Effect of key parameters on the refueling reactivity coefficient in the pebble-bed high temperature gas-cooled reactor

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Abstract

Online continuous refueling is one of the main features of a pebble-bed high-temperature gas-cooled reactor (PB-HTR). During the normal operation of a PB-HTR, positive reactivity is mainly introduced through refueling, whereas negative reactivity is introduced through depletion. Therefore, evaluating the refueling reactivity coefficient is crucial for the safe and stable operation of PB-HTRs. In this study, the perturbation theory is used to calculate the refueling reactivity coefficient, and the effect of key parameters on the refueling reactivity coefficient is examined based on the HTR-PM equilibrium core. The refueling reactivity introduced into the reactor core is driven by the gradient of the nuclide atomic density, particularly U-235. The neutron flux modulates the spatial distribution of the refueling reactivity. The loading fraction of the fresh fuel directly and positively influences the refueling reactivity coefficient. This study provides comprehensive insights into the effect of these parameters on the refueling of PB-HTRs, paving the way for efficient fuel management.

Full Text

Preamble

Effect of key parameters on the refueling reactivity coefficient in a pebble-bed high-temperature gas-cooled reactor∗ Zhong-Kai Sheng,1, 2 Bing Xia,1, † Hong-Wei Wu,2 Ding She,1 Fu Li,1 and Zuo-Yi Zhang1 1Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China 2Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Online continuous refueling is one of the main features of a pebble-bed high-temperature gas-cooled reactor (PB-HTR). During the normal operation of a PB-HTR, positive reactivity is mainly introduced through refuel- ing, whereas negative reactivity is introduced through depletion. Therefore, evaluating the refueling reactivity coefficient is crucial for the safe and stable operation of PB-HTRs. In this study, the perturbation theory is used to calculate the refueling reactivity coefficient, and the effect of key parameters on the refueling reactivity coef- ficient is examined based on the HTR-PM equilibrium core. The refueling reactivity introduced into the reactor core is driven by the gradient of the nuclide atomic density, particularly 235U. The neutron flux modulates the spatial distribution of the refueling reactivity. The loading fraction of the fresh fuel directly and positively in- fluences the refueling reactivity coefficient. This study provides comprehensive insights into the effect of these parameters on the refueling of PB-HTRs, paving the way for efficient fuel management.

Keywords: Refueling reactivity coefficient, PB-HTR, perturbation theory

INTRODUCTION

Inherent safety is the most typical feature of pebble-bed high-temperature gas-cooled reactor (PB-HTR) [1-4] candi- dates for Generation IV [5] advanced nuclear energy systems.

Under any circumstance, including natural disasters or sud- den failures, a PB-HTR can be safely shut down without ex- ternal human operation but only by natural laws. In addition to generating power, PH-HTRs can produce high-temperature steam, and have broad application prospects in hydrogen pro- duction, cogeneration and other fields.

A PB-HTR is developed based on a gas-cooled reac- tor. Based on the geometry of the fuel element, high- temperature gas-cooled reactors (HTGRs) can be divided into prismatic and pebble-bed reactors. Both types of HT- GRs use all-ceramic-coated fuels, and their key technology is the same. Germany and China have developed pebble- bed reactors, and Germany’ s experimental reactor AVR and the commercial demonstration reactor THTR-300 have been shut down. In 2000, the Institute of Nuclear and New En- ergy Technology (INET) at Tsinghua University built a 10 MWth HTGR test module (HTR-10), which verified the in- In 2006, “high- herent safety characteristics of HTGRs. temperature gas-cooled reactor nuclear power plant” became one of the main sub-items of major national science and technology projects “large advanced pressurized water reac- tors and high-temperature gas-cooled reactor nuclear power plants.” The high-temperature gas-cooled reactor pebble-bed module (HTR-PM) obtained the required construction per- mit and officially started in December 2012. The first grid- connected power generation was achieved in December 2021, and the HTR-PM began operation in November 2023. The ∗ This work was supported by the LingChuang Research Project of China National Nuclear Corporation. † Corresponding author, Bing Xia, Tsinghua University, Beijing, 100084, China, xiabing@tsinghua.edu.cn.

HTR-PM is currently in operation, and HTR-PM600, based on the HTR-PM, will be built in the future [6, 7].

PB-HTR and pressurized water reactors (PWRs) differ in terms of fuel management. The PB-HTR uses a high- temperature-resistant pebble as the fuel element, helium as the coolant, graphite as the moderator, and a core structural material. The unique design of the spherical fuel element determines the fuel-management mode, and the goals of the PB-HTR are fundamentally different from those of traditional PWRs. The fuel element of a PWR is a fuel rod, whose po- sition is fixed during operation. After running for a period of time (12–18 months), the PWR must shut down for refuel- ing and removing the exhausted fuel rods and for replenishing fresh fuel rods. Newly loaded fuel rods must exhibit sufficient reactivity to ensure that the reactor can continue to produce energy through nuclear fission reactions. However, excess reactivity also imposes stringent requirements on the safety of PWR. The fuel element of a PB-HTR is a full ceramic spherical fuel element with tri-structured isotropic (TRISO) coated particles [8–10], also known as a fuel pebble, which guarantees inherent safety. During operation of a PB-HTR, fresh fuel pebbles are filled from the top of the reactor to the core. The pebbles naturally fall into the core and flow down- ward because of gravity. The reacted fuel pebbles are then discharged from the bottom of the reactor. On-line continu- ous refueling greatly improves the operational efficiency as well as avoids excessive fuel in stages, thereby significantly reducing the excess reactivity and improving the safety of the reactor. From a fuel management perspective, the main goal of a PWR is to improve the utilization rate of nuclear fuel and reduce the cost of power generation to ensure safety.

The main goal of a PB-HTR is to determine a daily refuel- ing scheme and thus ensure the safe and stable operation of a nuclear power plant. Compared with the shutdown refuel- ing of PWRs, continuous refueling of PH-HTRs improves the availability factor of nuclear power plants.

Upon rationally arranging fuel elements and control poi- sons inside the PWR core, sufficient excess reactivity remains at the cycle end, resulting in a large excess reactivity. The main concern is the total reactor excess reactivity. The PB- HTR maintains reactivity through continuous online refuel- ing, having extremely small excess reactivity. The main con- cern is the small reactivity changes during refueling and in- creasing fuel consumption. Parameter changes in the reactor cause reactivity changes. The rate of reactivity change rela- tive to a parameter is called the reactivity coefficient. The re- activity change from unit refueling is the refueling reactivity coefficient, expressed as $\partial \rho \partial Q$. In PB-HTR, positive reactivity comes from refueling and negative from depletion, making the refueling coefficient positive. During PB-HTR refueling, nuclide atomic density changes affect core state, making the refueling reactivity coefficient important for safe operation.

While numerous studies [11-28]have focused on PB-HTR fuel management, including multi-pass and OTTO schemes, initial load design, thorium-based fuel cycle, and fuel peb- ble characteristics, the refueling reactivity coefficient remains understudied. In our previous work [29], perturbation theory was used to derive the refueling reactivity coefficient' s theo- retical expression, revealing the internal mechanism of reac- tivity in PB-HTR and calculating the coefficient for HTR-PM under typical conditions.

The key parameters of PB-HTR include reactor thermal power, enrichment of fresh fuel, and heavy metal loading per fuel pebble, which affect core reactivity through refueling.

Reactor thermal power is a basic parameter in operation and impacts the refueling reactivity coefficient. Fresh fuel enrich- ment and heavy metal loading are fundamental fuel pebble parameters affecting the refueling reactivity coefficient.

In this study, the effects of key parameters on the refuel- ing reactivity coefficient in the PB-HTR, are studied. Sec- tion II introduces the analysis methodology and the calcula- tion model. Section III presents and discusses the calculation results. Finally, Section IV concludes the paper. The equi- librium core of HTR-PM was modeled to study the effects of key parameters on the refueling reactivity coefficient.

II. METHODOLOGY A. Analysis methodology range. Calculation accuracy relates to the refueling amount - generally, smaller amounts yield higher accuracy, though very small amounts can affect calculation precision. Perturbation theory is more suitable for calculating refueling reactivity coefficient [30–33]. Previous work [29, 34] derived the theoreti- cal expression of refueling reactivity coefficient. Perturbation theory analyzes small perturbations' influence when there is no obvious distortion. From the one-group neutron diffusion equation, the reactivity introduced by the perturbation can be derived as (cid:90) (cid:20)(cid:18) $\Delta\nu\Sigma f$ (cid:19) $-$ $\Delta\Sigma a\ \phi\ 2 - \Delta D(\nabla\phi\ )2$ (cid:21) (cid:90) $\nu\Sigma f\phi$ 2dV where V is the volume, ϕ is the neutron flux, ν is the neutron yield per fission, Σf is the macroscopic fission cross-section, Σa is the macroscopic absorption cross-section, and D is the diffusion coefficient.

Equation (2) is the specific expression of the perturbation equation derived from the one-group neutron diffusion equa- tion. From Eq. (2), the contribution of fission or absorption cross-section to reactivity is weighted by the square of neutron flux, while the contribution of diffusion coefficient is weighted by the square of neutron flux gradient. In Eq. (2), the perturbation value of macroscopic cross-section is pre- sented as difference, hence it is called the difference formula.

When perturbation is small, the neutron flux generally re- mains undistorted. According to Eq. (2), reactivity change can be obtained by determining the perturbation values of neutron flux and macroscopic cross-section.

The expression αQ is derived based on the refueling char- acteristics of the PB-

HTR. Assuming that the flow velocity of fuel pebbles in the core is v, travel distance in the period Δt is $v\Delta t$. The change in $\Delta\nu\Sigma f$ at the space position r is $\Delta\nu\Sigma f(r) = \sum$ (cid:2)$Ni(r - v\Delta t)\nu\sigma f,i(r) - Ni(r)\nu\sigma f,i(r)$(cid:3) where Ni is the atomic density of the nuclide i and $\sigma f,i$ is the microscopic fission cross-section of nuclide i.

Using the first-order Taylor expansion, we obtain:

Refueling reactivity coefficient is expressed as follows:

$Ni(r - v\Delta t) = Ni(r) - v\Delta t \cdot \nabla Ni(r)$ where ρ is the reactivity, and Q is the number of refueling pebbles.

The calculation of refueling reactivity coefficient requires critical calculation before and after refueling. First, calculate the group constant of the core. Then calculate critically based on neutron diffusion equation to obtain effective multiplica- tion factor keff before and after refueling. Next, calculate the ratio of $\Delta\rho$ and ΔQ to obtain the refueling reactivity coeffi- cient. The result from this method is the average refueling reactivity coefficient within the calculated refueling amount The PB-HTR uses graphite as the reflector. The cladding and matrix of the fuel pebbles were composed of graphite.

The absorption cross-section of graphite is relatively small.

The diffusion length of the neutrons in graphite is long, and the distribution of the neutron flux in the core is relatively flat.

Simultaneously, the fuel pebbles were distributed randomly and evenly inside the core. The control rods are arranged in a reflector outside the core. Therefore, the neutron flux and other parameters do not exhibit relatively large local peaks.

Therefore, the PB-HTR exhibited better macroscopic unifor- mity in the reactor core. This is the theoretical reason for using Taylor expansion in Eq. (4) to preserve only first order term.

Some researchers have conducted experimental studies on pebble flow in PB-HTR. This result proved that our simpli- fication was reasonable.

In the study of Khane et al. [35–37], The pebble flow dynamics were studied in a scaled-down test reactor. Using a non-invasive radioactive particle track- ing (RPT) technique used a cobalt-60 based tracer to mimic the shape, size, and density of pebbles. The results show a plug-type flow in the cylindrical region of the reactor at all seeding positions. In a plug-type flow, the flow velocity is assumed to be constant at any cross-section perpendicular to the pipe axis. There was no velocity gradient in the plug, and the entire flow state moved forward at the same speed.

This study shows that the flow velocity can be considered uniform. In other words, the transient perturbations within the flow were sufficiently weak. In the study of Gatt [38] and Li et al. [39], The results indicated that the pebble motion paths were streamlined. and there was little interference or crossing between pebble trajectories. This also supports the simplification of Eq. (4).

Put the Eq. (4) into Eq. (3), and we can get $\Delta\nu\Sigma f(r) = -\sum v\Delta t \cdot \nabla Ni(r)\nu\sigma f,i(r)$ Similarly, $\Delta\Sigma a(r) = -\sum v\Delta t \cdot \nabla Ni(r)\sigma a,i(r)$ where $\sigma a,i$ is the microscopic absorption cross-section of nu- clide i.

The diffusion coefficient D is mainly attributed to the graphite in the PB-HTR. and remained unchanged before and after refueling. So, $\Delta D(r) = 0$ Put the Eq. (5 - 7) into Eq. (2), and we can get (cid:90) ϕ 2(r)$\sum$ (cid:90) (cid:20) σa,i(r) $-$ (cid:21) $\nu\sigma$f,i(r) v(r) $\cdot\nabla$Ni(r)dV ϕ 2(r)$\sum$ $\nu\sigma$f,i(r)Ni(r)dV Refueling speed q is defined asfollows:

Thus, the expression for αQ based on perturbation theory can be obtained as (cid:90) ϕ 2(r)$\sum$ (cid:90) (cid:20) σa,i(r) $-$ ϕ 2(r)$\sum$ (cid:21) $\nu\sigma$f,i(r) v(r) $\cdot\nabla$Ni(r)dV $\nu\sigma$f,i(r)Ni(r)dV During the operation of PB-HTR, the refueling changes the cross-section and other parameters. and causes a change in reactivity. Equation (10) can be used to directly solve the re- activity introduced by refueling according to the current state parameters of reactor, without critical calculations after refu- eling, which improved the calculation efficiency and ensured the accuracy of the calculation. In this study, perturbation the- ory was used to calculate the refueling reactivity coefficient, and the effects of the key parameters were studied.

The main innovation of this method is the first use of per- turbation theory. to analyze the continuous refueling of the PB-HTR. The fuel management scheme of the PB-HTR in- volves continuous online refueling. The fuel pebbles were loaded from the top of the reactor core, flowed to the bottom, and then unloaded. Positive reactivity can be replenished in the reactor core through continuous online refueling. The re- fueling speed of the equilibrium core in the HTR-PM was approximately 6,000 fuel pebbles per day. The average dis- tance travelled by the fuel pebbles was approximately 16 cm per day. which is very small compared to the height of the reactor core (11 m). Therefore, the continuous refueling of the PB-HTR can be regarded as the continuous introduction of small disturbances. Hence, it is reasonable to use the per- turbation theory to analyze the continuous refueling of the PB-HTR. The application of perturbation theory is simpler than that of prior methods. which only needs to calculate the reactivity of the reactor core status before refueling; without calculating the status after refueling. Previous methods must calculate the reactivities before and after refueling.

B. Calculation model HTR-PM demonstration power plant is a 2\$×\$250 MWth thermal reactor based on two modules: designed by INET at Tsinghua University. The HTR-PM reactor uses inert he- lium as the coolant, with a helium temperature of 250 $\circ$C at reactor inlet and 750 $\circ$C at reactor outlet. The primary helium pressure and flow rate were 7 MPa and 96 kg/s [1–4, 40]. The HTR-PM plant, which is the world’ s first modular PB-HTR, was connected to a grid in December 2021.

The HTR-PM reactor used a spherical fuel element of di- ameter 6 cm consisting of a 1 cm-thick graphite cladding and a 5 cm-diameter graphite matrix, and the densities of the graphite cladding and matrix are 1.74 g/cm3. TRISO coated particles were dispersed in a graphite matrix with a diame- ter of 0.92 mm. The fuel kernel for TRISO-coated particles was uranium dioxide with a diameter of 0.50 mm. and den- sity 10.4 g/cm3, that was successively coated with a porous carbon buffer (BufferC), inner pyrolytic carbon (Inner PyC), silicon carbide (SiC) and Outer PyC (Outer PyC) from the in- side to the outside (their thicknesses are 95, 40, 35, and 40 μm, respectively, and their density is 1.05, 1.90, 3.18, 1.90 g/cm3 in order) [8–10, 41].

The active zone of the HTR-PM unit was 3 m in diameter, with an average height of 11 m. and could accommodate ap- proximately 420,000 fuel pebbles randomly arranged in the core. The graphite reflectors, including the side reflectors, were placed immediately outside the core. top and bottom reflectors, respectively. The graphite reflector contains con- trol rods and helium channels. and carbon brick outside the graphite reflector. A schematic diagram of the core structure of the HTR-PM is shown in Fig. 1 [Figure 1: see original paper].

Fig. 1. (Color online) Core structure schematic diagram of the HTR- The fuel pebbles in the HTR-PM unit were cycled 15 times through the reactor before reaching the specified burnup. and the average discharged pebble burnup was 90 GWd/tHM.

The fuel pebbles initially installed in the reactor core are basi- cally not burnup. If fuel pebbles with high enrichment (8.5%) are directly loaded, The excess reactivity was relatively large and difficult to control. Therefore, the initial core loading of HTR-PM adopts a low-enrichment (4.2%) fuel pebble and graphite pebble mixed charging scheme. When the HTR-PM unit is in equilibrium and operates at full power,. Each re- actor module discharges 6,000 high-enrichment (8.5%) fuel pebbles per day where approximately 400 fuel pebbles were spent fuel. Approximately 5,600 fuel pebbles were reloaded into the reactor core, and approximately 400 fresh fuel peb- bles were replenished.

The VSOP code [42] can be used for the reactor physics calculations of the PB-HTR. According to the characteristics of the PB-HTR, VSOP code adopts the coupling of "energy calculation" for a certain space region and the whole reac- tor diffusion calculation, that is Before each reactor diffusion calculation, the spectrum was calculated according to the cur- rent core state. The nuclear database of VSOP code is stored in libraries, including the nuclear data required for resonance calculation. spectrum calculation and burnup calculation.

First, VSOP-ZUT code [43] was used to create the reso- nance integral table.

The neutron slowing-down equation of the inhomogeneous system is established, and the probability of neutrons escap- ing into the moderator is calculated using the cell' s geometric model. The narrow and wide resonance approximations simplify the neutron slowing-down equation, yielding the neu- tron slowing-down energy spectrum. The resonance integral is then solved. The effective resonance absorption cross- sections of 232Th, 238U, 240Pu, 242Pu and other nuclides at dif- ferent densities and temperatures are calculated based on fuel element design and composition, considering fuel pebbles and coated particles' double non-uniformity. The resonance integral table is added to the nuclear database. The effective resonance absorption cross-section is obtained through den- sity and temperature interpolation and added as background absorption cross-section to fast spectrum calculation. VSOP- MS code performs physical calculations, including spectrum, reactor diffusion, burnup, and thermal hydraulics calculations. The spectrum calculation merges nuclides' multi-group cross-sections into wide group cross sections, with 2–33 wide groups and 1 thermal group. PB-HTR uses 4 wide groups: 1 thermal and 3 fast groups. The finite-mesh finite difference method with CITATION code calculates reactor diffusion.

The neutron balance calculation determines neutron leakage for spectrum calculation feedback. The diffusion calculation provides neutron flux and power distributions for burnup and thermal hydraulics calculations. The burnup equation' s so- lution yields nuclide density distribution, while thermal hy- draulic calculation determines temperature distribution using power distribution. Both the nuclide density and temperature distributions must be fed back to the spectrum calculation to update the spectrum. Convergence results were obtained through repeated iterations.

The HTR-PM equilibrium core was modeled to study the factors influencing the refueling reactivity coefficient. The HTR-PM core was equivalent to a cylinder with a diameter of 3 m and height of 11 m. A two-dimensional model was used to simulate the fuel cycle of HTR-PM. The reactor core was divided into five channels, each of which was divided into 20 layers. There are 100 regions, each of which has the same volume. Based on this model, continuous refueling of HTR- PM can be simulated using the step method.

III. CALCULATION AND RESULTS A few key parameters for the fuel management of the PB- HTR were proposed in a previous study [44]. This study fo- cuses on the following key parameters: reactor thermal power P, enrichment of fresh fuel ϵ, and heavy metal loading per fuel pebble, mHM, and the loading fraction of fresh fuel, f .

Through this work, the internal mechanism of reactivity intro- duced by refueling in the PB-HTR can be determined using Eq. (10).

The background parameters included six significant digits in the calculation, thus ensuring the high precision of the per- turbation theory. Under this precision, an uncertainty analysis was performed. If the background parameter is perturbed by one part per million, then The reactivity calculated by perturbation theory does not change even with an accuracy of 0.01 The reliability of the calculated results was confirmed in a previous study [29]. using the VSOP code to calculate the reactivity refueling coefficients. in the equilibrium core and running-in phases of the HTR-PM. The VSOP code, which is widely used in the physical design of PB-HTR, has been certified for nuclear safety.

A. Reactor thermal power Reactor thermal power P is the most basic parameter of nu- clear reactor. When P increases, negative reactivity enters the core, called power loss. Positive reactivity must be introduced to compensate for this power loss to maintain stable reactor operation at the new power level. For the PB-HTR, positive reactivity can be introduced by raising the control rod and increasing refueling speed. At 250 MWth, the HTR-PM op- eration is simulated from transition to equilibrium core. We vary P from 125 to 250 MWth (125, 150, 175, 200, 225 and

250 MWth) to study the effect of P on refueling reactivity

coefficient, with other parameters remaining as designed. To maintain core criticality, control rods are raised and thermal hydraulic parameters adjusted according to power level.

Fig. 2 [Figure 2: see original paper]. Change of refueling coefficient reactivity with reactor ther- mal power.

Based on the current core state, the refueling reactivity coefficient was calculated using the following perturbation method, and the results are shown in Fig. 2. Evidently, with an increase in P, the refueling reactivity coefficient gradually increases primarily due to the distribution of the neutron flux.

It can be expressed as (cid:90) (cid:90) ϕ 2(r)A(r)dV ϕ 2(r)B(r)dV where A(r) and B(r) are functions of the nuclear cross- section.

Eq. (11) shows that the square of neutron flux, as the cross- section disturbance weight, correlates positively with reactiv- ity disturbance. After increasing reactor thermal power, 135Xe atomic density increases, requiring raised control rods to sup- plement reactivity, so the neutron flux peak moves up to the reactor core top with higher macroscopic cross-section distur- bance, as shown in Fig. 3 [Figure 3: see original paper], increasing the refueling reactivity coefficient.

To explain the neutron flux modulation effect, we calculate the axial distribution of refueling reactivity with flat neutron flux and compare it to normal neutron flux distribution. A sig- nificant difference exists between reactivity distributions in Fig. 3. (Color online) Neutron flux in the innermost channel and control rod positions for different powers. normal versus flat neutron flux cases. With identical nuclide atomic density, the neutron flux modulation makes axial refueling reactivity distribution closer to neutron flux distribution.

Reactor thermal power positively affects the refueling reactiv- ity coefficient by influencing neutron flux. As shown in Fig. 2, the refueling reactivity coefficient changes minimally with P - when P decreases from 250 MWth to 125 MWth, the co- efficient reduces by only 6.2%. In power regulation, neutron flux modulation dominates the relationship between refueling reactivity coefficient and P, though its effect is limited. As P increases, neutron flux distribution becomes steeper with an upward-shifting peak, enhancing modulation and upper core reactivity contribution, thereby increasing the refueling reac- tivity coefficient.

B. Enrichment of fresh fuel The HTR-PM is a typical thermal reactor. using the uranium-plutonium fuel cycle with 235U as the primary fis- sion nuclide. The enrichment of 235U in fresh fuel ϵ deter- mines the number of fissile nuclei in a reactor. We vary ϵ from 6 to 11% (6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5 and 11%) to study the effect of ϵ on the refueling reactivity co- efficient. The HTR-PM reactor reaches equilibrium core at

250 MWth, and refueling reactivity coefficients with enrich-

ment of fresh fuel at same and different discharge burnup are calculated, as shown in Fig. 4 [Figure 4: see original paper]. The change amplitude of re- fueling reactivity coefficient and ϵ are similar in both cases, as changes in ϵ affect refueling reactivity mainly through nu- clide atomic density gradient distribution, primarily of 235U.

The analysis uses Eq. (10). With same discharge burnup, re- fueling reactivity coefficient decreases as ϵ increases, shown in Fig. 4(a). When discharge burnup remains constant, fuel pebbles pass through the core 15 times with same cyclic bur- nup; thus, 235U atomic density gradient changes minimally with increasing ϵ. The numerator in Eq. (10) remains similar, while the denominator increases with ϵ, causing the refueling reactivity coefficient to decrease.

When fresh fuel pebbles with different ϵ are used, dis- efficient and 235U atomic density can be approximated as αQ C1 where αQ is the refueling reactivity coefficient, N5 is the av- erage atomic density of 235U along the reactor core axis, ΔN5 is the difference for the atomic density of 235U at the top and bottom of the reactor core, and C1 is constant.

Figure 5 Figure 5: see original paper shows the relationship between the refueling reactivity coefficient and ΔN5 in Eq. (13). As ϵ increases, ΔN5 rises faster than N5, increasing the refueling reactivity coefficient.

Fig. 4. Change in the refueling coefficient reactivity with enrichment of fresh fuel. (a) Discharge burnup is the same; (b) discharge burnup is different. charge burnup increases with ϵ, enabling full nuclear fuel utilization. The change of refueling reactivity coefficient with ϵ in different discharge burnup is emphasized. Taking

90 GWd/tHM discharge burnup at ϵ of 8.5% as benchmark,

the fuel pebble’ s average residence time is adjusted according to Eq. (12) for critical reactor state. (cid:90) T BUdis = where BUdis is the average discharge burnup, T is the average residence time of the fuel pebble in the reactor core, P is the reactor thermal power, and mHM is the heavy metal mass of the reactor core.

With different discharge burnup, the refueling reactivity coefficient increases with ϵ, as shown in Fig. 4(b). Figure 5(a) shows the 235U atomic density distribution in the innermost channel under different ϵ, where higher ϵ leads to greater axial density gradient. According to Eq. (12), ignoring the modulation effect of neutron flux and the influence of other nuclides, the relationship between the refueling reactivity co- Fig. 5. (Color online) Change of atomic density of 235U in the in- nermost channel and ΔN5 with enrichment of fresh fuel (Discharge burnup is different). (a) Atomic density of 235U in the innermost channel; (b) ΔN5 A comprehensive analysis of the impact of enrichment on the refueling re-activity coefficient underlines the gradient of nuclide atomic density within the PB-HTR as the primary fac- tor influencing the refueling reactivity introduced to the reac- tor core.

C. Loading fraction of fresh fuel Fuel pebbles discharged from the reactor core bottom re- turn to the top multiple times to reach specified burnup. Fresh and cycled fuel pebbles that haven’ t reached specified burnup return to the core, where the fresh fuel pebble proportion is called the loading fraction f , which is reciprocal to the num- ber of fuel pebble passing the core n:

We set n from 5 to 18 (5, 6, 7, 8, 10, 12, 15, and 18), and accordingly, f from 5.56 to 20% (5.56, 6.67, 8.33, 10, 12.5, 14.29, 16.67, and 20%). Then, we adjust n to match the cor- responding f , while maintaining the same discharge burnup.

The calculation results are presented in Fig. 6 [Figure 6: see original paper]. The refu- eling reactivity coefficient increases with increasing f , which is expected.

It can be expressed as αQ f The change in the refueling reactivity coefficient parallels the change in the f , increasing by 112% when f rises from 10% to 20%. The refueling reactivity coefficient represents reactivity change from unit refueling amount, including fresh and recycled fuel pebbles. When f increases, the introduced reactivity change increases, though not linearly. From Fig. 6, as f increases, the growth rate of refueling reactivity coeffi- cient gradually increases, due to neutron flux’ s modulating effect on refueling reactivity distribution. Figure 7 [Figure 7: see original paper] shows the neutron flux distribution in the reactor core’ s axial direc- tion under different f . As f increases, the neutron flux peak moves up toward the reactor core top with higher atomic den- sity gradient, causing faster increase in refueling reactivity coefficient.

Fig. 6. Change in the refueling coefficient reactivity with loading fraction of fresh fuel.

The analyzed effect of f on the refueling reactivity coef- ficient shows the ab-sence of a completely linear relationship between f and the refueling reactivity coefficient. This result is attributed to the modulating effect of the neutron flux on the Fig. 7. (Color online) Neutron flux in the innermost channel of the HTR-PM core for different fresh fuel loading fractions. distribution of refueling reactivity, according to the Eq. (10), affecting the refueling reactivity coefficient. Thus, curve fit- ting is used instead of linear fitting in Fig. 6.

D. Heavy metal loading per fuel pebble The fuel pebble in the HTR-PM contains 12,000 TRISO coated particles. The fuel kernel is uranium dioxide, sur- rounded by four coating layers for reactor safety. The design value of heavy metal loading per fuel pebble mHM is 7 g. The refueling reactivity coefficient is calculated based on Eq. (10).

We vary mHM from 6 to 10 g to study its effect on the refu- eling reactivity coefficient. The reactor thermal power and discharge burnup remain constant for different heavy metal loadings, with refueling speed adjusted to maintain core crit- icality.

The results are shown in Fig. 8 Figure 8: see original paper, showing the refueling re- activity coefficient gradually decreases as the mHM increases, with relatively large changes. When the mHM increases from 6 g to 10 g, the refueling reactivity coefficient decreases by 35%. This occurs because mHM affects the neutron spectrum and atomic density of 235U. As mHM increases, both the prod- uct of neutron yield with microscopic fission cross-section of 235U ($\nu\sigma$f5) and microscopic absorption cross-section of 235U (σa5) decrease due to neutron spectrum hardening. Conse- quently, N5 at the reactor core bottom increases significantly at the same discharge burnup. The increase of ΔN5 is less than the increase of N5 as mHM increases. According to Eq. (13), the ΔN5 in the inner- most channel for different heavy metal loadings are shown in Fig. 8(b), decreasing with increasing mHM, matching the- oretical analysis. Heavy metal loading negatively affects the refueling reactivity coefficient through neutron spectrum and atomic density of 235U. The driving force of refueling reac- tivity is the gradient of nuclide atomic density in PB-HTR.

Additionally, neutron flux modulation affects the refueling reactivity coefficient according to Eq. (10), making the re- lationship between mHM and refueling reactivity coefficient non-linear and thus necessitating curve fitting in Fig. 8(a). gradually decreases. The results of ΔN5 IV. CONCLUSION In this study, the theoretical expression of refueling reactiv- ity coefficient in the PB-HTR was derived from the perturba- tion theory. The effects of key parameters, including reactor thermal power P, enrichment of fresh fuel ϵ, loading fraction f , and heavy metal loading per fuel pebble mHM, were in- vestigated using the HTR-PM equilibrium model. Through analyses and calculations, we can draw the following conclu- sions: (1) We analyzed the effect of reactor thermal power P on the refueling reactivity coefficient, and the result indicated that the neutron flux modulated the spatial distribution of the refueling reactivity. In general, the distribution of refueling reactivity was close to that of the neutron flux. (2) The driving force of the refueling reactivity introduced into the reactor core was the gradient of the nuclide atomic density, especially 235U. This result was obtained by ana- lyzing the effect of fresh fuel enrichment ϵ and heavy metal loading per fuel pebble mHM on the refueling reactivity coef- ficient. (3) The loading fraction of fresh fuel f directly influenced the refueling reactivity coefficient, and the two parameters were positively correlated.

The following general conclusions can be drawn about the refueling of the PB-HTR: (1) According to the feature of on-line continuous refuel- ing in the PB-HTR, The perturbation theory was applied to the refueling of the PB-HTR.

the results revealed that the re- fueling reactivity coefficient mainly depended on the gradient distribution of the nuclide atomic density. (2) Our calculations showed that the reactivity introduced during refueling was approximately of the order of 10 pcm per thousand fuel pebbles. The overall effect of a single fuel pebble in the reactor core was negligible. Therefore, gener- ally, a single fuel pebble is not used as the base unit in a PB- HTR. Our results indicate that selecting 1,000 fuel pebbles as the base unit is reasonable and beneficial for the operational management of nuclear power plants.

This study provides deep insights into the internal mecha- nisms associated with the refueling reactivity introduced into a PB-HTR.

Fig. 8. Change in the refueling coefficient reactivity and ΔN5 heavy metal loading per fuel pebble. (a) Refueling coefficient reac- tivity; (b) ΔN5

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