IN-CORE RTP FUEL RELOCATION AND CRITICALITY BEHAVIOUR USING MCNP5/X CODE

Mohamad Hairie Rabir, Abi Muttaqin Jalal Bayar*, Julia Abdul Karim

Reactor Technology Centre, Technical Support Division, Malaysian Nuclear Agency,
Bangi 43000 Kajang, Selangor, Malaysia.
**Corresponding author: abi@nuclearmalaysia.gov.my*

ABSTRACT

Since 1982, the Malaysian PUSPATI TRIGA Reactor (RTP) has been in operation as a neutron source for various applications. The in-core fuel management strategy will ensure that RTP can continue to operate safely while meeting the growing demand for nuclear technology research. To ensure operability and maintain neutronic performance, RTP has had 15 cores reshuffled. The current 15th core configuration's performance and negative reactivity feedback have been examined, and a new 16th core configuration has been determined. The transition from Core-15 to Core-16 necessitates a significant amount of fuel element movement. Several movement steps involving multiple fuel element groups have been identified. Throughout this core change process, the safety aspect, particularly the k_{eff} value, must always be maintained in a sub-critical state. The k_{eff} value for each step of movement of a predefined group of fuel elements was determined using the MCNP5/X code. The input of actinide and fission products inventory data into the MCNP5/X model for each fuel element is based on different burnup values that are specific to each fuel element. Core inputs were developed for each of the fuel element groups' movement steps, with one having a core model with the control rod fully up and the other fully down. The k_{eff} value for each phase of movement of the fuel element group was always far below 1.0, whether the control rod was fully up or fully down, according to the simulation results. The actual plan and strategy for the movement of fuel elements in the Core-15 to Core-16 reshuffling activity that will be implemented in the near future will be safer and more orderly based on the results and analysis obtained.

ABSTRAK

Sejak 1982, Reaktor PUSPATI TRIGA Malaysia (RTP) telah beroperasi sebagai sumber neutron untuk pelbagai aplikasi. Strategi pengurusan bahan api dalam teras akan memastikan RTP boleh terus beroperasi dengan selamat sambil memenuhi permintaan yang semakin meningkat untuk penyelidikan teknologi nuklear. Untuk memastikan kebolehkendalian dan mengekalkan prestasi neutronik, RTP telah merombak 15 teras. Prestasi konfigurasi teras ke-15 semasa dan maklum balas kereaktifan negatif telah diperiksa dan konfigurasi teras ke-16 baharu telah ditentukan. Peralihan daripada Teras-15 kepada Teras-16 memerlukan sejumlah besar pergerakan elemen bahan api. Beberapa langkah pergerakan yang melibatkan beberapa kumpulan elemen bahan api telah dikenal pasti. Sepanjang proses perubahan teras ini, aspek keselamatan, terutamanya nilai keff, mesti sentiasa dikekalkan dalam keadaan sub-kritikal. Nilai keff untuk setiap langkah pergerakan kumpulan unsur bahan api yang telah ditetapkan telah ditentukan menggunakan kod MCNP5/X. Input data inventori produk aktinida dan pembelahan ke dalam model MCNP5/X untuk setiap elemen bahan api adalah berdasarkan nilai terbakar berbeza yang khusus untuk setiap elemen bahan api. Input teras telah dibangunkan untuk setiap langkah pergerakan kumpulan elemen bahan api, dengan satu mempunyai model teras dengan rod kawalan sepenuhnya ke atas dan *satu lagi ke bawah sepenuhnya. Nilai keff untuk setiap fasa pergerakan kumpulan elemen bahan api sentiasa jauh di bawah 1.0, sama ada rod kawalan sepenuhnya ke atas atau ke bawah, mengikut keputusan simulasi. Pelan dan strategi sebenar pergerakan elemen bahan api dalam aktiviti rombakan Teras-15 hingga Teras-16 yang akan dilaksanakan dalam masa terdekat adalah lebih selamat dan teratur berdasarkan keputusan dan analisis yang diperolehi.*

Keywords: PUSPATI TRIGA Reactor, core reshuffling, MCNP5/X simulation, criticality calculation

INTRODUCTION

The tasks involved with fuel assemblies, core component management, and reactivity control are referred to as "core management". The movement, storage, and control of fresh and irradiated fuel, whether manually or by automated systems, is referred to as "fuel handling”. The tools, devices, or other items that are inserted into the reactor core for monitoring, flow control, or other technological purposes and are treated as core elements are the elements of a reactor core, other than fuel assemblies, that are used to provide structural support of the core construction, or the tools, devices, or other items that are inserted into the reactor core for monitoring, flow control, or other technological purposes and are treated as core elements. Experimental devices that may be fixed in the core are among the core components. It's possible that other experimental devices will be movable.

The primary goal of core management is to ensure the safe, reliable, and optimal use of nuclear fuel in the reactor while remaining within the limits imposed by the design of the fuel assembly and the design of the reactor, based on the safety analysis contained in the Safety Analysis Report (SAR) and the Operational Limit Conditions (OLCs) derived from the safety analysis. The secondary purpose is to meet the requirements of the utilisation programme for example, the demand for neutron flux for research while remaining within the OLCs. The core management programme should achieve the following objectives: perform core design (fuel assembly loading and shuffle patterns to give optimum fuel burnup and desired fluxes), and identify core operating strategies that allow maximum operating flexibility for reactor utilisation and optimum fuel utilisation while staying within the OLCs. Validated methods and codes should be utilised to determine ideal locations in the core and the approved loading and unloading processes should be followed.

To predict reactor behaviour, the right methods and procedures must be in place. All nuclear data, computer models, and numerical methodologies should be validated. Calculation and measurement errors must be considered. It is necessary to predict and compare the core reactivity changes, fuel burnup and refuelling, and control rod motions that occur throughout reactor operation. This is to ensure that the reactor can be safely shut down and that it stays shut down following all routine operational processes, expected operational events, and design-based incidents. Applying established operating procedures, all fuel assembly movements and core modifications should be carefully monitored. To prevent damage to core components and an inadvertent criticality, core integrity and reactivity should be monitored throughout such changes. Intermediate fuel assembly patterns should not be more reactive than the most reactive configuration considered in the OLCs and validated during reactor commissioning. There should be a way to check that fuel assembly movements do not conflict with one another, as well as the option to reverse existing fuel assembly movements if necessary.

The procedures should detail the particular fuel assemblies and core components to be relocated from storage places, as well as the route they will follow and the positions they will take in the core. The fuel assembly to be shuffled or unloaded; its original position in the core; its new location in the core or in the storage regions; and the sequence for unloading and loading fuel should all be specified in the programme. The subcriticality should be monitored to avoid an unplanned loss in the shutdown margin (SDM) and unintended criticality. Shielding should be provided around any sites where irradiated fuel may be deposited, if necessary. This is required to safeguard employees and ensure that their exposure to direct radiation from fission products and activated materials is kept to a minimum [1].

This paper is part of the overall reshuffling process for the TRIGA PUSPATI Reactor (RTP) core management. This work includes a simulation (using MCNPX 2.7 / ENDF VII) and analysis of k_{eff} value determination to verify that each step in the fuel element's placement does not cause the core to become critical. This paper will also present in a simple and brief the analysis of the preparation before reshuffling, particularly the determination of the feedback reactivity value and the determination of the new core.

PRE-CORE RESHUFFLING ANALYSIS

Core excess and reactivity feedback

The results of the reactivity feedback were obtained earlier, prior to the new core determination, and are detailed in reference [2]. The briefs outcomes covered in the analysis are listed below. As RTP's present core configuration (Core-15) as shown in Figure 1, approached its seventh year of operation, it became vital to assess the extent of the reactivity impacts associated with reactor operation due to increased power and xenon buildup. These past analyses will serve as a baseline for defining the end of its core cycle and the foundation for a new core configuration. The present core's core excess reactivity was $ 4.43 (for updated burnup up to December 2020), and the control rods' reactivity worth is sufficient to allow total control of the reactor during operation from shutdown to full power (and it also meets the requirement that at least three control rods have the reactivity worth to shut down the reactor). The RTP required $ 2.50 in reactivity to overcome the temperature and run at 750 kW as shown in Figure 2. The temperature coefficient of reactivity is estimated to be -0.9 ^{o}C-1, which is roughly 10% less negative than a normal TRIGA reactor. Figure 3 shows that after 24 hours of operation at 750 kW, the negative reactivity introduced by the xenon in the reactor was around $ 1.90. Based on observed data and MCNP simulation, the core surplus reduction with increasing burnup was also determined. It is concluded that RTP Core-15 has more than 90 MWD (for updated burnup up to December 2020) of accumulated burnup and insufficient reactivity to maintain continuous 750 kW operation for more than 24 hours [2].

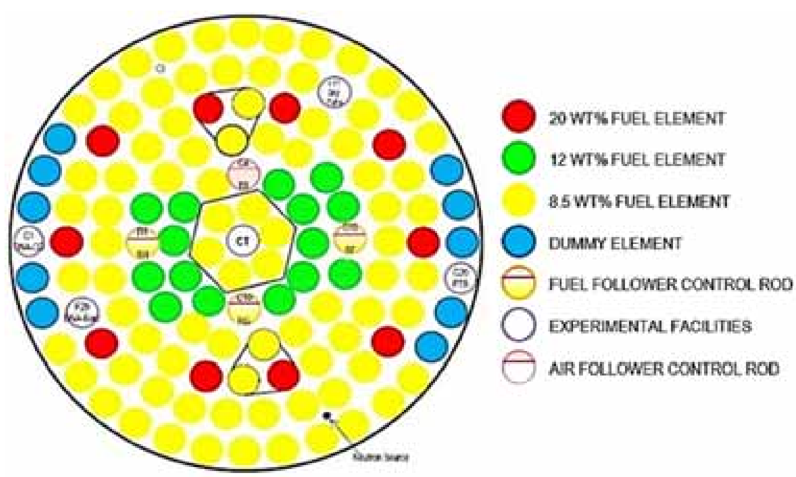


Figure 1: RTP core loaded with fuels, control rods, irradiation channels and dummy rods

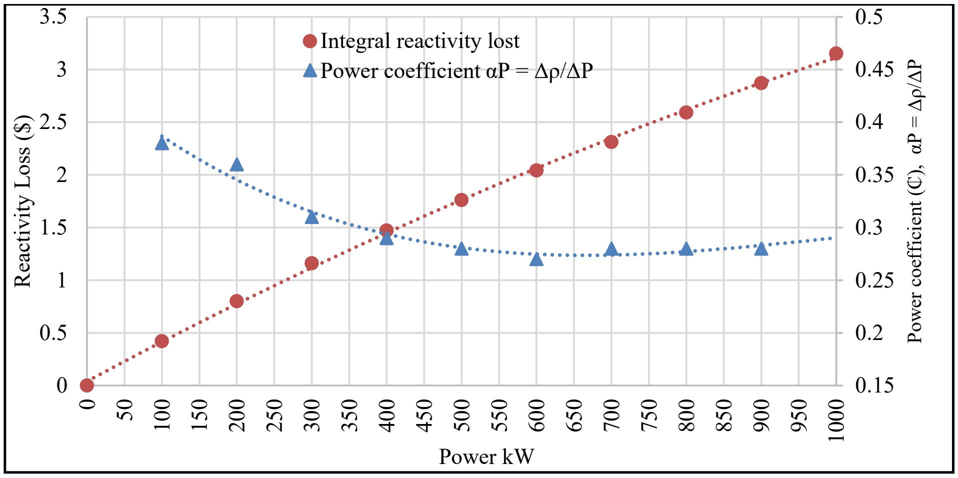


Figure 2: Power coefficient of reactivity and reactivity loss versus reactor power level

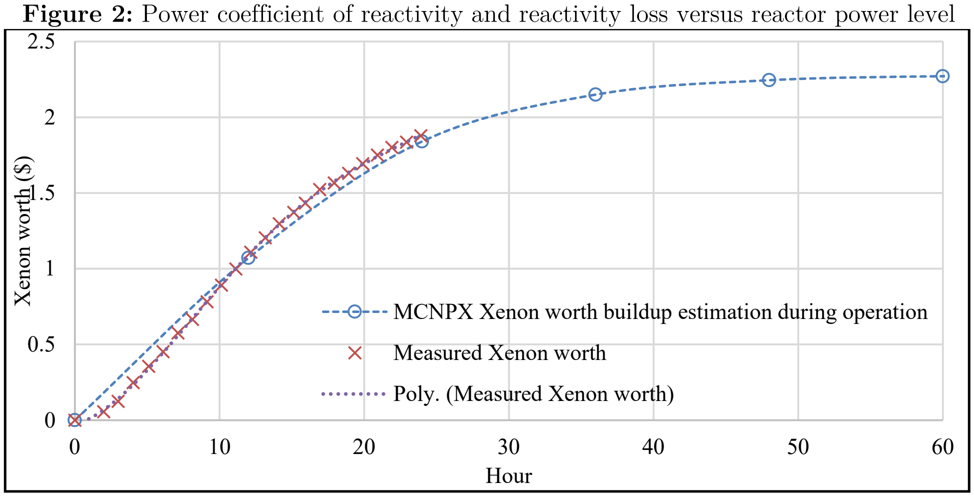


Figure 3: Measured and simulated ^{135}Xe worth buildup at 750 kW until it reach equilibrium.

Determination of Core-16 configuration

Since 1982, the RTP has been reshuffled 15 times. The following configuration (Figure 4) was proposed to raise the excess reactivity (as well as improve other neutronics parameters) for ongoing study and irradiation. The use of a new core (Core-16 configuration) necessitates a number of fuel position adjustments. The optimal configuration was chosen based on core excess reactivity and power peaking limits being met. As indicated in Figure 4, several core configuration adjustments from Core-15 were investigated. To raise the k_{eff}, these core arrangements essentially moved the fuel with the highest uranium content (20 wt% fuel type highlighted red in Figure 4) to the centre region. In Core-15, there are ten 20 wt% fuel rods, six in the F-ring and four in the E-ring. Except for Core-16b, which was moved to D-ring, all of these fuel rods were shifted to E-ring. To simplify the complexity of parameter adjustments, the 12 wt% fuel type positions were kept. The 20 wt% fuel type was divided into two in the E-ring by Core-16c1 through Core-16c4, but with various orientations. The arrangements were made as symmetrical as possible. The non-fuel elements of the core, such as the irradiation channels, graphite rods, and control rods, were left in their original placements. To find the optimal core design, a scoring method was developed in which neutronics characteristics were weighted depending on their importance in terms of safety (core excess, SDM, and power peaking) or utilisation (thermal flux). Table 1 shows the grading criteria. Based on the score in Table 2 (updated reactivity at burnup up to December 2020), it is found that Core-16c4 (reactivity is $ 0.53 higher than the current Core-15) is the best candidates for the new core configuration [3].

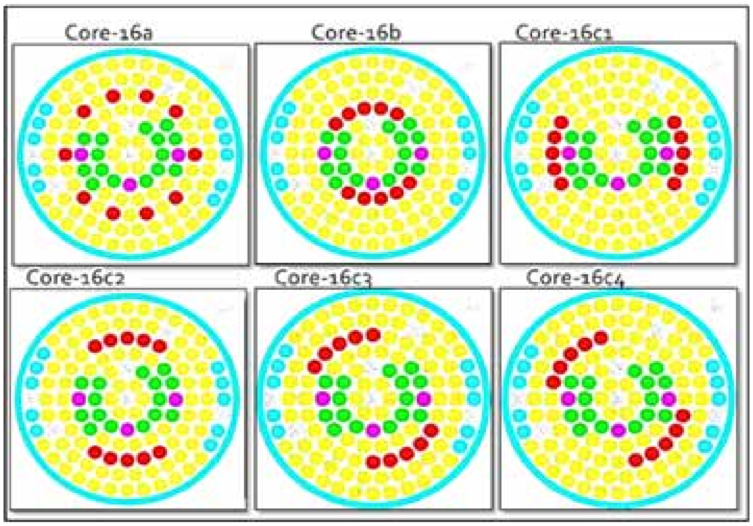


Figure 4: Several possible relocations of 20wt% fuel type in RTP core for Core-16 candidate

Table 1: Scoring criteria for RTP Core-16 candidates

***Parameters* (P)**	***Value***	***Justification***
Increased core excess (P_1)	> $ 1.0 = 2 $ 0.5 ~ 1.0 = 1 < $ 0.5 = 0	To achieve ~50MWD of burnup
SDM (P_2)	> $ 0.5 = 1 < $ 0.5 = 0	Higher margin is better
Max kW/FE (P_3)	> 18 kW = 0 17 ~ 18 kW = 1 < 17 kW = 2	Limit = 22 kW, the lower the better
Flux in PTS (P_4)	> 5 % = 2 0 ~ 5 % = 1 < 0 % = 0	Flux changes relative to Core15
Flux in RR (P_5)	> 5 % = 2 0 ~ 5 % = 1 < 0 % = 0	Flux changes relative to Core15
Total Score	$(P_1*P_2*P_3)*(P_4+P_5)$	P_1 , P_2 and P_3 are main criteria

Table 4: Score results to determine the best core configuration. Score is given in the bracket.

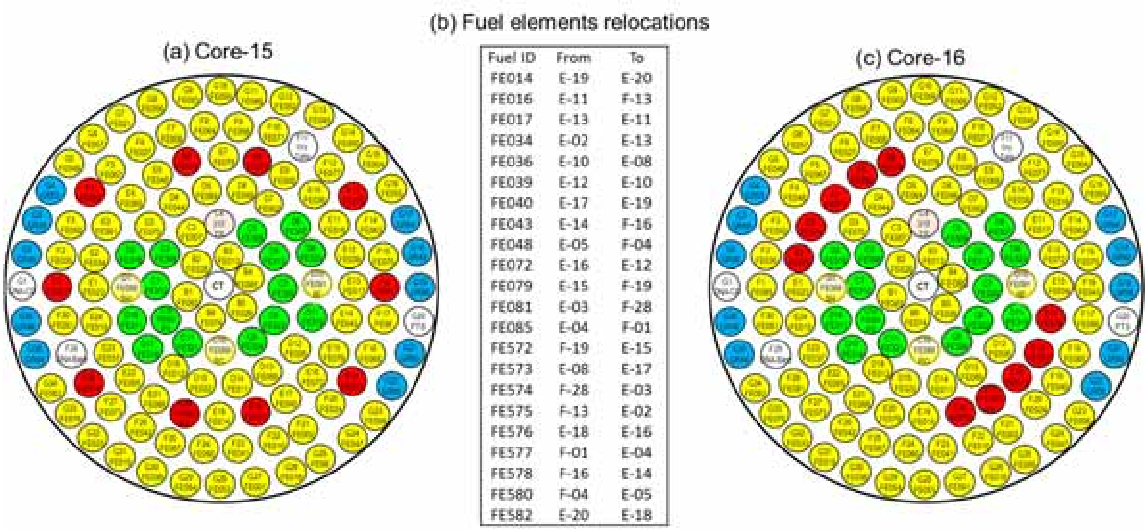
Core	Increased core excess ($)	(P_1)	Max kW/FE	(P_2)	SDM ($)	(P_3)	Thermal Flux PTS	(P_4)	Thermal Flux RR	(P_5)	Total Score
Core-16a	0.70	1	17.28	1	1.59	1	1.40%	1	-1.62%	0	1
Core-16b	1.40	2	18.17	0	0.37	0	-4.21%	0	-5.95%	0	0
Core-16c1	0.27	0	15.6	2	2.36	1	8.25%	2	-1.08%	0	0
Core-16c2	0.78	1	16.17	2	1.13	1	-4.21%	0	-1.80%	0	0
Core-16c3	0.68	1	16.08	2	1.34	1	0.97%	1	-2.09%	0	2
Core-16c4	0.53	1	16.01	2	1.63	1	5.09%	2	-1.62%	0	4

CORE RESHUFFLING STEPS AND CRITICALITY CALCULATION

Number and location of the fuel elements involved in reshuffling

The migration of the RTP core from Core-15 to Core-16 involves a change in the positions of 22 fuel elements, as illustrated in Figure 5. Figure 15(b) depicts the ID of the fuel elements (not the official ID) and their positions in Core-15 and Core-16. The RTP core has seven rings that house the fuel elements, beginning with the B-ring and progressing to the C-ring, D-ring, E-ring, F-ring, and the outermost ring, the G-ring. Each fuel position is named after the ring name and number, for example, the first place in the B-ring is called B1, while the tenth position in the E-ring is called E10. In actual case, not all 22 fuel elements must be removed from the core and reinserted in the sorted position. Furthermore, there aren't enough empty fuel storage racks in the reactor tank. As a result, the position of all fuel elements involved must be changed in stages in accordance with the sequence of movement of particular groupings of fuel elements.

It is up to the reactor personnel in charge of moving the fuel elements to decide which group should be removed or inserted first. There is no pattern or specific instruction about the movement of fuel elements. However, it is indirectly linked to existing fuel safety and management procedures. Normally, the fuel group in the centre is removed to limit the possibility of inadvertent criticality (to support the control rods). This group's movement is not restricted to reshuffling; it is also employed for control rod maintenance and other core component modification activities. In practise, the next group of fuel in the reactor tank that must be removed first is the group near the fuel storage rack.



Fuel ID	From	To
FE014	E-19	E-20
FE016	E-11	F-13
FE017	E-13	E-11
FE034	E-02	E-13
FE036	E-10	E-08
FE039	E-12	E-10
FE040	E-17	E-19
FE043	E-14	F-16
FE048	E-05	F-04
FE072	E-16	E-12
FE079	E-15	F-19
FE081	E-03	F-28
FE085	E-04	F-01
FE572	F-19	E-15
FE573	E-08	E-17
FE574	F-28	E-03
FE575	F-13	E-02
FE576	E-18	E-16
FE577	F-01	E-04
FE578	F-16	E-14
FE580	F-04	E-05
FE582	E-20	E-18

Figure 5: Core-15 (a) with fuel identification number, fuel elements relocations (b) and Core-16 (a) with fuel identification number

Steps for reshuffling fuel elements

There are three fuel storage racks (racks X, Y, and Z) in the reactor tank, each of which can hold ten fuel elements. Some positions, however, are already filled. The first fuel element group to be removed and transported to the nearest fuel storage rack's empty spaces is all six fuel elements in the B-ring. Each movement of the fuel elements, as shown in Figure 6(b), is labelled with a step number numbered from 1 to 6. To ensure subcriticality, four control rods are kept in fully down positions for all sequences. The same procedure is then used for the following sequence, as shown in Figure 7 and Figure 8. There are 45 steps in total for all 22 fuel elements involved. The first to second sequences only involve the extraction of fuel elements from the core to the storage racks. In the third sequence, there are four movements out of the fuel elements from the core and three movements into the core. In the fourth sequence, six fuel elements from the E-ring are removed from the core. As a result, the configuration in the fourth sequence has the fewest fuel elements in the core when compared to the sequences before and after it.

Beginning with the fifth sequence, there is only a movement of fuel elements from the storage rack into the core or a change in the position of the fuel elements in the core. The amount of fuel elements in the core begins to rise as well. It should be noted that the primary objective of the fuel reshuffling is to move the LEU fuel (20 wt% fuel type) closer to the centre of the core, specifically to the E-ring. These findings are based on the above-mentioned Core-16 core configuration determination analysis. In Core-15, all of the LEU fuel elements were scattered in the E-ring and F-ring. As can be seen in Figure 13, all LEU fuel elements were successfully moved to the E-ring in the ninth sequence. The last six steps involve returning the first six fuel elements that were removed from the core. All of the fuel elements are re-inserted into the B-ring in their original positions.

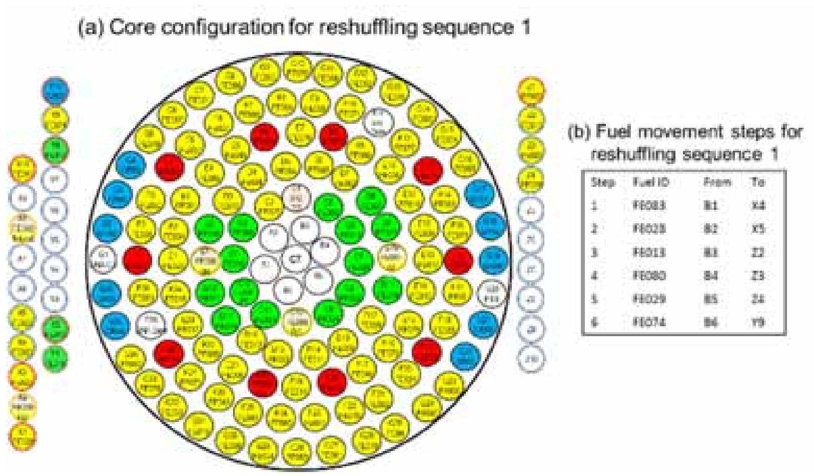


Figure 6: Core configuration for the first reshuffling sequence (a) and corresponding fuel elements movement steps (b)

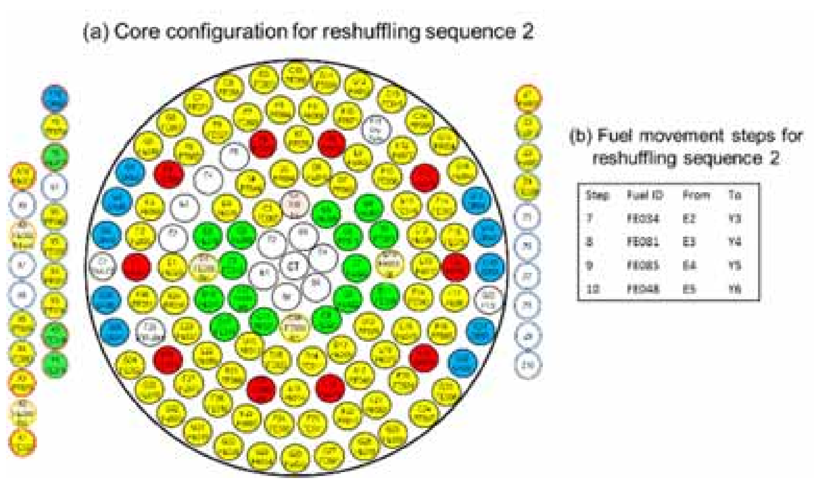


Figure 7: Reshuffling sequence #2

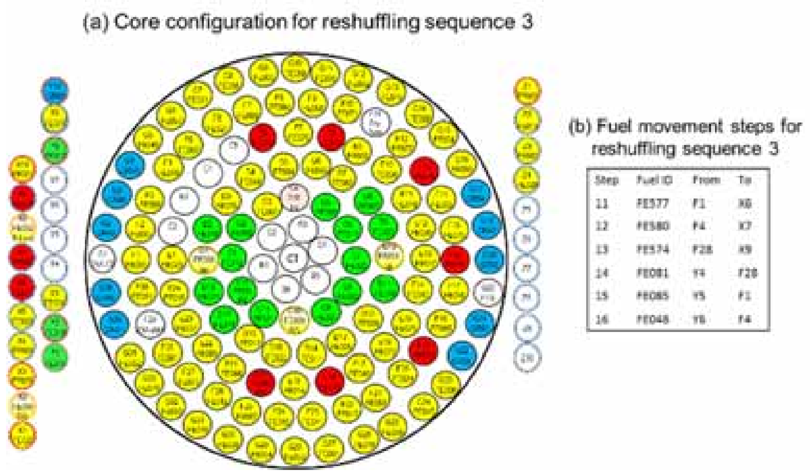


Figure 8: Reshuffling sequence #3

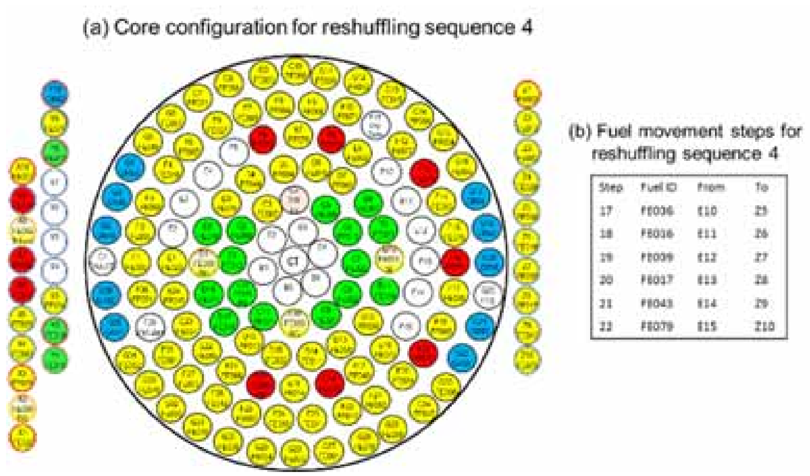


Figure 9: Reshuffling sequence #4

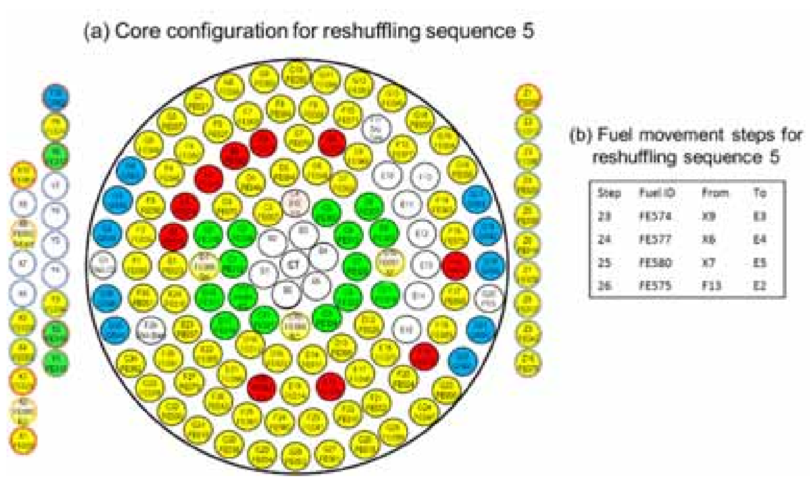
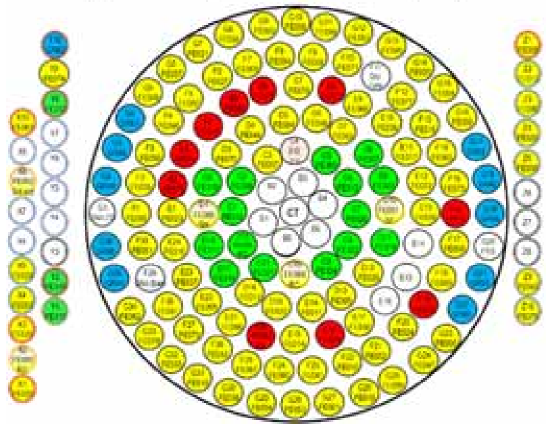


Figure 10: Reshuffling sequence #5

(a) Core configuration for reshuffling sequence 6

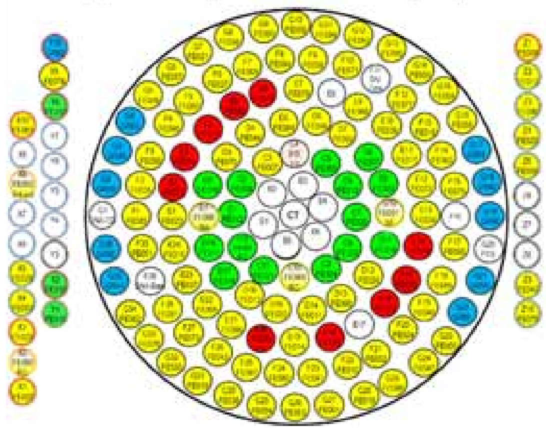


(b) Fuel movement steps for reshuffling sequence 6

Step	Fuel ID	From	To
27	FE039	Z7	E10
28	FE017	Z8	E11
29	FE072	E16	E12
30	FE034	Y3	E13
31	FE016	Z6	F13

Figure 11: Reshuffling sequence #6

(a) Core configuration for reshuffling sequence 7

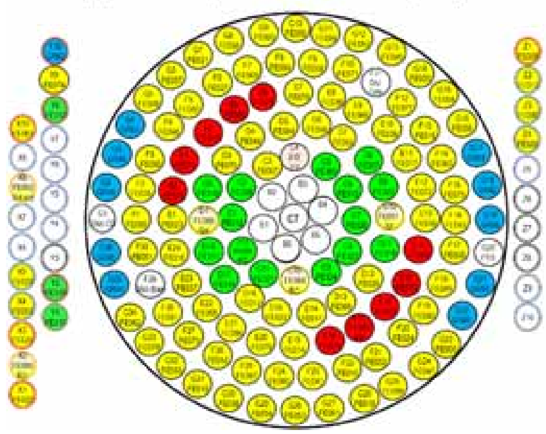


(b) Fuel movement steps for reshuffling sequence 7

Step	Fuel ID	From	To
32	FE573	E8	E15
33	FE578	F16	E14
34	FE572	F19	E16
35	FE040	E17	F19

Figure 12: Reshuffling sequence #7

(a) Core configuration for reshuffling sequence 8



(b) Fuel movement steps for reshuffling sequence 8

Step	Fuel ID	From	To
36	FE582 IFE	E20	E17
37	FE079	Z10	E20
38	FE043	Z9	F16
39	FE036	Z5	E8

Figure 13: Reshuffling sequence #8

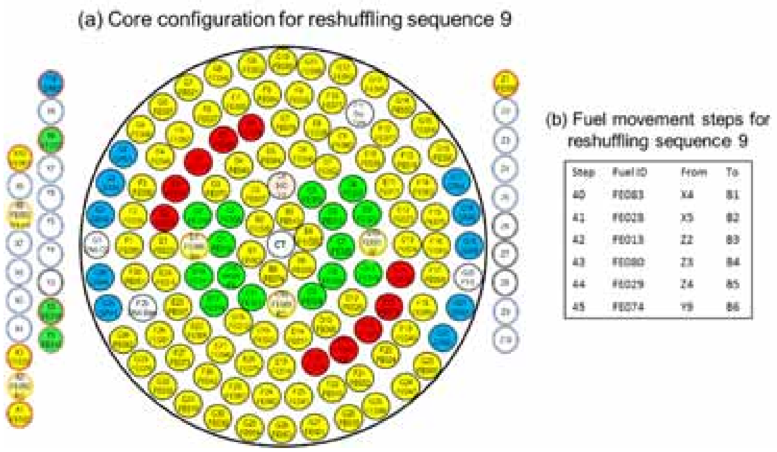


Figure 14: Reshuffling sequence #9

Criticality calculation

The developed RTP core MCNPX model is described in detail in references [5] and [6]. The core configuration model for each sequence takes not only the actual core and fuel dimension, but also consider the inventory of actinides fission products for each fuel element based on the burnup value (until December 2020). Figure 15 depicts the criticality calculation results for each sequence, with $k_{eff} = 1.0$ denoted by a red dotted line. For safety reasons, the k_{eff} value must always be kept below 1.0 during the reshuffling process (sequences 2–8), regardless of whether the control rods are fully-up or fully-down. Because the fuel in the B-ring did not change, the first and ninth sequences were not actually part of the reshuffling; rather, they were part of a safety measure to ensure a reasonably high safety margin to prevent criticality during the reshuffling. The configuration after the 9th sequence is the operational core configuration, after which the position of the fuel elements does not change. As a result, it is not included in the requirement to maintain subcriticality under the situation of fully-up control rods. The k_{eff} value, as illustrated in Figure 15, decreases as the amount of fuel elements present in the core decreases up to sequence #4. The fuel elements are then reinserted into the core starting with sequence #5. As a result, the value of k_{eff} rises once again. Based on the findings, the control rods could maintain subcriticality for all of the above-mentioned RTP core changes (with the determined fuel elements steps movements). The calculation of criticality with fully-up control rods does not imply that this reshuffling activity (sequences 1–8), can be performed in such circumstance. It is a safety analysis that demonstrates that all steps of fuel element movements are in a condition of subcriticality with a high safety margin, and that any unintentional reactivity insertion by control rods withdrawal would not result in inadvertent criticality.

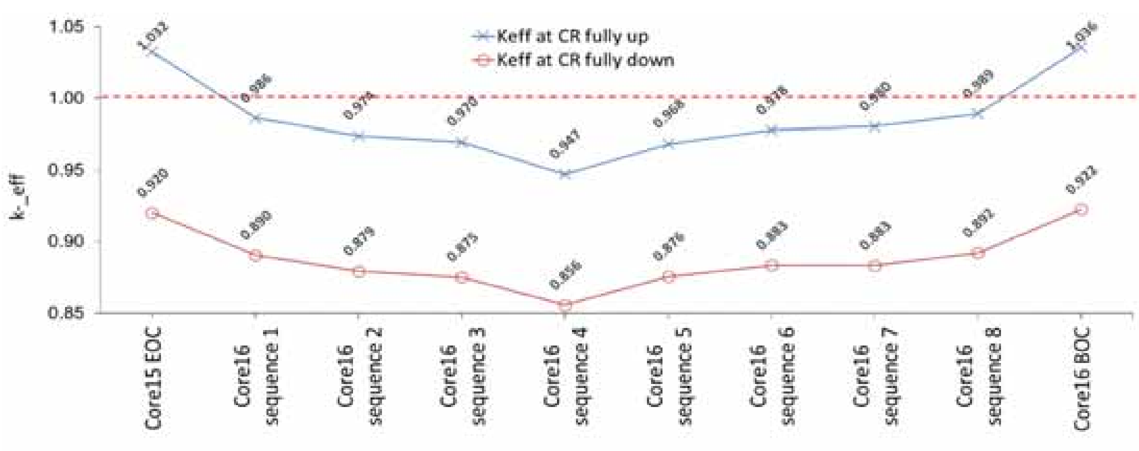


Figure 15: Criticality calculation results for reshuffling sequences

SUMMARY

In conclusion, the determination of k_{eff} values for core configurations that are being reshuffled from Core-15 core to Core-16 core has been performed successfully. This reshuffling involves 22 fuel elements and 9 sequences of movement out, in, and inside the core. The MCNPX code is used to model each core change in these reshuffling sequences, and the results have been shown above. In either the fully-down or fully up control rod conditions, the subcriticality of the reshuffling steps has been verified.

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