Analysis of MARIA Reactor Safety Based on Efficiency Measurement of Shim Rod Using Method of Fixed Period

Hafizh Fatah Rachmatulloh[1], Krzysztof Pytel[2], and Aulia Siti Aisjah[3]

Abstract— **An experiment was conducted in MARIA reactor as the part of reactivity measurement inside the reactor using method of fixed period while MARIA reactor was being started up. It was important as performance indicator that shim rod worked well and able to maintain reactivity on the level not exceeding the value of 1$ by compensating the excess reactivity to provide reactor safety. The measurement was done directly at MARIA reactor control room on April 28th, 2015 using digital reactimeter, therefore, it allowed performing continuous measurement of reactor reactivity. Data at shim rod – 5 (PK-5) was collected, with time interval 0.49 S. Preliminary calculations were done by neglecting the presence of photoneutrons. For the result, at full shim rod insertion (1067 mm) absorbed reactivity with value 0,92$ was obtained. The result showed that the shim rod worked well because the reactivity never exceeding 1$. The result as an early parameter that guarantees MARIA reactor safety from burning out the claddings of fuel elements and radiological accident.**

Keywords— **reactivity, shim rod, MARIA reactor, and safety.**

Abstrak— ***Sebuah eksperimen dilakukan di reaktor MARIA sebagai bagian dari pengukuran reaktivitas didalam reaktor menggunakan metode periode tetap ketika reaktor MARIA sedang mulai dioperasikan. Ini merupakan hal yang penting sebagai indikator performansi bahwa batang kompensasi berfungsi dengan baik dan mampu mempertahankan reaktivitas pada tingkat yang tidak melebihi dari nilai 1$ dengan mengkompensasi kelebihan reaktivitas untuk menjamin keamanan reaktor. Pengukuran dilakukan secara langsung di ruang kontrol reaktor MARIA pada 28 April 2015, menggunakan reaktimeter digital karena memberikan keleluasaan untuk melakukan pengukuran terus menerus terhadap reaktivitas reaktor. Pengumpulan data dilakukan di batang kompensasi – 5 (PK-5) dengan interval waktu 0,49 S. Perhitungan awal dilakukan dengan mengabaikan keberadaan dari fotoneutron. Hasilnya, diperoleh bahwa pada 0 mm penempatan batang kompensasi menyerap reaktivitas dengan nilai 0,92$. Hasil ini menunjukkan bahwa batang kompensasi berfungsi dengan baik karean reaktivitas tidak pernah melebihi nilai 1$. Hasil ini sebagai parameter awal yang menjamin keamanan reaktor MARIA dari terbakarnya selongsong elemen bahan bakar dan kecelakaan radiologi.***

Kata Kunci—***reaktivitas, batang kompensasi, reaktor MARIA dan keamanan.***

I. INTRODUCTION

Ensuring the safety and minimize the risk of accident, controlling the reactivity of nuclear reactor well and precisely while being operated is needed [1]. Controlling help to set the output fit with the set point that already made, however, its efficiency is one of the keys that explain the effectivity of one control method. In this work, the experiment was conducted using the method of fixed period to measure the reactivity in MARIA reactor. MARIA reactor is research nuclear reactor in Świerk, Poland. It is a pool-type reactor so it has beryllium and water as moderator and water cooling system [2]. The maximum amount of powers that can be produced by MARIA reactor is 30 MW [3].

In order to know about MARIA reactor safety while being operated, Performance analysis of shim rod efficiency to control and maintain the positive reactivity not surpassing 1$ was done. Reactor power control can be done by controlling the reactivity by adjusting the position of the control rods [4].

As it is known, there are three reactivities phase on nuclear reactor while it is being operated. Critical (when $\delta k = 0$), subcritical (when $\delta k < 0$), and supercritical (when $\delta k > 0$) [5]. A fundamental role in overtaking control of reactor is contributed by delayed neutrons. The necessary to increase the power of reactor obtained by higher multiplication factor than 1 is and can be achieved by means of the small addition of the delayed neutrons. However, the power of reactor would have been increasing exponentially in very quick time (order of milliseconds) endangering to burn-out the claddings of fuel elements and the radiological disaster is led when the reactivity value exceeding more than 1$.

The measurements of reactivity in research reactor as one of most substantial exploitation measurements, due to the development of Digital Meter of Reactivity (DMR) allowing to perform continuous measurement of reactor reactivity and made reactivity measurement more precise and simple[6]. In general using computer techniques to give the effective performance of such measurements.

II. METHOD

On April 28th, reactivity measurements on MARIA Reactor were performed. Data at shim rod PK-5 was collected, with time interval 0.49 S. Preliminary calculations were done by neglecting the presence of photoneutrons. At first, shim rod that is selected for measurement (PK-5) positioned fully inserted into the

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core (on lowest position). While another shim rod was in the highest position. The reactor started up and as the reactor reached a critical state, it was still manually controlled while recording the power run at least 60 seconds before lifting the rod PK-5. Lifting of the rod PK-5 from initial height to another height (Δh) slowly lead to increasing the power exponentially. Along with power growth, measured positive reactivity induced by rod lifting (Δρ) was being carried out. Then, controller intervened this condition by pulling down the other shim rod to control the reaction inside the reactor to reach a critical state in a new position of rod PK-5 settled at the previous step.

During this process, the reactivity is measured and monitored in control room using digital reactimeter so it allowed performing the continuous measurement. The data acquired from this experiment; reactivity, time, and rod movement in order to calculate reactivity calculation and make calibration curve for the rod.

A. Preliminary Calculation

At first, the value of the effective fraction of delayed neutrons was calculated and then obtained. The value of fractions and decay constants of neutrons and photoneutrons can be seen in table 1. Then, calculating relative fractions of 6 group of the delayed neutrons while neglecting the 9 groups of photoneutrons using equation as follows:

$$\beta_i' = \frac{\gamma^d \beta_i^d}{\beta_{ef}} \tag{1}$$

$$\beta_i' = \frac{\gamma^d \beta_i^d}{\beta_{ef}} \tag{2}$$

The initial power was obtained by averaging the value for an initial segment of the steady-state (critical), for each lifting movement of rod PK-5. In kinetics calculation, the ratio of the effective fraction of delayed neutrons with an effective lifetime of neutron generation at that time on MARIA reactor was 48 s-1 and can be considered as constant value for any core configuration[5]. As the power is measured in identical time intervals, numerical calculating of reactivity used the equation:

$$e_i = e^{-\lambda_i \Delta t} \tag{2}$$

$$b_i^1 = \frac{1}{\lambda_i} - \frac{1 - e_i}{\lambda_i^2 \Delta t} \tag{3}$$

$$b_1^0 = \frac{1 - e_i}{\lambda_i} - b_i^1 \tag{4}$$

$$\rho_0 = -\frac{\Lambda S}{\beta_{eff} . n_0} \tag{5}$$

B. Reactivity Calculation (Ignoring Neutron Source)

Describing the change of reactor power per unit of time is facilitated using point reactor kinetics equation for constant neutron source and existence of photoneutrons. Thus, it can be written as follows [5],

$$\frac{dn}{dt} = \frac{(\rho - 1)\beta_{eff}}{\Lambda} n + \sum_{i=1}^{6} \lambda_i C_i^d + \sum_{j=1}^{9} \lambda_j C_j^p + S \tag{6}$$

With power corresponding the delayed neutrons and photoneutrons,

$$\frac{dC_i^d}{dt} = \frac{\gamma^d \beta_i^d}{\Lambda} n - \lambda_i C_i^d, \ i = 1 \ldots 6 \tag{7}$$

$$\frac{dC_j^p}{dt} = \frac{\gamma^p \beta_j^p}{\Lambda} n - \lambda_j C_j^p, \ j = 1 \ldots 9 \tag{8}$$

The notion of the steady-state is bound with a determination of initial conditions for the set of equations (1), (2) and (7) to be indispensable for its solution. In the measuring practice, the initial conditions are to be determined for the steady-state corresponding the zeroing in reactivity ρ=0 (without the source) after an infinitely long period of time. These conditions are of the form:

$$n(0) = n_0 \tag{9}$$

$$C_i^d(0) = \frac{\gamma^d \beta_i^d}{\Lambda \lambda_i} n_0 \qquad i = 1 \ldots 6 \tag{10}$$

$$C_j^p(0) = \frac{\gamma^p \beta_j^p}{\Lambda \lambda_j} n_0 \qquad i = 1 \ldots 9 \tag{11}$$

to assume that the reactor operation time on constant power has been infinitely long (usually it is to be a dozen or several dozens of minutes), therefore both initial conditions (11) and (12) should be rewritten as:

$$n(0) = n_0 \tag{12}$$

$$C_i^d(0) = \frac{\gamma^d \beta_i^d}{\Lambda \lambda_i} n_0 (1 - e^{-\lambda_i \tau}) \qquad i = 1 \ldots 6 \tag{13}$$

$$C_j^p(0) = \frac{\gamma^p \beta_i^p}{\Lambda \lambda_j} n_0 (1 - e^{-\lambda_j \tau}) \qquad i = 1 \ldots 9 \tag{14}$$

Where τ is reactor operation time on stable power and assuming the initial conditions (13), (14) and (15), one can reduce the differential equations (7) to the differential-integral equation:

$$\frac{\Lambda}{\beta_{eff}}.\frac{dn(t)}{dt} = [\rho(t) - 1]n(t)$$

$$+ n_0\sum_{i=1}^{15}\beta'_i\left(1 - e^{-\lambda_i\tau}\right)e^{-\lambda_i\tau}$$

$$+ \sum_{i=1}^{15}\beta'_i\lambda_i\int_0^1 e^{-\lambda_i(t-x)}n(x)dx$$

$$+ \frac{\Lambda}{\beta_{eff}}S \tag{16}$$

After converting the equation (16) one receives a basic formula for reactor reactivity:

$$\rho(t) = 1 + \frac{\Lambda}{\beta_{eff}}.\frac{d\ln n(t)}{dt}$$

$$+ \frac{n_0}{n(t)}\sum_{i=1}^{15}\beta'_i\left(1 - e^{-\lambda_i\tau}\right)e^{-\lambda_i\tau}$$

$$+ \frac{1}{n(t)}\sum_{i=1}^{15}\beta'_i\lambda_i\int_0^1 e^{-\lambda_i(t-x)}n(x)dx$$

$$+ \frac{\Lambda S}{n(t).\ \beta_{eff}} \tag{17}$$

The only measurable value is the reactor power n(t) (by the reactor power one understands any parameter proportional to the reactor power, e.g. neutrons flux in the place where the neutron detector is positioned).The power is measured in identical time intervals Δt. When numerical calculating of the reactivity, instead of formula (17) a recurrent scheme is being used:

$$F_i(t) = e_iF_i(t - \Delta t) + n(t - \Delta t).\frac{b_i^0}{n_0} + n(t)\frac{b_i^0}{n_0} \tag{18}$$

$$G_i(t) = e_iG_i(t - \Delta t) \tag{19}$$

$$\rho(t) = 1 + \frac{\Lambda}{\beta_{eff}}.\frac{\ln\left(\frac{n(t)}{n(t - \Delta t)}\right)}{\Delta t}$$

$$-\left\{\sum_i\beta'_i[\lambda_iF_i(t) + G_i(t)] - \rho_0\right\}.\frac{n_0}{n(t)} \tag{20}$$

With the initial conditions,

$$F_i(0) = 0$$

$$G_i(0) = 1 - e^{-\lambda_i\tau}$$

$$n(0) = n_0 \tag{21}$$

C. *Reactivity Calculation with a Correction of The Neutron Source Effect*

In the case of the reactor with the source into another state with a constant reactivity: ρ1 = const. In the situation when reactivity ρ1 > 0 the time of reactivity change from ρ0 to ρ1 usually lasts several dozens of seconds. The reactivity change from ρ0 to ρ1 < 0 is to be achieved even very quickly (time span of ca. 0.5 sec) if one makes a drop of absorbing rod. A recurrent algorithm described by equation (16) should reconstruct the course of reactivity changes ρ(t) from the initial steady state ρ0 to the final state ρ1.

Substituting this equation below to equation (20):

$$\rho^{'(t)} = \rho(t) - \frac{n_0\rho_0}{n(t)} \tag{22}$$

Assuming that the source of neutrons is not taken into consideration in this calculation, therefore the recurrence equation for reactivity is in the form:

$$\rho'(t) = 1 + \frac{\Lambda}{\beta_{eff}}.\frac{\ln\left(\frac{n(t)}{n(t - \Delta t)}\right)}{\Delta t}$$

$$-\left\{\sum_i\beta'_i[\lambda_iF_i(t) + G_i(t)]\right\}.\frac{n_0}{n(t)} \tag{23}$$

And calculation real reactivity variation after correcting is done by the equation below:

$$\rho^{'(t)} = \rho(t) - \frac{n_0\rho_0}{n(t)} \tag{24}$$

III. RESULTS AND DISCUSSION

The calculation of relative fractions of 6 group of the delayed neutrons and initial power run basic has done in the preliminary calculations, as a result, the initial power run is the average value of power run per time unit for an early segment of the steady-state caused by control rod movement. The power runs increase exponentially in this process. The sum of relative fractions of 6 groups of the delayed neutrons is 1. The matter neglecting the presence of photoneutrons in the measurement of reactivity because its emergence brings serious difficulties in reactivity measurements on small power levels of the reactor (such as MARIA). The average life time for photoneutrons is 3.4 hours on the other hand for the delayed neutrons is 12.8 seconds [5]. Thus it creates a very hard situation to meet the conditions of steady-state during the measurements. In the other side both efficiency values for delayed neutrons and photoneutrons for MARIA reactor respectively 1.19 and 1.031[7]. Because of minor in comparison with delayed neutrons, the fraction of photoneutrons in over all balance of neutrons and inaccuracy caused by neglecting the photoneutrons presence on the results of reactivity measurements still acceptable.

By the data that has been recorded, 6 group of shim rod's movement specifically 0-258 mm, 258-360 mm, 360-463 mm, 463-568 mm, 568-706 mm, 706-1067 mm was created whilst the power run for each of group change per unit of time and for the initial power of reactor 587,07, 560,53, 570,03, 604, 46, 63781, 665,5. From figure 1 until figure 6 it clearly sees how reactivity response for each of shim rod adjusting movement.

The difficulties to define the reactivity reactor in steady state condition leads to determine reactor reactivity assuming that the initial condition is zero and assuming without neutron source. It has satisfied result as this result facilitate to determine the final value of reactivity after correction. Due to advanced and continuous measurement, the difference value of reactivity before correction and after correction occur at order 10-5 which it is not significant and not influencing the final result.

For each of the length of shim rod that left inside the reactor (by means of lifted up) at 1067 mm, 706 mm, 568 mm, 463 mm, 360 mm, 258 mm, and 0 mm reactor the value of reactivity respectively 0, -0.1, -0.23, -0.383, -0.546, -0.7185, -0.9185 was obtained.

CONCLUSION

From table 2. and by observing figure 7. It is clearly able to see that the curve resembling "S", indicate that for every distance while the rod is being pulled up away from its initial position (inside the reactor) the reactivity of reactor is going to be increased. Respectively for 1067 mm, 706 mm, 568 mm, 463 mm, 360 mm, 258 mm, and 0 mm shim rod insertion that left inside the reactor the value of reactivities are 0$, -0,1$, 0,23$, -0,383$, -0,546$, -0,7185$, and -0,9185$. Thanks to the good shim rod performances thus the reactivity of reactor never exceeding 1$ which means that the safety of MARIA reactor is satisfied and in good condition.

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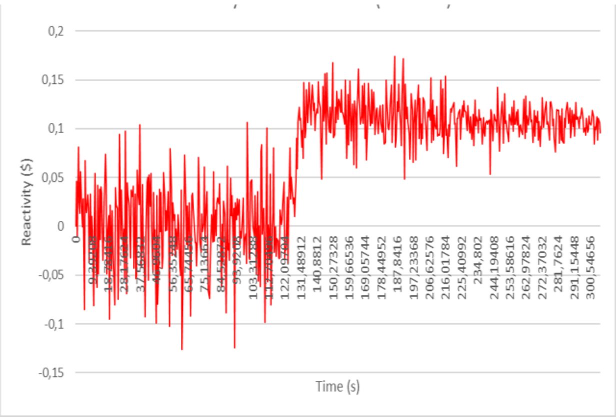

Figure 1. Reactivity after correction at 0-258 rod insertion

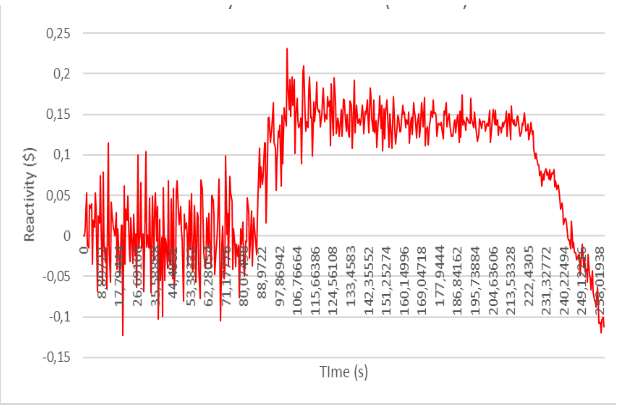

Figure 2. Reactivity after correction at 258-360 rod insertion

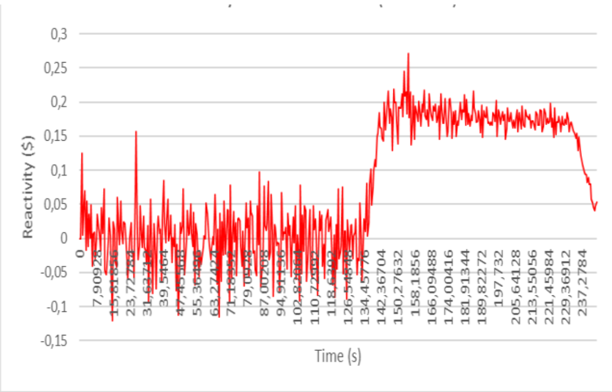

Figure 3. Reactivity after correction at 360-463 rod insertion

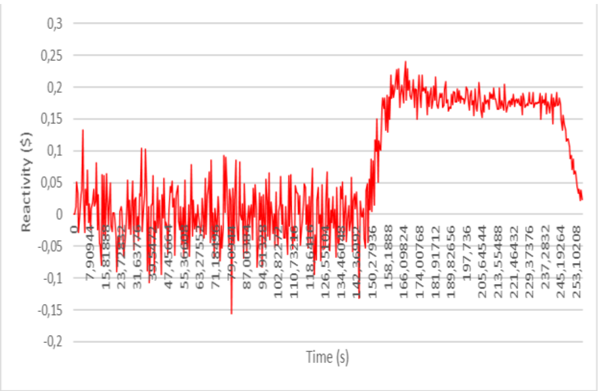

Figure 5. Reactivity after correction at 568-706 rod insertion

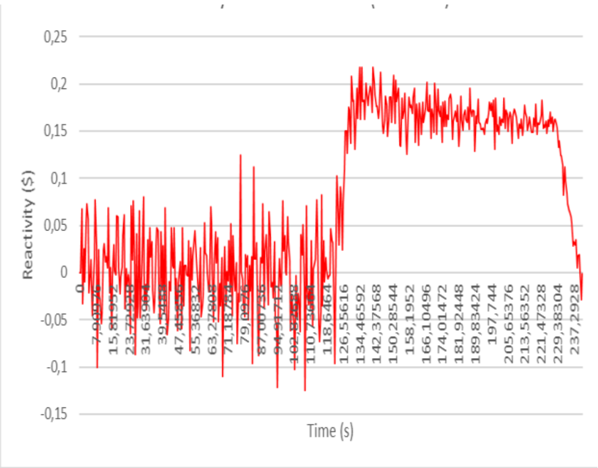

Figure 4. Reactivity after correction at 463-568 rod insertion

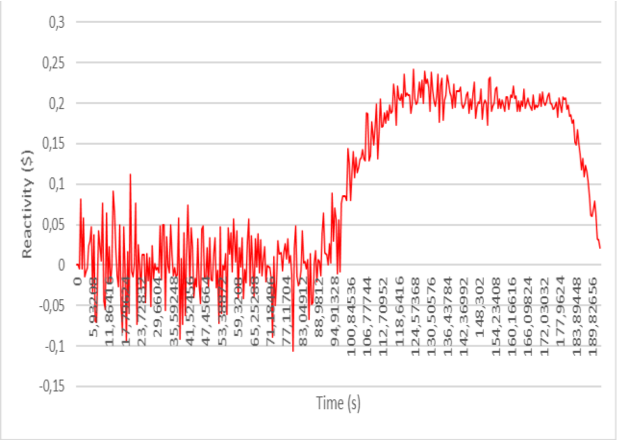

Figure 6. Reactivity after correction at 706-1067 rod insertion

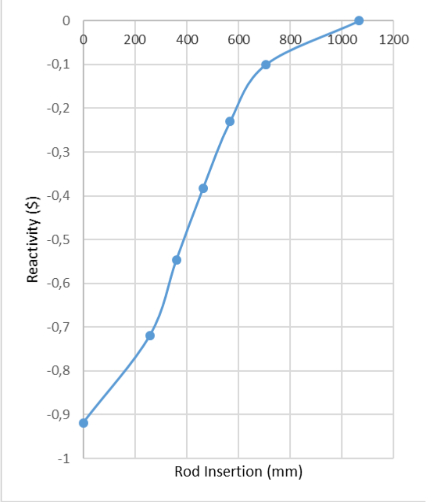

Figure 7. Calibration curve for shim rod

TABLE 1.
FRACTIONS AND DECAY CONSTANTS OF NEUTRONS AND PHOTONEUTRONS

	Delayed Neutrons			Photoneutrons	
NO	$\beta_i^d.10^3$	$\lambda_i 1/s$	NO	$\beta_j^p.10^6$	$\lambda_i 1/s$
1	0.243	0.0127	1	20.7	2.265E-2
2	1.363	0.0317	2	36.6	8.886E-3
3	1.203	0.115	3	18.5	3.610E-3
4	2.605	0.311	4	36.8	7.453E-4
5	0.819	1.4	5	3.66	2.674E-4
6	0.167	3.87	6	32.0	6.191E-5
			7	2.60	1.591E-5
			8	0.38	2.478E-6
			9	0.57	6.098E-7
	$\sum \beta_i^d = 6.4 \times 10^{-3}$			$\sum \beta_j^p = 1.5175 \times 10^{-4}$	

TABLE 2.
ROD INSERTION VERSUS REACTIVITY

The length of the Rod (mm)	Reactivity ($)	Positive Reactivity Step ($)
1067	0	0
706	-0.1	0.1
568	-0.23	0.13
463	-0.383	0.153
360	-0.546	0.163
258	-0.7185	0.1725
0	-0.9185	0.2