Full Fuel Cycle Technoeconomic Analysis and Core Design Strategies for 24-Month High-Burnup PWRs Using LEU+ Fuel

Hyeongtak Kang, Chansoo Lee, SungHoon Joung, Seungmin Kwak, Youho Lee*
Department of Nuclear Engineering, Seoul National University, Gwanak-ro 1, Gwanak-gu,
Seoul 08826, Republic of Korea
**Corresponding author: leeyouho@snu.ac.kr*

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1. Introduction

Extending fuel burnup in nuclear reactors has long been studied because it can improve fuel-cycle economics and reduce the amount of spent nuclear fuel generated[1, 2]. In this context, many studies have examined 24-month operating cycles for pressurized water reactors (PWRs), considering seasonal electricity demand and typical maintenance schedules. Recently, considerable efforts have been directed toward achieving discharge burnups approaching 75,000 MWd/kgU using LEU+ (low-enriched uranium+) fuels enriched above 5 wt% U-235, to further enhance fuel utilization and enable extended cycle operation.

However, high-burnup PWR operation introduces several technical challenges across normal operation, accident conditions, and spent fuel storage[1, 3]. Many of these challenges stem from harsher in-reactor conditions at high burnup, such as increased rod internal pressure due to fission gas release and elevated cladding hoop stress driven by pellet–cladding interaction (PCI). Under large-break loss-of-coolant accident (LBLOCA) conditions, high-burnup fuel rods may be more susceptible to rod burst, and the potential for fuel fragmentation, relocation, and dispersal (FFRD) following rod burst should be evaluated. Furthermore, high burnup fuel complicates spent fuel management. Increased decay heat and rod internal pressure may necessitate extended wet storage periods and compromise cladding integrity during dry storage due to phenomena like creep and hydride reorientation. Addressing these issues requires full-core fuel analysis within an integrated framework that links core design, fuel performance analysis, LBLOCA rod-burst evaluation, and dry-storage assessment.

In this study, a 24-month core design for an APR1400-type Korean large PWR was developed using an integrated framework that considers high-burnup challenges and related mitigation measures. Within this framework, multiple candidate core designs were evaluated iteratively to identify limiting phenomena and to derive practical design constraints for high-burnup operation. Based on these results, a final core configuration was designed and assessed. An economic evaluation was also performed to quantify the benefits of extending the cycle length and increasing discharge burnup.

2. Methodology

The overall analysis consists of three stages: core design, fuel performance evaluation, and subsequent assessments (Fig. 1). PRAGMA, a Monte Carlo–based code, is used to generate assembly cross sections, which are then provided to SPHINCS for core-level analysis[4]. The loading pattern is iteratively adjusted until core performance targets (e.g., peaking factor limits) are satisfied. The resulting pin-wise power histories are transferred to the fuel performance code GIFT to check compliance with normal-operation fuel limits[5, 6]. Based on the GIFT results, high-burnup issues are identified, mitigation measures are defined, and the resulting design constraints are incorporated into the core design. If any criterion is not met, the core design is revised and the workflow is repeated.

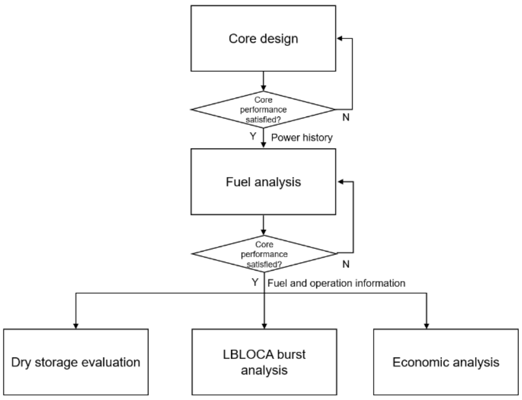

Fig. 1. Framework of core design and further analysis

After the final core design is established, additional evaluations are performed to address high-burnup concerns. Rod-burst potential under LBLOCA conditions is assessed using the KINS rod-burst boundary based on rod-average burnup and peak axial power[7]. Dry-storage performance is evaluated using coupled GIFT–COBRA-SFS calculations[8], focusing

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*leeyouho@snu.ac.kr

on pins with the highest plenum pressure and the highest burnup. Finally, an economic evaluation is conducted using an in-house levelized cost of electricity (LCOE) tool that accounts for additional electricity generation from the extended cycle and cost impacts associated with higher enrichment, enabling a direct comparison between the designed 24-month core and a conventional 18-month core.

3. Technical challenge and mitigation strategy

In the high-burnup fuel analysis, rod internal pressure and cladding hoop stress were identified as major technical challenges (Section 4). To mitigate rod pressurization, two strategies were applied. From a core-design perspective, assembly-level enrichment zoning was strengthened to reduce local power peaking. In conventional PWR designs, lower-enriched uranium is placed near guide tubes and in corner regions (Fig.2 (a)), but the reduction is often limited. As a result, corner pins can still show relatively high power due to enhanced moderation. In this study, corner pins were assigned significantly lower enrichment to suppress corner power peaking (Fig.2(b)), thereby reducing fission gas release and the associated increase in rod internal pressure.

From a fuel-design perspective, the plenum length was increased relative to conventional PWR designs from 18.66 cm to 24.66 cm to expand the available free volume and directly lower rod internal pressure. This change can require a small reduction in active fuel length, which may increase the linear heat generation rate. However, because the active length remains much larger than the plenum length, the increase in free volume (and the resulting pressure reduction) is substantial, while the change in linear power is comparatively modest.

Moreover, the change in active fuel length is relatively small, and the initial fill pressure remains unchanged. Therefore, the overall mass and structural characteristics of the fuel rod are expected to remain largely unchanged. From a mechanical standpoint, including considerations of structural integrity at the upper region of the fuel rod and flow-induced vibration (FIV) behavior, the impact of the increased plenum length is expected to be minimal.

To mitigate cladding hoop stress, an out-in refueling strategy was adopted. In conventional PWR loading patterns, higher-burnup (e.g., thrice-burned) fuel is often positioned toward the core interior because this arrangement is favorable for controlling peaking factors (Fig.2(c)). In contrast, because high hoop stress is likely when both burnup and power are high, the present design places high-burnup rods at relatively low power (Fig.2(d)). Accordingly, thrice-burned assemblies were kept at the core periphery to suppress their relative power and to reduce PCI-driven stress during operation and restart.

This out-in arrangement can also be beneficial for leakage management, which supports achieving higher burnup. However, it can increase radial power imbalance because relatively fresh, higher-reactivity fuel becomes concentrated in the core interior. To control the resulting power skew, three assembly enrichment levels (5.5, 6.0, and 6.5 wt% U-235) were applied based on core location. In addition, lower-enriche assemblies were placed in the central region to suppress excess reactivity and to mitigate radial power peaking. In addition, integrated burnable poison with an increased gadolinium-bearing rod fraction of 10% was employed to improve early cycle reactivity control for high enrichment uranium.

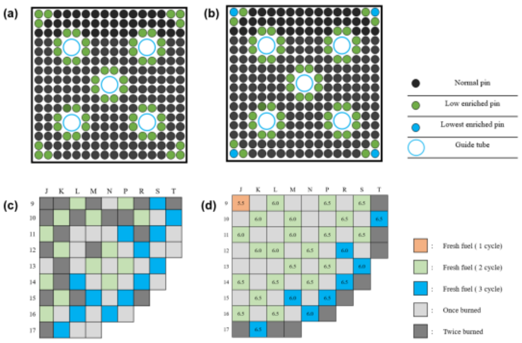

Fig.2. Assembly and core design comparison between conventional and 24-month cycle core; (a) Assembly design of conventional APR1400-like, (b) Assembly design of 24-month core, (c) Assembly position of conventional APR1400-like, (d) Assembly potion of 24-month core

4. Results and discussion

4.1. Core performance

The core performance of the designed core, relative to a conventional 18-month core, is summarized in Table I. The effective full-power days (EFPD) are extended to 700 days, which corresponds to a 24-month cycle when the outage period is included. The average discharge burnup increases to 63.2 MWd/kgU, and the peak burnup increases to 77.5 MWd/kgU. Owing to the reduced active fuel length, the average linear heat generation rate (LHGR) increases to 18.66 kW/m. The critical boron concentration increases to 1634 ppm despite extensive use of burnable absorbers. The peak peaking factor (Fq) increases slightly from 1.82 to 1.85. Although both the average LHGR and Fq increase, the peak Fq remains below the APR1400 limit derived from the LHGR acceptance criterion specified in the APR1400 Final Safety Analysis Report (FSAR).

Table.I. Core performance comparison between 18-month conventional core and 24-month core

Features	18-month	24-month
Cycle length	478	700
Avg burnup [MWd/kgU]	49.2	63.2

Peak burnup [MWd/kgU]	61.1	77.5
Avg LHGR [kW/m]	18.37	18.66
Peak CBC (ppm)	1204	1634
Peaking factor (Fq)	1.82	1.85

4.2. Fuel performance

Fig. 3 summarizes key fuel-performance results for the 24-month core. The average discharge burnup is classified into four groups: standard rods in twice- and thrice-burned assemblies, burnable poison rods in twice- and thrice-burned assemblies, standard rods in once-burned assemblies, and burnable poison rods in once-burned assemblies. The predicted rod internal pressure remains below ~15.5 MPa, which is comparable to typical PWR system pressure. Some rods exceed 200 MPa in cladding hoop stress, with peak values occurring at startup after the second refueling outage. Owing to the use of PRXA cladding, the oxide thickness and hydrogen pickup remain low, with peak values of ~20 µm and ~120 ppm, respectively. However, several rods show elevated radial hydride fraction (RHF) operation because of the high stress level. This trend suggests an additional technical concern for high-burnup cores experiencing high cladding hoop stress.

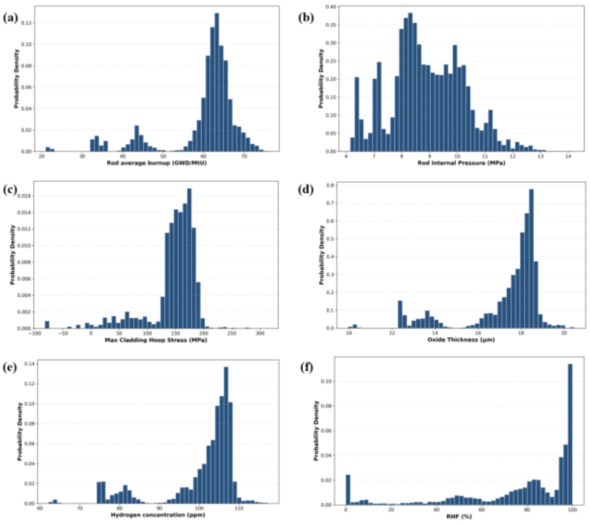

Fig.3. Fuel performance of 24-month core; (a) Rod average burnup, (b) Rod internal pressure, (c) Peak Cladding hoop stress, (d) Oxide thickness, (e) Hydrogen concentration, (f) RHF

4.3. LBLOCA rod burst analysis

Fig. 4 shows the number of fuel rods exceeding the 1% burst probability criterion. The number of rods is high at the beginning of the cycle and increases again after approximately 350 days. The initial peak is mainly caused by pronounced axial power peaking associated with early core power imbalance. The later increase results from the combined influence of elevated Fq and increased burnup, both of which increase susceptibility to burst.

Fig. 5 shows the spatial distribution of rods that exceed the burst criterion within the core. Fig. 5(a) presents the burst map at the beginning of the cycle, where exceedances are concentrated in fresh fuel assemblies with high power, consistent with the strong axial power peaking observed in the early stage. Fig. 5(b) shows the burst map at 600 days, corresponding to the period with the highest number of burst susceptible rods after the initial stage. In contrast to the early cycle behavior, the exceedances at 600 days are located in intermediate core regions where power becomes relatively higher as the cycle progresses. This shift indicates that burst susceptible rods move from high power fresh fuel regions toward intermediate core locations over the course of the cycle.

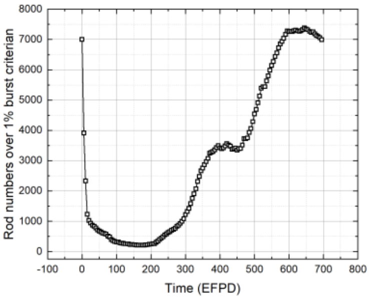

Fig.4. Rod numbers with burst probability greater than 1%

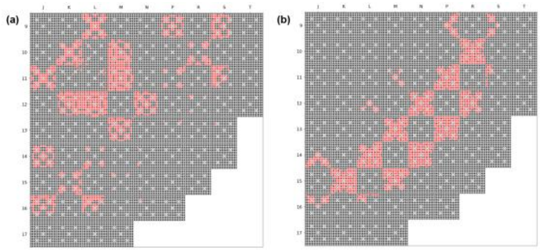

Fig. 5. Rods with burst probability greater than 1% of 24-month core; (a) 5 days, (b) 600 days

4.4. Dry storage analysis

The dry storage analysis was performed for the peak-burnup pin and the peak rod internal pressure pin. At discharge, their conditions were 77 MWd/kgU and 9.8 MPa, and 68 MWd/kgU and 14.1 MPa, respectively. The dry-storage results depend on the assumed wet-storage duration. For each case, the wet-storage period was first determined as the time required for the peak cladding temperature, a key NRC criterion, to drop below 400 °C. The resulting wet-storage times were 5.75 years and 5.0 years, respectively (Fig. 6(a)). This difference arises because the peak burnup pin has a higher decay power over time due to the larger burnup.

For cladding hoop stress, the values were 70 MPa and 86 MPa, with the peak rod internal pressure pin showing the larger stress because of the higher internal pressure. Although this satisfies the NRC criterion of 90 MPa, the margin is limited, indicating the potential need for a longer wet-storage period (Fig. 6(b)). The cladding hoop creep strain also exceeded the previous NRC criterion of 1% (Fig. 6(c)). In addition, the RHF values for both cases exceed 10% at the initial stage of precipitation. This also indicates that a longer wet-storage period is necessary for high burnup reactor (Fig. 6(d)).

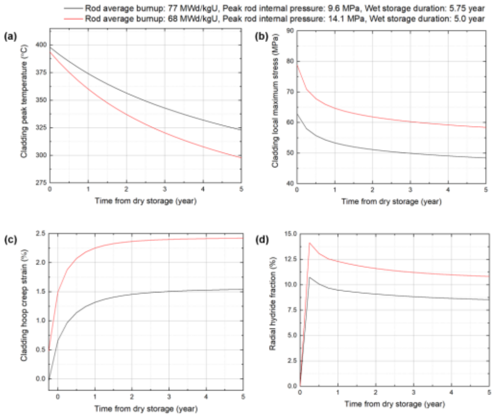

Fig.6. Dry storage analysis result of peak burnup pin and peak rod internal pin; (a) Cladding peak temperature, (b)Cladding hoop stress, (c) Cladding hoop creep strain, (d) RHF

4.5. Economic analysis

Fig. 7 compares the economic analysis results for the 18-month and 24-month cores under two SWU price assumptions of 120 $/SWU and 180 $/SWU, respectively. Non-fuel costs (i.e., all costs except fuel) are lower for the 24-month core, primarily because its higher capacity factor spreads fixed costs over a larger amount of electricity generation. In contrast, the 24-month core exhibits higher fuel costs due to its higher uranium enrichment requirement, which increases SWU consumption. Quantitatively, when the SWU cost is 120 $/SWU, the total LCOE of the 24-month core decreases by 1.3% relative to the 18-month core, whereas when the SWU cost increases to 180 $/SWU, the reduction narrows to 1.1%. This trend indicates that the relative economic advantage between the two core options can change depending on the SWU cost level, because the contribution of enrichment-related fuel cost becomes more significant as SWU prices rise.

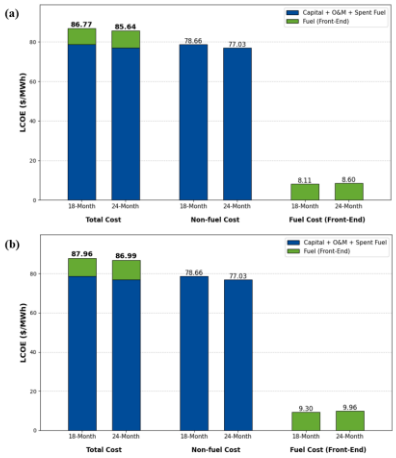

Fig.7. Economic analysis result comparison between 18-month conventional and 24-month core depending on SWU cost; (a) 120$/SWU, (b) 180$/SWU

5. Conclusion

This study developed and evaluated a 24-month high-burnup LEU+ fuel cycle for an APR1400-type large PWR to extend a conventional 18-month cycle. An integrated PRAGMA–SPHINCS–GIFT framework was used to support core design and full-core, pin-wise fuel performance evaluation, followed by LBLOCA rod-burst screening and dry-storage assessment.

The optimized loading pattern with multi-enrichment LEU+ fuel achieved 700 EFPD, with a slight increase in Fq (1.82 to 1.85) and critical boron concentration (1204 to 1634 ppm), while meeting the APR1400 Fq limit derived from the LHGR acceptance criterion. Fuel-performance results indicated rod internal pressure below ~15.5 MPa and low corrosion metrics for PRXA cladding (peak oxide thickness ~20 μm and hydrogen pickup ~120 ppm); however, some rods exhibited cladding hoop stress above 200 MPa and elevated RHF, highlighting the importance of full-core evaluation.

LBLOCA analysis using the KINS rod burst boundary showed that rods exceeding the 1% burst-probability criterion are concentrated in the initial stage and increase again after ~350 days, driven by initial axial power peaking and the combined effects of elevated Fq and burnup. Dry-storage evaluation for the peak-burnup pin and the highest-pressure pin determined wet-storage times of 5.75 and 5.0 years to reduce peak cladding temperature below 400 °C; cladding hoop stress remained below 90 MPa with limited margin, and cladding hoop creep strain exceeded a previously used 1% criterion. The economic analysis showed that the total LCOE decreases by 1.3% at 120 $/SWU and by 1.1% at 180 $/SWU relative to the 18-month core, reflecting higher electricity generation despite increased enrichment-related fuel costs.

These results demonstrate the technical and economic feasibility of the proposed 24-month high-burnup LEU+ cycle while also identifying the remaining technical challenges. In particular, the development of engineering measures to effectively mitigate fuel rod internal pressure and cladding hoop stress, the accurate assessment of potential fuel fragmentation and dispersal behavior under LBLOCA conditions, and the establishment of a robust spent fuel management strategy will be essential for the successful implementation of a 24-month, three-batch fuel cycle in PWRs.

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REFERENCES

[1] P. Rudling, R. Adamson, B. Cox, F. Garzatolli, and A. Strasser, "High burnup fuel issues," Nuclear Engineering and Technology, vol. 40, no. 1, pp. 1-8, 2008.

[2] Z. Xu, M. S. Kazimi, and M. J. Driscoll, "Impact of high burnup on PWR spent fuel characteristics," Nuclear Science and Engineering, vol. 151, no. 3, pp. 261-273, 2005.

[3] A. Halimi, Y. Che, and K. Shirvan, "Design and full core fuel performance assessment of high burnup cores for 4-loop PWRs," Progress in Nuclear Energy, vol. 186, p. 105791, 2025.

[4] C. Lim, S. J. Kwon, and J. Yoon, "Performance analysis of a two-step calculation procedure based on Monte Carlo and pin-wise diffusion methods for PWR core design," Nuclear Engineering and Technology, vol. 57, no. 8, p. 103596, 2025.

[5] K. Shim, H. Rho, C. Lee, C. Jo, and Y. Lee, "GIFT-1.0: Advanced light water reactor fuel performance code," Nuclear Engineering and Technology, p. 103567, 2025.

[6] C. Lee, K. Shim, H. Rho, J. Yoon, H. Jeong, and Y. Lee, "Full-Core Fuel Analysis of a Soluble Boron-Free SMR: Pellet-Cladding Interaction Issues and Enhancing Fuel Safety through Loading Pattern Design," Nuclear Engineering and Technology, p. 103709, 2025.

[7] J. Lee and Y.-S. Bang, "Evaluation of core-wide fuel pin burst during LOCA in APR1400," Nuclear Engineering and Design, vol. 371, p. 110955, 2021.

[8] C. Lee and Y. Lee, "Development of a coupled fuel (GIFT) and thermal (COBRA-SFS) analysis code for dry storage analysis and its application for the spent fuel safety analyses," Nuclear Engineering and Design, vol. 428, p. 113501, 2024.