetics equation in order to get the reactivity evolution during the change of core configuration of the reactor. The study of the obtained experimental values shows the existence of spatial effects in the reactivity estimation, which were confirmed by numerical simulations carried out with the diffusive neutron code PUMA.

1. INTRODUCTION

In the normal operation cycle of the research and production reactor RA-3 it is necessary to make a refueling in order to compensate for the burn-up of the fissile material. During such refueling operations fuel elements are inserted, rotated and extracted; as well as control rods are withdrawn (in the case of refueling a control fuel element). All these movements produce significant variations in the reactivity of the reactor core. While these operations are conducted under procedures that ensure subcriticality at all states, it is of great interest for the reactor safety to have a measurement system that allows an on-line monitoring of the reactivity during these refueling operations.

The change of core configuration must be done in subcritical states with a neutron source. Even though the RA-3 is light-water moderated, the small concentration of deuterium present in natural hydrogen is capable of producing enough photoneutron reactions that can be used as a neutron source [1]. This photoneutron source is characterized by its effectiveness γ^{ph} [2], which takes into account the amount of deuterium and its spatial distribution in the reactor.

On the present work, measurements were taken for the first time in the RA-3 reactor at subcritical states to determine kinetic parameters of interest. The estimation was performed using the point reactor model (PRM) and methods based on inverse kinetics and neutron noise technique. As the measurements were done during the outage of the reactor (three days), the background gamma exposure rate was greater than 10^6 R/h. For that reason a fission chamber was used, despite its low efficiency, with a fast pulse amplifier working in current collector mode (no pre-amplifier needed). The detector was placed inside and outside the core with an absolute efficiency (ε) in the range of $0.3–1.3\times10^{-4}$, and count rates (R) of $10^3–10^6$ cps (corresponding to powers from 30 to 200 mW).

For the neutron noise measurements, the α-Feynman method was used [3][4] in order to obtain the prompt neutron evolution constant (α), ε and the power for several subcritical states. Using a linear fit of α vs. 1/R, it was possible to obtain the prompt neutron evolution constant at critical state (α_c) as well as the neutron source strength (S). Using the estimations of the power obtained with the α-Feynman method, it was possible to estimate for the first time the photoneutron effectiveness γ^{ph} of the RA-3 reactor.

For the inverse kinetic technique, the least square inverse kinetic method (LSIKM) was used [5] based on the measurement of the count rate evolution during a rod-drop between two subcritical states. By means of a linear fit, S and the reactivity of the final state could be obtained. The reactivity worth of the control rods were found to agree to a 6% with measurements previously performed at critical state. Once the value of S in known, it can be used on the inverse point kinetic equations in order to get the reactivity evolution $(t) measuring R(t), allowing the implementation of an on-line monitoring system for improving the safe operation of the reactor.

The study of the experimental values obtained, showed the existence of spatial effects in the reactivity estimation using the method mentioned above. These effects were produced due to the shape function change between successive subcritical states which were incompatible with the PRM hypothesis [6]. In order to study the spatial effects, a numerical study was carried out with the diffusive neutron code PUMA [7].

2. THEORY

The effective neutron fraction (β_{eff}) is defined as:

$$\beta_{eff} = \gamma^d \sum_{i=1}^{6} \beta_i^d + \gamma^{ph} \sum_{j=1}^{9} \beta_i^{ph} \qquad (1)$$

Where β_i^d and β_i^{ph} are the nuclear fraction of delayed neutrons and photoneutrons respectively. The effectiveness of the delayed neutrons (γ^d) is known for the RA-3 reactor. So the effectiveness of the photoneutrons is the only unknown parameter. Inserting this definition in the PRM results in a set of equations that simulates the power for a given reactivity. Then it is possible to make a parametric variation of β_i^{ph} and fit the simulated power with the measured one.

2.1. *Least square inverse kinetics method*

It is based on the measurement of a rod-drop between to subcritical states. Using a linear fit of the delayed evolution of the count rate it is possible to estimate both the final reactivity and the source strength. In this work we used a combination of variables that were shown to reduce the fluctuation of the signals [5].

The value of the source strength obtained by this method was used on the inverse kinetics equations in order to monitor the reactivity of the refueling operations [8].

2. 2. α *-Feynman method*

The α -Feynman method was used for the estimation of the reactivity and the power at different stationary subcritical levels. It is based on the study of the correlated part of the count rate fluctuations. During a time interval τ, the number of counts detected (N) are measured, and then the variance of N is calculated. If this were a Poisson process, then the variance would be equal to the mean value of N. However, as the nuclear reactor is a multiplicative medium, that equality does not hold. It is calculated the Y(τ) parameter, which is a measure of the deviation of the statistics of N from a Poisson process:

$$Y(\tau) = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle} - 1 = \frac{\varepsilon D}{\alpha^2 \Lambda^2}\left(1 - \frac{1 - e^{-\alpha\tau}}{\alpha\tau}\right) - 2Rd \qquad (2)$$

Where <> = mean value

D = Diven factor
α = prompt neutron constant
Λ = generation time
R = mean count rate
d = dead time of the measuring system

An estimation of ε, α and d can be obtained by a non-linear fit of the measured Y(τ) values. It can be shown that the relation between alpha and R for subcritical states is given by:

$$\alpha = \frac{\tilde{S}}{R} + \alpha_c \qquad (3)$$

So by measuring α and R at different subcritical levels it is possible to make a linear fit and obtain the α_c value.

3. EXPERIMENTAL PROCEDURE

The subcritical measurements were performed with a fission chamber. Even though this type of detector has a lower intrinsic efficiency than a helium-3 detector, it was chosen because of the high gamma background present in the reactor (10^6 R/h). The intrinsic efficiency of the fission chamber used was $\varepsilon_{int} = 0.36$ cps/nv.

The measuring system used was a fast pulse amplifier CANBERRA ADS-7820 directly connected to the detector by a 25 m special cable. The system allows high count rates measurements (up to 10^6 cps), with an excellent signal to noise ratio.

In FIG. 1. the core configuration of the RA-3 reactor is shown. The neutron detector was placed in three different positions during the different experiences (G4, B1 and G8). When placed in the G4 position the uranium irradiation plates were removed from the core. In all the cases, the active length of the detector was centered with the fuel elements of the core.

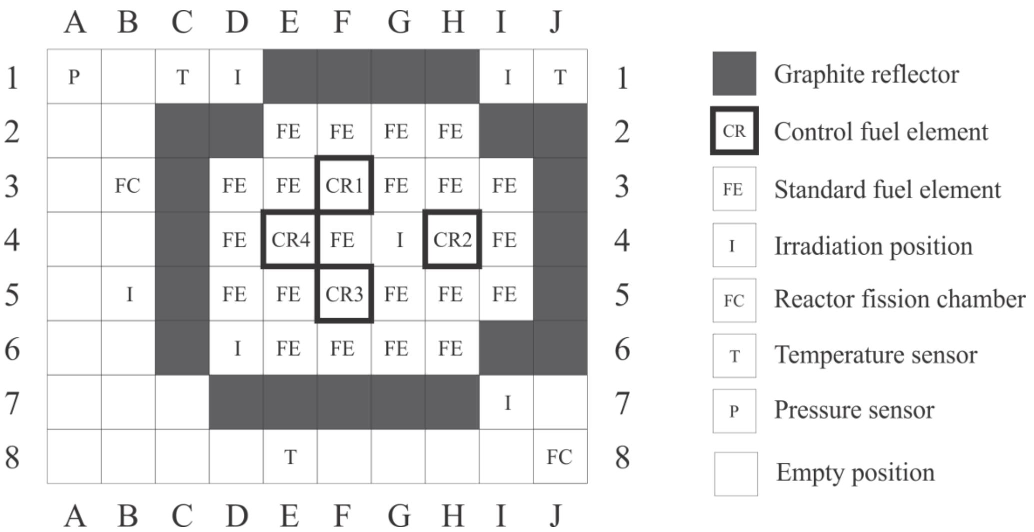

FIG. 1. Core configuration of the RA-3 reactor. The neutron detector was placed in the B1, G4 and G8 positions during all the measurements.

4. RESULTS AND DISCUSSIONS

The α-Feynman method was used to estimate the α value at different subcritical levels. In FIG.2 (L) the plot of α vs. 1/R at five subcritical levels is shown, with the linear fit of the equation 3 performed. The results obtained are:

$$\alpha_c = (106 \pm 1)s^{-1} \qquad \tilde{S} = (3.56\ \pm 0.05)10^7\ cps\ s^{-1}$$

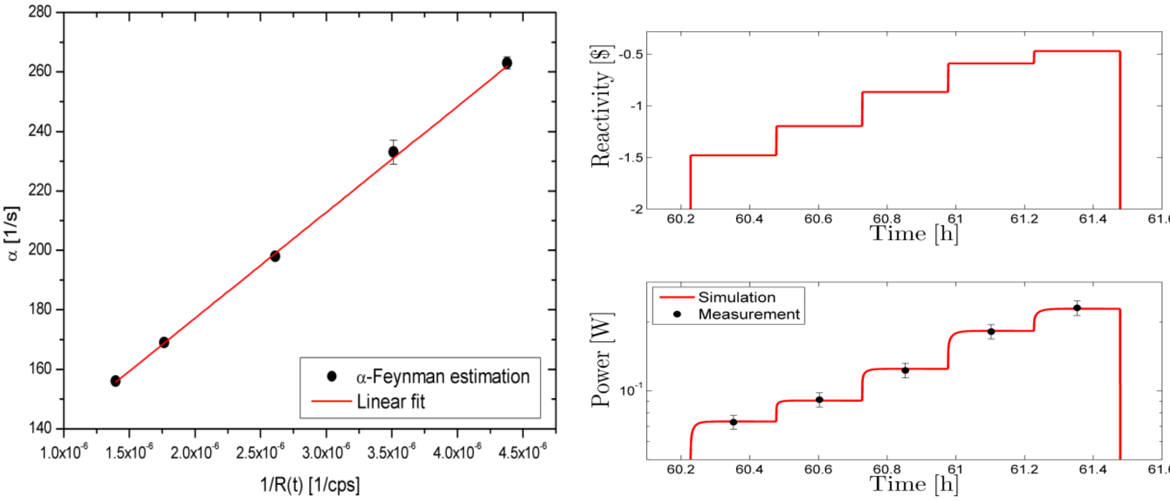

FIG. 2. Linear fit of a vs. 1/R used to estimate the α_c and the source strength (L). Simulated evolution of the power where the γ^{ph} was obtained with a parametric fit of the measured power (R).

To determine the photoneutron effectiveness a simulation was used to fit the experimental power measurements. On this simulation, the reactivity at each subcritical state is needed, so the changes in reactivity were analyzed taking into account the variation due to the SCRAM, the poisoning of ^{135}Xe and the extraction of the control rod. In FIG.2.(R) the reactivity evolution for this simulation is shown. Then a parametric variation of the γ^{ph} was performed to obtain the simulation that best fits the experimental power values. In FIG.2(R) the simulation from which the γ^{ph} was obtained along with the power measurements are shown. The result for the effectiveness is:

$$\gamma^{ph} = (1.11\pm 0.05)\ 10^{-4}$$

Although typical values of γ^{ph} for light water reactors were not found in the bibliography, by means of a simple analysis based on data of a heavy water MTR reactor [9] it was possible to verify that the value obtained is of the expected order of magnitude [8].

4.1. Monitoring refueling operations

Once the value of the photoneutron source was found with the LSIKM, it was used in the inverse kinetics equations in order to obtain the reactivity by measuring the count rate changes during a refueling operation. The detector was placed outside the core in the B1 position to avoid interfering with the movements of the fuel elements (FE). The refueling operations monitored started with the 212 core and finished once the 213 core was reached. The detailed movements performed were:

— FE extraction from E2;
— FE from H6 to E2;
— FE from D4 to H6;

- — FE from E3 to D4;
- — FE from F4 to E3;
- — Fresh FE into F4.

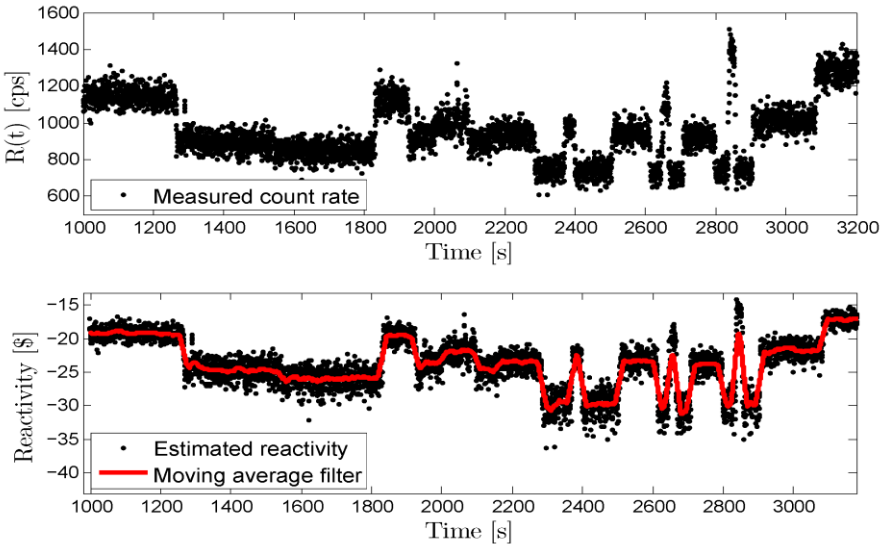

FIG.3 Change of core configuration in the RA-3 reactor. A burned-up fuel element is removed, then several fuel element rotations are performed, and finally a fresh fuel element is introduced.

In FIG.3 (Top) the count rate evolution during the refueling operation and the reactivity estimated with the inverse kinetics equations (Bottom) are shown. In all the intermediate states the subcritically is far below -15 dollars, assuring a safe operation. However, performing a more detailed analysis of the estimated reactivity values for the core configuration changes, some discrepancies were found with the available reference values. These discrepancies were attributed to spatial effects that appear when working with highly subcritical cores.

In order to analyze more thoroughly the spatial effects found during the reactivity monitoring, a model of the RA-3 core was made with de diffusive code PUMA. As the photoneutron source was not known at this stage of the modeling, a uniform neutron source was assumed in all the fuel channels of the core (and zero in the graphite reflector and elsewhere). The absolute value was arbitrary, in such a way that only a relative comparison was possible. All the core configurations between the 212 and 213 core were simulated for the stationary subcritical states.

TABLE I shows the comparison between the experimental values and the calculated ones, all of them normalized to the initial subcritical state. According to the PRM for a subcritical reactor with external neutron source, the relation $R_i/R_0= \rho_0/\rho_i$ holds for any two arbitrary subcritical states. A good agreement was found between the local parameters R_i/R_0 and the thermal flux ratio Φ_i/Φ_0 (which are assumed to be proportional). However, the global parameters such as the power P_i/P_0 and ρ_0/ρ_i show discrepancies with the measured values. This confirmed the presence of spatial effects which are disregarded in the PRM.

TABLE I: COMPARISON BETWEEN THE EXPERIMENTAL VALUES AND THE CALCULATED WITH THE PUMA CODE.

Core configuration i	Experimental		PUMA		
	R_i/R_0	ρ_0/ρ_i	Φ_i/Φ_0	P_i/P_0	ρ_0/ρ_i
Core 212 0	1	1	1	1	1
1	0.78 (3)	0.8 (1)	0.784	0.910	0.928
2	0.74 (3)	0.7 (1)	0.740	0.788	0.809
3	0.98 (4)	1.00 (5)	0.962	0.878	0.885
4	0.82 (3)	0.8 (1)	0.806	0.915	0.939
5	0.81 (3)	0.8 (1)	0.787	0.884	0.901
6	0.88 (4)	0.9 (1)	0.821	0.783	0.787
Core 213 7	1.11 (4)	1.12 (5)	1.113	1.090	1.081

5. CONCLUSIONS

For the first time in the RA-3 reactor, measurements were taken at subcritical core configurations. The measurements were done in the presence of a high background gamma radiation, greater than 10^6 R/h, and with ^{135}Xe. A detector and a measuring system that allowed measuring count rates of up to 10^6 cps with an excellent signal to noise ratio were used.

Using the neutron noise technique, the α-Feynman method was applied to estimate the kinetic parameters of interest. In particular, the α value and the power for different subcritical states were estimated. With them it was possible to calculate the α_c extrapolating from the subcritical measurements taken with reactivities between -0.5 and -6 dollars. The value obtained is α_c = (106 ± 1) s^{-1}, which is10% smaller with respect to the reference value measured in critical state.

During all the experiences the photoneutron source present in the reactor was used. This source was considered quasi-stationary, so that it could be assumed constant during each measurement. This was possible because in the subcritical experiences neutron flux was low enough and therefore most photoneutrons came from precursors formed during the previous operation of the reactor at full power.

First estimates were made of the photoneutron effectiveness of the RA-3 research and production reactor, resulting in γ^{ph} = (1.11 ± 0.05) 10^{-4}. The value was obtained from simulations of the evolution of the power after reactor shutdown, with which the estimated power values could be adjusted by the α-Feynman method. With the value of the neutron source $\tilde{S}$ obtained by the LSIKM it was possible to use the inverse kinetic equations to estimate reactivities from the measured count rate (a subcritical digital reactimeter). With this method the reactivity evolution during the core changes could be monitored. The existence of a system capable of monitoring the subcritical state during these movements of fuel and control rods is useful from the point of view of nuclear safety.

A detailed analysis of the reactivity estimated during the refueling showed discrepancies in comparison with the reference values. These came from spatial effects present in highly subcritical core configurations. By means of the diffusive code PUMA with a neutron source, it was possible to find that those discrepancies can be explained by the change in the shape function between the different configurations, producing a bias on the reactivity estimation.

The need of continuing this work arises, with a comparative analysis between the experimental estimates of reactivity and the change in the shape function, allowing to limit such bias as a function of the reactivity This work should include a detailed study of the spatial and energy distribution of the photoneutron source in order to get a better representation of the reactor in the subcritical states.

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