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The Effect of Burnup on ITU TRIGA Mark II Research Reactor Control Parameters

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ABSTRACT

The fuel temperature, control rod worth, pool water temperature, reactor power, and prompt temperature coefficient are important parameters to define the research reactor system design basis. In this study, change in control rod worth, excess reactivity, neutron flux, and delayed neutron fraction of ITU TRIGA Mark II Research Reactor was calculated for fresh and 55 day-burnt fuel. 3D full core MCNP 6.2 model was used for burnup calculations to obtain the fuel composition in each of the 69 fuel elements. The new core configuration was modelled numerically to create integral rod worth curves of transient, safety, and regulating rods. ENDF/B-VII.1 library was used for the cross section data and rod insertion method was employed for numerical analysis of control rod worth. The rod worth calculation methodology, as well as MCNP model and simulations were benchmarked against the fresh core configuration results for validation and verification. The results showed the change in safety related parameters. The rod worth and excess reactivity are decreased with the burnup. Therefore, a new core configuration is necessary to retrieve the lost reactivity due to burnup by shuffling and/or fresh fuel addition.

1 INTRODUCTION

The ITU TRIGA Mark II Research Reactor is located at Energy Institute in Istanbul Technical University Ayazağa campus. The pool type reactor reached its first criticality in 1979. It has steady state power of 250 kW and has a 1200 MW pulse capacity with its 69 fuel elements [1]. The axial and radial views of the ITU TRIGA Mark II Research Reactor are shown in Figure 1. The control of the reactor is achieved with 3 boron carbide (B_4C) control rods namely transient, safety, and regulating. The reactor is mainly utilized for research and training purposes. The reactor has in-core and out-of-core irradiation ports. The maximum thermal neutron flux occurs in the central thimble of the core (Figure 2).

Since control rods are important for reactor safety, the accuracy in calculating the control rod worth value is very important. Having a reliable computational model rather than doing experiments is an advantage because it increases the time efficiency while decreasing the dependency on experiments. On the other hand, experimental data provide opportunity to validate numerical models. Another important concept of reactor control and core lifetime is excess reactivity. Enough excess reactivity must be provided at the beginning of fuel cycle to achieve fuel management requirements. On the other hand, since large excess reactivity requires insertion of large amount of poisons in the reactor core to compensate it, the value of excess reactivity must be carefully selected by taking into account the fact that large excess reactivity requires bigger space and may require removal of fuel elements from the core [2]. In addition, it is known that delayed neutrons generated during the fission process in the reactor are important in terms of controlling the reactor. Since delayed neutrons are situated at lower energy compared to prompt neutrons that are generated at the time of the fission, the probability for them to survive from leakage and resonance absorption is higher than prompt neutrons. Therefore, they become effective when it comes controlling the reactor [3]. From the point of utilisation, research reactors are used for irradiation purposes therefore it is important to know neutron flux distribution in the core. Not only the total flux but also the thermal, epithermal, and fast neutron flux distributions must be known precisely for different reactor utilisation requirements. All the parameters mentioned before change with burnup. As the reactor operates, excess reactivity decreases and neutron flux distribution changes, therefore the value of these parameters must be calculated and/or measured throughout the lifetime of the reactor.

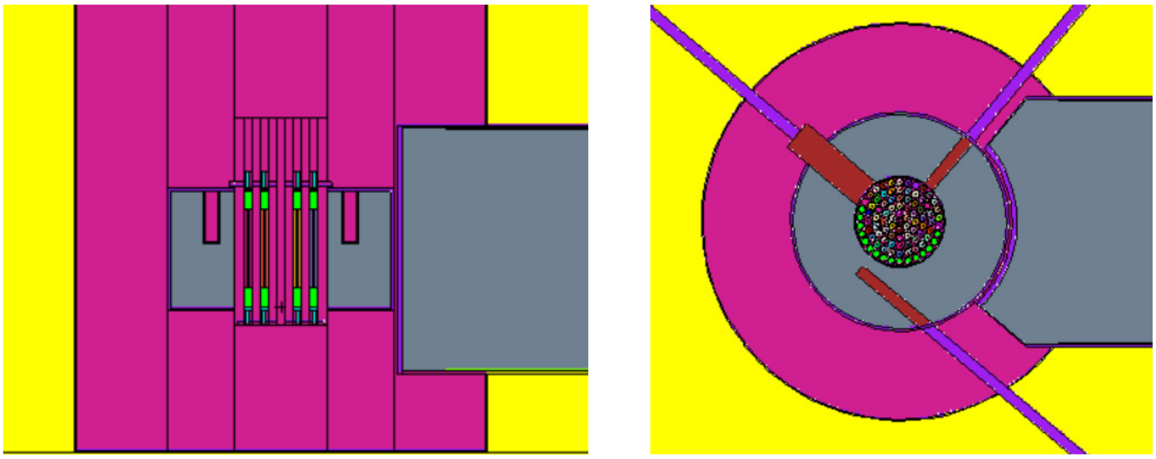

Figure 1 : The axial (left) and radial (right) views of ITU TRIGA Mark II research reactor [1]

In the scope of this study, the integral worth of 3 control rods, excess reactivity of the core, neutron flux behaviour in the central thimble, and delayed neutron fraction of the core of ITU TRIGA Mark II Research Reactor for both fresh and burnt fuel were calculated by using MCNP 6.2 Monte Carlo code [4]. As a result, their behaviour with burnup therefore with time was analysed.

2 METHODS

There are two main purposes of using control rods in nuclear reactors; setting up the reactor power at a preferred level and keeping the reactor critical during the changes in reactivity. Therefore, the accuracy of analysis performed for control rods in nuclear reactors, in terms of safety, is crucial. The rod worth can be calculated from the change in multiplication factor, which is the ratio of number of neutrons in one generation to number of neutrons in preceding generation in the nuclear reactor, that the rod should compensate to keep the reactor at critical state [5]. Since the number of fission events determines the number of neutrons generated, multiplication factor heavily depends on the amount of fission in the reactor. Multiplication factor is represented with “k” and is defined as in Eq. (1) [6].

$$k = \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in preceding generation}} \tag{1}$$

The relation between multiplication factor and the reactivity is shown in Eq. (2) [5]:

$$\rho = \frac{k-k_0}{k}, \tag{2}$$

Where ρ represents the reactivity, k and k_0 represent the multiplication factors of two sequential generations. The control rod worth (ρ_w) can then be calculated by the difference between the reactivity of two states where the control rod is fully out and in (ρ_{out}, ρ_{in}) positions (Eq. (3)).

$$\rho_w = \rho_{out} - \rho_{in}, \tag{3}$$

For the numerical analyses, creating a correct simulation for control rod worth calculations is very important since even small differences in the simulation model may create momentous errors for the calculated multiplication factor values [7]. Therefore, making benchmark analysis between the numerical and experimental results is important to be able to validate the numerical models.

In this study, the integral control rod worth curves of ITU TRIGA Mark II research reactor were numerically obtained via rod insertion method by using 3D MCNP model of the reactor and Eq. (3) although the rod worth analysis of ITU TRIGA Mark II research reactor was experimentally done by using the positive period method. The positive period method and theory behind it are explained by Asuku et al. [8]. In Monte Carlo simulations, the control rod of interest was inserted in the core by using the same step size of the experiments. Reactivity difference between steps then gave the reactivity inserted per unit movement of the rod. The static integral control rod worth then was obtained from the total inserted reactivity. The procedure described was performed for both fresh and burnt fuel compositions for each individual control rod. In order to calculate the rod worth of each control rod for burnt fuel case, the burnup calculations were performed by considering the total usage of the reactor since first criticality in 1979 with MCNP 6.2 Monte Carlo code. It was assumed that the reactor was operated for 55 effective full power days, i.e., at 250 kW power. The fuel element compositions from burnup calculations were extracted individually for all 69 fuel elements to create new model with new fuel compositions. Together with control rod calculations, excess reactivity (ρ_{ex}) was obtained by using multiplication factors of the cases where the all control rods are out of the core. Multiplication factors for this part of the study were estimated with criticality analysis by using the KCODE feature of the MCNP code.

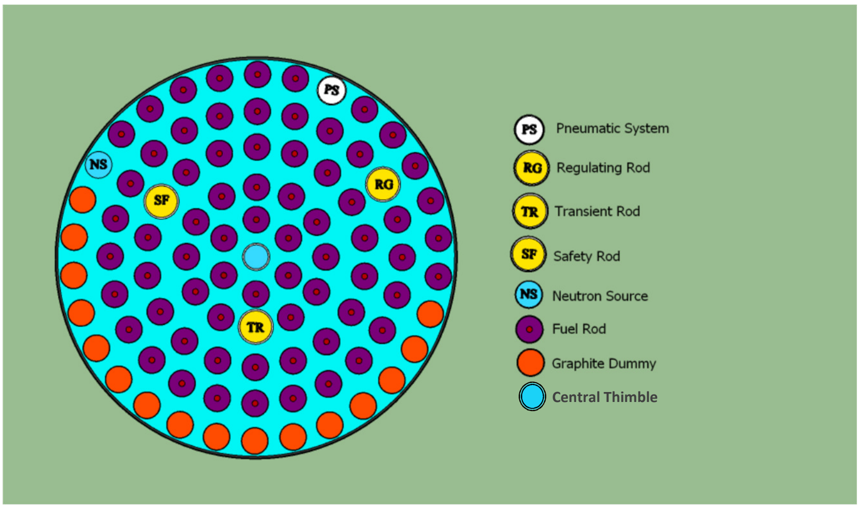

Figure 2: Radial view of ITU TRIGA Mark II research reactor with a central thimble in the center [1]

The delayed neutron fraction (β) is the ratio of delayed neutrons to the all generated neutrons. The ratio of delayed neutrons born in thermal energies to all fission neutrons represents the effective delayed neutron fraction (β_{eff}). β_{eff} for both fresh fuel and burnt fuel core configurations were estimated using the KOPTS card in MCNP 6.2 code. This calculation was performed because of the fact that rod worth results are generally presented in the unit of dollars using the delayed neutron fraction since effective delayed neutron fraction represents one dollar of reactivity [9]. Relation between the delayed neutron fraction and the reactivity in dollars is given in Eq. (3) [10].

$$\$1 = \frac{\rho}{\beta}, 1 \text{ cent} = \$\frac{1}{100} = \frac{\rho}{100\beta} \tag{3}$$

Finally, the axial neutron flux distribution was obtained in the central thimble of the core for fresh and burnt fuel configurations. Neutron flux simulations were done when all control rods are fully out for both fresh and burnt fuel configurations. For numerical flux analysis, FMESH tally card of the MCNP code was implemented with F4 flux tally. Since MCNP results are normalised to one source neutron, calculated F4 tally flux values (φ_{F4}) were scaled by using Eq. (5) [11].

$$\varphi = \frac{P\bar{\vartheta}}{\left(1.6022 * 10^{-13}\frac{J}{MeV}\right)w_f}\frac{1}{k_{eff}}\varphi_{F4} \tag{5}$$

Here, φ is the actual flux (neutrons/cm^{2}s), P is the power level of reactor which is 250 kW, $\bar{\vartheta}$ is the average number of neutrons generated per fission wich is 2.439 according to MCNP simulations, w_f is energy released per fission event which is about 200 MeV, k_{eff} is the effective multiplication factor which is taken from MCNP KCODE simulation, and φ_{F4} is F4 tally flux (1/cm^2) obtained from MCNP output. In order to show the group fluxes, the group energy boundaries were taken as 0-0.625 eV for thermal, 0.625 eV-0.1 MeV for epithermal and 0.1-20 MeV for fast neutrons for flux calculations.

3 RESULTS

Total control rod worth of transient, safety and regulating rods can be seen from Table 1. It can be seen from the table that experimental and numerical method results for fresh fuel configuration are in good agreement. Additionally, as it is expected, rod worth values for burnt fuel configuration is lower than the ones for fresh fuel. Standard deviation value for criticality (k) values obtained from MCNP results that are used for the calculation of control rod worth values is about 10^{-4}, which is very low.

Table 1: Control rod worth values from experimental and numerical methods

Control Rod	Dynamic Rod Worth Values from Experiment	Static Rod Worth Values from Simulaitons (Fresh Fuel)	Relative Error between experimental and numerical results for fresh fuel (%)	Static Rod Worth Values from Simulations (Burnt Fuel)
Transient	\$3.16	\$3.120	1.96	\$2.878
Safety	\$2.18	\$2.220	1.83	\$1.982
Regulating	\$1.84	\$1.864	1.30	\$1.618
Total	\$7.18	\$7.204	~0.00	\$6.478

Integral rod worth curves can be seen from Figure 3, Figure 4, and Figure 5 for transient, safety and regulating control rods respectively for both fresh and burnt fuel configurations. As it can be seen from these figures, the “S” shape for integral rod worth curves are obtained from numerical (MCNP) analysis as in the experiment for fresh fuel configuration. It can also be seen that integral worth curves are in very good agreement for safety and regulating control rods. Even though total integral rod worth value for transient rod is in good agreement with the experimental value, the shape of the curve does not match completely with the experimental one, especially in the middle region of the core. This happens because of the fact that in Monte Carlo simulations homogeneous composition distribution in the fuel element was assumed. In reality, there is a cosine axial distribution of burnup in fuel element [12]. The results also show that the transient rod has the highest worth in the core because it is closer to the centre of the core than other control rods. Therefore, its effect on absorption is the highest compared to the other rods and integral worth curve differs mostly for transient rod, even though the total rod worth is in good agreement with experimental result. Besides all, the starting point of rod insertion method and the step size for movement also have effects when it comes comparing the shape of the curves [13].

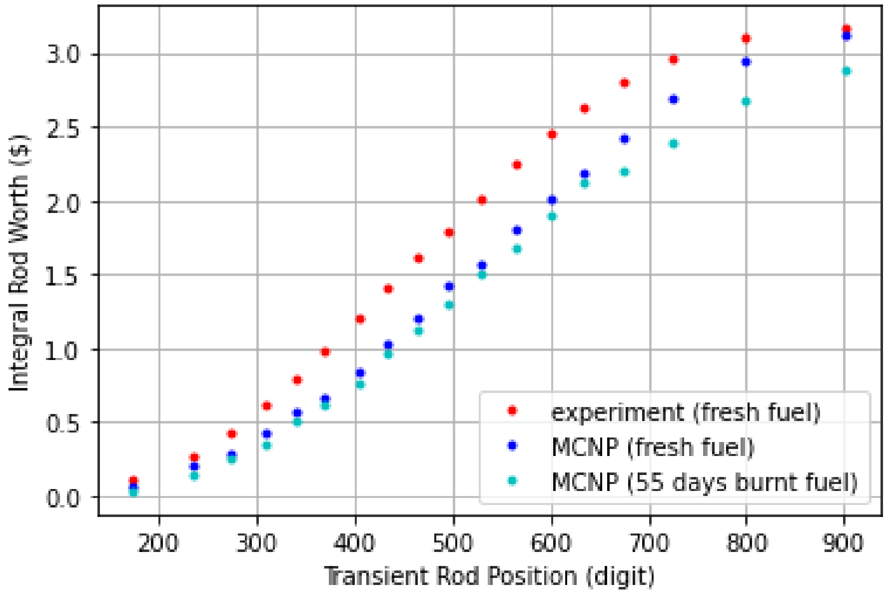

Figure 3: Integral rod worth curves of transient control rod

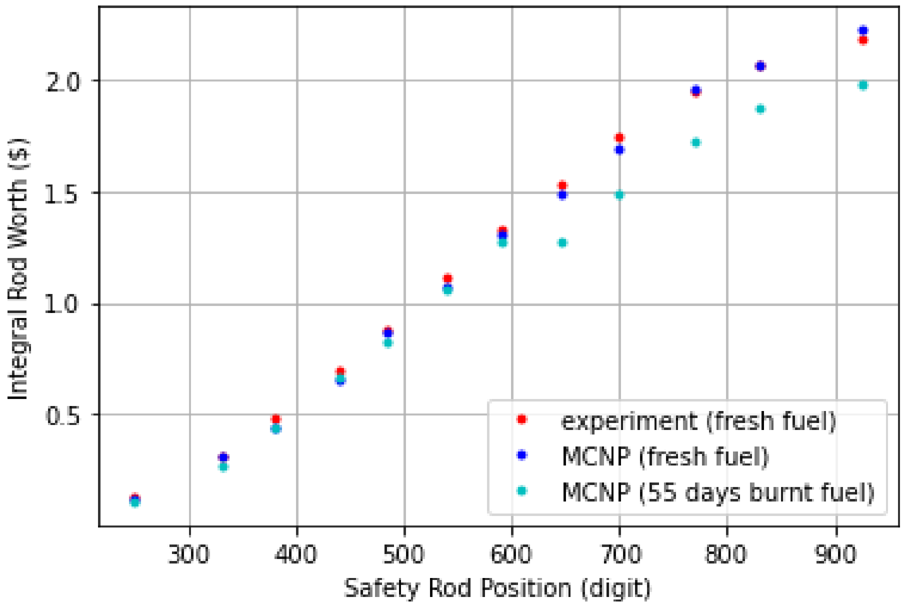

Figure 4: Integral rod worth curves of safety control rod

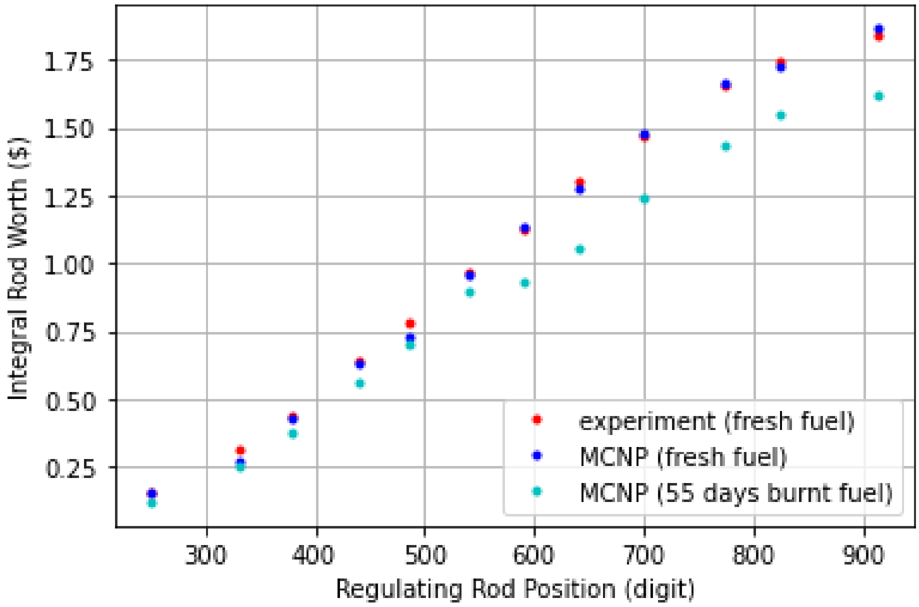

Figure 5: Integral rod worth curves of regulating control rod

As it is expected and seen in Figures 3, 4, and 5, the reactivity inserted per unit movement for 55 days burnt fuel with full power is lower. This happens because of the increase of neutron absorbers which are some of fission products, and the decrease in fissile content in the reactor core. The decrease in the worth can be seen from the integral rod worth curves, especially after the middle of the core where the neutron flux is the highest.

Table 2 shows the k_{eff}, β_{eff}, and ρ_{ex} values for both fresh fuel and burnt fuel configurations out of MCNP simulations. Table 2 indicates that β_{eff} and ρ_{ex} values decreased with the burnup as a result of decrease in the amount of fissile content in the fuel elements. According to Safety Analysis Report and experimental data for fresh fuel configuration; the total reactivity worth of the control rod system is about $7.18 with a maximum core excess reactivity of $3, the shutdown margin with all rods down is about $4.18 and with the most reactive rod stuck out is about $1.02 [14]. For the MCNP simulation results; the total reactivity worth of the control rod system is about $7.204 with a maximum core excess reactivity of $3.11, the shutdown margin with all rods down is about $4.094 and with the most reactive rod stuck out is about $0.974 for fresh fuel configuration. This shows that the relative errors between shutdown margins are 2.1% and 4.5% for all control rods down and most reactive rod stuck cases respectively. The shutdown margin for 55 days burnt fuel according to MCNP simulation results with all control rods down is about $5.68 and with the most reactive rod stuck is $2.8.

Table 2: k_{eff}, β_{eff}, and ρ_{ex} values for both fresh fuel and burnt fuel configurations

	k_{eff} (MCNP)	β_{eff} (MCNP)	ρ_{ex} ($)
Fresh fuel	1.02293 ± 0.0001	0.00721	~ 3.11
55 days burnt fuel	1.00609 ± 0.0001	0.00755	~ 0.80

Figure 6 shows the axial group flux distributions at the radial centre of the central thimble. Since central thimble is placed 60 cm above of the reactor tank bottom, the axial legend starts from 60 in the Figure 6. The zero flux values at the top of the cental thimble are because of the fact that corresponding axial regions in the fuel do not contain fissile materials. These regions of the fuel elements are called top graphite plugs. Here, BOL (Beginning of Life) and EOL (End of Life) represent the fresh fuel and 55 days burnt fuel core configurations respectively. It can be seen from Figure 6 that the peak thermal neutron flux at the central thimble of the core is approximately 10^{13} neutrons/cm^{2}s as expected [15]. The statistical uncertainty of the calculated flux values is on the order of 10^{-2}. The obtained spectra for neutron flux with different energies for BOL and EOL is nearly the same, since the burnup is not high for 55 days.

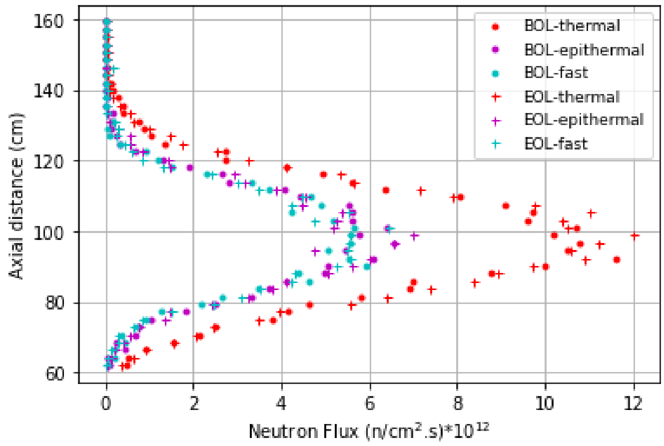

Figure 6: Thermal, epithermal, and fast neutron flux distributions in the central thimble

4 CONCLUSIONS

In this study, change in control rod worth, excess reactivity, neutron flux, and delayed neutron fraction of ITU TRIGA Mark II Research Reactor was calculated for fresh and 55 days burnt fuel. For numerical analyses including burnup calculations, 3D full core MCNP 6.2 model is used. It has been seen that the results for the integral rod worth values of transient, safety and regulating control rods obtained from numerical and experimental methods are in good agreement. Furthermore, the rod worth values decreases with burnup. Additionally, while excess reactivity is \$3.11 for fresh fuel configuration, it decreases to \$0.80 for 55 days burnt fuel configuration. This means that the new core configuration is necessary to compensate the lost reactivity due to burnup by shuffling and/or fresh fuel addition. β_{eff} values for both core configurations are obtained numerically to represent rod worth values and reactivity values in units of dollars. It is 0.00721 for fresh fuel, and 0.00755 for burnt fuel. Finally, the axial neutron flux distributions for different energy groups are obtained at the central thimble which has the highest flux values in the reactor core. Results for the flux values showed a similar behaviour for both fresh and burnt fuel configurations. In general, the results of this study showed the change in safety related parameters of ITU TRIGA Mark II research reactor.

ACKNOWLEDGMENTS

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