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EXPERIMENTAL ESTIMATION OF MODERATOR TEMPERATURE COEFFICIENT OF REACTIVITY OF THE IPEN/MB-01 RESEARCH REACTOR

Rubens C. da Silva[1], Ulysses D. Bitelli[2] and Luiz Ernesto C. Mura[3]

[1] Naval Architecture and Ocean Engineering Department (PNV-POLI USP)
School of Engineering - University of São Paulo
Av. Professor Mello Moraes, 2231
05508-030 São Paulo, SP
rubensrcs@usp.br

[2] Nuclear and Energy Research Institute (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
ubitelli@ipen.br

[3] Nuclear and Energy Research Institute (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
credidiomura@gmail.com

ABSTRACT

The aim of this article is to present the procedure for the experimental estimation of the Moderator Temperature Coefficient of Reactivity of the IPEN/MB-01 Research Reactor, a parameter that has an important role in the physics and the control operations of any reactor facility. At the experiment, the IPEN/MB-01 reactor went critical at the power of 1W (1% of its total power), and whose core configuration was 28x26 rectangular array of UO_2 fuel rods, inside a light water (moderator) tank. In addition, there was a heavy water (D_2O) reflector installed in the West side of the core to obtain an adequate neutron reflection along the experiment. The moderator temperature was increased in steps of 4ºC, and the measurement of the mean moderator temperature was acquired using twelve calibrated thermocouples, placed around the reactor core. As a result, the mean value of -4.81 pcm/°C was obtained for such coefficient. The curves of $\rho(T)$ (Reactivity x Temperature) and $\alpha_T^M(T)$ (Moderator Temperature Coefficient of Reactivity x Temperature) were developed using data from an experimental measurement of the integral reactivity curves through the Stable Period and Inverse Kinetics Methods, that was carried out at the reactor with the same core configuration. Such curves were compared and showed a very similar behavior between them.

1. INTRODUCTION

The moderator temperature coefficient of reactivity α_T^M of water moderated reactors is an important operational parameter that is strongly associated with safety issues of the nuclear installation [3]. According to [7], the α_T^M substantially varies based on the geometry, the moderator temperature, the concentration of substances in the moderator (like boron), among others. The usual values of such coefficient for Boiling Water Reactors (BWR) are -5pcm/ºC (at 20ºC) and -25 pcm/ ºC (at 280ºC) and, for Pressurized Water Reactors (PWR), between -5 and -30 pcm/°C.

In water moderated reactors, the moderator temperature coefficient of reactivity causes variations in the liquid density and in the energy spectrum of thermal neutrons [6]. Such modification changes the balance between fission and absorption rates in the core, since these factors are function of the energy of neutrons [8].

Fig. 1 shows the change in the energy spectrum of neutrons caused by a temperature variation. The average neutron energy is proportional to the absolute temperature, so the shift in the spectrum for a temperature change from 20°C to 300°C (293K to 573K) almost doubles the energy at the peak of the curve. According to [13], the shift of the neutron spectrum to higher temperatures changes the rates of thermal neutron absorption in the fissile isotopes.

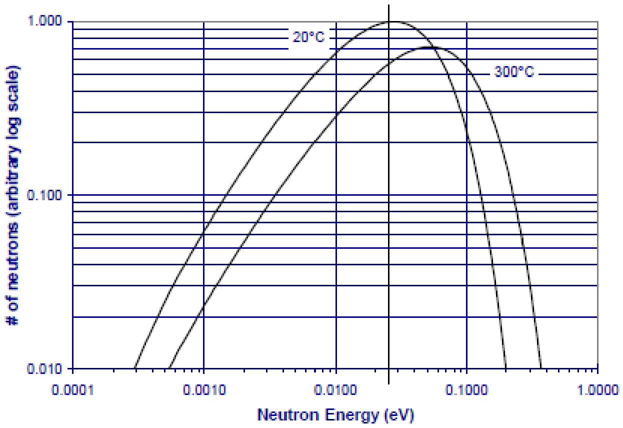

Figure 1: Temperature Effect on Neutron Energy Spectrum [13].

Additionally, temperature variations in a reactor core influence the value of the multiplication factor (K) through the change in the reactivity of the core components, which in turn, change the microscopic cross sections (Doppler Broadening) [1].

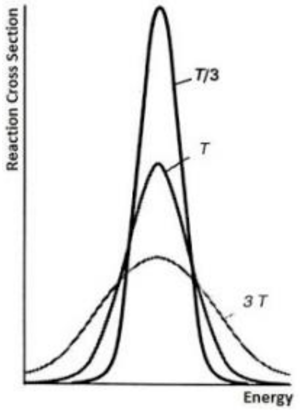

Figure 2: Doppler Broadening [9].

The cross sections depend on the relative velocity between the neutrons and the target nuclei. Temperature variation results in change of neutron energy, and if it is found in a resonance region, the neutron will be absorbed by the fuel (especially ^{238}U) [9]. Therefore, it is an undesirable effect in certain circumstances and in others it acts because of the reactor safety system. In general, a reactor is designed to have $\alpha_T^M < 0$, thus ensuring that a negative reactivity feedback will be performed in the event of a power increase. However, accidents may happen if the value is excessively negative due to the cooling system, especially in PWR [3].

Fig. 3 shows the closed-loop model that explains the influence of the temperature coefficient of reactivity in the reactor core reactivity. If $\alpha_T^M > 0$, a temperature increase produces reactivity increase (ρ) and, consequently, a power increase, which would in turn, raise temperature. In contrast, if $\alpha_T^M < 0$, a temperature increase would cause a decrease in ρ, which would in turn, decrease both power and temperature [5].

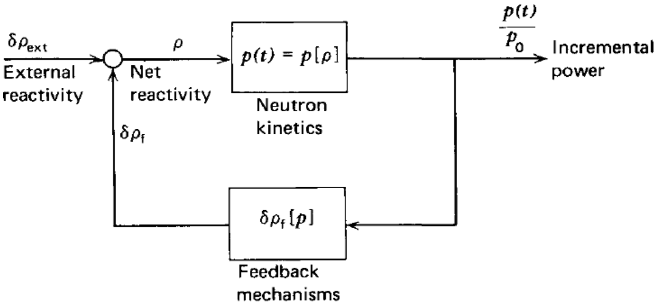

Figure 3: Closed-loop Model of the Relation between Temperature and Reactivity [5].

Therefore, the most advantageous situation would be $\alpha_T^M < 0$ or, more generally, $\alpha_T < 0$ (Temperature Coefficient of Reactivity), which would make the reactor achieve a stable power level due to temperature increase.

2. THE IPEN/MB-01 RESEARCH REACTOR FACILITY

The IPEN/MB-01 research reactor is a zero-power critical facility especially designed for measurements of a wide variety of reactor physics parameters to be used as benchmark experimental data for checking the calculational methodologies 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 instructional laboratory system.

According to [11] and [12], the IPEN/MB- 01 reactor core when assembled on standard configuration is a fuel rods rectangular array (28×26) immersed in a demineralized light water (as a moderator) tank. The standard fuel rod comprises a column of ceramic pellets of uranium oxide 4.3% (in weight) enriched, cladding with stainless steel (type 304). The maximum allowed operation power is 100W. Moreover, the control banks are composed of 12 Ag−In−Cd rods and the safety banks of 12 B_4C rods (both banks are diagonally opposed each other). 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. Fig. 4 shows the upper view of the IPEN/MB- 01 reactor core.

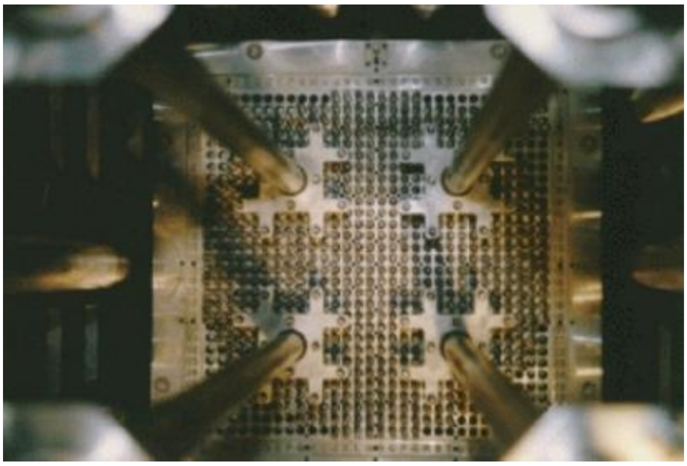

Figure 4: The IPEN/MB-01 Reactor Core [11].

3. DETERMINATION OF THE TEMPERATURE COEFFICIENT OF REACTIVITY (α_T)

In general, the temperature coefficient of reactivity (α_T) is defined as the variation of reactor core reactivity due to temperature variation, i.e.:

$$\alpha_T \equiv \frac{\partial \rho}{\partial T} \equiv \frac{\Delta \rho}{\Delta T} \tag{1}$$

According to [5], several parts of temperature coefficients of reactivity are usually added due to the major components of the reactor core, such as fuel, moderator, and structure, among others. Thus, the formation of α_T is the sum of these ‘j’ parts:

$$\alpha_T = \sum_j \alpha_j \equiv \frac{\partial \rho_j}{\partial T_j} \tag{2}$$

Particularly, [1] only consider alterations in water and nuclear fuel temperature, as a study simplicity. Therefore, the dominant temperature effects are alterations in resonance absorbance (Doppler Broadening) due to changes in fuel and in the energy spectrum of neutrons, which were caused by alterations in the moderator density.

Therewith, α_T is comprised only of fuel (α_T^F) and moderator (α_T^M) parts:

$$\alpha_T = \alpha_T^F + \alpha_T^M \tag{3}$$

As to the IPENMB-01 reactor, temperature variations are small in a way that the effect of α_T^F is small if compared with α_T^M [1]. Thus:

$$\alpha_T \approx \alpha_T^M \tag{4}$$

Based on equations (1), (3) and (4), it is possible to determine the moderator temperature coefficient of reactivity of IPEN/MB-01 reactor.

4. THE EXPERIMENTAL PROCEDURE

The IPEN/MB-01 has a water heating, cooling and circulation system that allows the accurate temperature control of the moderator, which can be maintained in the range of 7^{o} to 90^{o}C [4]. Twelve calibrated thermocouples (T_1 to T_{12}) were used in this experiment as well as their mean temperature value. The next figure shows the placement of such thermocouples in the reactor core.

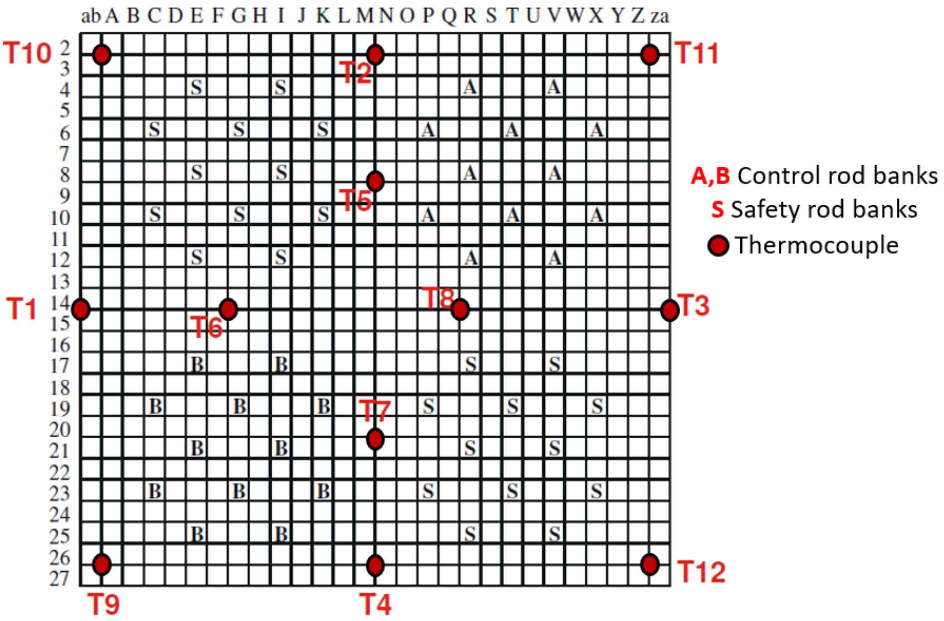

Figure 5: Location of Thermocouples at the IPEN/MB-01 Reactor Core [4].

4.1. Initial Conditions

The initial conditions of the experiment were:

- Critical Reactor Power = 1W;
- Moderator Temperature = $18.42^{o} \pm 0.05^{o}$C;
- Position of the Control Rods (CR) = %CR1=%CR2= 49.13 % withdrawn;
- Position of the Safety Rods (SR) = %SR1=%SR2=135% withdrawn.

This experiment was performed with a standard core configuration with a heavy water reflector on the west side (Fig. 6).

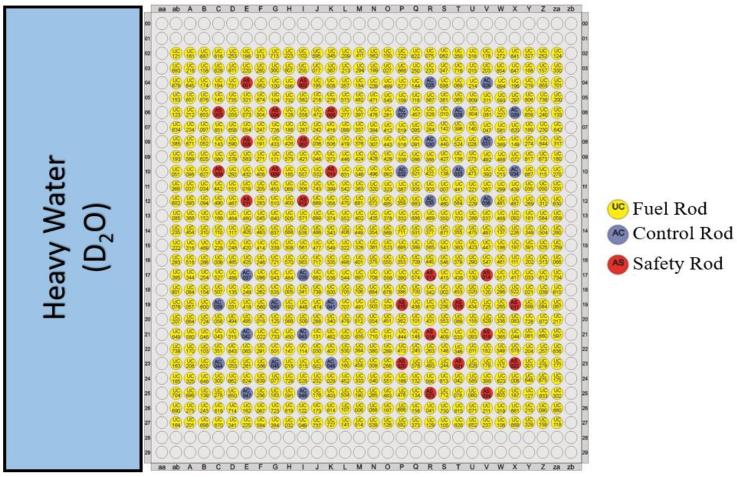

Figure 6: Configuration of the IPEN/MB-01 Reactor Core.

4.2. Adopted Procedure

The moderator was heated through 3 electrical resistances (110kW each). In every approximate 4°C increments (steps) in the moderator temperature, the heaters were turned off until the thermocouples mean temperature value stabilizes (with a standard deviation around ±0.05°C). After the temperature increased, the reactor went subcritical. Then, the CR2 position was altered in a way that the criticality was once more achieved.

This process was carried out until the moderator temperature achieved the highest degree of about 40°C. The next figure shows the variation steps of thermocouples temperature during the experiment.

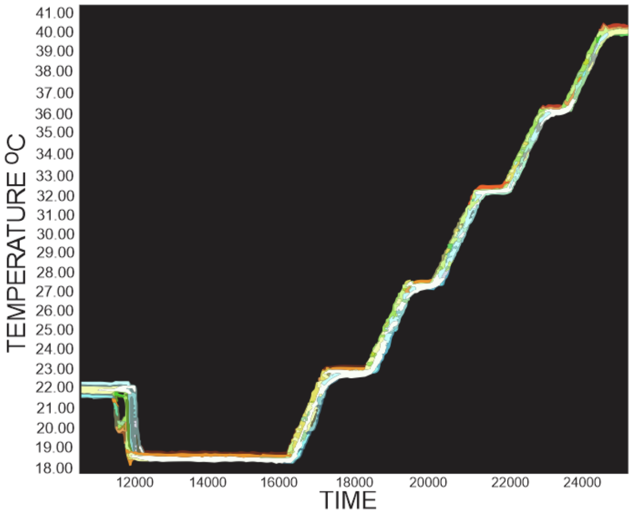

Figure 7: Variation of the Thermocouples Temperature.

Table 1 shows the data obtained during the experimental procedures, that is, the positions of control rods (CR1 and CR2 in % withdrawn), the reactivity variation ($\Delta\rho$), and the thermocouples mean temperature.

Table 1: Experimental Data

Time	Positions (% withdrawn)		Δρ (pcm)	Thermocouples Mean Temperature (ºC)	Comments
	CR1	**CR2**			
14:22	49.13	49.13	-	18.42 ± 0.05	Heaters On
14:34	49.13	49.13	-	22.42 ± 0.26	Heaters Off
14:44	**49.13**	**49.38**	**-14.6**	**23.02 ± 0.08**	**Critical Reactor**
14:48	49.13	49.38	-	-	Heaters On
15:02	49.13	49.38	-	27.03 ± 0.3	Heaters Off
15:10	**49.13**	**49.7**	**-18.2**	**27.49 ± 0.06**	**Critical Reactor**
15:11	49.13	49.7	-	-	Heaters On
15:25	49.13	49.7	-	31.5 ± 0.31	Heaters Off
15:32	**49.13**	**50.07**	**-22.5**	**32.28 ± 0.07**	**Critical Reactor**
15:33	49.13	50.07	-	-	Heaters On
15:46	49.13	50.07	-	35.78 ± 0.28	Heaters Off
15:50	**49.13**	**50.45**	**-22.8**	**36.16 ± 0.07**	**Critical Reactor**
15:53	49.13	50.45	-	-	Heaters On
16:05	49.13	50.45	-	39.66 ± 0.27	Heaters Off
16:12	**49.13**	**50.88**	**-25.85**	**40.1 ± 0.07**	**Critical Reactor**
16:15	49.13	49.13	-104.33	-	CR2 at the initial position

5. RESULTS

5.1. α_T^M Values

By the values of the mean temperature of the thermocouples and $\Delta\rho$, it was possible to calculate the value of moderator temperature coefficient of reactivity through equations (1) and (4) for each CR2 position. Table 2 shows the α_T^M results.

Table 2: Values of Moderator Temperature Coefficient of Reactivity

% CR2 (withdrawn)	Δρ (pcm)	Thermocouples Temperature Mean Value (ºC)	ΔT (ºC)	α_T^M (pcm/ ºC)
49.13	-	18.42	-	-
49.38	-14.6	23.02	4.6	-3.17
49.7	-18.2	27.49	4.47	-4.07
50.07	-22.5	32.28	4.79	-4.69
50.45	-22.8	36.16	3.88	-5.87
50.88	-25.85	40.1	3.94	-6.56

5.2. ρ(T) Curves

By means of the CR2 position values (% withdrawn), the integral reactivity values were calculated based on the calibration curves obtained in [10] (Inverse Kinetics and Stable Period Methods) and then, the ρ(T) curves were developed. Equations (5) and (6) are the calibration curves (fitted by a Boltzmann equation) obtained by the stable period and inverse kinetic methods, respectively.

$$\rho_{SP}(\%CR2) = 3282.23 - (3312.06)/[1 + \exp\left(\frac{\%CR2-48.22}{12.27}\right)] \tag{5}$$

$$\rho_{IK}(\%CR2) = 3263.37 - (3332.91)/[1 + \exp\left(\frac{\%CR2-48.46}{12.92}\right)] \tag{6}$$

where $\rho_{SP}(\%CR2)$ and $\rho_{IK}(\%CR2)$ are the reactivity value inserted by the %CR2, obtained by the stable period and inverse kinetics methods, respectively.

By adding the %CR2 values in equations (5) and (6), the moderator temperature reactivity coefficients were calculated (Table 3) based on the integral reactivity curves values obtained by the stable period method ($\alpha^M_{T\_SP}$) and inverse kinetics ($\alpha^M_{T\_IK}$) method.

Table 3: $\alpha^M_{T\_SP}$ and $\alpha^M_{T\_IK}$ Values

Step	% CR2 (withdrawn)	ρ_{SP} (pcm)	$\Delta\rho_{SP}$ (pcm)	ρ_{IK} (pcm)	$\Delta\rho_{IK}$ (pcm)	Thermocouples Temperature Mean Value (ºC)	$\alpha^M_{T\_SP}$ (pcm/ ºC)	$\alpha^M_{T\_IK}$ (pcm/ ºC)
	49.13	1687		1639		18.42	-	-
1	49.38	1704	17	1656	17	23.02	-3.66	-3.50
2	49.7	1725	21	1676	20	27.49	-4.81	-4.61
3	50.07	1750	25	1700	24	32.28	-5.18	-4.96
4	50.45	1776	26	1724	24	36.16	-6.56	-6.28
5	50.88	1804	28	1752	28	40.1	-7.29	-6.98

Fig. 8 illustrates the ρ(T) curves obtained from integral reactivity curves values calculated from equations (5) and (6). Such curves were adjusted with second-degree polynomial equations:

$$\rho_{SP}(T) = 0.1014T^2 - 0.5319T + 1663 \tag{7}$$

$$\rho_{IK}(T) = 0.09728T^2 - 0.5246T + 1617 \tag{8}$$

The inversion points (IP) indicated in Fig. 8 correspond to the temperature in which the α^M_T value changes its signal. The IP were calculated through the basic formulation of a parabola minimum point ($\frac{\partial\rho(T)}{\partial T} = 0$), to both cases of inverse kinetics (IP_{KI}) and stable period (IP_{SP}) Methods:

- $IP_{SP} = 2.6$;
- $IP_{IK} = 5.3$;

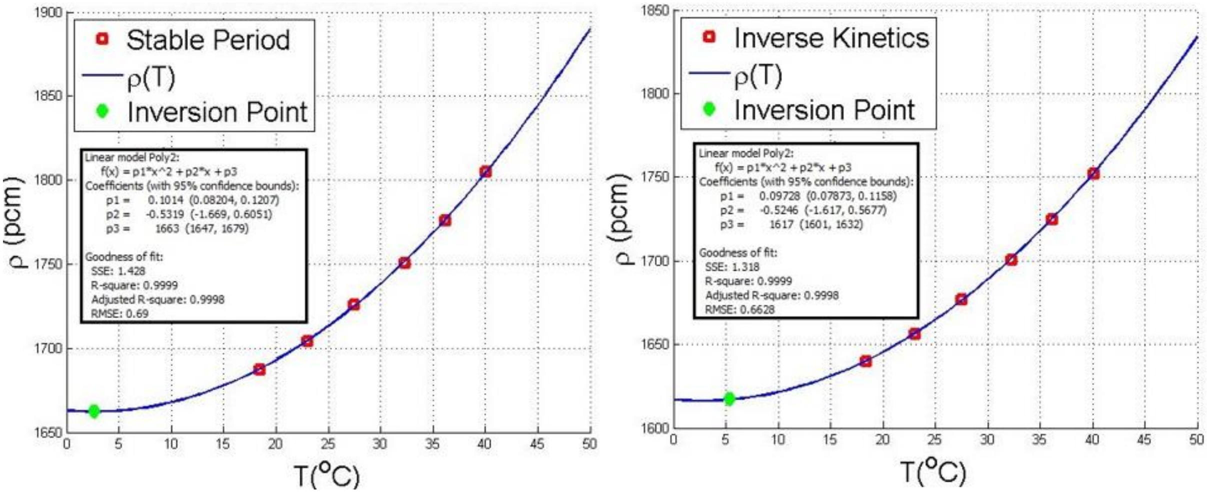

Figure 8: ρ(T) Curves (Stable Period and Inverse Kinetics Methods).

5.3. $\alpha_T^M(T)$ Curves

Based on the reactivity values calculated in the previous item, the $\alpha_T^M(T)$ curves were developed for the experiment values (Fig. 9), and for those ones calculated by the stable period and inverse kinetics methods (Fig. 10).

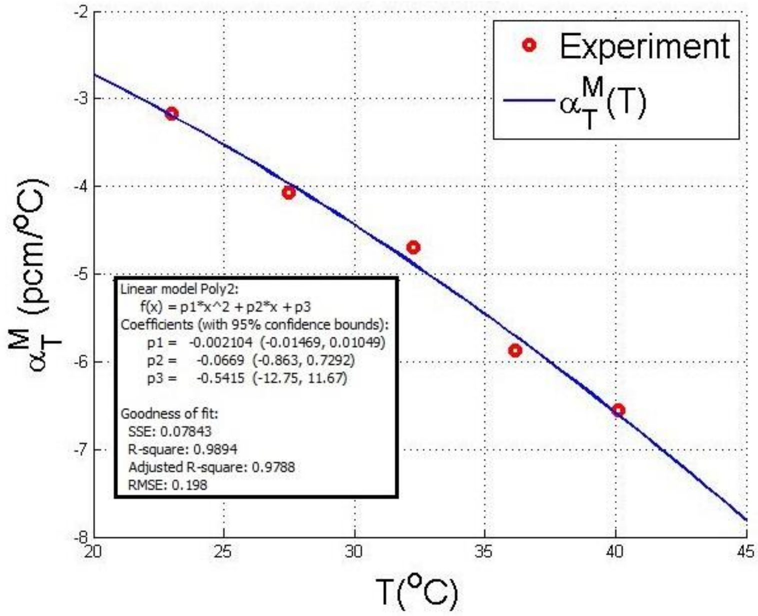

Figure 9: $\alpha_T^M(T)$ Curve (Experiment).

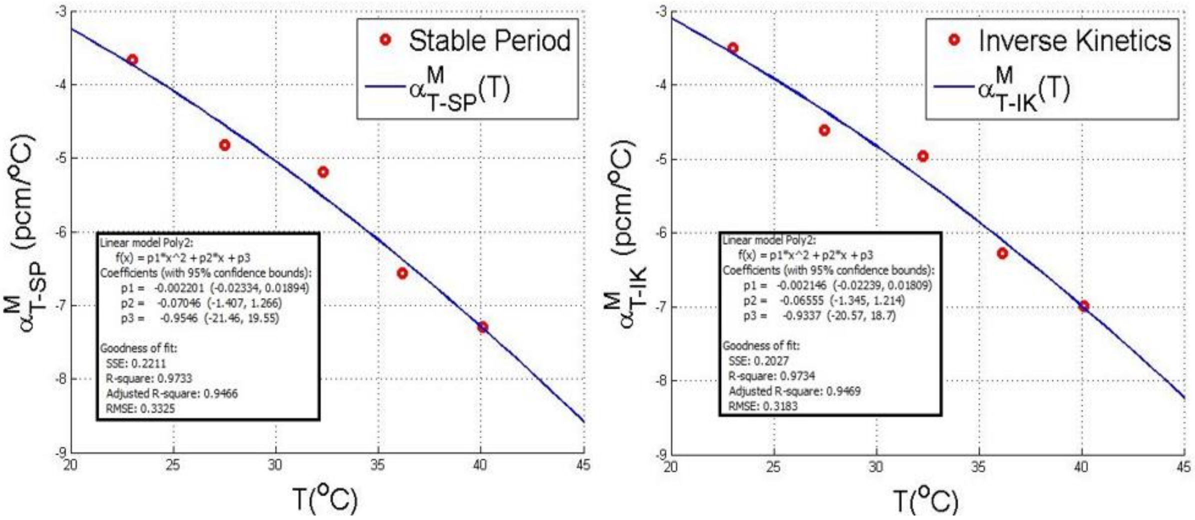

Figure 10: $\alpha_T^M(T)$ Curves (Stable Period and Inverse Kinetics Methods).

The $\alpha_T^M(T)$ curves, represented by equations 9, 10 and 11, are second-degree polynomials with determination coefficients (R^2) close to the unit, which shows adherence between regressions and values of the moderator temperature coefficient of reactivity. Moreover, Fig. 11 shows the comparison between the obtained $\alpha_T^M(T)$ curves.

$$\alpha_{\mathrm{T}}^{\mathrm{M}}(\mathrm{T}) = -0.002104\mathrm{T}^2 - 0.0669\mathrm{T} - 0.5415 \quad (9)$$

$$\alpha_{\mathrm{T\,SP}}^{\mathrm{M}}(\mathrm{T}) = -0.002201\mathrm{T}^2 - 0.07046\mathrm{T} - 0.9546 \quad (10)$$

$$\alpha_{\mathrm{T\,IK}}^{\mathrm{M}}(\mathrm{T}) = -0.002146\mathrm{T}^2 - 0.06555\mathrm{T} - 0.9337 \quad (11)$$

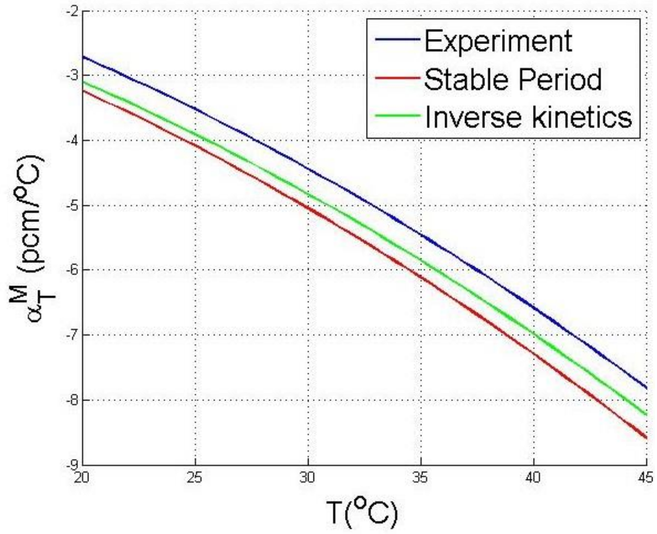

Figure 11: Comparison between $\alpha_{\mathrm{T}}^{\mathrm{M}}(\mathrm{T})$, $\alpha_{\mathrm{T\,SP}}^{\mathrm{M}}(\mathrm{T})$ and $\alpha_{\mathrm{T}\,IK}^{\mathrm{M}}(\mathrm{T})$ Curves.

Based on the obtained values from equations (9), (10) and (11), mean differences of 13.3% were found between $\alpha_{\mathrm{T\,SP}}^{\mathrm{M}}(\mathrm{T})$ and $\alpha_{\mathrm{T}}^{\mathrm{M}}(\mathrm{T})$, and 8.5% between $\alpha_{\mathrm{T\,IK}}^{\mathrm{M}}(\mathrm{T})$ and $\alpha_{\mathrm{T}}^{\mathrm{M}}(\mathrm{T})$. It is worth mentioning that the differential reactivity curves obtained in [10] could be used; however, since the results were not significantly different, only the values obtained in the integral reactivity curves were used.

5.4. Mean Value of $\alpha_{\mathrm{T}}^{\mathrm{M}}$

The CR2 was inserted until its initial position and the value of -104.33 pcm of reactivity of the interval considered was obtained. Thus, it is possible to calculate the mean value of $\alpha_{\mathrm{T}}^{\mathrm{M}}$ for the adopted temperature interval:

- $\overline{\alpha_{\mathrm{T}}^{\mathrm{M}}} = \frac{\Delta\rho}{\Delta\mathrm{T}} = \frac{-104.33}{40.1-18.42}$ = -4.81 pcm/°C;

In the same way, the mean values of $\alpha_{\mathrm{T\,SP}}^{\mathrm{M}}$ and $\alpha_{\mathrm{T\,IK}}^{\mathrm{M}}$ were calculated using the value of $\Delta\rho$ obtained using the equations (5) and (6) and the temperature variations:

- $\overline{\alpha_{\mathrm{T\,SP}}^{\mathrm{M}}} = \frac{\Delta\rho_{SP}}{\Delta\mathrm{T}} = \frac{-117.41}{40.1-18.42}$ = -5.41 pcm/°C;
- $\overline{\alpha_{\mathrm{T\,IK}}^{\mathrm{M}}} = \frac{\Delta\rho_{IK}}{\Delta\mathrm{T}} = \frac{-112.39}{40.1-18.42}$ = -5.18 pcm/°C;

6. CONCLUSIONS

Based on the obtained results, it was found negative values of moderator temperature coefficient of reactivity, which module increases with temperature. Such fact is desirable to achieve a safe reactor, since temperature and reactivity are anti-correlated magnitudes. The obtained $\alpha_{T}^{M}(T)$ curves are important to study the behavior of the core reactivity with a heavy water reflector.

This experiment may be considered an important benchmark in the IPEN/MB-01 reactor, providing data about how a heavy water reflector can affect some reactor physics parameters. Moreover, it was possible to notice that the temperature coefficients of reactivity, as well as the role of a heavy water reflector, are very important in the safety and stability of nuclear reactors. The correct determination of this parameter by experimental or analytical methods in early stage of the project design, is highly important to achieve a safe and effective reactor operation.

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