METHODOLOGY OF ON-LINE PREDICTION AND FUEL MANAGEMENT OF THE MODULAR PEBBLE-BED HIGH-TEMPERATURE REACTORS

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Abstract

The modular pebble-bed high-temperature reactors (PB-HTRs), featured by the inherent safety and modular design concept, are considered as one of the promising candidates for the nuclear system of next generation. The characteristics of on-line successive fueling, as well as the features of small excess reactivity and lack of reactivity control methods, make the fuel management and operation of PB-HTRs coupled tightly with each other. The on-line fuel management of PB-HTRs needs the capability of on-line prediction for future operation scenarios based on the combination of several tightly coupled key parameters of the reactor core, including the power level of reactor core, the unloading speed and loading ratio of fuel/dummy pebbles, and the control rod positions. The methodology of on-line prediction is proposed, and then verified by the model of the HTR-10, a small test modular PB-HTR with nominal power of 10 MW. For different combinations, the prediction sequences are calculated by using the computer code system of VSOP for both equilibrium state and running-in phase, especially the latter. The prediction results are analyzed by using a series of data processing based on the polynomial interpolation to determine the optimized parameters for fuel management and core operation of next step. The verification of methodology on the HTR-10 model demonstrates the feasibility of the on-line prediction and fuel management of modular PH-HTRs.

1. Introduction

The modular pebble-bed high-temperature reactor (modular PB-HTR), with the inherent safety features, is considered as one of the promising candidates for the well-known Generation IV nuclear energy systems. The on-line fuel management is an essential feature of the PB-HTRs, which is strongly coupled with the normal operation of the reactor. The fueling process of PB-HTRs is implemented by the fuel handling system (FHS) in continuous manner, and the fuel pebbles flow downward within the core driven by gravity. The negative reactivity effect of depletion of fissile materials and accumulation of fission products can be compensated by simply adding fresh fuels and discharging spent fuels continuously to maintain the neutron balance in the reactor, without adjusting the control rods remarkably. This feature is absolutely different from the conventional PWRs, in which large excess reactivity is required at the beginning of shuffling cycle and the compensation of reactivity during the cycle is achieved by using boric acid solution, burnable poisons and control rods. Hence, the fuel shuffling and normal operation in PWRs are decoupled and the major aim of fuel management, including fuel shuffling analysis and optimization, is to enhance the economy of fuel cycle. However, the fuel shuffling is the most important method to control and adjust the long term operation of the reactor for PB-HTRs, since the methods of boric acid and burnable poisons are not available and the adjusting capability of control rods is limited. The major aim of the fuel management of PB-HTRs is to keep the reactor under steady and safe operation, which indicates that the fuel management and normal operation of PB-HTRs are strongly coupled with each other.

One of the most important goals of PB-HTR's fuel management is the on-line determination of appropriate fuel shuffling scheme for the future operation. In previous work [1], the methodology of follow simulation on the PB-HTR's long term operation was proposed, through which the current status of an instant during the reactor operation can be determined. The optimized fuel shuffling scheme for the next time interval of operation should be proposed on line based on the knowledge of the core status at current instant and the prediction analysis on the future trends of operation. The on-line prediction and fuel management are usually connected with the concepts of analysis, screening and optimization for all the possible fuel shuffling schemes. Fortunately, only a few key parameters of the PB-HTRs, coupled with each other, play major roles in the on-line fuel management, including the power level of reactor core, the unloading speed and loading ratio of fuel/dummy pebbles, and the control rod positions. It is noticeable that there are no spatial patterns like the PWR's fuel management to be considered in the PB-HTR's one, if the radial zoning fueling is excluded. Hence, the methodology of on-line prediction and fuel management is greatly simplified compared with the PWR's fuel management analysis, and mainly focused on the choice of combination of the coupled parameters mentioned above. For example, by using the on-line prediction method, the unloading speed of the fuel pebbles and the control rod positions could be determined after the power level of future operation is specified, indicating that the major goal of fuel management is achieved.

The HTR-10 [2, 3] is a small test modular PB-HTR with nominal power of 10 MW, located at northwest of the Beijing city. The core of the HTR-10 is formed as a pebble bed with 27,000 fuel pebbles. Each fuel pebble contains about 8,000 TRISO coated particles with 0.5-mm-diameter UO_2 kernels. The first criticality of the HTR-10 was reached on December, 2000, and the power operation started on August, 2002. According to the design, the initial core was formed as a mixture of 57% fresh fuel pebbles and 43% graphite pebbles. After about 820 EFPDs, all the graphite pebbles would be unloaded from the pebble-bed core, and the equilibrium state would be reached. However, the HTR-10 still remains in the running-in phase by far after a series of intermittent operation, due to the features and limits of a test reactor. During the operation, a lot of operation data including power history, fuel shuffling history, control rod positions and thermal-hydraulics data have been recorded, from which one can establish the follow simulation model for the HTR-10's operation. Based on the reactor status of arbitrary instant obtained from the follow simulation, the method of prediction and fuel management can be applied and verified.

In this work, the methodology of on-line prediction and fuel management is proposed, and verified by using the HTR-10's operation data. Section 2 describes the method and formulation of the on-line prediction and fuel management. Section 3 gives the verification model and results. Some discussion is presented in Section 4, and the conclusions are drawn in Section 5.

2. Description of Methodology

The continuous fuel (re)loading is one of the crucial features of the PB-HTRs. Let us consider a sufficiently short time interval *dt* so that the core status can be treated as constant within this interval. $d\rho^+$, the increment of reactivity within *dt*, is expressed as

$$d\rho^+ = F\left(t, v, f, \varepsilon, BU_{dis}\right)dt \tag{1}$$

in which *F* is the indicator of the increase rate of reactivity resulted from fuel shuffling, as the function of time *t*, shuffling speed *v*, fresh/spent fuel fraction in the loaded/unloaded fuels *f*, fuel enrichment ε, and discharge burn-up BU_{dis}. On the other hand, $d\rho^-$, the decrement of reactivity within *dt*, can be expressed as

$$d\rho^- = -G\left(t, P, \varepsilon, BU\right)dt \tag{2}$$

in which *G* is the indicator of the absolute value of decrease rate of reactivity resulted from depletion, as the function of time *t*, reactor power *P*, fuel enrichment ε, and average burn-up of reactor core *BU*. It is easy to suppose that the reactor core remains critical at any instant during operation, so that the natural result of $d\rho^+ = -d\rho^-$ corresponding to the same *dt* can be obtained. Consequently, the equation as below must hold for a certain time interval Δt

$$\int_{\Delta t} F\left(t, v, f, \varepsilon, BU_{dis}\right)dt = \int_{\Delta t} G\left(t, P, \varepsilon, BU\right)dt \qquad (3).$$

Eq. 3 is the necessary condition for the steady operation of PB-HTRs, and also the essential correlation for the fuel management of PB-HTRs.

Since the analytical forms of *F* and *G* in Eq. 3 are difficult to derive, numerical calculations must be taken into account in the PB-HTR's fuel management. In the numerical calculations, the pebble-bed core is divided into a series of discrete spatial regions. Correspondingly, the continuous fuel cycling have to be also discretized. Thus, the introduction of positive reactivity corresponding to fuel loading/unloading and the introduction of negative reactivity corresponding to fuel depletion are decoupled with each other. The fuel shuffling is performed at an instant, at which the fuel composition in one region is directly transferred into the next region downward. During the time interval the same amount of fuels would have been shuffled after that instant, usually called "shuffling cycle", the calculations of neutronics and depletion are performed with all the fuel compositions remaining unmoved. Thus, the evolution of k_{eff} during this kind of numerical calculation behaves like a series of saw teeth as shown in Figure 1, which should have behaved like a horizontal line just at the level of 1 during real operation. For the arbitrary time interval one fuel shuffling and the corresponding depletion calculation are performed, the equation below must hold according to Eq. 3

$$\left|\Delta\rho^+\right| = \left|\Delta\rho^-\right| \qquad (4).$$

If the shuffling cycle is chosen sufficiently small so that the physical status of the core can be approximately treated as unchanged, Eq. 4 can be approximately expressed as

$$\rho_2 - \rho_1 = \rho_2 - \rho_3 \qquad (5).$$

The meanings of the symbols in Eq. 5 are explained in Figure 1. Consequently, Eq. 5 presents the necessary condition under which the PB-HTR's operation remains critical in the approximate numerical calculations. If Eq. 5 is violated, the trends of k_{eff} will deviate from criticality more and more, as shown in Figure 1.

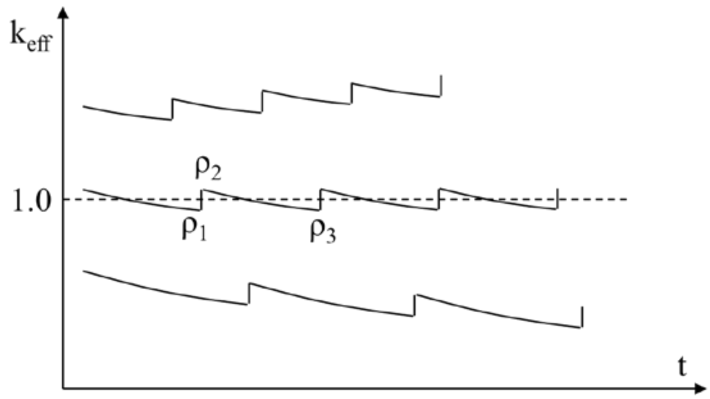

Figure 1 Schematic figure of the evolution of k_{eff} in the approximate calculations under different conditions.

However, Eq. 5 is not the sufficient condition for the criticality in the numerical calculations mentioned above. The criticality in the numerical calculations is also affected by the temperature, xenon concentration and the control rod positions, in which the former two parameters are mainly determined by the reactor power. For the upper curve and lower curve in Figure 1, criticality could not be achieved even if Eq. 5 is satisfied, since the baselines of both the evolutions deviate from criticality. That means one must adjust the control rod position and the power level to keep the reactor core critical. An obvious criterion is that the averaged value of k_{eff} within a shuffling cycle should be equal to 1, as illustrated by the middle curve in Figure 1. If this criterion is violated, as the upper and lower curves in Figure 1, the reactor core cannot be considered critical.

Consequently, two criteria are proposed to judge the criticality in the numerical calculations of PB-HTR's fuel cycling: 1) the increment and decrement of reactivity within a shuffling cycle must be equal; 2) the averaged effective multiplication factor during this shuffling cycle must be equal to 1.0. There are usually four important parameters concerning the on-line fuel management: a) power of the reactor; b) fuel shuffling speed; c) fresh fuel fraction (FFF) in loaded fuels; d) control rod position. These four parameters are strongly coupled with each other, because the reactor must remain critical. Since there are two criteria to judge the criticality, one have to fix two of the four parameters mentioned above and determine the other two based on a series of prediction calculations. In common sense, the fresh fuel fraction in loaded fuels should keep unchanged during operation unless no other ways could be used to adjust the core operation, because this parameter directly influence the discharge burn-up, and make the status of reactor deviate from the design scheme. Hence, the major aim of prediction calculation becomes to find appropriate fuel shuffling speed and control rod position for specific reactor power.

Based on the current core status at any instant during operation, a series of prediction calculations corresponding to different reactor power will be performed. For one certain power level, calculations corresponding to different fuel shuffling speeds and control rod positions will be carried out. Each calculation can give the results of the reactivity difference $\Delta\rho = \rho_3 - \rho_1$ and the averaged effective multiplication factor $\overline{k}_{eff}$. Subsequently, quadratic interpolations are performed to determine the combination of shuffling speed and control rod position which satisfy both $\Delta\rho = 0$ and $\overline{k}_{eff}$ =1. Finally, the combinations of shuffling speed and control rod position corresponding to different values of reactor power can be proposed to provide reference for the operator of nuclear power plant.

3. Results of Analysis and Verification

A lot of operation data have been accumulated during the operation of the HTR-10. These data, as well as the well-verified calculation model of the HTR-10, provide good opportunities to demonstrate and verify the methodology presented in this work. According to the experiments and theoretical analysis on the fuel pebble flow, the pebble-bed core is divided into 5 radial flow channels and different numbers of regions are assigned to different channels to simulate the radial difference of pebble flow speed. The pebble-bed core is divided into 264 regions with equal volumes. Thus, about 511 pebbles should be unloaded from the bottom of the core in a single discretized fuel shuffling. A follow simulation model has been established to follow the whole operation history of the HTR-10[1], which still remains far from the equilibrium state. An instant during the operation is chosen as the reference point of core status. From this point, corresponding to three power levels, i.e. 3 MW, 6 MW and 10 MW, a series of prediction calculations are implemented for each of them with different combinations of shuffling cycle (easily to be converted to the shuffling speed) and control rod position. The fresh fuel fraction in loaded fuels is set as 20%, the same as the design of running-in phase. Notice that during the operation of the HTR-10, 2 safety rods in the 10 control rods remained drawn from the core, hence the control rod position is the averaged value of positions of the other 8 rods, counted upward from the bottom of the pebble-bed core. These calculations will demonstrate the process of on-line prediction calculation and fuel management.

The VSOP code system[4] is utilized for the prediction calculations. One of the challenges in the prediction calculation described above is that the xenon dynamics when changing the reactor power instantaneously will disturb the reactivity evolution just caused by nuclide depletion. Hence, a revised version of VSOP code system is utilized for this work, by which one can directly set the equilibrium xenon concentration for specific reactor power instead of the gradual simulation for the dynamics after changing power. After that, the fuel shuffling and depletion calculation are implemented in turn.

The results of $\Delta\rho$ and $\overline{k}_{eff}$ are presented in Figure 2~4. Obviously, $\Delta\rho$ is mainly affected by the shuffling cycle, while $\overline{k}_{eff}$ mainly affected by the control rod position. Firstly, quadratic interpolations are carried out over the shuffling cycles to find out the values making $\Delta\rho$ equal to zero for each control rod position. Secondly, quadratic interpolations are carried out over the control rod positions to find out the values making $\overline{k}_{eff}$ equal to 1 for each shuffling cycle. Based on these interpolation results, two curves in the 2-dimensional space spanned by shuffling cycle and control rod position, which satisfy $\Delta\rho = 0$ and $\overline{k}_{eff} = 1$ respectively, are given by further quadratic interpolations, as shown in Figure 5~7. Subsequently, the point of intersection between these two curves can be obtained, i.e. the predicted combination of shuffling cycle and control rod position for the near future operation of the reactor.

The results of prediction calculation are listed in Table 1. Obviously, when the reactor power increases, both the predicted control rod position and the shuffling speed increase. It is noticeable that for this instant in running-in phase, the fuel shuffling speed at full power is 105 pebble/day, lower than that for equilibrium state, namely 125 pebble/day. Since the reactor status varies rapidly and drastically in running-in phase, it is ordinary that the shuffling speed also varies and deviates from the equilibrium value. Hence, the on-line prediction calculation is important for the operation of PB-HTRs.

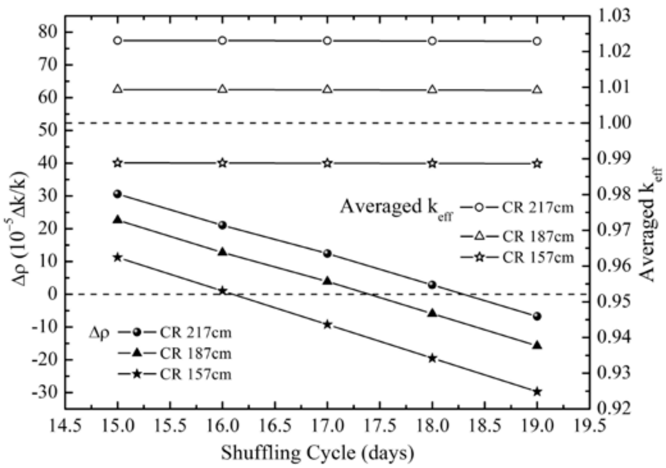

Figure 2 Results of $\Delta\rho$ and $\overline{k}_{eff}$ for power of 3 MW and FFF of 20%.

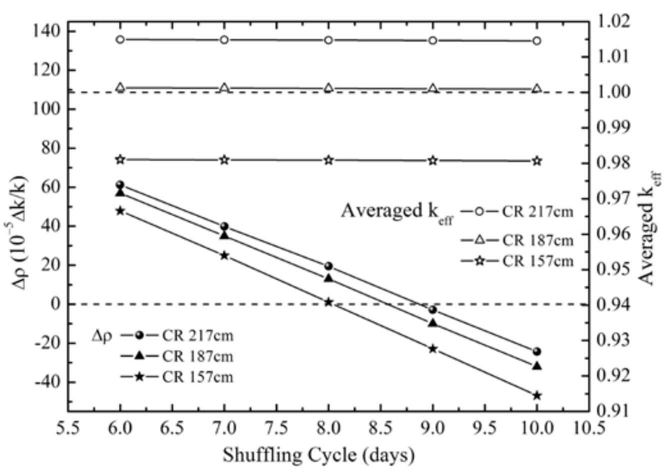

Figure 3 Results of $\Delta\rho$ and $\overline{k}_{eff}$ for power of 6 MW and FFF of 20%.

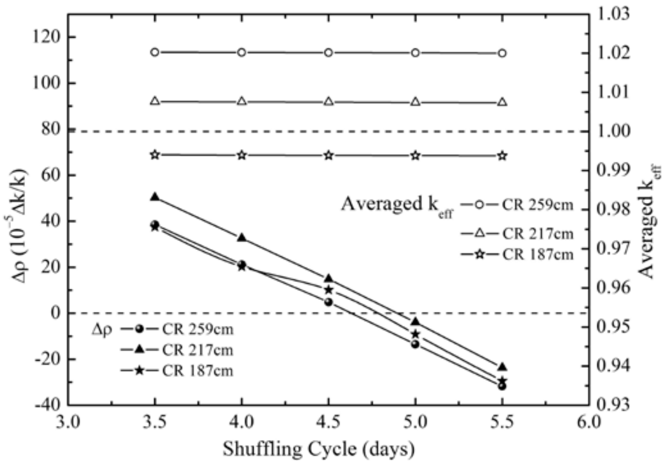

Figure 4 Results of $\Delta\rho$ and $\overline{k}_{eff}$ for power of 10 MW and FFF of 20%.

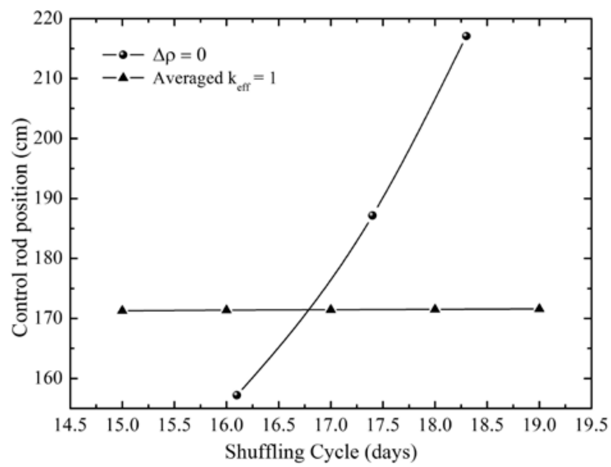

Figure 5 Results of interpolations and the 2-D curves for power of 3 MW and FFF of 20%.

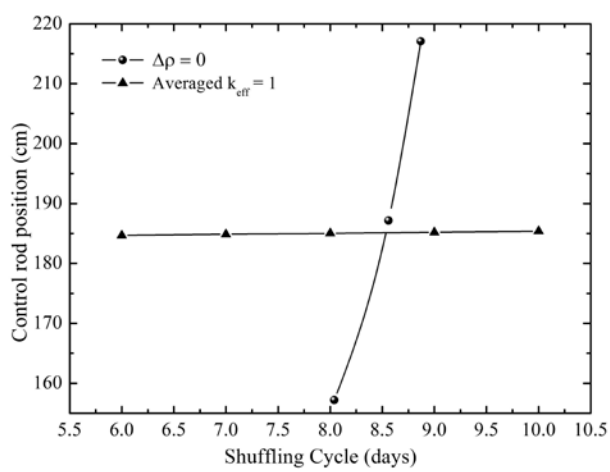

Figure 6 Results of interpolations and the 2-D curves for power of 6 MW and FFF of 20%.

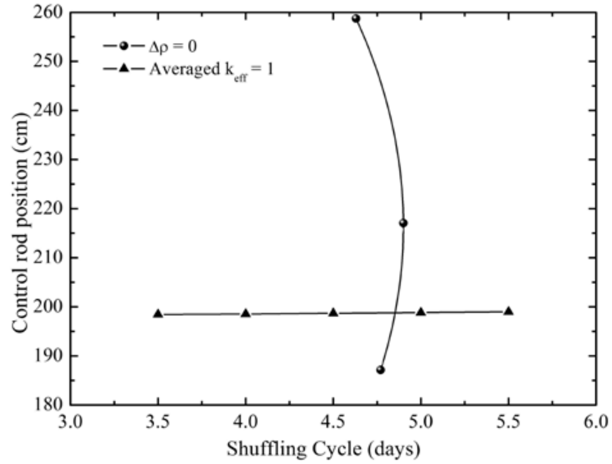

Figure 7 Results of interpolations and the 2-D curves for power of 10 MW and FFF of 20%.

Table 1 Results of Predicted Parameters for Different Power Levels

Reactor Power (MW)	3.0	6.0	10.0
Control Rod Position (cm)	171.4	185.1	198.8
Shuffling Cycle (days)	16.8	8.53	4.85
Shuffling Speed (pebbles/day)	30.4	59.9	105

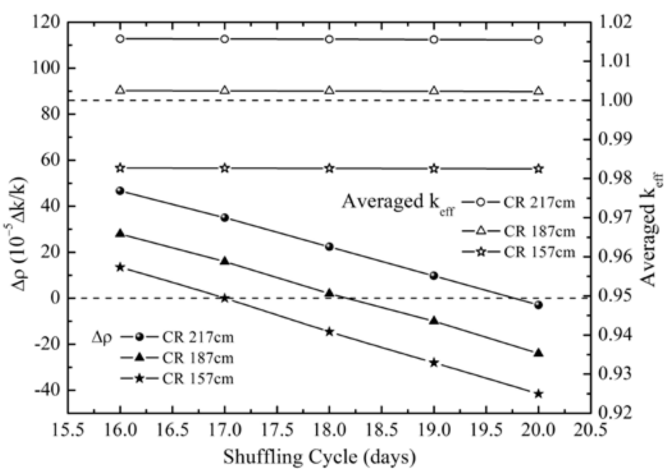

Figure 8 Results of $\Delta\rho$ and $\overline{k}_{eff}$ for the verification calculation.

In order to verify the method proposed in this work, another instant during the HTR-10's operation is chosen to perform the prediction calculation, and then the calculation results will be compared with the operation data. Within the actual shuffling cycle following this instant, the reactor power varied slightly, and so does the control rod position and shuffling speed. The values of FFF and thermal-hydraulic parameters used for the calculations are taken from the operation data of the HTR-10. Similar to the calculations above, the results of $\Delta\rho$ and $\overline{k}_{eff}$ are shown in Figure 8~9. The predicted results are shown in Table 2. The averaged values of power, control rod position and shuffling speed from operation data are also listed in Table 2 for comparison. It is obvious that the prediction calculation results agrees with the actual operation data well. That verifies the high precision of the methodology presented in this work.

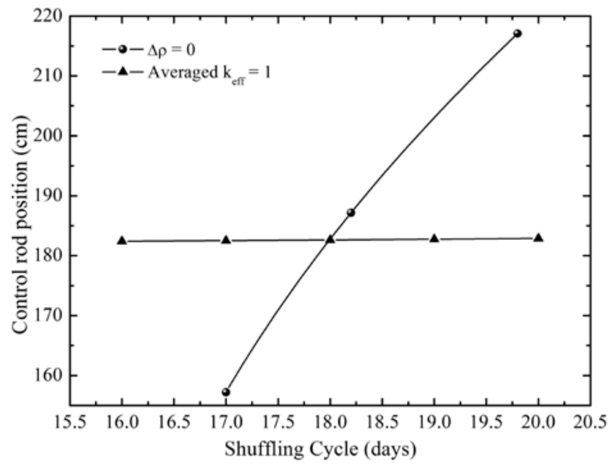

Figure 9 Results of interpolations and the 2-D curves for the verification calculation.

Table 2 Results of Predicted Parameters in the Verification Calculation

	Predicted Results	Operation Data
Reactor Power (MW)	3.83	3.83
FFF in Loaded Fuels (%)	34.2	34.2
Control Rod Position (cm)	182.6	185.9
Shuffling Speed (pebble/day)	28.4	29.5

4. Conclusion

The on-line fuel cycling of PB-HTRs requires the on-line fuel management methodology. The future operation and fuel management parameters must be determined by predicting the future trend of PB-HTR's operation. In this work, the theoretical model of positive reactivity from fuel loading/unloading and negative reactivity from burn-up during successive on-line refueling is discussed. Then the necessary condition for the numerical calculation simulating the actual operation correctly is proposed: the summation of positive reactivity from the instantaneous fuel shuffling in a sufficiently short time interval, namely "shuffling cycle", is equal to the summation of negative reactivity from the following depletion calculation in the same shuffling cycle. Furthermore, another condition that the average effective multiplication factor within a shuffling cycle must be equal to 1 is proposed. These two conditions make sure the reactor critical in the future operation, hence play important roles in the prediction calculations. Since there are four major parameters concerning the steady operation, one has to fix two of them and determine the other two parameters by using both conditions mentioned above.

The model and operation data of the HTR-10 is utilized to demonstrate and verify the methodology presented in this work. An instant of the operation is chosen as the start point of the prediction calculation. The power and FFF are both fixed, and the shuffling speed (cycle) and control rod position are assigned different values and the corresponding prediction calculations are performed. After a series of quadratic interpolations, the combination of shuffling speed and control rod position is obtained for each combination of power and FFF. Some actual operation data are utilized to verify this method. The prediction calculations are performed with the actual power and FFF in the next shuffling cycle, and the predicted shuffling speed and control rod position are in good agreement with the ones from operation data. That verifies the high precision of the methodology presented in this work.

5. Acknowledgment

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6. References

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