Feasibility Study of Gadolinium Rod Optimization Technology for 157-Assembly Core Fuel Management

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Abstract

Utilizing gadolinium rod optimization technology, a feasibility study was performed on 18-month refueling fuel management for a 157-core configuration. An equilibrium cycle fuel management scheme employing the gadolinium rod optimization approach was developed, and principal computational results were presented for both the reference and gadolinium rod optimization schemes. The results demonstrate that through rational arrangement of fuel assemblies and burnable poisons, the gadolinium rod optimization scheme meets design criteria requirements for 18-month refueling cycle operation. Under equivalent cycle lengths, the gadolinium rod optimization fuel management design achieves higher core average discharge burnup, lower fuel assembly usage costs, and improved economic performance.

Full Text

Preamble

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Abstract

A feasibility study on 18-month refueling fuel management for the 157-core was conducted using gadolinium rod optimization technology. The equilibrium cycle fuel management scheme for the gadolinium rod optimization design was developed, and the main calculation results for both the reference scheme and the gadolinium rod optimization scheme were presented. The results demonstrate that through rational arrangement of fuel assemblies and burnable poison, the gadolinium rod optimization scheme can satisfy the design criteria for 18-month refueling cycle operation. Under the same cycle length, the core with gadolinium rod optimized fuel management design achieves higher average discharge burnup, lower fuel assembly usage costs, and better economic performance.

Keywords: gadolinium rod optimization technique; 157-core; fuel management

During nuclear power plant operation, maintenance costs are largely determined by outage expenses and fuel costs for each refueling cycle. To reduce the number of outages over the plant lifetime and improve fuel utilization efficiency, both operating Generation II+ nuclear units [1-3] and other Generation III units represented by Hualong One [4-5] currently widely adopt the long-cycle fuel management mode of 18-month refueling [6-9].

As the scale of nuclear units under construction and in operation continues to expand in China, the demand for uranium resources is also increasing, posing significant challenges to the stable supply of natural uranium in the country. Under the circumstance of increasingly tight natural uranium supply, nuclear industry professionals in China have conducted research on advanced fuel management technologies—including stretch-out operation technology [10-11], dual-enrichment 18-month refueling technology [12], first-cycle equilibrium core design [13], and gadolinium rod optimization technology [14]—to further improve fuel utilization efficiency of operating units, with some technologies already successfully applied in engineering design.

Among these, gadolinium rod optimization technology was first designed for the equilibrium cycle core design of the Hualong One 177-core. This technology draws on the axial zoning fuel management technology of AP1000 nuclear power plants [9] and optimizes the original equilibrium cycle scheme through axial zoning design of gadolinium rods in fuel assemblies and increasing the 235U enrichment in UO2-Gd2O3 pellets. The results indicate that after adopting gadolinium rod optimization technology, the axial power distribution of the core can be improved, the safety margin of the gadolinium-containing core can be enhanced, and approximately 23 million RMB in fuel costs can be saved per cycle.

Currently, neither the Hualong One 177-core nor the Generation II+ unit 157-core has any actual engineering application cases of gadolinium rod optimization technology in domestic nuclear power units. To demonstrate the applicability of gadolinium rod optimization technology in different core types and its economic benefits when applied to Generation II+ unit 157-core, this paper employs the SCIENCE code package to conduct fuel management design and economic evaluation of gadolinium rod optimization technology applied to the 157-core.

2.1 Fuel Management Objectives and Design Criteria

Since current Generation II+ unit 157-core designs basically adopt the 18-month refueling long-cycle mode, the following requirements were proposed for gadolinium rod optimization fuel management design to satisfy power generation planning and core safety requirements, referencing existing 157-core fuel management design objectives and criteria: (1) design cycle length not less than 490 EFPD; (2) core enthalpy rise factor $F\Delta H \leq 1.65$, with an 11.4% calculation uncertainty considered, requiring core nuclear enthalpy rise factor calculation value ≤ 1.481; (3) moderator temperature coefficient at beginning of life, hot zero power, and all control rods out to be negative or zero; (4) shutdown margin at end of life not less than 2300 pcm; (5) discharge assembly burnup not exceeding 52000 MWd/tU.

2.2 Fuel Assembly Selection

The gadolinium rod optimization fuel management plans to adopt full M5 AFA3G fuel assemblies with 235U enrichment of 4.45%. Compared with traditional gadolinium rod design, the difference in gadolinium rod optimization design mainly lies in the different 235U enrichment in gadolinium-containing pellets and whether appropriate axial zoning is adopted for gadolinium rods. The cold-state parameters for gadolinium rod optimization design and traditional gadolinium rod design are shown in Table 1 .

As shown in Table 1, the mass fraction of Gd2O3 in gadolinium rod optimization design remains at 8.0%, but the 235U enrichment in gadolinium-containing pellets is increased from the original 2.5% to 4.45%, and axial zoning is adopted in gadolinium rod optimization design, with the upper and lower sections of the gadolinium rod (each 22.86 cm) loaded with UO2 pellets of 4.45% enrichment, while the middle section contains gadolinium pellets.

3 Scheme Introduction

This study selects the existing 18-month refueling equilibrium cycle core loading scheme for the 157-core as the reference scheme, and the equilibrium cycle scheme employing gadolinium rod optimization technology as the gadolinium rod optimization scheme. The feasibility of gadolinium rod optimization fuel management is demonstrated by comparing the loading patterns and calculated main core parameters of both schemes.

3.1 Reference Scheme Equilibrium Cycle

The 1/4 core loading diagram for the reference scheme equilibrium cycle is shown in Figure 1 [Figure 1: see original paper], adopting a low-leakage core loading pattern using 72 fresh fuel assemblies of full M5 AFA3G with 4.45% enrichment, including 24 assemblies with 8 gadolinium rods, 24 assemblies with 16 gadolinium rods, and 24 assemblies with 20 gadolinium rods, all using traditional gadolinium rod design. In addition to fresh fuel assemblies loaded for the first time, 72 fuel assemblies remain in the core for 2 cycles, and 13 assemblies remain for 3 cycles (including 1 central assembly).

As shown in Figure 1, 12 fuel assemblies that have experienced 3 cycles are placed at the flat-end assembly positions in the outermost core ring, primarily considering that flat-end assemblies are closer to the pressure vessel inner wall. Placing high-burnup assemblies can reduce neutron fluence on the pressure vessel, benefiting pressure vessel lifetime extension, while also satisfying the burnup requirements for source-free startup.

The calculation results for the reference scheme equilibrium cycle are shown in Table 2 . The reference scheme equilibrium cycle has a cycle length of 496 EFPD; the maximum nuclear enthalpy rise factor calculation value excluding uncertainty is 1.446; the moderator temperature coefficient is -2.62 pcm/℃ at beginning of life (BOL), hot zero power (HZP), and all rods out (ARO); the shutdown margin at end of life (EOL) is 3298 pcm.

The maximum discharge burnup of fuel assemblies at EOL is 51.0 GWd/tU (central assembly). The average discharge burnup of assemblies that have experienced 2 cycles is 44.1 GWd/tU, while that of assemblies that have experienced 3 cycles is 42.4 GWd/tU. The average discharge burnup of all discharged assemblies is 43.8 GWd/tU, satisfying the assembly discharge burnup limit requirements.

3.2 Gadolinium Rod Optimization Scheme Equilibrium Cycle

The 1/4 core loading diagram for the gadolinium rod optimization scheme equilibrium cycle is shown in Figure 2 [Figure 2: see original paper], adopting a low-leakage core loading pattern using 68 fresh fuel assemblies of full M5 AFA3G with 4.45% enrichment, including 24 assemblies with 8 gadolinium rods and 44 assemblies with 20 gadolinium rods, all using gadolinium rod optimization design. In addition to fresh fuel assemblies loaded for the first time, 68 fuel assemblies remain in the core for 2 cycles, 13 assemblies remain for 3 cycles (including 1 central assembly), and 8 assemblies remain for 4 cycles.

As shown in Figure 2, 4 assemblies that have experienced 3 cycles and 8 assemblies that have experienced 4 cycles are placed at the flat-end assembly positions in the outermost core ring, primarily considering that flat-end assemblies are closer to the pressure vessel inner wall. Placing high-burnup assemblies can reduce neutron fluence on the pressure vessel, benefiting pressure vessel lifetime extension, while also satisfying the burnup requirements for source-free startup.

The calculation results for the gadolinium rod optimization scheme equilibrium cycle are shown in Table 3 . The gadolinium rod optimization scheme equilibrium cycle has a cycle length of 494 EFPD; the maximum core nuclear enthalpy rise factor calculation value excluding uncertainty is 1.447; the moderator temperature coefficient is -0.07 pcm/℃ at BOL, HZP, and ARO; the shutdown margin at EOL is 2890 pcm.

Excluding the central assembly, the maximum discharge burnup of fuel assemblies at EOL is 50.8 GWd/tU. The average discharge burnup of assemblies that have experienced 2 cycles is 45.6 GWd/tU, that of assemblies that have experienced 3 cycles is 45.2 GWd/tU, and that of assemblies that have experienced 4 cycles is 50.8 GWd/tU. The average discharge burnup of all discharged assemblies is 46.2 GWd/tU, satisfying the assembly discharge burnup limit requirements. The central assembly has a maximum discharge burnup of 53.2 GWd/tU, which exceeds the maximum limit for full M5 AFA3G fuel assemblies. However, since there is considerable flexibility in selecting the central assembly during actual refueling, fuel assemblies with lower burnup from previous cycles can be chosen as the central assembly to avoid the problem of fuel assembly discharge burnup exceeding the limit.

4.1 Core Characteristics Comparison

Tables 2 and 3 only compare the design results of the reference scheme and gadolinium rod optimization scheme equilibrium cycles against the 18-month refueling design limits from the perspective of whether they meet the requirements, without presenting the variation of core parameters throughout the entire cycle. To better compare the core characteristics of the two schemes, Figures 3 [Figure 3: see original paper] through 5 [Figure 5: see original paper] present the variation of maximum core nuclear enthalpy rise factor calculation values, critical boron concentration, and core axial power offset with burnup for both schemes.

As shown in Figure 3, the maximum nuclear enthalpy rise factor calculation values for both the gadolinium rod optimization scheme and reference scheme meet the existing 18-month refueling limit requirements throughout the entire cycle. However, the locations of maximum values differ between the two schemes. The maximum nuclear enthalpy rise factor calculation value for the gadolinium rod optimization scheme appears at xenon equilibrium at beginning of life (corresponding to 150 MWd/tU burnup), while that for the reference scheme appears at mid-life (corresponding to 11000 MWd/tU burnup). Additionally, compared with the reference scheme, the gadolinium rod optimization scheme exhibits more gradual variation in nuclear enthalpy rise factor calculation values throughout the cycle without obvious gadolinium peaks, indicating that gadolinium rod optimization design can better flatten the core radial power distribution.

As shown in Figure 4 [Figure 4: see original paper], the critical boron concentrations for both schemes at BOL, hot full power, and ARO are below 2000 ppm. Except in the vicinity of 11000 MWd/tU burnup where the reference scheme' s critical boron concentration is slightly higher than that of the gadolinium rod optimization scheme, the variation of critical boron concentration with core burnup is essentially consistent between the two schemes throughout the cycle. This demonstrates that adopting gadolinium rod optimization technology has minimal impact on critical boron concentration during the entire operation period and will not increase the difficulty of core reactivity control and operational management.

As shown in Figure 5, the axial power offset for both schemes varies within the range of -7% to +2% throughout the cycle, with essentially similar trends. The axial power offset of the gadolinium rod optimization scheme is slightly more positive than that of the reference scheme at xenon equilibrium at BOL (corresponding to 150 MWd/tU burnup), approaching +2%. The axial power offset of both schemes reaches its most negative value around 11000 MWd/tU burnup (corresponding to the gadolinium peak location), then gradually shifts toward positive values, approaching zero around 17000 MWd/tU burnup (corresponding to 85% EOL), with the gadolinium rod optimization scheme also being slightly more positive than the reference scheme at EOL. This indicates that gadolinium rod optimization design has certain impacts on core axial power distribution, and the effects of axial zoning on specific reactivity accidents need to be emphasized in subsequent safety analyses.

4.2 Economic Analysis of Gadolinium Rod Optimization

As shown in Tables 2 and 3, the cycle lengths for the gadolinium rod optimization scheme and reference scheme equilibrium cycles are 19991 MWd/tU (494 EFPD) and 20090 MWd/tU (496 EFPD), respectively, with corresponding average discharge burnups of discharged assemblies being 46.2 GWd/tU and 43.8 GWd/tU. It can be seen that with similar cycle lengths, the gadolinium rod optimization scheme uses only 68 fresh fuel assemblies, 4 fewer than the reference scheme, resulting in significantly higher average discharge burnup of discharged assemblies, higher fuel utilization efficiency, and better fuel economics.

To more precisely demonstrate the economics of the gadolinium rod optimization scheme, it is necessary to comprehensively consider factors including fuel assembly costs, power generation revenue, outage expenses, and spent fuel treatment costs. The specific analysis methods, parameter settings, and comparison results are described below.

4.2.1 Analysis Method

Since the cycle lengths of the gadolinium rod optimization scheme and reference scheme are not identical, to eliminate the influence of factors such as power generation revenue, outage expenses, and spent fuel treatment costs, the economic evaluation of fuel management schemes was conducted by comparing fuel costs under the same cycle length. As the gadolinium rod optimization scheme has a slightly shorter cycle length, the comparison was made targeting the cycle length of the gadolinium rod optimization scheme. The specific approach is as follows: conduct equilibrium cycle design using 68 full M5 AFA3G fuel assemblies without adopting gadolinium rod optimization technology, calculate the corresponding cycle length and fuel cost, then combine with the cycle length and fuel cost of the reference scheme (72 fuel assemblies) to calculate the fuel cost of the reference scheme at the same cycle length as the gadolinium rod optimization scheme through interpolation, serving as the benchmark for economic comparison between the two schemes.

4.2.2 Main Parameter Settings

Fuel assembly cost calculation requires consideration of parameters including natural uranium unit price, conversion unit price, separative work unit price, fuel assembly manufacturing unit price, inflation rate, and pre-operation interest rate, with relevant parameter assumptions detailed in Table 4 .

Influenced by supply-demand relationships, geopolitics, and market expectations, natural uranium prices have fluctuated significantly in recent years. Referencing international natural uranium spot price trends, this study conservatively uses 75 USD per pound, with USD to RMB exchange rate at 1:7.1. Conversion unit price and separative work unit price reference actual prices, with manufacturing costs assumed to be the same for traditional and optimized gadolinium rods.

4.2.3 Analysis Results

Based on the assumptions in Table 4, the average unit price of each full M5 AFA3G fuel assembly with traditional gadolinium rods is approximately 13.14 million RMB, while that with optimized gadolinium rods is approximately 13.45 million RMB. As shown in Table 5 , under the same cycle length, the gadolinium rod optimization scheme equilibrium cycle uses 68 fuel assemblies with optimized gadolinium rods, corresponding to fresh fuel assembly costs of 914.6 million RMB; whereas the reference scheme uses 71.5 assemblies (obtained through interpolation calculation) with traditional gadolinium rods, corresponding to fresh fuel assembly costs of 939.51 million RMB. The gadolinium rod optimization scheme can save 24.91 million RMB in fuel costs per cycle on average, demonstrating significant economic benefits.

Conclusions

Based on the existing design requirements for 18-month refueling fuel management of 157-core, this study conducted feasibility research and economic analysis of gadolinium rod optimization technology applied to 157-core fuel management design. By comparing the core characteristics and economic analysis results of the gadolinium rod optimization scheme and reference scheme, the following conclusions are drawn:

(1) The gadolinium rod optimization scheme can satisfy the design requirements of 18-month refueling for domestic Generation II+ nuclear power plants in terms of cycle length, discharge burnup, radial power peaking factor, moderator temperature coefficient, shutdown margin, and other parameters, with deeper average discharge burnup than the reference scheme.

(2) The impact of the gadolinium rod optimization scheme on core characteristics is mainly reflected in radial power flattening and axial power offset, with minimal effect on core critical boron concentration.

(3) Under the same cycle length, the gadolinium rod optimization scheme can save nearly 25 million RMB in fuel costs per cycle, demonstrating good economic performance.

Additionally, calculations on the impact of gadolinium rod optimization design on core generic nuclear data and key neutronic parameters for the 157-core have been completed. The results indicate that the calculated results of the gadolinium rod optimization scheme can satisfy the existing safety analysis limits for 18-month refueling of the 157-core. Subsequent work will focus on evaluating and calculating the impact of the gadolinium rod optimization scheme on specific reactivity accidents to more comprehensively assess the safety of the gadolinium rod optimization scheme and achieve early engineering application.

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