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Evaluation of fast fission factor in a typical pool type research reactor

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ABSTRACT

One of the important factors of a nuclear reactor core is the fast fission factor. This paper calculates this parameter based on space and energy-dependent method using the PTRAC card of MCNPX code. Tehran research reactor (TRR) is taken as a case study, and the parameter analyses are performed on the reactor core. Fast fission factor in TRR is evaluated regarding temperature effect, control rod positions, and fuel assembly positions. Using the PTRAC card, helpful information on fast fission factors is achieved throughout the reactor core. One MCNPX runs to return a data file about neutron interaction that can be analyzed many times in different manners to reveal this useful information. The method is simple and can be applied to any nuclear reactor core. The results obtained by this method can help nuclear reactor designers and nuclear reactor fuel managers to have a precise evaluation of the parameter. The method proposed in this paper for fast fission factor calculation is compared with the results previously published in the literature.

Keywords: Fast Fission Factor, MCNPX, PTRAC, Tehran Research Reactor

I. INTRODUCTION

However, almost the total energy produced in a thermal reactor is due to the thermal fission of the fissile material. A small fraction of the energy production is owing to the fertile material. In a reactor with natural uranium or slightly enriched fuel, fission with fertile material is more intensive as more fertile material is loaded into the core. During the slowing down of fission neutrons, neutrons collide with the fuel material. Therefore, more fertile material causes more probability of fast fission, which is usually taken into account as a fast fission factor in thermal reactors. The fast fission fraction in thermal reactors is about five percent depending on the core composition (like fuel material, enrichment, and neutron flux spectrum). Moreover, in heterogeneous systems, the immediate effects are more important than homogenous types reactors. In breeder reactors also fast fission helps to make $\varepsilon\eta$ to be greater than 2.

For an infinite multiplying system, the quantity of fast fission factor is defined as the ratio of the total number of neutrons produced by all thermal and fast fissions to the number of neutrons produced by thermal fissions only. Fast fission factor is just greater than one, which is denoted as ε defined as below [1]:

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$$\varepsilon = \frac{\int_0^{\infty} \nu(E)\Sigma_f(E)\phi(E)dE}{\int_0^{E_{th}} \nu(E)\Sigma_f(E)\phi(E)dE} \quad (1)$$

where:

ε: Fast Fission Factor

E: Neutron energy

E_{th}: Threshold energy for fast fission

$\nu(E)$: Number of neutrons produced by fission in energy E

$\Sigma_f(E)$: Fission cross-section in energy E

$\phi(E)$: Neutron flux in energy E

For a system with uranium loaded as fuel material, Equation (1) can be rewritten as a function of fissile and fertile materials of the fuel as below [2]:

$$\varepsilon = \frac{\int_0^{\infty} \left(\nu^{25}(E)\Sigma_f^{25}(E)+\nu^{28}(E)\Sigma_f^{28}(E)\right)\phi(E)dE}{\int_0^{E_{th}} \nu^{25}(E)\Sigma_f^{25}(E)\phi(E)dE} \quad (2)$$

where:

$\nu^{25}(E)$: Number of neutrons produced by fission of U^{25} in energy E

$\nu^{28}(E)$: Number of neutrons produced by fission of U^{28} in energy E

$\Sigma_f^{25}(E)$: Fission cross-section of U^{25} in energy E

$\Sigma_f^{28}(E)$: Fission cross-section of U^{28} in energy E

The threshold energy to distinguish between fast fission and thermal fission is expressed in the literature [2]. The standard energy thresholds are 0.5 eV (the Cadmium cut off energy) [3], 1.46 eV (the Indium resonance energy), and 0.6 MeV (the threshold energy for U^{28} fission) [2, 3]. This work considers 1.46 eV and 0.6 MeV as threshold energies for fast fission factor calculations.

Fast fission factors can be determined either experimentally or theoretically. For example, an experimental method, activation foils of uranium are activated by neutron bombardment between fuel material of nuclear reactors, with Cadmium cover and without any coverage. Therefore, the fast fission factor might be determined without information about cross-sections experimentally in this way. In another experimental research, the fast fission factor is measured in a heavy water zero power reactor based on Shi and Li's solid-state nuclear track detectors [4]. The fast fission factor is estimated as 1.050 for the system experimentally. According to the reported results, the overall error of the method is about 7.9%. Spinrad, Fleishman, and Soodak's (SFS) method is a theoretical means of fast fission factor calculation [1]. In this method, it is assumed that the neutrons escaping to the moderator from fuel materials slowdown in the moderator and do not return to the fuel with the energy above the fission threshold for fast fission. A variety of methods for fast effect evaluations are published elsewhere in the literature [4-9]. The Monte Carlo method is another alternative for fast fission factor determination [2, 10].

In a previous related publication [2], a new method for fast fission factor calculation has been proposed based on the manipulation of MCNP libraries. The ν parameter is manually made zero above the threshold energy in the library. Therefore, critical calculation of the system based on MCNP code returns [11]:

$$k' = \frac{\int_0^{E_{th}} \nu^{25}(E)\Sigma_f^{25}(E)\phi(E)dE}{\int_0^{\infty} \Sigma_a(E)\phi(E)dE} P_{TN} \quad (3)$$

The effective multiplication factor without any manipulation of the libraries is defined as below:

$$k = \frac{\int_0^{E_{th}} \left(\nu^{25}(E)\Sigma_f^{25}(E) + \nu^{28}(E)\Sigma_f^{28}(E)\right)\phi(E)dE}{\int_0^{\infty} \Sigma_a(E)\phi(E)dE} P_{TN} \quad (4)$$

Dividing effective multiplication factor, k, by k, k' the following result is met, which is the definition for fast fission factor as Equation (1):

$$\varepsilon = \frac{k}{k'} = \frac{\int_0^{\infty} \left(\nu^{25}(E)\Sigma_f^{25}(E) + \nu^{28}(E)\Sigma_f^{28}(E)\right)\phi(E)dE}{\int_0^{E_{th}} \nu^{25}(E)\Sigma_f^{25}(E)\phi(E)dE} P_{TN} \quad (5)$$

k and k' are calculated by MCNP code. Therefore, two different runs of the code are needed. Although this method is practical, two different runs of MCNP code and, more importantly, manipulation of the code library and its compilation are necessary. These drawbacks are time-consuming and might be the sources of errors in the results.

In this work, based on PTRAC card in MCNPX code, a method, which is named as area ratio method, is introduced. This is a one-run method without the need for any change on the libraries of the code. The data logged by the PTRAC card is then processed, and valuable information for fast fission factor calculation is extracted. Note that neutrons induced fission are tracked by this method and are logged in the output file of the card with the data on energy, direction, location, and time. As a result, any arbitrary reprocessing of the data might be possible based on the problem.

II. Tehran Research Reactor (TRR) and its MCNPX Simulation

TRR is a five MW thermal research reactor [12]. This is a pool-type material testing reactor. The core is located about 8 m in depth of the pool water. This research reactor has been in operation for more than 50 years. TRR first operating core configuration is shown in Figure 1. There are 54 locations for core elements on the grid plate of the core. The shutdown system of the reactor consists of four safety control rods (SR1 to SR4) which are dropped into the core under the gravity force in terms of any failure or reactivity accident. A single regulating control rod (RR) is also incorporated in the design for reactor power regulation. Fuel elements are in two types, control fuel elements and standard fuel elements; referring to Figure 2 for a visual demonstration of these elements. Both of them are low enriched uranium fuel types (less than 20% enrichment). The core is surrounded by light water as a reflector, moderator, and biological shield for neutrons. The summary of important TRR specifications, is shown in Table 1. The core plus 30 cm water layer around it is simulated using MCNPX code [11]. The simulated geometry is shown in Figure 3. MCNPX simulation is validated by the experimental critical point of the core. In Table 2, the calculated effective multiplication of the core at the experimental critical point is demonstrated. The MCNPX estimation for effective core multiplication is 0.99483 ± 0.00009 with an absolute error of about -517 pcm. This error is mainly due to the cross-section libraries used for the simulation.

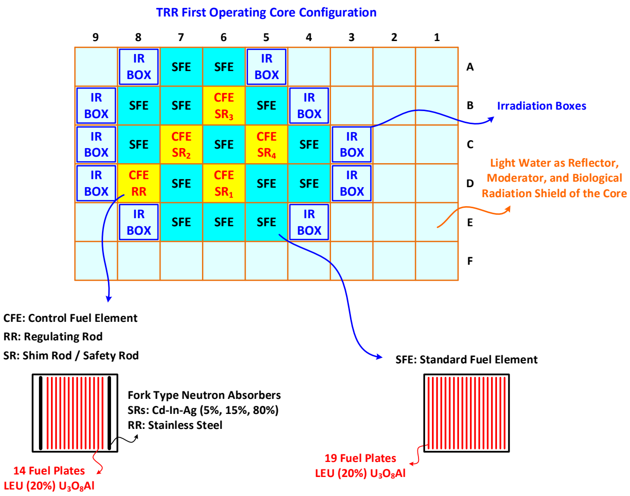

Fig. 1. TRR first operating core configuration. Elements of the reactor core are illustrated graphically and mentioned in the figure.

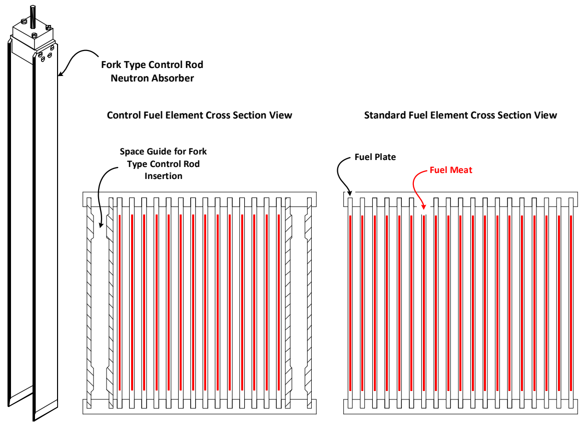

Fig. 2. From the left, control rod, control fuel element, and standard fuel element of TRR core

Table 1
Important Specifications of TRR

Reactor Design	MTR Pool Type
Nominal Power	5 MW
Fuel Material	U_3O_8Al
Fuel Geometry	Plate
Lattice Pitch [cm]	8.1 × 7.1
Number of Fuel Plates in each Standard Fuel Element	19
Number of Fuel Plates in each Control Fuel Element	14
Fuel Enrichment	20 %

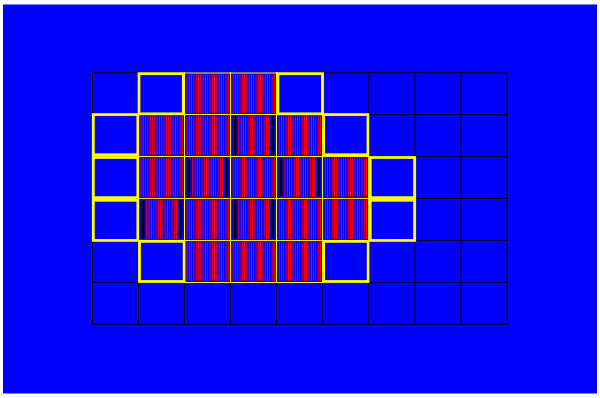

Fig. 3. Simulated geometry of TTR first operating core configuration in MCNPX code

Table 2
Calculated effective multiplication factor at experimental critical point of the first TRR core configuration

Experimental Critical Point (%out)					k_{eff}(MCNPX)	Absolute Error* [pcm]
SR_1	SR_2	SR_3	SR_4	RR		
42.8	55.0	55.0	50.0	42.0	0.99483 ± 0.00009	-517 ± 9

* In comparison with the experimental critical point

III. Fast Fission Factor Calculation using PTRAC Card

The PTRAC card in MCNPX code generates a binary file containing the information about energy, direction, location, and time of the desired interactions of particles. Information on neutron energy induced fission is necessary to calculate fast fission factor, fission interaction is chosen in the PTRAC card options. To calculate the fast fission factor using the information provided by PTRAC card, it is assumed that the $\nu^{25}(E)$ and $\nu^{28}(E)$ are approximately the same; however, the correction of this assumption can easily be incorporated in the calculations. Based on this assumption, Equation (2) is modified as below:

$$\varepsilon = \frac{\int_0^\infty \left(\Sigma_f^{25}(E)+\Sigma_f^{28}(E)\right)\phi(E)\,dE}{\int_0^{E_{th}} \Sigma_f^{25}(E)\phi(E)\,dE} \tag{6}$$

Note that below the threshold energy, the fission cross-section of U^{28} is assumed to be zero. That is why the fission cross-section of U^{25} is written only in the denominator. Using the PTRAC card of MCNPX code, the relative spectrum of the neutron energy induced fission throughout the core is calculated in Figure 4. In this figure, the two different threshold energies for distinguishing the fast fissions and thermal fissions are mentioned. Using Equation (6), the data shown in Figure 4 is used to calculate fast fission factor using numerical integration. The results are shown in Figure 5. In this case, the threshold energy varies from less than 1 eV up to more than 10 MeV. At the two threshold energies, fast fission factors are labelled. Note that all reprocessing of the data provided by PTRAC card of MCNPX code, is performed by MATLAB software engineering tool [13]. In Table 3, the results obtained by the present method are compared with the previously published results [2] for the first TRR operating core configuration. Obviously, the error's percents are less than one percent, and a good agreement is seen between the results within the uncertainties.

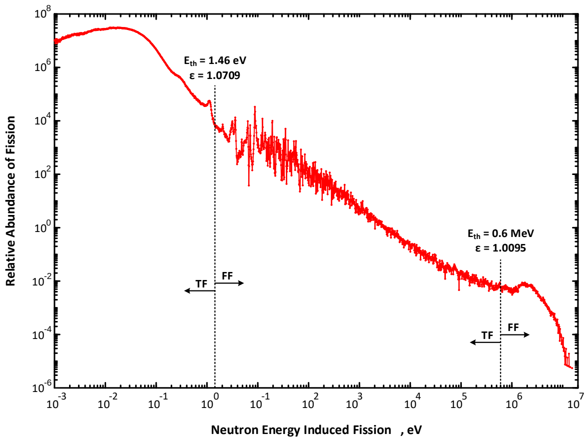

Fig. 4. Relative spectrum of the neutron energy induced fission throughout the reactor core (All control rods are out of the reactor core)

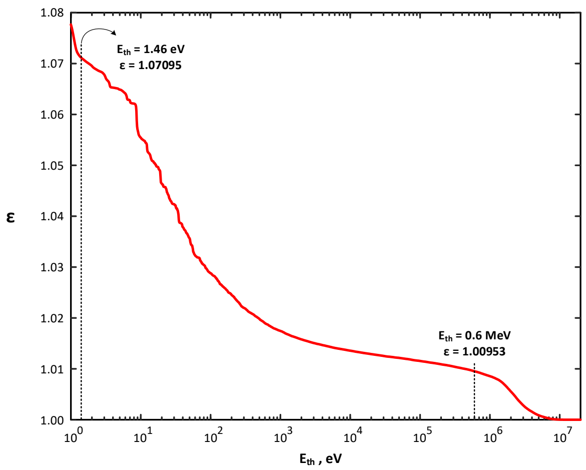

Fig. 5. Fast fission factor of the reactor core as a function of threshold energy (all control rods are out of the reactor core). Fast fission factors at energies 1.46 eV and 0.6 MeV are mentioned in the figure

Table 3
Comparison of fast fission factor of TRR first operating core configuration

All Control Rod Positions	Fully Exited		Error %***
E_{th} = 1.46 eV	PW*	1.07095 ± 0.0036	0.37
	TRM** [2]	1.07489 ± 0.00035	
E_{th} = 0.6 MeV	PW*	1.00953 ± 0.0037	0.14
	TRM** [2]	1.01092 ± 0.00033	

A. Spatial Effects

It is evident that the neutron spectrum is changed in different locations of the reactor core. As the fast fission factor is a function of the neutron energy spectrum, can also be changed over the reactor core regions.

In Figure 6, the relative neutron energy spectrum in fuel regions is illustrated. In order to make a connection between fast fission factor and neutron energy spectrum, a new parameter named as hardening factor is introduced as below:

$$\delta HF = \frac{\int_0^{\infty}\int_{Core} \psi(r,E)\,drdE}{\int_0^{E_{th}}\int_{Core} \psi(r,E)\,drdE} - 1 \qquad (2)$$

where:

δHF: Hardening factor

$\psi(r,E)$: Space and energy-dependent neutron spectrum over the fuel regions of the reactor core

In Figure 7, on the left-hand side, at the two different threshold energies, the hardening factor of the fuel assemblies is illustrated. While, on the right-hand side, the corresponding fast fission factors of the positions are shown. As fast fission is increased by shifting the neutron spectrum towards the higher neutron energies, it is clear that everywhere that the neutron spectrum is more hardened, the fast fission factor is also more significant. Note that the data shown in Figure 7 is for the case that all control rods are out of the reactor core. In Figure 8, the fast fission factor of three different fuel assemblies (refer to Figure 1, fuel assemblies positioned in locations A6, B6, and C6) at different energies for visual illustration and comparison of the spatial effects. Due to the water reflector as a blanket around the core, the neutron spectrum is more oftened at the periphery of the reactor core. Therefore, the fast fission factors of these fuel elements are smaller in these regions (refer to Figures 7 and 8 and compare the corresponding results). Position A6 has the lowest fast fission factor at all energies in comparison with B6 and C6 positions. Note that the C6 location is the central position of the reactor core; therefore, the fast fission factor of this location is more significant than the others.

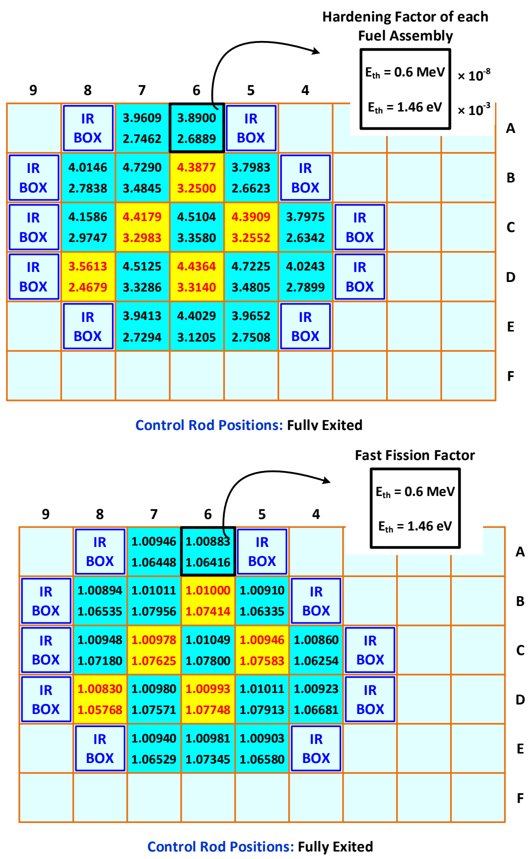

Fig. 7. Hardening factor (on the left-hand side figure) and fast fission factor (on the right-hand side figure) in two different threshold energies for each fuel assembly of the reactor core are shown (all control rods are out of the core).

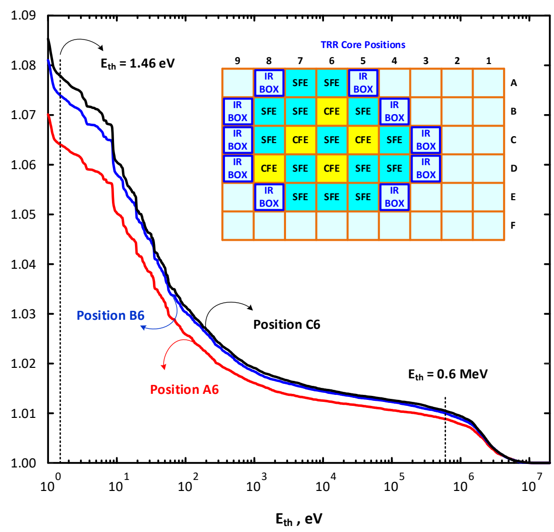

Fig. 8. Fast fission factor of three different fuel assemblies in the reactor core as a function of threshold energy for fast fission (all control rods are out of the reactor core)

B. Effect of Control Rod Position

Control rods are strong neutron absorbers specifically for thermal neutrons in the core. They are active actuators of the instrumentation and control systems of the reactor facility. Inserting the control rods into the core makes a distortion on the neutron flux distribution throughout the reactor core, which is named control rod shadowing or neutron flux depression. Therefore, the neutron spectrum is also changed as the control rod insertion changes the core composition. Consequently, the hardening factor and fast fission factor are also changed. In Figure 9, the hardening factor of the core at different positions of the control rods is illustrated for the first TRR core configuration. More control rod insertion causes a greater hardening factor of the fuel elements within the reactor core. Take two extreme cases of fully exited control rods and fully inserted control rods into the reactor core. The hardening factor for the first case in position A6 for threshold energies of 0.6 MeV and 1.46 eV are 3.89 and 2.69, respectively. These are 4.68 and 2.94 for the second case (fully inserted control rods into the reactor core). As the control rods are gradually inserted, the hardening factors are changed increasingly in all positions for the two threshold energies.

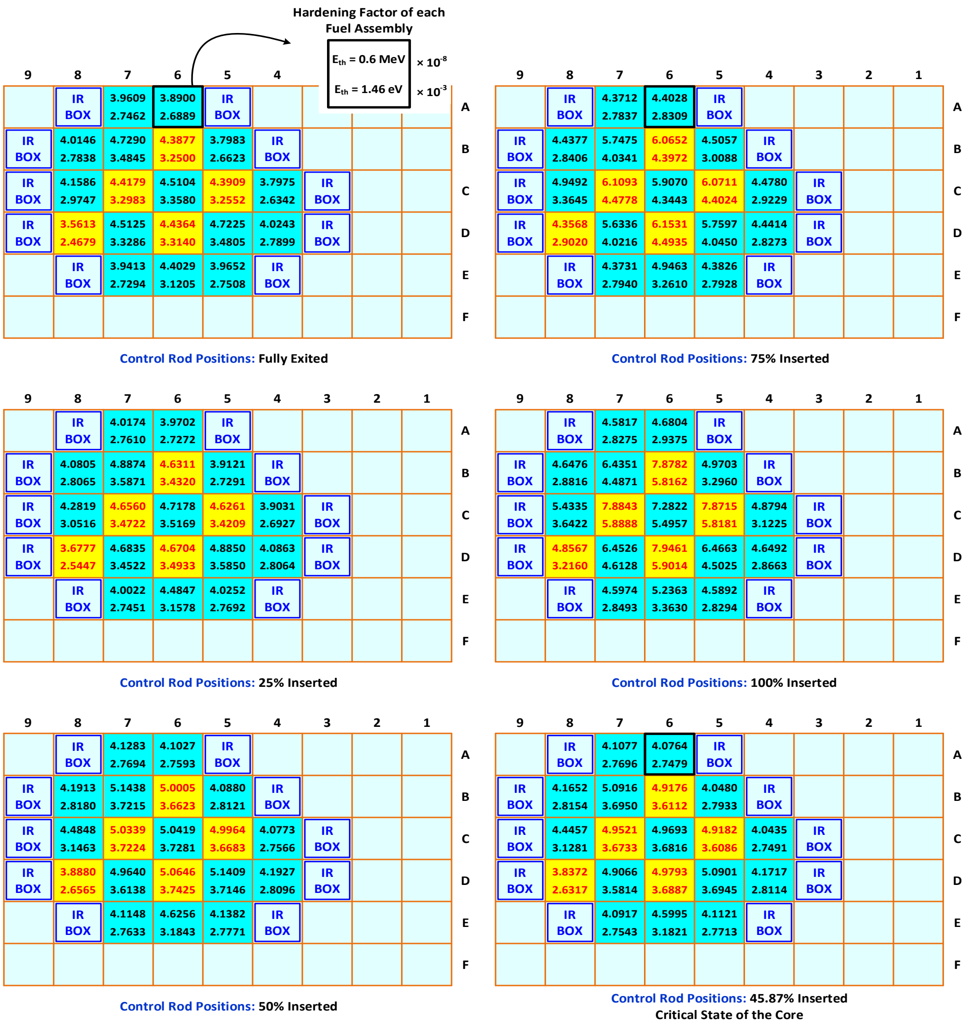

Fig. 9. Hardening factor of each fuel assembly for different control rod positions in TRR first operating core configuration.

In Figure 10, the fast fission factor of the core elements at different control rod positions is shown in detail for the two threshold energies. As the control rods are inserted, thermal neutrons are absorbed. Therefore, the neutron spectrum is more hardened, the same concept explained in the previous figure. Like the interpretation given for the hardening factor (refer to Figure 9 and its explanation), the same phenomenon is observed for the fast fission factor throughout the core. Again, take two extreme cases of fully exited and fully inserted control rods into the reactor core. The fast fission factor for 0.6 MeV and 1.46 eV threshold energies (at A6 position of the core) are 1.008 and 1.064 for the first case, fully exited control rods. While these are 1.011 and 1.072 for the other case (fully inserted control rods). Other cases (different insertions of the control rods) show the same behavior. That is why the fast fission factor of the core components, especially those positions in which control fuel elements are located, have greater fast fission factors compared to the cases with a lower amount of control rod insertion.

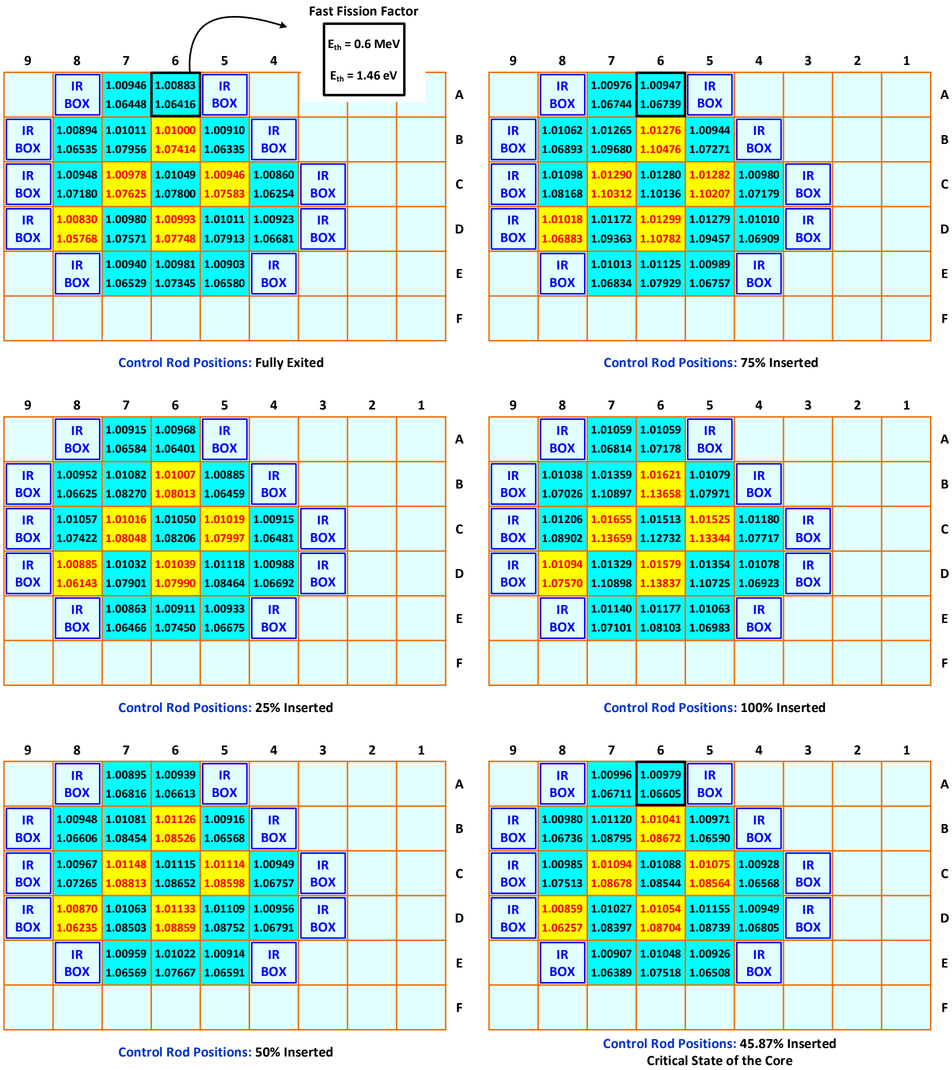

Fig. 10. Fast Fission Factor of each fuel assembly at different control rod positions for the two threshold energies.

In Figure 11, the fast fission factor of the reactor core at different control rod positions (from 0% up to 100% control rod insertion). Based on the concept explained in Figures 9 and 10, the control rod insertion effects on the neutron spectrum within the reactor core. Therefore, the fast fission factor is changed accordingly. The results shown in Figure 11 prove that the control rods' insertion causesan increase in the fast fission factor of the reactor core for all threshold energies.

The detailed numerical results are written in Table 4. The control rod position changes from 0% insertion (fully exited from the core) to 100% insertion (fully inserted into the core). The effective multiplication factor is from 0.82286 (fully inserted control rods) to 1.06037 (fully exited control rods) with an uncertainty of about ±0.00006. Considering the two threshold energies, the relative hardening and f

aast fission factors are also written in the table. As it is evident, compared to the first raw, the case with fully exited control rods, any insertion of control rods increases the relative hardening factor.

Similarly, the fast fission factor is also dependent on the control rod's position. The deeper insertion of control rods increases the fast fission factor. The concept explained above is the same for the two threshold energies.

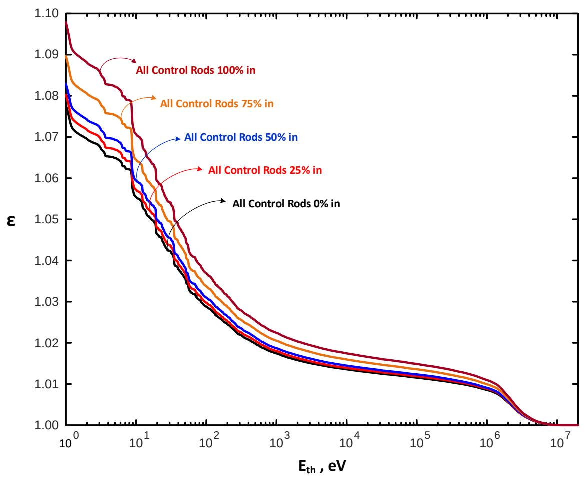

Fig. 11. Fast Fission Factor of the core as a function of threshold energy at different control rod positions of the reactor core (from 1 eV to more than 10 MeV)

C. Effect of Fuel Temperature

Changes in fuel temperature impact the fission cross-section of the fuel material. Therefore, the effective multiplication factor of the core is changed. In Table 5, the effective multiplication factor, relative hardening factor, and fast fission factor of the core at different fuel temperatures (from 300 K to 500 K) are reported. Note that calculations are performed for the case that all control rods are out of the reactor core. As it is obvious, the effective multiplication factor of the core decreases due to the temperature increase. At the same time, no meaningful changes are seen for the hardening factor and fast fission factor (for the two threshold energies) within the temperature range and uncertainties of the results. Variations in fuel temperature change the fuel cross-section at all energies. Therefore, as the fast fission factor is a ratio of the fission rates in different energy ranges (refer to Equation (3)), fuel temperature does not significantly affect the hardening factor and fast fission factor of the reactor core.

D. Effect of Moderator Temperature

To evaluate moderator temperature effect on fast fission factor, the temperature of the moderator is examined from 300 K to 360 K. It is noticeable that the effect of moderator temperature is only studied in this section of the paper (refer to section 3.6 for moderator density effect on fast fission factor). Table 6 shows the results for the simulation of moderator temperature effects on fast fission factor. Similar to what has been resulted in fuel temperature effect, no sensible dependency is seen on the fast fission factor of the core. At the same time, the effective multiplication factor has a decreasing trend over the range of temperature changes. Note that the relative hardening factor is increased less than 6 percent within the temperature changes. Variations in moderator temperature changes scattering and absorption cross-sections of the moderator. An increase in the absorption cross-section decreases the effective multiplication factor, while the increase in the scattering cross-section increases the effective multiplication factor of the reactor core. The overall effect of the moderator temperature is the gross effects of these positive and negative reactivities.

Table 4
Fast Fission Factor of TRR first operating core configuration at different control rod positions.

All Control Rod Positions (in%)	Effective Multiplication Factor	Relative Hardening Factor of the Core*		Fast Fission Factor of the Core	
		E_{th} = 1.46 eV	E_{th} = 0.6 MeV	Eth = 1.46 eV	Eth = 0.6 MeV
0 (Fully Exited)	1.06037 ± 0.00006	1.0000 ± 0.00010	1.0000 ± 0.00010	1.07095 ± 0.0036	1.00953 ± 0.0037
25	1.04413 ± 0.00006	1.0268 ± 0.00010	1.0313 ± 0.00010	1.07329 ± 0.0036	1.00985 ± 0.0037
45.87 Nearly Critical	1.00011 ± 0.00006	1.0518 ± 0.00010	1.0705 ± 0.00010	1.07569 ± 0.0036	1.01014 ± 0.0037
50	0.98814 ± 0.00006	1.0582 ± 0.00010	1.0808 ± 0.00010	1.07581 ± 0.0036	1.01014 ± 0.0037
75	0.88510 ± 0.00006	1.1318 ± 0.00010	1.1950 ± 0.00010	1.08219 ± 0.0036	1.01113 ± 0.0037
100	0.82286 ± 0.00006	1.2293 ± 0.00010	1.3155 ± 0.00010	1.08988 ± 0.0036	1.01226 ± 0.0037

* Note that the hardening factors are normalized based on the case that control rod positions are fully exited from the reactor core. As it is obvious, control rod insertion to the core, make the neutron spectrum more harden (refer to the column entitles as "Relative Hardening Factor of the Core").

Table 5
Fast Fission Factor of the core at different fuel temperatures (all control rods are out of the reactor core).

Fuel Temperature [K]	Effective Multiplication Factor	Relative Hardening Factor of the Core*		Fast Fission Factor	
		E_{th} = 1.46 eV	E_{th} = 0.6 MeV	Eth = 1.46 eV	Eth = 0.6 MeV
300	1.08525 ± 0.00010	1.0000 ± 0.0001	1.0000 ± 0.0001	1.08048 ± 0.0036	1.01120 ± 0.0037
350	1.08398 ± 0.00010	0.9999 ± 0.0001	1.0016 ± 0.0001	1.08008 ± 0.0036	1.01105 ± 0.0037
400	1.08304 ± 0.00010	0.9992 ± 0.0001	1.0024 ± 0.0001	1.08036 ± 0.0036	1.01112 ± 0.0037
450	1.08176 ± 0.00010	0.9991 ± 0.0001	1.0035 ± 0.0001	1.08023 ± 0.0036	1.01125 ± 0.0037
500	1.08076 ± 0.00010	0.9986 ± 0.0001	1.0040 ± 0.0001	1.08051 ± 0.0036	1.01106 ± 0.0037

* Note that the hardening factors are normalized based on the case that fuel temperature is 300 K.

Table 6
Fast Fission Factor of the core at different moderator temperatures (all control rods are out of the reactor core).

Moderator Temperature [K]	Effective Multiplication Factor	Relative Hardening Factor of the Core*		Fast Fission Factor	
		E_{th} = 1.46 eV	E_{th} = 0.6 MeV	E_{th} = 1.46 eV	E_{th} = 0.6 MeV
300	1.08525 ± 0.00010	1.0000 ± 0.0001	1.0000 ± 0.0001	1.08048 ± 0.0036	1.01120 ± 0.0037
315	1.08594 ± 0.00010	1.0153 ± 0.0001	1.0157 ± 0.0001	1.08047 ± 0.0036	1.01118 ± 0.0037
330	1.08656 ± 0.00010	1.0307 ± 0.0001	1.0305 ± 0.0001	1.07959 ± 0.0036	1.01112 ± 0.0037
345	1.08717 ± 0.00010	1.0452 ± 0.0001	1.0452 ± 0.0001	1.08002 ± 0.0036	1.01103 ± 0.0037
360	1.08749 ± 0.00010	1.0598 ± 0.0001	1.0590 ± 0.0001	1.08010 ± 0.0036	1.01101 ± 0.0037

* Note that the hardening factors are normalized based on the case that moderator temperature is 300 K.

E. Effect of Moderator Density

As the density of the moderator decreases, the neutron moderation power and neutron absorption are reduced. The TRR core owns an under-moderated design. Therefore, a decrease in water density reduces the effective multiplication factor of the core (refer to Table 7). Reduction in moderation means hardening of the neutron spectrum. Therefore, the hardening factor increases as the moderator density decrease. This is numerically investigated using MCNPX code. The data is shown in Table 7. Variations in the spectrum cause the increase in the fast fission factor of the reactor core. This behavior is the same for the two threshold energies.

F. Effect of Fuel Enrichment

Since fuel enrichment affects the neutron spectrum directly, the fast fission factor of the core will change. In Table 8, results of numerical investigation on effects of fuel enrichment on the fast fission factor are demonstrated. lowering the fuel enrichment causes a decrease in the hardening factors of the two threshold energies. Accordingly, the fast fission factor is also reduced. A comparison of the results reported in Table 8 approves this behavior.

Table 7
Fast Fission Factor of the TRR first operating core configuration at different moderator densities (all control rods are out of the reactor core).

Moderator Density g/cm^3	Effective Multiplication Factor	Relative Hardening Factor of the Core*		Fast Fission Factor	
		Eth = 1.46 eV	Eth = 0.6 MeV	Eth = 1.46 eV	Eth = 0.6 MeV
1.0	1.08594 ± 0.00010	1.0000 ± 0.0001	1.0000 ± 0.0001	1.07140 ± 0.0036	1.00973 ± 0.0037
0.95	1.06787 ± 0.00010	1.0369 ± 0.0001	1.0484 ± 0.0001	1.07216 ± 0.0036	1.00984 ± 0.0037
0.90	1.04809 ± 0.00010	1.0770 ± 0.0001	1.1023 ± 0.0001	1.07476 ± 0.0036	1.01025 ± 0.0037
0.85	1.02613 ± 0.00010	1.1199 ± 0.0001	1.1623 ± 0.0001	1.07810 ± 0.0036	1.01070 ± 0.0037
0.80	1.00252 ± 0.00010	1.1669 ± 0.0001	1.2310 ± 0.0001	1.08118 ± 0.0036	1.01108 ± 0.0037

* Note that the hardening factors are normalized based on the case that moderator density is 1.0 [g/cm^3].

Table 8
Fast Fission Factor of the core at different fuel enrichments (all control rods are out of the reactor core).

Fuel Enrichment	Effective Multiplication Factor	Relative Hardening Factor of the Core*		Fast Fission Factor	
		Eth = 1.46 eV	Eth = 0.6 MeV	Eth = 1.46 eV	Eth = 0.6 MeV
20	1.06988 ± 0.00008	1.0000 ± 0.0001	1.0000 ± 0.0001	1.07135 ± 0.0036	1.00957 ± 0.0037
19	1.06038 ± 0.00008	0.9553 ± 0.0001	0.9526 ± 0.0001	1.06872 ± 0.0036	1.00946 ± 0.0037
18	1.04960 ± 0.00008	0.9109 ± 0.0001	0.9058 ± 0.0001	1.06627 ± 0.0036	1.00924 ± 0.0037
17	1.03834 ± 0.00008	0.8664 ± 0.0001	0.8594 ± 0.0001	1.06396 ± 0.0036	1.00935 ± 0.0037
16	1.02558 ± 0.00008	0.8223 ± 0.0001	0.8132 ± 0.0001	1.06137 ± 0.0036	1.00930 ± 0.0037
15	1.01177 ± 0.00008	0.7777 ± 0.0001	0.7671 ± 0.0001	1.05849 ± 0.0036	1.00927 ± 0.0037

* Note that the hardening factors are normalized based on the case that the fuel enrichment is 20%.

IV. CONCLUSION

A fraction of thermal power in thermal nuclear reactors is generated by the fast fission (less than 10 percent depending on the core composition). Therefore, the information about the fast fission factor is beneficial to better understand the core configuration. This paper proposes a new method of fast fission factor based on the PTRAC card of MCNPX code. The method is first validated by previously published results for the fast fission factor in TRR. Then, TRR first operating core configuration is taken as a case study to analyze the fast fission factor. The relation between fast fission factor and core configuration is a complicated function which is exanimated in this work, and the following results are concluded:

- The method introduced in this work can be implemented in MCNP code for future enhancements.
- The fast Fission Factor is greater in the central region of the core. Therefore, special care must be taken to perform the best fuel management strategy to produce energy from U^{238}.

- The previous method is a two-run method that needs massive work for cross-section library generation of MCNP code. In contrast, the method introduced in this work is a one-run methodology for the fast fission factor calculation without any need for library compilation.
- Full flexibility for data analysis of fast fission factor using the output file of PTRAC card is achieved. It means that one run of MCNPX code generates the output file, which can be analyzed many times to extract desired information for the problem.
- No changes in the fast fission factor are seen due to variations of the fuel and moderator temperatures in TRR.
- A brilliant point of the proposed method is the capability for energy-dependent calculation of fast fission factor.

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