IMPROVED ON-LINE FUEL MANAGEMENT METHODOLOGY FOR THE TEST PEBBLE BED HIGH TEMPERATURE REACTOR

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ABSTRACT

The HTR-10 is a test and research reactor of pebble bed high temperature reactors (PB-HTRs), featured by the inherent safety and modular design concept. 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. In previous works, two of four major operational and fueling parameters, i.e. the reactor power, the fuel unloading speed (FUS), the fresh fuel fraction (FFF) and the control rod position (CRP), were optimized to keep the reactor critical in the future operations, based on a matrix of calculations spanned by different values of those two parameters. However, the 2-dimensional matrix of calculations was time-consuming, and the two-from-four optimization was arbitrary and less practical for the operations of the HTR-10. In this work, an improved on-line fuel management methodology is proposed. In order to ensure acceptable axial power profile, the FFF in fuel loading remains constant. On the other hand, the power level of future operation should be determined by the operators according to the actual circumstances such as the grid load, the confinement of fuel handling system and so on. Therefore, the FUS and the CRP are the only parameters to be determined during on-line fuel management. Furthermore, since the average k_{eff} in a refueling cycle is extremely insensitive to the FUS, the appropriate CRP satisfying the criterion of average k_{eff} equal to 1 is firstly determined based on a series of calculations corresponding to different CRPs. Afterwards, a cut-off k_{eff} of the next refueling cycle is calculated to keep the reactivity increment from refueling equal to the reactivity decrement from burnup. Finally, an automatic search of the appropriate FUS is implemented by simply stopping the burnup calculation after the fuel shuffling calculation when the cut-off k_{eff} is reached. Hence, the on-line fuel management calculations are simplified as a series of 1-d calculations for searching appropriate CRP and a single fuel shuffling and burnup calculation for searching appropriate FUS. The methodology is verified by the operation data of the HTR-10, and the results are in good agreement with the actual data.

1. Introduction

The HTR-10[1] is a test and research reactor of pebble bed high temperature reactors (PB-HTRs), featured by the inherent safety and modular design concept. As a test and research reactor, the HTR-10 has been operated for nearly two decades intermittently, along with frequent startup, shutdown and power adjustment[2]. Since the on-line continuous refueling is the key feature of PB-HTRs, the on-line fuel management of the HTR-10 is a great challenge for the intermittent operation of the HTR-10, which urgently demands the methodology of on-line fuel management for the PB-HTRs. However, the fuel management of the HTR-10 are still carried out mainly by the operators' experience by far. Hence, a series of efforts have been devoted to the development of the on-line fuel management methods for PB-HTRs.

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 continuous fuel recycling is the most important method to control and adjust the long term operation of the PB-HTRs, since the methods of boric acid and burnable poisons are not available and the adjusting capability of control rods is limited. Hence, the fuel management of PB-HTRs, featured by the on-line manner and strong coupling with the normal operation, is quite different from the PWRs'. The major aim of the on-line fuel management of PB-HTRs is to keep the reactor under steady and safe operation.

In the previous works[3, 4], four parameters were selected to be analyzed for fuel management, i.e. the power level of reactor core, the fuel unloading speed (FUS), fresh fuel fraction (FFF), and the control rod positions (CRP). One has two criteria for the simulated future operation which must be critical: 1) reactivity increment and reactivity decrement of the next refueling cycle must be equal to each other; 2) the averaged k_{eff} during the next cycle must be equal to 1.0. These two criteria determined the optimized values of two varied parameters from the four mentioned above by performing the calculations corresponding to a 2-dimentional matrix spanned by those two parameters, while the other two had to be set fixed. Quadratic interpolations were utilized to obtain the optimization results. However, it is obvious that this method is time-consuming since N^2 calculations have to be performed for N points for each varied parameter.

Furthermore, the method mentioned above has another drawback. For the burnup calculations of the previous method, most of calculations were performed under false conditions, i.e. most of the average k_{eff} values corresponding to different control rod positions were far from 1.0, which lead to significant deviation of power profiles from the actual critical ones. Thus, except for the burnup calculations near criticality, most of the values of $\Delta\rho$ were not realistic. Consequently, the method mentioned above was built upon unrealistic depletion calculations, although it provided acceptable results in engineering.

2. Description of the improved fuel management method

Since there were drawbacks in the previous method, an improved method is proposed in this work. The calculation tool is the V.S.O.P.[5] coed package, the same as previous works. From the discussion above, the key issue in the on-line fuel management is to determine the appropriate control rod position which keeps the reactor critical. An example of a refueling cycle meeting both criteria mentioned above in the numerical calculation is illustrated in Fig 1. In order to meet the criterion of $\Delta\rho = 0$, ρ_3 has to be equal to ρ_1. On the other hand, the average value of k_{eff} during the depletion process should be equal to 1.0, which can be approximated as below

$$\overline{k}_{eff} = \frac{k_{eff,1} + k_{eff,2}}{2} \quad (1),$$

since k_{eff} values after fuel shuffling can be approximated as linear decrease. It is noticeable that this approximation may introduce k_{eff} deviation of degree of magnitude of 10^{-4}, corresponding to the CRP deviation about several millimeters which is negligible from the point of view of engineering. Thus, the average value of k_{eff} can be determined approximately before the burnup calculation by just performing two steady state calculations before and after the fuel shuffling.

Moreover, the FFF, one of the four parameters in the PB-HTR's fuel management, should not be varied arbitrarily because it influences the average passage number and then the axial power profile significantly. In the improved method, the usual scenario is to determine the FUS and CRP for the future operation with a certain reactor power and a predefined FFF. Under this scenario, the reactor power of future operation is proposed firstly. Subsequently, a series of $\bar{k}_{eff}$ discrete CRP points are selected to calculate the values of $k_{eff,1}$ and $k_{eff,2}$, with instantaneous equilibrium xenon concentration and thermal-hydraulic feedback. As in previous works, a gray curtain with appropriate effective boron concentration is employed to simulate the control rods. Then a series of values are obtained corresponding to different CRP values, according to Eq. 1. Finally, the critical CRP corresponding to $\bar{k}_{eff}$ = 1.0 can be calculated by using interpolations.

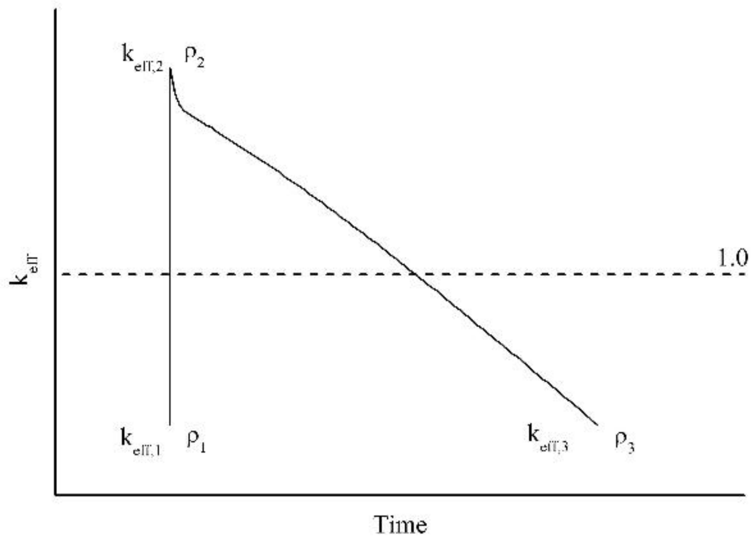

Fig 1. The schematic figure of refueling simulation of PB-HTRs. In the figure, $k_{eff,1}$ and ρ_1 are the k_{eff} and reactivity before the fuel shuffling, $k_{eff,2}$ and ρ_2 are the k_{eff} and reactivity after the fuel shuffling, and $k_{eff,3}$ and ρ_3 are the k_{eff} and reactivity at the end of refueling cycle.

After determining the critical CRP for the next refueling cycle, i.e. meeting the second criterion mentioned above, the depletion calculation has to be implemented subsequently and the first criterion of $\Delta\rho = 0$ must be met. The next refueling cycle with unknown cycle length is divided into a series of small interval with fixed length, and the k_{eff} value of each interval is calculated in turn. Once the k_{eff} value of a certain interval reaches $k_{eff,1}$, the burnup calculation is terminated and the current cycle length is recorded as the optimized result of refueling cycle length. Then the optimized FUS for the future operation is obtained from this cycle length.

Roughly, only N+1 calculations are included in the improved method for N points of CRP, compared with the N^2 calculations in the previous method. Furthermore, since the CRP is usually near the top of pebble bed during power operation, the critical CRP can be searched downward from the all-rod-out position and the CRP points has no need to cover all the reactor core height, which decreases N further. Hence, the improved method presented in this work is not only based on the realistic simulation of actual refueling process, but also reduces the computing time remarkably.

If one wants to determine the appropriate power according to a predefined value of FUS, the process mentioned above can be duplicated corresponding to different reactor power. Then the FUS values are interpolated to determine the power corresponding to the predefined FUS value.

3. Results and discussions

The operation data of the HTR-10 are utilized to demonstrate and verify the improved method presented in this work. The HTR-10 is now in the running-in phase, during which the neutronic properties of reactor vary drastically with time evolution. Two instances are carefully selected as the reference status points to ensure the k_{eff} and CRP values in the next stages of operation to keep steady, so that the optimized FUS and CRP values can be compared with the actual ones.

Instance No.	**1**		**2**	
Parameters	Fuel management	Actual	Fuel management	Actual
Power (MW)	6.80	6.80	3.75	3.75
FFF (%)	50.0	50.0	34.9	34.9
FUS (pebble/day)	49.2	52.5	27.5	29.5
CRP (cm)	184.7	188.1	181.3	185.9

Tab 1: Results of improved method and the actual operation data

The calculations results are listed in Table I, along with the actual parameters for the next stages for comparison, in which the CRP is the average height of the ends of control rods from the bottom of pebble bed. The power and FFF values in Table I are predefined as the same as the actual average operation data in the next time intervals. Also, for the columns corresponding to the actual data, the values of FUS and CRP are averaged from the operation data. The calculated values of FUS from the improved fuel management method have relative deviations less than 7% for both cases, compared with the actual data. On the other hand, the relative deviations of the calculated CRP values compared with the actual data are less than 3%. Obviously, the calculated values in the improved fuel management method have good agreement with the actual operation data of the HTR-10.

For the first instance in Table 1, the optimized FUS and CRP values corresponding to different reactor power are calculated, as illustrated in Fig 2 and Fig 3, respectively. The FUS is generally proportional to the reactor power, and the CRP increases as the reactor power increases. Both dependencies can be employed to interpolate the reactor power corresponding to a certain FUS value.

4. Conclusions

In summary, the improved on-line fuel management method divides the fuel management into two steps: the first is to determine the appropriate CRP for the next cycle by calculating the k_{eff} values before and after fuel shuffling, and the second is to determine the appropriate FUS by the realistic depletion calculation. Compared with the previous method, the improved method can lower the computing time by about one degree of magnitude. It is verified that the improved method presented in this work agrees with the actual operation data well. This on-line fuel management method of PB-HTRs shall be utilized in the operation and fuel management of commercial PB-HTR plants.

5. References

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