Investigating Core Axial Power Distribution with Multi-concentration Gadolinium in PWR (Post-print)

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Abstract

Core axial power distribution is an essential topic in pressurized water reactor (PWR) reactivity control. Traditional PWRs limit stability against axial core power oscillations at a high-cycle burnup. Because the "camel" peak power shape typically occurs with increasing depletion, the approaches used for the axial power control deserve special attention. This study aims to investigate the performance of different gadolinium rod design schemes in core axial power control during power operation based on the reactivity balance strategy, and to propose new multi-concentration gadolinium rod design schemes. In the new design schemes, low-concentration gadolinium pellets are filled in the axial hump part of the gadolinium rod, and high-concentration gadolinium pellets are filled in the other parts. The impact of different gadolinium rod design schemes on the main core characteristics was evaluated using the nuclear design code package PCM developed by CGN. The results show that the new gadolinium rod design significantly impacts the core axial power shape. The new design schemes can efficiently improve the core axial power distribution along the entire cycle by reducing the core axial power peak at the end of a cycle, enhancing the reactor operation stability, and achieving a better core safety margin, revealing a sizeable potential application.

Full Text

Preamble

Investigating Core Axial Power Distribution with Multi-Concentration Gadolinium in PWR

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Abstract: Core axial power distribution is a critical consideration in pressurized water reactor (PWR) reactivity control. Traditional PWRs face stability challenges against axial power oscillations during high-burnup cycles. The characteristic "camel-shaped" power peak that emerges with increasing depletion necessitates special attention to axial power control methods. This study investigates the performance of various gadolinium rod design schemes for core axial power control during power operation, based on a reactivity balance strategy, and proposes novel multi-concentration gadolinium rod designs. In these new schemes, low-concentration gadolinium pellets are loaded in the axial hump regions of gadolinium rods, while high-concentration pellets occupy the remaining sections. The impact of different gadolinium rod designs on key core characteristics was evaluated using the PCM nuclear design code package developed by CGN. Results demonstrate that the new gadolinium rod designs significantly influence the core axial power shape. These innovative schemes effectively improve core axial power distribution throughout the entire cycle by reducing axial power peaks at cycle end, enhancing reactor operational stability, and achieving superior safety margins, thereby revealing substantial potential for practical application.

Key words: Gadolinium; PCM software package; Fuel assembly; Core axial power distribution; Reactivity

1. Introduction

Long-cycle fuel management is widely implemented in contemporary pressurized water reactor designs to enhance economic performance. For example, most CGN CPR1000 reactors in China have adopted 18-month fuel management cycles in place of traditional 12-month cycles, thereby increasing annual power generation and delivering economic and social benefits. However, long-cycle fuel management requires higher critical boron concentrations at the beginning of cycle (BOC), which leads to uneven power distributions. To mitigate boron concentration requirements and flatten power distributions, burnable poison rods are incorporated into fuel assemblies.

Gadolinium addition represents a mature burnable poison design with proven performance in nuclear power plants worldwide. Numerous studies have investigated gadolinium burnable poisons in the context of long-cycle refueling. Asou and Porta examined the neutronics behavior of various burnable poisons and identified potential applications for gadolinium burnable poisons [1]. Huang et al. reviewed burnable poison development and analyzed properties of different burnable poison materials [2]. Frybortova investigated limitations of burnable absorbers in VVER fuel assemblies, concluding that gadolinium exerts the most significant influence on fuel characteristics [3]. Vnukov et al. analyzed how gadolinium arrangement affects the neutronic performance of VVER-1200 fuel assemblies [4]. Tran et al. studied the neutronics design of VVER-1000 fuel assemblies containing gadolinium burnable poison particles [5]. Huang et al. investigated selection criteria for integrated and separated burnable poisons in long-cycle reactor cores, recommending enhanced long-cycle core performance through proper matching of burnable poisons with varying burnup rates [6]. Yang and Wu applied different optimization methods for in-core burnable poison loading in PWRs [7]. Xia et al. analyzed burnup characteristics of homogeneously mixed burnable poisons for PWRs [8]. Xian et al. examined how different gadolinium concentrations affect in-core fuel management for 18-month PWR reload cycles [9].

Zhang et al. studied fuel management with gadolinium in 18-month fuel cycles employing quarter-core refueling for various nuclear power stations [10, 11]. Bai et al. analyzed first startup physics tests for a nuclear power plant loaded with gadolinium [12]. Galahom investigated the effects of gadolinium burnable absorbers on PWR assembly neutronic characteristics over extended cycles [13]. Mustafa and Amin studied how gadolinium distribution affects neutronic parameters in small modular reactor assemblies [14]. Reda et al. investigated PWR performance and safety features using gadolinium poison based on the Vera core physics benchmark [15]. Bejmer and Seveborn studied enriched gadolinium as a burnable absorber for PWRs [16]. Hu et al. utilized gadolinium as part of backup reactivity in a 400 MW pool-type low-temperature heating reactor core [17].

At BOC, the axial burnup distribution in fresh fuel assemblies is uniform, with axial relative power typically higher in the middle than at the ends. As fuel burnup increases, power peaks gradually migrate toward the ends, forming "camel peaks" at high-cycle burnup.

Control rods serve as the primary means of adjusting core axial power shape. Since they are implemented at the top of the vessel, only one of the two "camel peaks" can be effectively suppressed. Consequently, axial power perturbations can readily trigger divergent axial power oscillations. This phenomenon challenges axial power control and enforces restrictive heterogeneity power peak factors, thereby limiting load-following capacity and operational flexibility, particularly for reactors employing long-period refueling strategies.

Several studies have specifically addressed core axial power distribution in relation to gadolinium. Given the substantially different axial power shapes at various cycle burnups, controlling the power shape throughout the entire fuel cycle presents a significant challenge for fuel and core designers. Drumm et al. optimized axial gadolinium distribution in PWRs using the Pontryagin maximum principle with the conjugate gradient method [18]. Hida et al. developed a method to optimize axial enrichment and gadolinium distribution in boiling water reactor fuel to minimize enrichment requirements [19]. Li et al. studied core power capability during stretched-out operation and analyzed core axial power distribution at different burnups [20]. Zhao et al. investigated core axial power distribution using a 3-D core power capability methodology [21]. Ma et al. studied long-cycle and low-leakage loading techniques for the first and equilibrium cycles of HPR1000 with gadolinium, proposing a method to optimize core axial power shape by replacing gadolinium pellets at the ends with uranium pellets [22, 23]. Saad et al. performed comparative analysis of fuels with different gadolinium axial distributions in advanced PWR cores, proposing a configuration where gadolinium fuel rods were divided into three parts with gadolinium fuel pellets in the central region [24].

In summary, conventional approaches to improving core axial power shape involve replacing portions of uranium and gadolinium pellets. This study proposes a novel method to enhance core axial power shape by adjusting the axial distribution of Gd_2O_3 concentration according to reactivity rates. Pellets with low Gd_2O_3 concentrations are placed at the ends of fresh fuel where "camel peaks" occur, while traditional gadolinium pellets occupy other regions. Results demonstrate that this method significantly dampens axial power "camel peaks," improves core axial power distribution, and enhances operational flexibility.

2. Computer Code

Analyzing the impact of gadolinium rod design on core performance requires a neutronics code system for assembly-level and full-core analysis. Alternative code systems include CASMO/SIMULATE [17] and Serpent/PARCS [25]. This study employs the PCM nuclear design code package developed by CGN for analysis and calculations. The PCM code package comprises the lattice code PINE and the core code COCO.

PINE performs 2-D transport-depletion calculations on fuel assemblies to generate equivalent homogenized parameters required by the 3-D core code COCO for coarse-mesh nodal analysis. These parameters include: (1) neutron diffusion coefficients; (2) average macroscopic cross-sections for various assembly types; and (3) assembly surface discontinuity factors.

PINE utilizes a 69-group cross-section library issued by the IAEA WLUP, which contains 175 nuclides and materials including 23 actinides and 72 fission products. The library includes a detailed burnup chain for gadolinium. PINE's kinetic parameters were derived from JENDL-4.0. The method of characteristics (MOC) is applied for 2-D heterogeneous transport calculations, with the coarse-mesh finite difference (CMFD) technique accelerating the MOC solver. The B_1 approximation model corrects neutron spectra calculated under reflective boundary conditions. Two predictor-corrector methods—the linear rate (LR) method and the linear leakage rate (LLR) method—are applied in PINE's depletion calculations. The code uses the LR method for fuel rods without gadolinium and the LLR method for gadolinium-containing rods to accelerate calculations.

COCO performs analyses including reloading and reshuffling, depletion calculations, criticality searches, control rod worth calculations, calibration curve calculations, and xenon transient calculations. As a 3-D core code, COCO uses two-group assembly parameters generated by PINE to perform neutron diffusion calculations. A non-linear iterative semi-analytical nodal method solves the diffusion equation. The code's depletion module includes both macroscopic and microscopic burnup calculations. Macroscopic burnup calculation addresses burnup distribution in the core, while microscopic burnup calculation handles isotopic concentrations. The microscopic depletion module solves the depletion equation to obtain each isotope's concentration at every burnup step. Neutron reactions analyzed in COCO include capture and induced fission, while α decay and β decay reactions are also incorporated.

COCO analyzes gadolinium isotopes ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, and ^{158}Gd. With its microscopic depletion module, COCO can accurately simulate gadolinium burnup behavior.

Extensive testing, verification, and validation studies have been conducted for the PCM code package to ensure calculation precision in PWR design [26–30]. The JAEA benchmark, criticality experiments, and operational data from CGN nuclear power plants with gadolinium are used to validate PCM's gadolinium calculation capabilities. Verification and validation results demonstrate that the PCM code package achieves high accuracy in its gadolinium module and can reliably analyze gadolinium behavior.

This study uses PINE to analyze fuel assembly reactivity changes with burnup for different gadolinium schemes and COCO to investigate core neutronic characteristics and power distributions in cores loaded with gadolinium rods.

3. Gadolinium Burnable Poison Reactivity Analysis

Natural gadolinium comprises seven isotopes: ^{152}Gd, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd, and ^{160}Gd. The most important isotopes for neutron absorption are ^{155}Gd and ^{157}Gd, which possess large neutron absorption cross-sections and significant natural abundances. Although ^{154}Gd and ^{156}Gd have smaller neutron absorption cross-sections, they occur in relatively significant natural proportions. Upon neutron absorption, these two isotopes transform into ^{155}Gd and ^{157}Gd, warranting careful analysis.

Due to these excellent neutron absorption properties, gadolinium is widely used as a burnable poison in reactor design to control core reactivity and flatten power distributions. During manufacturing, gadolinium burnable poison is produced as a powder homogeneously mixed with Gd_2O_3 and UO_2, then sintered into gadolinium pellets. Compared with UO_2 pellets, gadolinium pellets exhibit lower thermal conductivity and lower melting points.

Consequently, to ensure gadolinium rod integrity in reactor design, the ^{235}U enrichment in gadolinium pellets is kept lower than that in uranium pellets, and the Gd_2O_3 concentration in gadolinium pellets is limited to \$ \$10%. The ^{235}U enrichment in gadolinium pellets ( ), Gd_2O_3 concentration in gadolinium pellets ( ), and ^{235}U enrichment in uranium pellets ( ) in a fuel assembly must generally satisfy the following criterion:

$$\theta \leq \varepsilon - c\mu \tag{1}$$

where c is a constant.

Owing to gadolinium's strong neutron absorption capability, thermal neutrons are rapidly absorbed when passing through the outer layer of gadolinium pellets, making it difficult to penetrate to the inner layers. This creates a pronounced spatial self-shielding effect, which PINE accounts for in detail when calculating gadolinium burnable poison reactivity characteristics.

Traditional gadolinium burnable poison designs typically employ an integral arrangement, with several gadolinium rods placed in the fuel assembly and loaded with gadolinium pellets. This design imposes no constraints on loading patterns, allowing gadolinium rods to be mixed with fuel rods. Theoretically, gadolinium pellets can be placed anywhere within the fuel assembly, enabling arbitrary changes to both axial and radial gadolinium pellet concentration distributions.

Compared with other burnable poisons such as IFBA and WABA, gadolinium burnable poison offers greater design flexibility. For instance, a 12-foot 17$×$17 fuel assembly contains 264 fuel rods, each with a fixed number of fuel pellets. A certain number of gadolinium rods [17] can be flexibly positioned within the fuel assembly. Two typical layouts containing 8 and 24 gadolinium rods are shown in Fig. 1 [Figure 1: see original paper].

The number of gadolinium rods significantly influences fuel assembly reactivity. Fig. 2a [Figure 2: see original paper] presents infinite multiplication factor ($k\infty$) curves for fuel assemblies with varying numbers of gadolinium rods. The initial ^{235}U enrichment in UO_2 pellets was set to 4.45 wt%, the initial ^{235}U enrichment in gadolinium pellets to 2.5 wt%, and the initial Gd_2O_3 concentration to 8%. Fig. 2a shows that fuel assemblies with more gadolinium rods exhibit lower initial reactivity. Fuel assemblies with different numbers of gadolinium rods share the same burnup inflection point and reactivity decline rate after the inflection point.

Gd_2O_3 concentration in pellets also significantly impacts fuel assembly reactivity. Fig. 2b shows $k\infty$ curves for fuel assemblies with different Gd_2O_3 concentrations. The initial ^{235}U enrichment in UO_2 pellets was set to 4.45 wt%, the initial ^{235}U enrichment in gadolinium pellets to 2.5 wt%, and the number of gadolinium rods to 24. Fig. 2b demonstrates that fuel assemblies with lower Gd_2O_3 concentrations exhibit higher initial reactivity for the same number of gadolinium rods. Both the reactivity peak during burnup and the burnup inflection point vary with Gd_2O_3 concentration. Fuel assemblies with lower Gd_2O_3 concentrations reach higher reactivity peaks earlier in burnup, while those with higher Gd_2O_3 concentrations achieve lower peaks later in burnup. After the reactivity peaks, fuel assemblies with different Gd_2O_3 concentrations display identical reactivity decline rates.

Fig. 2 reveals a specific reactivity penalty associated with gadolinium burnable poison in later burnup stages. This reactivity penalty increases with both the number of gadolinium rods and the Gd_2O_3 concentration. This characteristic must be comprehensively considered in reactor core design.

4. New Gadolinium Rod Design Scheme

Gadolinium burnable poison design primarily involves optimizing four parameters: (1) Gd_2O_3 concentration in gadolinium pellets; (2) ^{235}U enrichment in gadolinium pellets; (3) number of gadolinium rods per assembly; and (4) gadolinium rod locations within the assembly.

In traditional fuel assembly design, to simplify manufacturing, fresh fuel pellets in a fuel rod are typically uniform throughout the entire axial height, as are gadolinium pellets (see "Traditional design" in Fig. 3a [Figure 3: see original paper]).

Although the number of gadolinium rods in a fuel assembly is limited (typically less than one-tenth of all fuel rods), gadolinium significantly affects both radial and axial core power distributions due to its excellent neutron absorption characteristics. To optimize radial power distribution, gadolinium rods are typically positioned near guide tube locations in the fuel assembly to reduce fuel rod power through improved neutron moderation. Concurrently, ongoing research into gadolinium burnable poisons has continuously improved axial gadolinium rod design to optimize core axial power distribution. One modified design involves loading uranium pellets with identical ^{235}U enrichment at both ends of the gadolinium rod (see "Modified design" in Fig. 3b), which improves core axial power distribution through replacement of gadolinium and UO_2 pellets [21–22].

As discussed in Section 3, fuel assembly reactivity decline rates vary with different gadolinium concentrations. By employing a reactivity peak shifting strategy for different gadolinium concentrations, it becomes possible to flatten the axial power shape by releasing local reactivity in regions where "camel peaks" appear before the power peak emerges.

Based on this strategy, to improve the axial power shape throughout the entire fuel cycle—primarily to flatten "camel peaks" appearing at end of cycle (EOC)—this study proposes a novel gadolinium rod design method using different concentration gadolinium pellets: low Gd_2O_3 concentration pellets are placed where "camel peaks" occur, while high Gd_2O_3 concentration pellets occupy other regions. Adopting this approach, two new gadolinium rod arrangement schemes were designed, as shown in Fig. 3c (New design-I) and Fig. 3d (New design-II). The main feature of "New design-I" is symmetric arrangement of lower-concentration gadolinium pellets at "camel peak" locations (the "Top Camel" and "Bottom Camel" regions in Fig. 3c). The main feature of "New design-II" is that, in addition to placing low-concentration gadolinium pellets in the hump regions, lower Gd_2O_3 concentration pellets are also placed at the bottom and top of the core ("Bottom End" and "Top End" regions in Fig. 3d). The "New design-II" scheme comprehensively considers the various reactivity contributions of different gadolinium burnable poisons, creating a certain gadolinium concentration gradient distribution from the hump regions to the ends.

Whether implementing the "Modified design," "New design-I," or "New design-II" schemes, the new gadolinium rod designs leverage the flexibility of gadolinium pellets in axial arrangements within gadolinium rods, presenting no manufacturing difficulties.

Compared with other gadolinium design schemes for improving core axial power distribution (such as the "Modified design"), the new schemes in this study feature two main characteristics: (1) Low Gd_2O_3 concentration gadolinium pellets are used instead of UO_2 pellets to replace high Gd_2O_3 concentration gadolinium pellets, enabling precise adjustment of axial power distribution; and (2) Low Gd_2O_3 concentration gadolinium pellets are employed in the hump regions rather than only in the top/bottom parts, allowing local adjustment of axial power distribution near the hump regions.

5. Influence on Core Characteristics

This study is based on the CGN PWR fleet CPR1000 with 18-month fuel management. The equilibrium cycle contains 157 fuel assemblies with 4.45 wt% enrichment, including 72 fresh assemblies. Fresh assemblies contain either 8 or 20 gadolinium rods. Core thermal power is 2895 MW, and the core average coolant temperature at full power is 310 °C. The CPR1000 employs "Mode G" load-following operation. Main core characteristics at 100% nominal power are listed in Table 1 .

To analyze the influence of the new design schemes on core characteristics, the parameters for each gadolinium rod design scheme in Fig. 3 are defined as follows:

1. **Traditional design scheme** (Fig. 3a): Gd_2O_3 concentration in gadolinium pellets uniformly set to 8%.
2. **Modified design scheme** (Fig. 3b): Gd_2O_3 concentration in gadolinium pellets in the main section set to 8%, with "Top End" and "Bottom End" sections using uranium pellets of 4.45 wt% ^{235}U enrichment.
3. **New design-I scheme** (Fig. 3c): Gd_2O_3 concentration in gadolinium pellets at "Top Camel" and "Bottom Camel" regions set to 6%, with remaining regions using 8% Gd_2O_3 concentration pellets.
4. **New design-II scheme** (Fig. 3d): Gd_2O_3 concentration of 6% used for "Top Camel" and "Bottom Camel" regions. From the hump regions to the ends ("Top End" and "Bottom End"), gadolinium pellets with 4% Gd_2O_3 concentration are used, with 8% Gd_2O_3 concentration pellets for the remainder.

The ^{235}U enrichment in all gadolinium pellets was set to 2.5%. In this study, all new assemblies loaded in the core used only one specific gadolinium rod design scheme among the four options; combinations of different schemes were not considered.

In the original CPR1000 18-month fuel management design, the equilibrium cycle core is loaded with fresh assemblies containing gadolinium rods of the "Traditional design" scheme shown in Fig. 3a. In this study, gadolinium rods in fresh assemblies were replaced with the design schemes shown in Figs. 3b, 3c, and 3d. The quarter-core loading pattern for this equilibrium cycle is shown in Fig. 4a [Figure 4: see original paper]. All other fuel and core design features remain identical across all schemes.

Table 2 compares main core neutronic parameters including critical boron concentration (CB), moderator temperature coefficient (MTC), and Doppler temperature coefficient (DTC) under BOC, hot zero power, and all-control-rods-out conditions. CB values are similar across the four schemes, and both MTC and DTC are negative, meeting all design requirements.

Core boron letdown curves for different design schemes are shown in Fig. 4b. The boron concentration trends throughout the cycle are similar across schemes, which is understandable because local design changes to gadolinium rods in new fuel assemblies have minimal impact on total core reactivity.

The impact of different design schemes on radial power distribution was further investigated. Variation of the core radial power peak factor (FΔH) with burnup at full power is shown in Fig. 4c. All FΔH values for different schemes satisfy design requirements. However, Fig. 4c shows that the "Modified design" scheme achieves the lowest FΔH and the most flattened radial power distribution throughout the cycle. The FΔH of "New design-I" is close to "Traditional design" at BOC but slightly higher at gadolinium peak burnup. The FΔH of "New design-II" is similar to "Traditional design" throughout the cycle.

Figure 4d illustrates the effects of different design schemes on core axial power offset (AO) with burnup. All four schemes exhibit similar AO variation characteristics: AO is relatively positive at BOC, gradually becomes negative and reaches a maximum negative absolute value as fuel depletes, then reverses trend and becomes progressively positive with further depletion, reaching a positive maximum before gradually decreasing toward EOC. This complex AO variation is primarily determined by the non-linear reactivity variation of gadolinium-containing fuel assemblies with burnup. Compared with "Traditional design," the other three schemes show slightly larger maximum AO values at gadolinium peak burnup. Although AO for these three new schemes still meets operational requirements, this phenomenon warrants careful attention in nuclear design.

This study further investigated the effects of different design schemes on core axial power distribution in greater detail. Figure 5 [Figure 5: see original paper] compares core axial power distributions (P_z) under full-power steady-state conditions at different cycle burnups. Generally, as cycle burnup increases, core axial power becomes increasingly concentrated at both ends, and the axial power shape gradually transitions from “olive” to “camel.” Simultaneously, each scheme exhibits distinct features with burnup:

1. **Modified design**: Compared with “Traditional design,” the use of UO_2 pellets at gadolinium rod ends results in relatively high core axial power at the top and bottom at BOC. With fuel depletion, this evolves into a hump-shaped power distribution.
2. **New design-I**: Replacing gadolinium pellets in “Top Camel” and “Bottom Camel” regions with lower Gd_2O_3 concentration pellets yields slightly higher local reactivity in hump regions at BOC, which helps flatten the “olive” core axial power distribution at that time. As cycle burnup increases, the lower Gd_2O_3 concentration in hump regions causes faster reactivity decrease compared to other regions, which benefits flattening of hump-shaped power distribution in later cycle stages.
3. **New design-II**: Building upon “New design-I,” this scheme additionally uses lower Gd_2O_3 concentration gadolinium pellets at the top and bottom ends of gadolinium rods. Consequently, compared with “New design-I,” the core axial power shape is more inclined toward the upper and lower core ends, which better flattens the “olive” power distribution at BOC. Because lower Gd_2O_3 concentration gadolinium pellets at the ends exhibit faster reactivity depletion, this helps reduce reactivity in hump regions as burnup increases. Therefore, “New design-II” outperforms “New design-I” in optimizing core axial power shape throughout the entire cycle, achieving performance comparable to “Modified design.”

In general, whether at the beginning, middle, or end of the cycle, both “Modified design” and “New design-II” provide better improvement to core axial power shape than “Traditional design,” while “New design-I” shows less pronounced effects.

Compared with “Traditional design,” the other three schemes reduce local power in core hump regions during later cycle stages, which benefits xenon transient control and reduces xenon oscillation risk. Using a xenon transient with power disturbance introduced at EOC as an example—where reactor power drops instantaneously from 100% FP to 95% FP and the control system remains inactive—COCO simulated core behavior for 72 hours across the four schemes. Figures 6a [Figure 6: see original paper] and 6b compare core axial power deviation (ΔI) and core power peak factor (F_q) during this xenon transient.

Figure 6a shows that ΔI tends to diverge gradually for the core using “Traditional design,” while remaining relatively stable for cores using the other three schemes. The “New design-II” core is most stable in this transient, followed by “Modified design” and “New design-I.” Figure 6b shows that F_q for “Traditional design” exhibits a significant upward trend, while F_q values for the other schemes remain relatively stable and substantially lower than “Traditional design.” “New design-II” achieves the lowest F_q in this transient, followed by “Modified design” and “New design-I.”

Compared with "Traditional design," the other three schemes improve xenon transient control performance, thereby enhancing core load-following capability. Through 3-D core power capability analysis of key penalizing states, this study evaluated core power peaks under normal operating conditions. The axial power peak shape under the most penalizing conditions for the four schemes is shown in Fig. 6c. Results demonstrate that the three alternative schemes smooth the axial power shape under transient conditions. F_q at this penalizing state is 2.41 for "Traditional design," while "Modified design," "New design-I," and "New design-II" achieve values of 2.03, 2.16, and 2.04, respectively—representing reductions of 15%, 10%, and 15% compared with "Traditional design." This evidence supports the conclusion that the new design schemes enhance safety margins and possess strong application potential.

Therefore, "Modified design," "New design-I," and "New design-II" can significantly improve core power shape, enhance control capability, and increase core safety margins.

6. Sensitivity Analysis on Gadolinium Concentration

In the analyses presented in Sections 4 and 5, the Gd_2O_3 concentration in hump regions was set to 6%. However, as shown in Fig. 2, reactivity behavior versus burnup differs for gadolinium pellets with different Gd_2O_3 concentrations. To analyze characteristics of different Gd_2O_3 concentrations, this study performed a sensitivity analysis of axial power shape using 4% Gd_2O_3 concentration in hump regions. The sensitivity study is based on "New design-II" and adopts 4% Gd_2O_3 concentration in the "Top Camel" and "Bottom Camel" regions.

Figure 7 [Figure 7: see original paper] presents the core axial power distribution (P_z) for this sensitivity study at different cycle burnups. These curves show that the power shape exhibits distinctly different features from the design schemes in Section 5. For the sensitivity study scheme, the core displays a "camel" axial power shape at BOC, gradually transitioning to an "olive" shape with burnup. The initial reactivity is relatively higher for gadolinium pellets with 4% Gd_2O_3 concentration, leading to elevated local power in these regions. From this sensitivity analysis, we conclude that Gd_2O_3 concentration in hump regions must be carefully designed with an appropriate value to balance reactivity between hump regions and other regions, thereby improving axial power shape throughout the entire cycle.

7. Conclusion and Outlook

Traditional PWRs face significant limitations due to axial core power oscillations. Gadolinium burnable poison design substantially affects core axial power shape. To improve axial power shape and dampen axial camel peak power at EOC, this study investigated four different gadolinium rod design schemes and compared their core characteristics using the PCM code package for fuel assembly and core behavior analysis.

The analysis shows that all four design schemes exhibit similar core characteristics regarding FΔH and AO variation with cycle burnup. Compared with "Traditional design," "Modified design" uses ^{235}U uranium pellets at gadolinium rod ends and achieves good axial power shape throughout the cycle. "New design-I" places low Gd_2O_3 concentration pellets in hump regions, reducing core axial power peaks to a certain degree. Building upon "New design-I," "New design-II" additionally adopts lower gadolinium concentration pellets at gadolinium rod ends, achieving better performance than "New design-I." Overall, both new design schemes effectively improve core axial power shape. Furthermore, "Modified design" and "New design-II" reduce the core power peak factor by approximately 15% compared with "Traditional design" under transient conditions. "Modified design" and "New design-II" most effectively improve core axial power shape and significantly reduce power peak factors in key transient states.

To optimize axial power shape throughout the entire cycle, Gd_2O_3 concentration in hump regions must be carefully selected to balance reactivity between hump regions and other regions.

All new design schemes require minimal cost and only slight modifications to current designs while significantly improving core axial power distribution.

Therefore, these new gadolinium rod design schemes can improve core safety margins, expand load-following capability and operational flexibility, and demonstrate promising application prospects.

Although the new designs proposed in this study are beneficial, we believe they can be further extended and optimized. Potential improvements include: (1) implementing different gadolinium pellet concentrations at top and bottom hump regions rather than identical concentrations, which may further benefit core axial power shape; and (2) employing higher gadolinium concentrations in different axial regions rather than focusing solely on hump and end regions, which may provide additional benefits to core axial power shape.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Jing-Gang Li, Jing-Han Peng, Chao Wang, Jun Chen, Fei Xu, and Yun-Fan Ma. The first draft was written by Jing-Gang Li, and all authors commented on previous versions. All authors read and approved the final manuscript.

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Note: Figure translations are in progress. See original paper for figures.