A STUDY FOR OBTAINING A BETTER CORE CONFIGURATION OF THE TRIGA MARK-II RESEARCH REACTOR AT AERE

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ABSTRACT

The aim of this study is to get an original idea for a better core configuration of the 3 Mega Watt (MW) TRIGA Mark-II Research Reactor at AERE, Savar, Dhaka. This study is an essential part to support the reactor up gradation project that has been initiated by Bangladesh Atomic Energy Commission (BAEC) to upgrade the 3 MW TRIGA Research Reactor at Atomic Energy Research Establishment, Savar, Dhaka to Higher flux and Power level. This objective was achieved through the analysis of the present core of the reactor to observe the effects of burn-up on some important core parameters such as xenon value, power defect, reactivity worth, flux and power distribution etc. This study includes the optimization of burn-up steps for core lifetime calculation at different power levels, power defect calculation at zero burn-up and at different burn-up steps, flux and power distributions as the function of burn-up, xenon value calculation and reactivity worth calculation. All these calculations are performed with the help of one standard computer code TRIGAP that was specially designed for this TRIGA reactor calculation. Based on all the calculations the initial loading pattern of the core has been modified to obtain a number of new core configurations. The results of the modified core configurations on the thermal flux, fast flux at central thimble and other locations are also studied. The studies with the modified core configuration established that it is possible to upgrade the present core configuration to obtain a better core configuration of higher flux and power level within the safety margin of the 3 MW TRIGA Mark-II Research Reactor.

Key Words: Core parameters, Power defect, Reactivity worth, Flux and Power distribution, TRIGA and TRIGAP.

1.0 INTRODUCTION

The 3 MW TRIGA MARK-II Research Reactor [1] of the Atomic Energy Research Establishment (AERE), Savar, Dhaka is the only reactor of the country. It is a tank type light water cooled, graphite reflected reactor that was designed for training, research and isotope production for their uses in agriculture, medicine and industry. At present the flux level of this reactor at power level 3 MW is 7.46 x1013 neutrons/sq.cm/sec. With the objective of developing a self confidence in nuclear engineering research and for efficient fuel utilization, a project has been initiated by Bangladesh Atomic Energy [2] to upgrade this reactor to higher flux and power level. The aim of the proposed configuration is to increase the flux level at desired locations such as, central thimble and lazy Susan. The goal of the work was the general purpose analysis of the present core of the reactor to examine the effects of burn-up on some important core parameters using the computer code TRIGAP [3]. TRIGAP code was developed for research reactor calculations especially for TRIGA type reactors. TRIGAP package is based on two-group diffusion equation (group boundary at 1 eV). It is solved in the finite differences approximation by fission density iteration method. A database for the TRIGAP code was generated for the

Bangladesh TRIGA Mark-II research reactor [4]. The library was created using the WIMS-D/4 code [5]. The original WIMS cross-section library extended for TRIGA reactor specific nuclides (hydrogen bound in zirconium lattice, erbium) is used.

The reactor core parameters like xenon value, reactivity worth, temperature co-efficient, excess reactivity etc, strongly depend on the number of different fuel rods and also on their loading pattern in the core [6]. In order to determine modified core configurations the reactivity worth of the fuel rod of each ring for fresh core and at different burn-ups were calculated using the computer code TRIGAP. For this calculation a fuel rod was replaced from each ring by water/void respectively. The lowest reactivity worth at different burn-up steps found in D-ring and the worth increases gradually for the E, F and G-ring respectively.

Based on these results four modified (new) core configurations were studied. In the new configuration a graphite rod of C-ring was exchanged with a fuel rod from (D, E, F and G) ring respectively. Consequently four new (modified) core configurations were obtained. The results obtained will be used for better core configuration of this reactor. The core analysis [7] was performed by utilizing five basic types of information such as criticality predictions, flux and power at different burn-ups, xenon-value calculation, power defect and reactivity worth calculation. Therefore, it is observed that 500 MWh burn-up step is the optimum step for core lifetime calculations. With this optimum step the core lifetimes at 1 MWt, 2 MWt and 3 MWt power were calculated. First the validity of the calculation and the generated library were examined. The core excess reactivity at 50 watt was $10.26 which was in good agreement with the experimental value at $10.27. This analysis gives the confidence level for the core loaded with Low Enrichment Uranium (LEU) fuel of this reactor using the computer code TRIGAP and also validates the TRIGA library developed by the WIMS-D/4 code in Bangladesh.

2.0 SOME RELEVANT ASPECTS OF THE REACTOR

The TRIGA MARK-II Research Reactor is situated entirely on the ground. The reactor and experimental facilities are surrounded by a concrete shield structure. Table-1 gives the principal design parameters of the reactor [1].

Table 1: Principal Design Parameters of the TRIGA Mark-II Research Reactor.

Sl. No.	Principal Design Parameters	
1.	Reactor type and Shape	TRIGA Mark-II and Cylindrical
2.	Maximum steady state power level	3000 kW
3.	Maximum pulse	1.4% $\delta k/k$, $ 2.00, 852 MW
4.	Fuel moderator material	U-ZrH (The ratio of H/Zr is 1.6)
5.	Uranium content and enrichment	20 wt% and 19.7% ^{235}U
6.	Burnable poison	0.47 wt% ^{166}Er and ^{166}Er
7.	Length of fuel and its outer diameter	38.1 cm (15 inch) and 3.63 cm (1.43 inch)
8.	Cladding material and its thickness	Type 304 stainless steel and 0.051 cm
9.	Number of fuel elements	100
10.	Total reactivity worth of control rods	10% $\delta k/k$
11.	Maximum excess reactivity	7.0% $\delta k/k$
12.	Number of Control Rods	6
13.	Shim/Safety, Regulating and Transient	4, 1 and 1
14.	Reactor cooling	Forced down flow of pool water

3.0 THE PRESENT CORE CONFIGURATION

The present TRIGA core consists of 100 fuel elements (including 5 fuel follower control rod), 6 control rods, 18 graphite dummy elements, 1 central thimble, 1 pneumatic transfer and 6 source locations. All these elements are placed and supported in between the top and bottom grid plates and arranged in seven concentric hexagonal rings (A, B, C, D, E, F, and G) of a hexagonal lattice. The reactor core and reflector assembly is located at the bottom of 2 meter diameter aluminum tank 8.2 meter deep. About 6.4 meter of water above the core acts as vertical shielding. A 20.3 cm thick graphite radial reflector surrounds the core. The graphite is surrounded by 5 cm of lead except in the adjacent to the beam tubes and the thermal column structure water occupies about one-third of the core volume.

4.0 CORE LIFETIME CALCULATION

The core lifetime in MWh for power level at 1 MW, 2 MW and 3 MW respectively was calculated with optimum burnup step 500 MWh. Two strategies have been formulated to determine the optimum core lifetime: (a) to reshuffle the core at every 20000 MWh and before subcritical at 1 MW and 2 MW power level for only one step interval 500 MWh and (b) without reshuffling before subcritical at 1 MW, 2 MW and 3 MW power level for deferent burn-up steps (250 MWh, 500 MWh, 1000 MWh, 2000 MWh, 2500 MWh).

The reactor core was reshuffled in the steps of 20,000 MWh and before subcritical at the power level of 1 MW and 2 MW. The core life time for this arrangement was 57500 MWh and 48500 MWh respectively. On the other hand, if the reactor core was not reshuffled in these two power levels then the program stopped giving the message, "burn-up exceeds the library limit" at 44500 MWh and 43500 MWh respectively. At last at 3 MW power level the reactor core was not also reshuffled and the core life for different steps (250 MWh, 500 MWh, 1000 MWh, 2000 MWh and 2500 MWh) was calculated. The calculated core lifetimes at different power levels are shown in Table 2.

Table 2: Calculated Results of Core Lifetimes at Different Power Level

Power (MW)	Step	Core Lifetime without Reshuffling (MWh)	Core Lifetime with Reshuffling (MWh)
1	500	44500	57500
2	500	43500	48500
3	250	37500	
	500	38000	
	1000	39000	
	2000	40000	
	2500	40000	

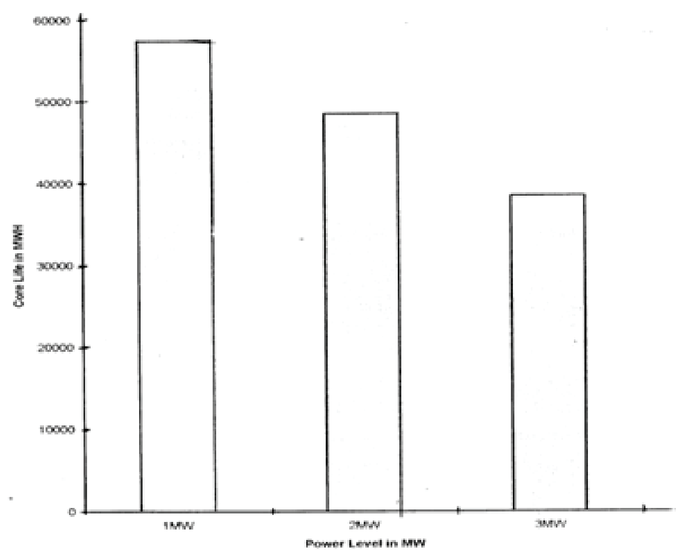


Fig 1: Core Lifetime vs Power Level.

From these results it is possible to estimate about the optimum burn-up step in MWh for which reactor becomes subcritical, and after reaching this subcritical position the burn-up will have no effect on core lifetime of the reactor. Finally, the core life time was plotted against the operating power level shown in the Figure1.

Form figure 1 it is observed that the core lifetime for 3 MW power at 500 MWh burn-up step is 38000 MWh which is minimum and for 1 MW power with the same burn-up step is 57500 MWh with reshuffling core which is maximum compared to 2 MW power level. From this observation it is confirmed that the core lifetime varies with the operating power level.

5.0 POWER DEFECT CALCULATION

Nuclear reactors must be initially loaded with significantly larger amount of fuel than that required merely to achieve criticality. Since the intrinsic multiplication of the core will change during core operation due to processes such as fuel burn-up and fission product production. Sufficient excess reactivity must also be provided to compensate for negative feedback effects such as temperature of power defects of reactivity. Therefore for control management of nuclear reactor, the power defect is a measuring tool and is defined as the change of reactivity between zero power and operating power [8].

The following formulae were used to calculate the temperature or power defect

$$\rho_0 = \frac{K_{eff} - 1}{K_{eff} \times \beta} \text{ in \$ at zero power (50 W)}$$

$$\rho_t = \frac{K_{eff} - 1}{K_{eff} \times \beta} \text{ in \$ at operating power}$$

The temperature or power defect is defined as

$$\Delta\rho = (\rho_1 0 - \rho_1 t) \text{ in \$}$$

Where, K_{eff} = Effective multiplication factor, β =Delayed neutron fraction, ρ_0 = Reactivity at zero power and ρ_t = Reactivity at operating power.

Calculations were done in two strategies viz. (a) power defect calculation at zero burn- up and (b) power defect calculation at burn-up step 5000 MWh. The calculated results are given in Table 3 (at zero burn-up) and Table 4 (at 5000 MWh).

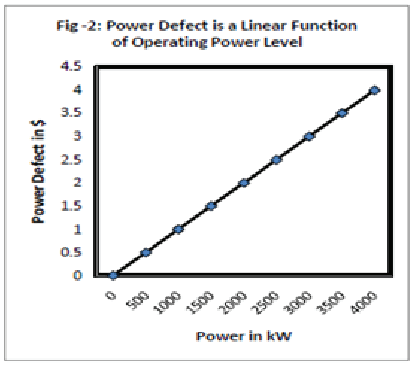
Table 3: Power Defect Calculation at Zero MWh (ρ 0=10.2677 $ at 50 W and no xenon)

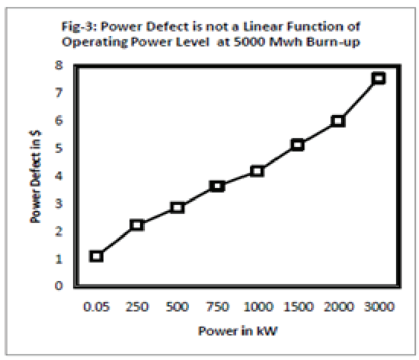
Power (kW)	k_{eff}	Reactivity (ρ_t) in $	Power Defect $\Delta\rho=(\rho_0-\rho_t)$ in $
0.05	1.07744	10.2677	0
250	1.07516	9.98590	0.2818
500	1.07286	9.70145	0.5663
750	1.07055	9.41401	0.8537
1000	1.06822	9.12330	1.1444
1500	1.06351	8.53150	1.1736
2000	1.05875	7.92701	2.3407
2500	1.05392	7.30870	2.9540
3000	1.04902	6.67610	3.5916

Table 4: Power Defect Calculation at 5000 MWh with Xenon equilibrium (ρ0=10.2677 $ at 50 W and no xenon)

Power (kW)	k_{eff}	Reactivity (ρ_t) in $	Power Defect $\Delta\rho=(\rho_0-\rho_t)$ in $
0.05	1.068604	9.1714	1.0963
250	1.059672	8.0445	2.2232
500	1.053462	7.2498	2.8690
750	1.048551	6.6147	3.6530
1000	1.044367	6.0689	4.1988
1500	1.037177	5.1206	5.1471
2000	1.030807	4.2695	5.9983
3000	1.019122	2.6805	7.5873

In temperature defect calculation, different operation powers such as 50 W, 250 kW, 500 kW, 750 kW, 1000 kW, 1500 kW, 2000 kW, 2500 kW and 3000 kW are chosen for all calculations and a single and same burn-up step as zero to 5000 MWh. The core configuration and fuel arrangement is the same for all operations.





It is observed in figure 2 that the temperature defect or power defect is absolutely liner function of operating power at zero born-up step. On the other hand, it is not linear in figure 3 with operating power at burn-up step 5000 MWh. Again when the operating power increases the temperature also increase in the core and hence as it is known form "Doppler broadening" effect that the cross-section depends on temperature, therefore, the total rate of neutron absorption is changing with the change of absorption cross-section of neutrons and consequently increases the power defect.

6.0 XENON VALUE CALCULATION

The most important fission-product poison is xenon-135 because of its remarkably large capture cross-section about 3.0 x 10^6 barns for thermal neutrons. This isotope is formed to a small extent (about 0.3 %) as a direct production of fission, but the main proportion in a reactor originates from the radioactive decay of Tellurim-135and iodine-135 produced in 6.1 percent of the slow-neutron fissions of uranium-235 [9].

By choosing the burn-up steps (0 MWh, 50 MWh, 350 MWh, 750 MWh, 1000 MWh, 2000 MWh, 2500 MWh, 3000 MWh and 3500 MWh) the operating history of the reactor core under consideration was covered. The second burn-up step was deliberately kept very short (50 MWh) to take into account the xenon build up. The xenon-value was calculated as the difference in reactivity between reactivity without xenon and with xenon at power level 1 MW for each burn-up step. The xenon value for each burn-up step at 1 MW power level was given in Table 5. From table 5 it is found that the xenon value after 50 MWh becomes almost equal.

Table 5: Xenon Value at 1 MW Power Level

Operating Power (MW)	Burnup Step (MWh)	Reactivity without Xenon (X) in $	Reactivity with Xenon (Y) in $	Xenon Value = (X-Y) in $
1	50	9.0807421	7.111876	1.9696
	350	9.0259754	7.055571	1.9704
	750	8.9786922	7.007531	1.9712
	1000	8.948323	6.977424	1.9709
	2000	8.9202004	6.948467	1.9717
	2500	8.8916891	6.919757	1.9719
	3000	8.8625373	6.890776	1.9718
	3500	8.8340013	6.819114	1.9721

7.0 FUEL ELEMENT REACTIVITY WORTH CALCULATION

Two strategies have been followed in the reactivity worth calculation for water and void such as (i) Reactivity worth calculation for fresh core at zero burn-up and (ii) for worth calculation at different burn-up steps (10000 MWh, 20000 MWh, 30000 MWh, 40000 MWh). The reactivity worths were calculated by withdrawing different fuel rods from some selected locations of each ring and those locations were filled with water and air. The reactivity worth was calculated by the difference in excess reactivity for the present (when the fuel rod was exchanged by water and air) and initial (without changing any fuel rod) core configuration. It was observed that the reactivity worth in E-ring is the lowest at zero burn-up step for water. But in the case of other burn-up steps (10000 MWh, 20000 MWh, 30000 MWh etc.) the lowest reactivity worth was found in D-ring for water. The excess reactivity and the fuel reactivity worth at zero MWh and 10000 MWh at zero power level are shown in Table 6 and Table 7. The results will help to study the modified core configuration. It was also observed that for the fresh core the reactivity worth in C-ring is the highest. This is because the increase of power will increase the thermal flux of this ring and hence the reactivity worth of the fuel rod will be increased. On the other hand, the ring possessing the lowest power decreases the thermal flux of that ring. Hence the reactivity worth of the fuel rod will be decreased.

Table 6: Excess Reactivity and Fuel Reactivity Worth at Zero Burnup and Zero Power Level

Ring Type	Conditions	k_{eff}	k_{eff} for Initial Core and Reactivity (ρ_0) in $	Excess Reactivity ρ in $	Fuel Reactivity Worth (ρ_0-ρ) in $
C	water	1.073686	k_{eff}=1.077440 and ρ_0=10.267724	9.8041	0.4636
	air	1.071952		9.5889	0.6788
D	water	1.076558		10.1591	0.1087
	air	1.073533		9.7852	0.4825
E	water	1.077053		10.2201	0.0476
	air	1.074163		9.8632	0.4045
F	water	1.077011		10.2149	0.0528
	air	1.074858		9.9492	0.3185
G	water	1.076346		10.1330	0.1348
	air	1.075292		10.0029	0.2649

Table 7: Excess Reactivity and Fuel Reactivity Worth at 10000 MWh at Zero Power Level

Ring Type	Conditions	k_{eff}	k_{eff} for Initial Core and Reactivity (ρ_0) in $	Excess Reactivity ρ in $	Fuel Reactivity Worth (ρ0-ρ) in $
C	water	1.06216	k_{eff}=1.065895 and ρ_0=8.83161	8.3605	0.4636
	air	1.06217		8.1138	0.7118
D	water	1.064456		8.6504	0.1812
	air	1.061209		8.2398	0.5918
E	water	1.064412		8.6449	0.1867
	air	1.061246		8.2449	0.5871
F	water	1.063797		8.5673	0.2643
	air	1.061347		8.2573	0.5743
G	water	1.062506		8.4041	0.4275
	air	1.061125		8.2291	0.6025

8.0 STUDIES ON MODIFIED CORE CONFIGURATION

In modified core configuration the following basic core parameters have been studied using the computer code TRIGAP:

(a) Effective multiplication factor, k_{eff} prediction

(b) Excess reactivity and

(c) Neutron flux and power distributions etc.

At first k_{eff} for the present core configuration (before modification) was computed. The flux and power distribution for the present core configuration have been analyzed and shown graphically in Figure 4 and Figure 5 respectively.

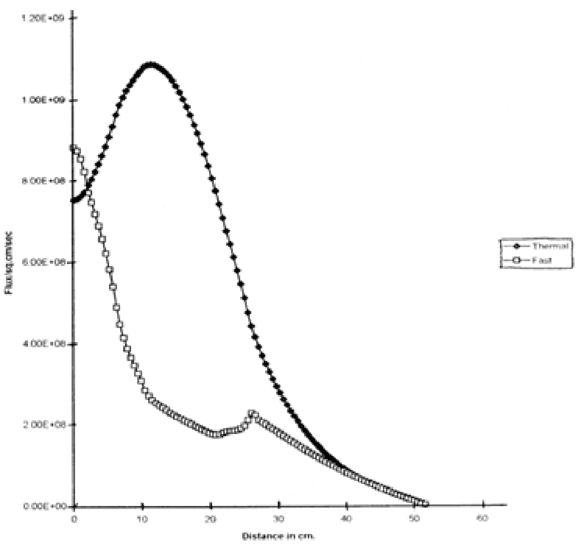


Fig 4: Flux Distribution of the Present Core Configuration.

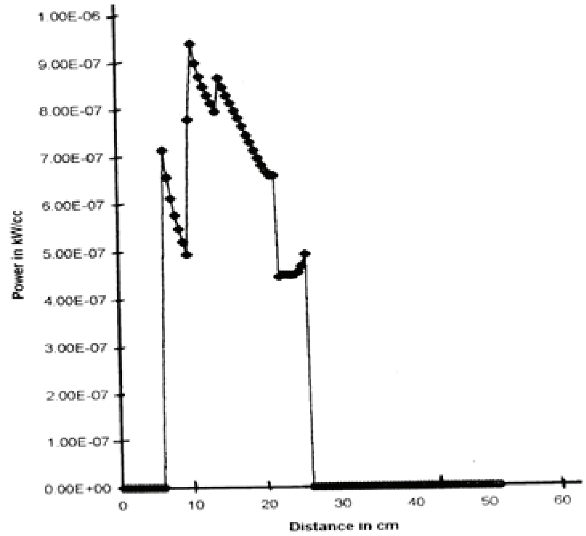


Fig 5: Power Distribution of the Present Core Configuration.

Altogether four modified core configurations were proposed for this study. Calculations had been done for these configurations one after another. Firstly, a graphite rod from C-ring was replaced by a fuel rod from D-ring, this core configuration is defined as modified core configuration (I). By replacing a graphite rod from the C-ring with the fuel rod from the E, F, and G-ring respectively the E, F, and G-ring respectively defined as modified core configuration (II), (III) and (IV) respectively.

For each of these modified core configurations, the effective multiplication factor keff, excess reactivity and the spatial distributions of thermal and fast fluxes were found. The excess reactivities obtained for these core configurations have been shown in Table 8.

Table 8: Results of the Modified Core Configuration

Used Fuel Rod Number in C-Ring from others	k_{eff} for New Core Configuration	Excess Reactivity (ρ_n) in \$ and Type of New Core Configuration	k_{eff} and Excess Reactivity (ρ_0) in \$ for Previous Core Configuration	Change in Reactivity between Two Configuration $\Delta\rho=(\rho_0-\rho_n)$ in \$
From D-ring 9360	1.078723	10.425422 (I)	k_{eff}=1.077440 and ρ_0=10.267725	0.157697
From E-ring 9455	1.079235	10.488249 (II)		0.220524
From F-ring 9386	1.079749	10.551261 (III)		0.283536
From G-ring 9394	1.079934	10.573927 (IV)		0.306202

From table 8 it is observed that the excess reactivity of the modified core configuration (IV) is maximum and that of (I) is minimum. The excess reactivity of the modified core configuration (IV) is maximum because of a large number of thermal neutrons is entering into the G-ring region from the reflector region and as a result the fission rate increases. A comparison of spatial distributions of thermal and fast fluxes of the present core and each of the modified cores has been made and shown in Figure 6. The power distribution of the present core and each of the modified cores has also been investigated. Figure 7 shows one such arrangement.

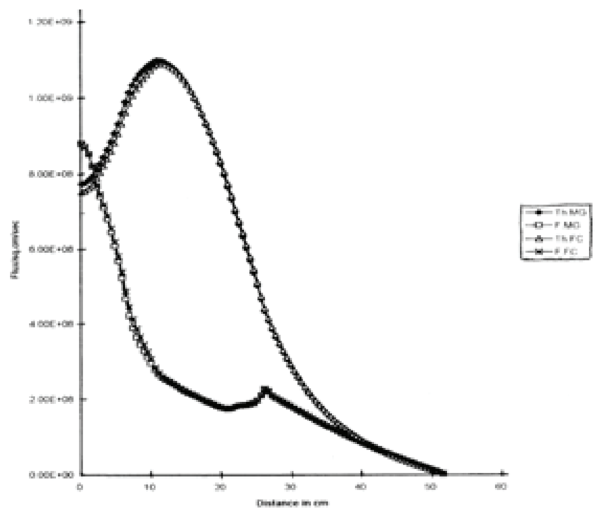


Fig 6: Observed Change in Flux Distribution between the Present and Modified Core Configuration.

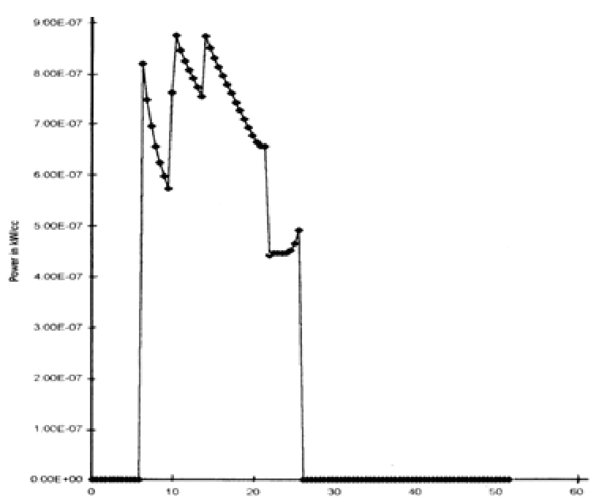


Fig 7: Power Distribution of the Modified Core Configuration.

It is observed form figure 6 that the flux of the modified core configuration has been increased in the central thimble and other desired positions than that of the present core. The power distributions for the present and one of the modified core configuration are pictured in figure 5 and figure 7. It is observed from these figures that the flux level of the modified core configuration shall be changed at the ratio of 1.58 from the original flux value. This result is very much encouraging for undertaking the up gradation project.

9.0 CONCLUSION

The TRIGA core was analyzed and found some important aspects such as the core-life and power defect varies with power level, the optimal burn-up step for the present core configuration is 500 MWh. The other relevant study shown that the reshuffling of the core at every 20000 MWh and before subcritical gives the maximum utilization of fuel rods initially loaded and the xenon equilibrium is reached at around 50 MWh of continuous operation in Table 5 for 1 MW power level. In case of the study of the new core configuration it was observed that the reactivity worth in E-ring is the lowest at zero burn-up step for water. But in the case of other burn-up steps (10000 MWh, 20000 MWh, 30000 MWh etc.) the lowest reactivity worth was found in D-ring for water. The studies on the modified core configuration show that it is possible to improve present core configuration with respect to up-gradation of the flux in the desired locations and optimum fuel utilization. All these findings will contribute significantly for the best utilization of the core and also this study can give an original idea to redesign a better and efficient core configuration than the present one using the same fuel elements, which has been taken as a priority project by BAEC. All these findings will be used by the TRIGA Reactor up-gradation group as the future step for their advanced calculation with more sophisticated 2-dimensional and 3-dimensional codes.

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