

Burnup Enhancement Strategies in a PWR with an H₂O/D₂O Moderator

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1. Introduction

Conventional pressurized water reactors (PWRs) and PWR-based small modular reactors (SMRs) control reactivity primarily through neutron absorption reactions. In conventional PWRs, an excessively high concentration of soluble-boron at the beginning of cycle (BOC) may result in a positive moderator temperature coefficient (MTC). Therefore, the excess reactivity at BOC must be carefully controlled.

Spectral shift control reactors (SSCRs) regulate reactivity through neutron spectrum hardening [1][2]. Among these concepts, reactors employing a mixture of light water (H₂O) and heavy water (D₂O) as moderator and coolant manage excess reactivity at BOC by adopting a higher D₂O fraction to achieve a harder neutron spectrum. As burnup proceeds, the D₂O fraction is gradually reduced to maintain criticality. In an H₂O/D₂O moderator environment, the reduced neutron absorption cross section of the moderator and the hardened neutron spectrum lead to several distinct physical characteristics compared to a conventional light-water-moderated system [3]. In particular, the harder neutron spectrum, relative to conventional PWRs, can improve fuel utilization by achieving a higher conversion ratio during burnup [4].

In this study, parametric neutronic analyses were performed from the pin-cell level to the assembly level under relevant safety constraints for the H₂O/D₂O moderator system. In addition to the parametric investigation, design approaches for enhancing discharge burnup within the prescribed safety limits were also explored. All calculations were conducted using the Monte Carlo code MCS [5].

2. Methods and Results

The reference pin-cell geometry is based on a 16×16 fuel assembly employed in large conventional PWR (APR 1400) [6]. The assembly features a pin pitch of 1.285 cm and a fuel pin diameter of 0.95 cm, resulting in a moderator-to-heavy-metal ratio (M/HM) of 1.78 on a volumetric basis. All neutronic and burnup calculations were conducted assuming UO₂ fuel enriched to 4.95 wt%. A constant neutron leakage of 4% was assumed in the pin-cell and assembly calculations. However, for a more realistic evaluation, the actual core size and the D₂O fraction should be considered [2].

2.1 Moderation Effects on Lattice Geometry

In conventional PWRs that control reactivity using soluble-boron, a high boron concentration is required at BOC to suppress the large excess reactivity, resulting in a less negative MTC. This raises the risk of a positive MTC, thereby limiting the allowable excess reactivity at the BOC.

However, when reactivity is controlled using D₂O, a different behavior is observed. Fig. 1 and Fig. 2 show the infinite multiplication factor (k_{∞}) as a function of M/HM in a pin-cell under various moderator conditions, including the soluble-boron moderated case and H₂O/D₂O mixtures with different D₂O volume fractions. Fig. 1 presents the results obtained by varying the pin pitch, whereas Fig. 2 shows the results obtained by varying the fuel pin diameter. In both figures, similar trends are observed. For the H₂O/D₂O moderator cases, k_{∞} continues to increase with increasing M/HM (i.e., under wetter lattice conditions) over the investigated range. The red line, corresponding to the conventional PWR pin-cell geometry, indicates that in the soluble-boron case the operating point is already near the optimal M/HM, and the slope is relatively shallow, implying a less negative MTC. In contrast, in the H₂O/D₂O moderator environment, the MTC remains negative even at higher D₂O fractions. The steeper slope observed at increased D₂O fractions indicates that a more negative MTC can be achieved compared to the pure H₂O moderator case. In addition, for the 0% D₂O case at end of cycle (EOC), the optimal point occurs near M/HM ≈ 4.0. Therefore, increasing the M/HM ratio up to approximately 4.0 can improve fuel utilization while maintaining a negative MTC.

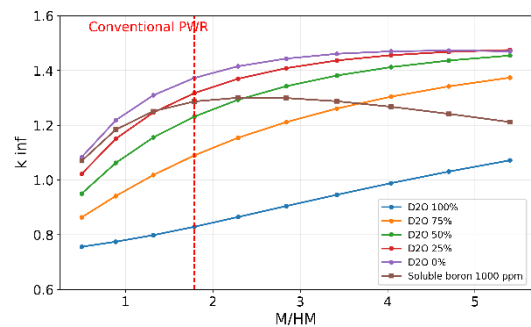


Fig. 1. M/HM vs k_{∞} for various moderator conditions (pin pitch variation).

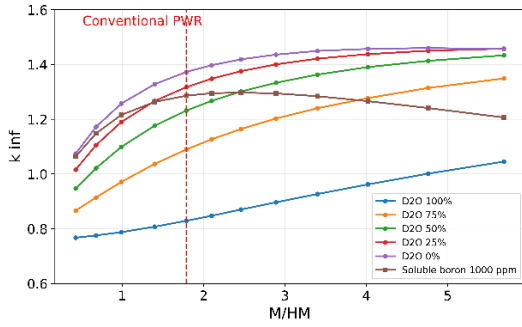


Fig. 2. M/HM vs k_{∞} for various moderator conditions (pin radius variation).

2.2 Spectrum Comparison

Fig. 3 and Fig. 4 show the neutron spectra in the fuel region at the fresh condition as M/HM is varied by changing the pin pitch. Fig. 3 corresponds to the pure H₂O moderator case, whereas Fig. 4 presents the spectrum for the H₂O/D₂O moderator mixture adjusted to achieve criticality. In the pure H₂O case, as the moderator fraction increases (i.e., higher M/HM), the neutron spectrum becomes progressively softer, leading to a significant increase in excess reactivity. In contrast, although the spectrum becomes slightly softer with increasing moderator fraction in the H₂O/D₂O cases, it remains substantially harder than that of a conventional PWR. The hardened spectrum enables a higher conversion ratio and improved fuel utilization. Overall, a wetter geometry with an H₂O/D₂O moderator allows both higher excess reactivity and an improved conversion ratio, resulting in enhanced fuel utilization.

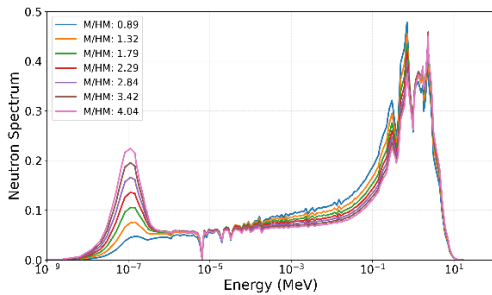


Fig. 3. Comparison of neutron spectra for different M/HM values achieved by varying the pin pitch.

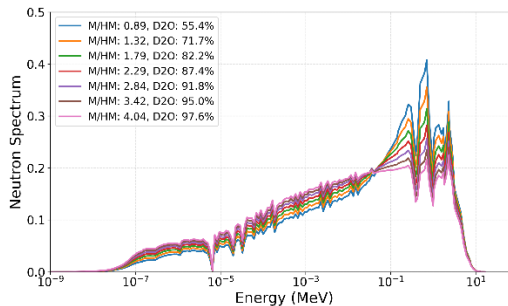


Fig. 4. Comparison of neutron spectra at critical condition for varying M/HM (D₂O adjusted).

2.3 Burnup Increase Strategies

A wetter geometry improves fuel utilization by increasing M/HM. However, under fixed core power and volume conditions, a wetter lattice reduces the total fuel loading and increases the specific power, which could lead to a shorter cycle length. Furthermore, the lattice geometry must be designed within limits that satisfy key safety constraints, including thermal-hydraulic margins and a negative MTC. Burnup calculations were performed over the feasible design space defined by three constraint criteria, all referenced to the conventional PWR power and geometry conditions: (1) the average surface heat flux was limited to the reference value of the large PWR (61.6 W/cm²); (2) the maximum fuel temperature, evaluated as a function of fuel pin radius and lattice pitch, was constrained not to exceed the reference maximum fuel temperature calculated for the large PWR condition (1929 K); and (3) M/HM was restricted to less than 4.0 to ensure a negative MTC.

The fuel temperature was calculated using a simplified two-dimensional pin-cell finite difference method (FDM). The reference fuel temperature was also obtained using the same FDM model by applying the linear heat rate of the reference large PWR as the input condition. For each candidate geometry, the maximum fuel temperature was evaluated by applying a typical peaking factor (F_q) of 2.0 to the average specific power density.

The resulting discharge burnup and cycle length were evaluated within this constrained design region. The feasible design space was constructed under two different assumptions. The first assumes a constant volumetric power density of 111.3 W/cm³, under which the total power is determined by the pin pitch. The second assumes a constant specific power density of 38.4 W/g, under which the total power is determined by the fuel pellet radius.

Fig. 5 and Fig. 6 show the feasible regions satisfying all three constraints under the respective assumptions. Under the constant volumetric power density condition, the surface heat flux constraint limits the simultaneous increase of pin pitch and fuel pin radius required to achieve higher M/HM. In addition, the maximum fuel temperature constraint restricts further increases in pin pitch beyond the reference geometry. Under the constant specific power density condition, both the surface heat flux and maximum fuel temperature constraints limit the increase in fuel pin radius, thereby restricting the achievable design space.

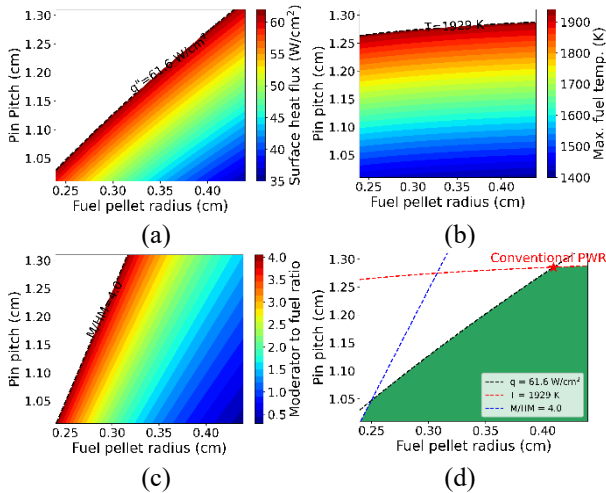


Fig. 5. Feasible design region under the constant volumetric power density condition: (a) surface heat flux constraint, (b) maximum fuel temperature constraint, (c) M/HM constraint, and (d) combined feasible region satisfying all three constraints.

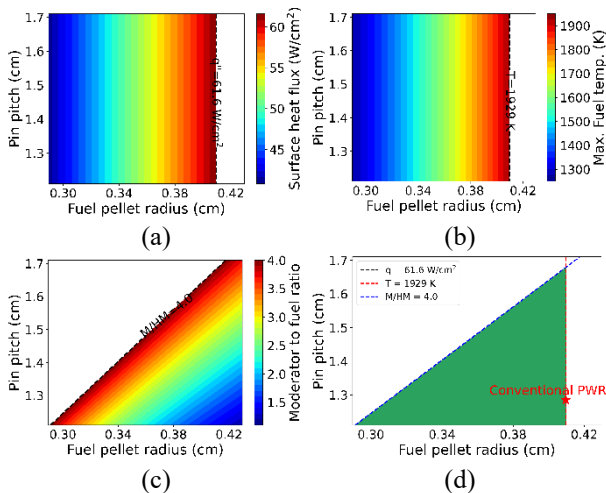


Fig. 6. Feasible design region under the constant specific power density condition: (a) surface heat flux constraint, (b) maximum fuel temperature constraint, (c) M/HM constraint, and (d) combined feasible region satisfying all three constraints.

Fig. 7 and 8 present the burnup calculation results under the constant volumetric power density condition. Near the intersection of the negative MTC constraint and the surface heat flux constraint line, the maximum achievable discharge burnup is 56.5 MWd/kgU. However, within the fixed core volume, a wetter geometry reduces the fuel loading and increases the specific power density, resulting in a significantly shorter cycle length. Cycle length for a given pin pitch is maximized in the M/HM range of 1.6–2.0, and the maximum cycle length within each pitch increases as the fuel pin diameter increases. Consequently, the maximum cycle length occurs at the reference pin-cell geometry.

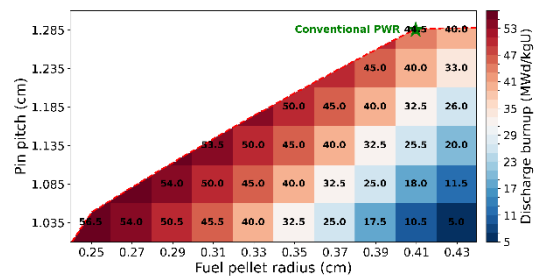


Fig. 7. Discharge burnup distribution under the constant volumetric power density condition.

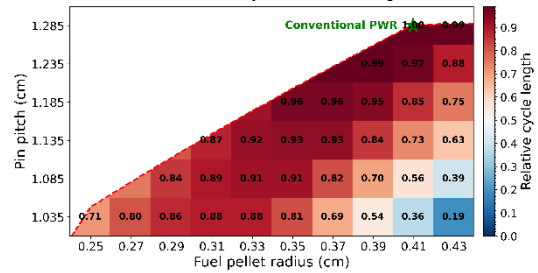


Fig. 8. Relative cycle length distribution under the constant volumetric power density condition

Fig. 9 and Fig. 10 present the burnup calculation results under the constant specific power density condition. In this case, both the maximum discharge burnup and the maximum cycle length occur along the negative MTC boundary line. At the design point corresponding to the largest fuel pin radius and lattice pitch, a discharge burnup of 61 MWd/kgU is achieved, and the cycle length increases by approximately 37% relative to the reference geometry.

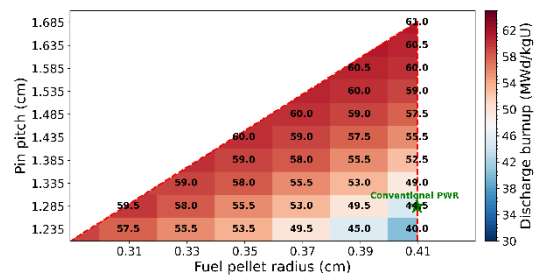


Fig. 9. Discharge burnup distribution under the constant specific power density condition

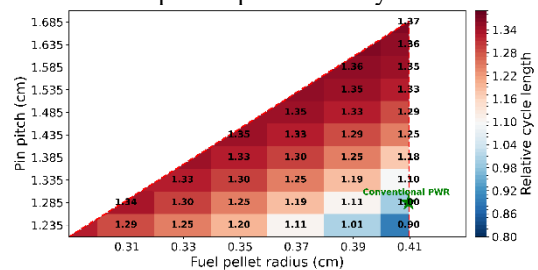


Fig. 10. Relative cycle length distribution under the constant specific power density condition

However, under the constant specific power density condition with a fixed total core power, achieving higher discharge burnup and longer cycle length through a

wetter lattice requires an increase in core volume. Because the specific power is fixed, an increase in fuel inventory directly necessitates a larger number of fuel pins to maintain the same total power. Fig. 11 shows the relative effective core radius compared to the reference geometry. The relative effective core radius was determined from the number of pin-cells required to generate the reference large PWR power. To achieve the maximum discharge burnup and cycle length, the effective core radius must be increased by approximately 31% relative to the reference.

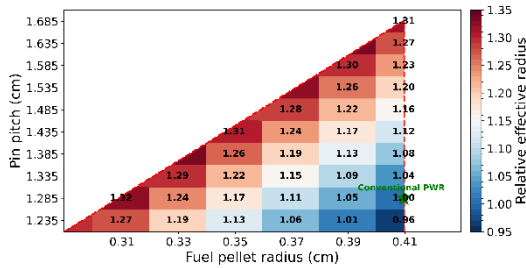


Fig. 11. Relative effective core radius distribution under the constant specific power density condition.

2.4 Assembly Calculations

Based on the reference pin-cell geometry and the wetter geometries that yield the maximum discharge burnup under each of the two constant power density conditions, 16×16 fuel assemblies were constructed. Depletion calculations and MTC evaluations were subsequently performed for each assembly design.

Table I summarizes the MTC values at three burnup points for each geometry under critical conditions. For the reference geometry, the discharge burnup is slightly higher than that obtained from the pin-cell calculation due to the presence of water holes in the assembly. Across all cases examined, a higher D₂O fraction consistently produces a more negative MTC. At EOC, although the wetter geometries exhibit a reduced magnitude of negative MTC compared to the reference geometry, the MTC remains negative.

Table I: MTC at three burnup points for each assembly geometry under critical state.

Case (Pin radius, Pitch)	Burnup (MWd/kgU)	D ₂ O fraction (VF%)	MTC (pcm/K)
Case1 (0.475cm, 1.285cm)	0.0	84.7	-80.8
	25.0	48.5	-77.6
	48.5	2.7	-68.4
Case2 (0.315cm, 1.035cm)	0.0	95.6	-92.6
	45.0	48.5	-68.6
	57.0	3.5	-27.3
Case3 (0.475cm, 1.685cm)	0.0	99.0	-96.8
	52.5	49.6	-63.5
	61.0	4.0	-10.9

3. Conclusions

This study evaluated the neutronic and burnup performance of an H₂O/D₂O moderator system employing spectral shift control. The results show that increasing the D₂O fraction hardens the neutron spectrum and improves the conversion ratio, enabling higher discharge burnup while maintaining a negative moderator temperature coefficient (MTC) in the wetter lattice.

Under the constant volumetric power density condition, wetter lattice geometries increase discharge burnup but reduce cycle length due to higher specific power and reduced fuel loading. In this case, the reference pin-cell geometry provides the longest cycle length.

Under the constant specific power density condition, both discharge burnup and cycle length can be significantly improved. A discharge burnup of 61 MWd/kgU and a 37% increase in cycle length were achieved. However, this requires an increase in core size. Assembly-level calculations confirmed that wetter geometries exhibit a less negative MTC at end of cycle. Overall, the results demonstrate that the H₂O/D₂O spectral shift concept can enhance fuel utilization, but the achievable benefit depends strongly on power constraints and core size considerations.

Acknowledgments

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