Journal of
Nuclear Engineering

Review

Core Physics Characteristics of Extended Enrichment and High Burnup Boiling Water Reactor Fuel [†]

Ugur Mertyurek *, Riley Cumberland and William A. Wieselquist

Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA; cumberlandrm@ornl.gov (R.C.); wieselquiswa@ornl.gov (W.A.W.)
* Correspondence: mertyureku@ornl.gov

[†] This article is an extended version of our paper presented as "Core Physics Characteristics of Extended Enrichment and Higher Burnup Boiling Water Reactor Fuel" in International Conference on Physics of Reactors (PHYSOR 2024), San Francisco, CA, USA, 21–24 April 2024.

Abstract: This paper presents the highlights of boiling water reactor (BWR) core physics studies performed at Oak Ridge National Laboratory as part of a series of studies conducted to compare low-enriched uranium (LEU) with LEU+ fuel. The studies analyzed isotopic fuel content, lattice parameters (Phase 1), and core physics (Phase 2) to identify challenges in operation, storage, and transportation for BWRs and pressurized water reactors (PWRs). Because of a lack of publicly available lattice and core designs for modern BWR fuel assemblies and reactor cores, several optimized lattice designs were generated, and different core loading strategies were investigated. Twelve optimized lattice designs with ^{235}U enrichments ranging from 1.6% to 9% and gadolinia loadings ranging from 3 to 8 wt% were used to model axial enrichment and geometry variations in fuel assemblies for core designs. Each core shares a common set of approximations in design and analysis to allow for consistent comparisons between LEU and LEU+ fuel. The objective is to highlight anticipated changes in core behavior with respect to the reference LEU core. The results of this study show that the differences in LEU and LEU+ core reactor physics characteristics are less significant than the differences in lattice physics characteristics reported in the Phase 1 studies.

Keywords: BWR; HALEU; LEU+; SCALE; POLARIS; PARCS

check for updates

Academic Editor: Dan Gabriel Cacuci

Received: 3 December 2024
Revised: 18 January 2025
Accepted: 24 January 2025
Published: 31 January 2025

Citation: Mertyurek, U.; Cumberland, R.; Wieselquist, W.A. Core Physics Characteristics of Extended Enrichment and High Burnup Boiling Water Reactor Fuel. *J. Nucl. Eng.* **2025**, *6*, 4. https://doi.org/10.3390/jne6010004

1. Introduction

Nuclear fuel vendors and utilities are investigating possible changes to fuel contents and fuel designs to develop more economical, safer reactor operations [1]. Accident-tolerant fuel (ATF) designs are intended to improve fuel and cladding performance under accident conditions. More economical reactor operations can be achieved by extending reactor operation periods or by reducing fresh fuel batch sizes. Both objectives require extending existing fuel enrichment limits beyond 5% ^{235}U (all percent enrichments refer to weight percent) and extending assembly average fuel burnup limits beyond 50 GWd/MTU [2]. A subset of high-assay low-enriched uranium (HALEU) fuel that limits the extended enrichments up to 10% ^{235}U is called *low-enriched uranium plus* (LEU+), which differs from low-enriched uranium (LEU), which comprises fuel enrichments below 5% ^{235}U. LEU+ is being developed for use in the existing light-water reactor (LWR) fleet.

Recently, studies were conducted at Oak Ridge National Laboratory (ORNL) [3–9] to identify the effects of challenges in the operation, storage, and transportation of extended fuel enrichments and burnup on fuel assembly characteristics by investigating reactivity coefficients, isotopic content, and decay heat for pressurized water reactors (PWRs) and boiling water reactors (BWRs). Similar to a two-step core analysis, the project is divided into phases: Phase 1 focuses on the lattice physics parameter and the used fuel isotopic changes for conventional lattice designs, and Phase 2 assesses the impacts of LEU+ and high-burnup (HBU) fuel on core physics characteristics of the current fleet of PWR and BWR reactors. These studies intend to help extend LEU fuel experience to LEU+ fuel by comparing important lattice and core parameters (e.g., isotopic distribution, reactivity parameters) that drive different applications (e.g., shielding, criticality and thermal limit calculations). Core physics characteristics of PWR LEU and LEU+ cores were compared in a previous study [8]. Both cores were optimized by the same utility company, and an extension from an 18-month cycle to a 24-month cycle was targeted by the new LEU+ design. The study showed that for those particular LEU and LEU+ cores, the difference in radial peaking factors is less than 0.1, and differences in reactivity coefficients are significantly less than the values calculated in Phase 1 studies.

Unlike PWRs, publicly available core and assembly design information for BWRs is limited. Although there are accident-tolerant fuel core designs with limited optimization for advanced boiling water reactors [10], no candidate design for a BWR LEU+ core was available at the time this study was conducted. Furthermore, the BWR LEU core designs that are publicly available [11,12] are from early cycles of BWRs, so their core designs are not representative of the current fleet. Therefore, two representative reference LEU cores and three LEU+ cores were designed with limited optimization based on the Hatch 1 reactor core geometry [8].

The cycle lengths used for LEU+ cores were based on the assumption that utilities will either (1) seek to lower the fresh fuel batch size (i.e., number of fresh fuel assemblies) while keeping the cycle length to 24 months or (2) extend the fuel cycle to 36 months with a minimum number of fresh fuel assemblies. The cycle length, batch size, and number of batches are expected to be decided based on cost and maintenance feasibility studies. This paper only provides highlights from core physics comparisons for a 24-month-cycle LEU core vs. a 36-month-cycle LEU+ core.

2. Phase 1 Lattice Physics

The objective of the first phase of the BWR study [4] was to enhance the understanding of the best-estimate effects of LEU+ and HBU fuel with respect to LEU fuel by comparing neutron flux spectra, reactivity coefficients, decay heat, and isotope concentrations important for shielding, severe accident analysis, and criticality during storage. Because lattice-average effects were considered in this study, for a typical GE14 10 × 10 lattice design [13], dominant (DOM) and vanishing (VAN) regions were modified from 5% maximum enrichment (4.5% average enrichment) to satisfy the LEU+ lattice-average enrichments required for this study (8.5% maximum—6.5% average, and 10% maximum—7.4% average). All lattices were depleted up to 80 GWd/MTU at 10%, 40%, and 70% void fractions. SCALE 6.2.4 Polaris lattice calculations were performed for Evaluated Nuclear Data File (ENDF)/B-VII.1 56-group and 252-group AMPX neutron libraries. Gadolinia fuel pins were modeled with 10 equal-volume rings. The fuel temperature was assumed to be uniform at 900 K.

In general, decay heat at discharge decreases with burnup and increases with enrichment. The largest difference is 33 kW/MTU, and it corresponds to less than a 2% difference compared to the reference LEU case. The differences in decay heat dissipate to less than 5 kW/MTU after 100 days of cooling, as shown in Figure 1. After the short-lived, high-heat fission products decay, decay heat shows the opposite trend with burnup and enrichment. While the magnitude of the difference is small, the relative difference in comparison to the reference LEU case is significant (40%). This can influence the cooling time before the assemblies can be loaded into dry storage canisters due to the low heat transfer ability of gas in comparison to water.

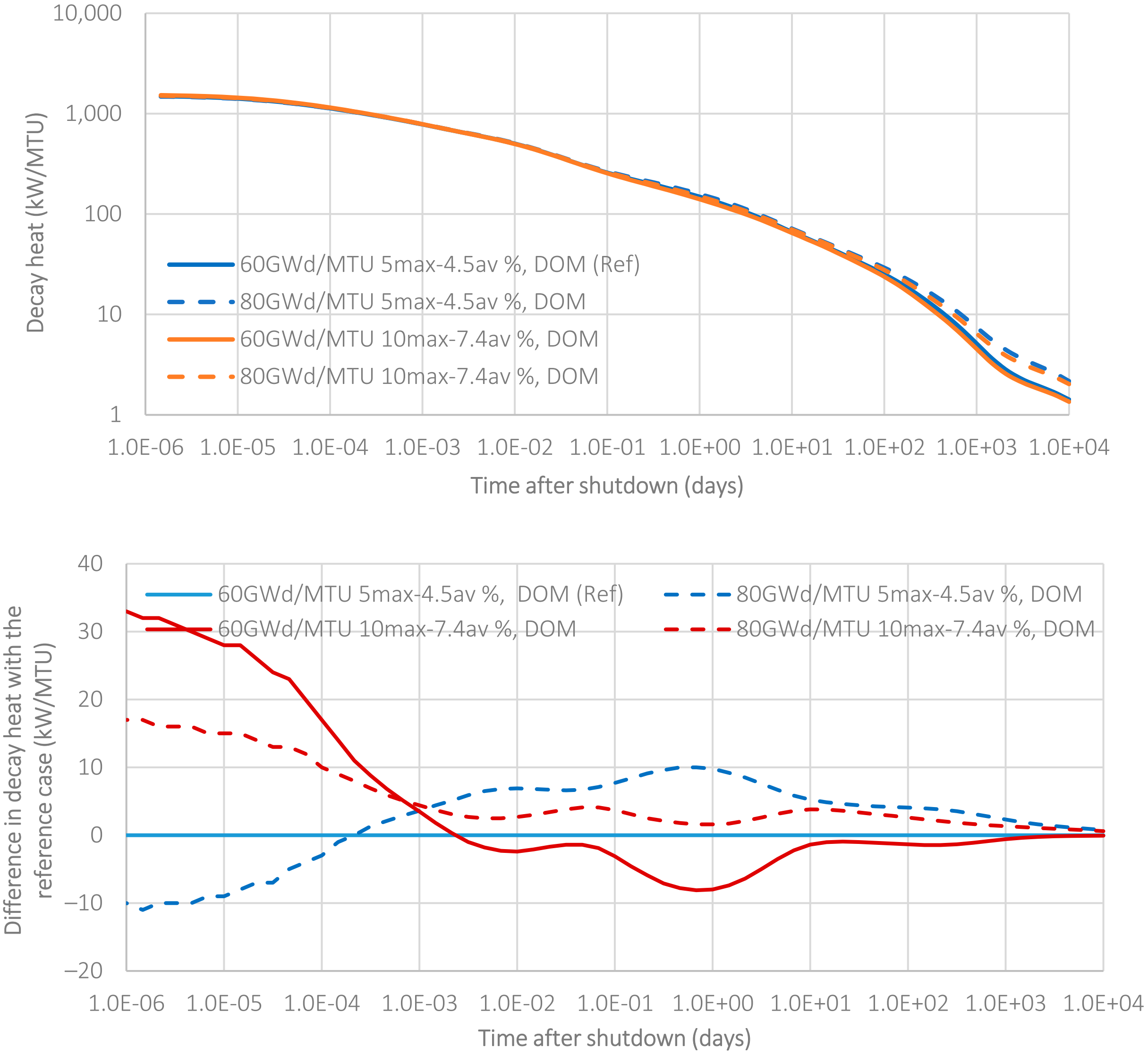


Figure 1. Lattice decay heat (**top**) and difference in decay heat with reference (**bottom**) after shutdown at 40% void fraction for different lattice designs with maximum (max) and average (av) enrichments.

The Doppler temperature coefficient (DTC) becomes smaller in magnitude with increasing enrichment at the beginning of cycle (BOC). The difference in DTC decreases with increasing burnup. However, the relative difference can reach up to 20% in the midcycle (7–10 GWd/MTU), decreasing to 3% with burnup at the end of cycle (EOC). When relative cycle lengths are considered (black dots, Figure 2), EOC values remain the same for all enrichments.

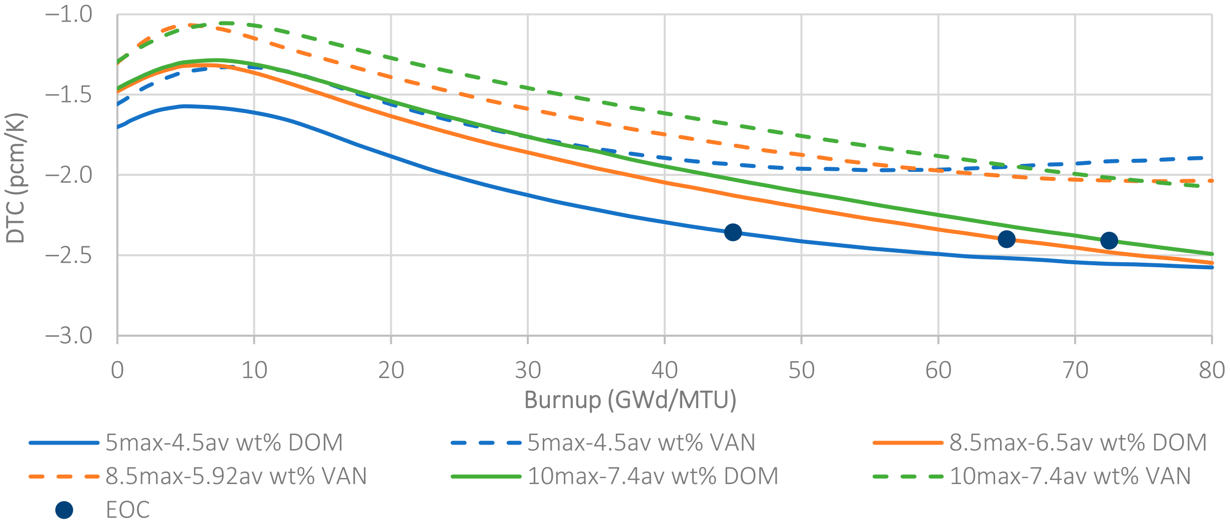


Figure 2. Lattice hot full power DTC at 40% void fraction.

3. Phase 2 Core Physics

The objective of the second phase of this study was to verify Phase 1 findings and to provide realistic burnup values for back-end spent fuel pool, shielding, and transport package calculations. Therefore, this study aimed to provide a generic comparison of reactor physics characteristics of cores with LEU and LEU+ fuel rather than for a specific core design. To avoid the use of any proprietary correlations, typical BWR thermal limit calculations were replaced by 3D pin peaking factor (Fq) calculations and 2D radial peaking factor (FdH) calculations used in PWR analysis. Because no power updates are currently planned for LEU+ cores, and thermal limits are highly dependent on peaking factors, a comparison of Fq and FdH should provide a reasonable measure of the expected changes in the thermal limits of an LEU+ core compared to an LEU core.

The core design process for a BWR is more complex than that of a PWR. Core optimization requires the simultaneous consideration of fuel design, control rod exchange sequences, thermal margins, operational limitations, and fuel economics. Planning control rod exchange sequences can be particularly challenging because they must be optimized for reactivity control, historical effects, and fuel performance, and they must adhere to insertion limits to mitigate channel distortion and rod shadowing effects.

It is difficult to provide a generalized comparison of core physics characteristics between optimized LEU and LEU+ cores. Because the two cores would differ significantly in terms of fuel loading and control rod patterns, any differences in core behavior could be attributed to changes in fuel or specific core designs. Therefore, in this study, the same equilibrium core design with simplified generic design criteria was used for both LEU and LEU+ fuel loadings for consistent comparison.

Representative anticipated core loading patterns and relevant fuel assemblies were designed using Hatch 1 core parameters (i.e., number of fuel assemblies, flow rate, control blade map) with several simplifications to allow for the generalization of core designs and to enable the capture of the cores' general reactor physics properties instead of being design-specific (optimized). The main simplifications are as follows:

- Other than for blade worth calculations, all control blades "are rods out" (ARO).
- Core flow rate is constant during operation except for a 4% increase in the final three months of operation.
- Each core design consists of one replicated fuel assembly design to reduce iterations.

3.1. Computational Modeling

Each core design was modeled with the PARCS [14] v3.3.6 3D nodal core simulator to calculate core-wide quantities of interest such as k_{eff}, 3D pin power, and burnup distributions. Two-phase thermal hydraulic properties for core calculations were provided by the PATHS v1.06 [15] code based on Hatch 1 operating parameters [16]. Nuclear data for PARCS calculations (nodal cross-sections) were generated by the SCALE 6.3.b16 Polaris [17] lattice physics code using the Evaluated Nuclear Data File (ENDF)/B-VII.1 56-group AMPX cross-section library. The two-group nodal cross-sections were generated at different burnup histories with instantaneous state conditions for control blade, fuel temperature, fuel, and coolant void fraction, and they were processed by the GenPMAXS code [18] before use in PARCS calculations. Using a process similar to that used in Phase 1 studies, all gadolinia pins were modeled with 10 equal-volume rings. The form factors for PARCS pin power calculations included locally deposited gamma energy contributions.

3.1.1. BWR Lattice Modeling

Each BWR 10 × 10 lattice was modeled with specifications as close as possible to those of a GE14 design using design parameters collected from public resources [13,19]. A representative Polaris model is shown in Figure 3. Considering the most important axial variations, only natural top (N-T), VAN, DOM, and natural bottom (N-B) lattices were included in the assembly design. In order to use realistic lattice designs anticipated to be used in LEU and LEU+ core loadings while avoiding computationally expensive iterative optimization studies, a selected set of lattices with several enrichment variations was generated in a previous study [7] to support follow-on core design calculations. DOM and VAN lattices with maximum enrichments of 6%, 7%, 8%, 9%, and 10% were designed using a machine learning optimization algorithm with the following lattice physics objectives to capture general characteristics of a realistic lattice design:

- Pin peaking factors below 1.4;
- Beginning-of-cycle (BOC) k_{inf} below 1.03 and 1.05;
- Maximum k_{inf} less than 1.15.

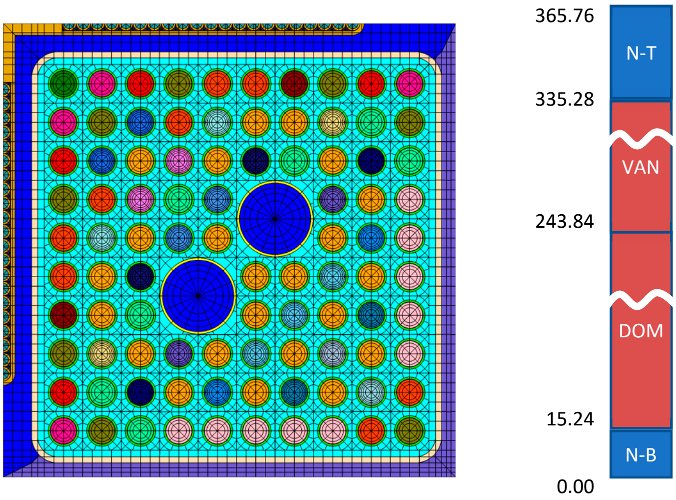
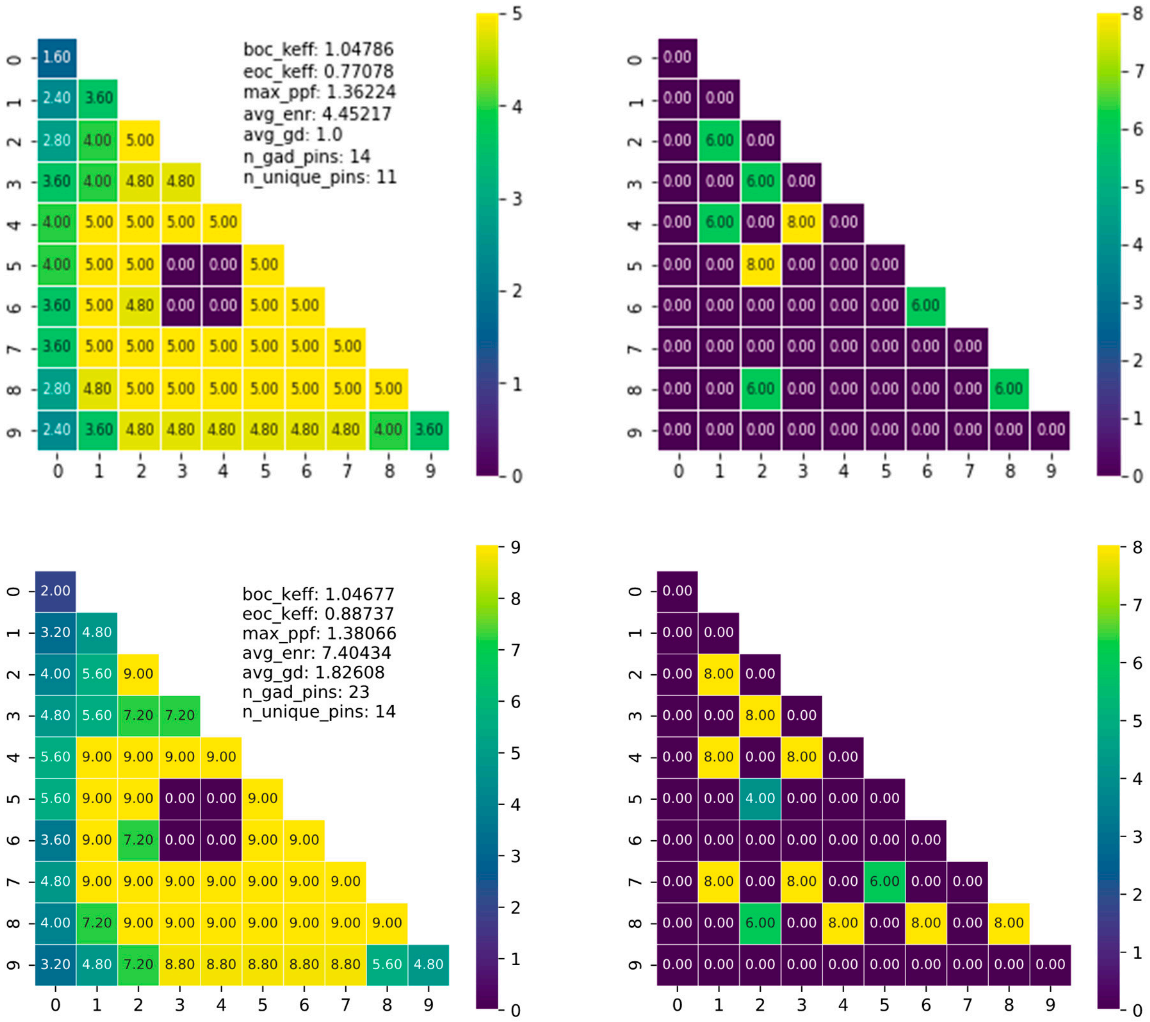


Figure 3. Lattice and bundle designs showing different pin enrichments and axial segments.

The selected lattice enrichment and gadolinia loading maps from the optimization study are shown in Figure 4 for DOM lattices.



boc_keff: 1.04786
eoc_keff: 0.77078
max_ppf: 1.36224
avg_enr: 4.45217
avg_gd: 1.0
n_gad_pins: 14
n_unique_pins: 11

	0	1	2	3	4	5	6	7	8	9
0	1.60									
1	2.40	3.60								
2	2.80	4.00	5.00							
3	3.60	4.00	4.80	4.80						
4	4.00	5.00	5.00	5.00	5.00					
5	4.00	5.00	5.00	0.00	0.00	5.00				
6	3.60	5.00	4.80	0.00	0.00	5.00	5.00			
7	3.60	5.00	5.00	5.00	5.00	5.00	5.00	5.00		
8	2.80	4.80	5.00	5.00	5.00	5.00	5.00	5.00	5.00	
9	2.40	3.60	4.80	4.80	4.80	4.80	4.80	4.80	4.00	3.60

	0	1	2	3	4	5	6	7	8	9
0	0.00									
1	0.00	0.00								
2	0.00	6.00	0.00							
3	0.00	0.00	6.00	0.00						
4	0.00	6.00	0.00	8.00	0.00					
5	0.00	0.00	8.00	0.00	0.00	0.00				
6	0.00	0.00	0.00	0.00	0.00	0.00	6.00			
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
8	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	6.00	
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

boc_keff: 1.04677
eoc_keff: 0.88737
max_ppf: 1.38066
avg_enr: 7.40434
avg_gd: 1.82608
n_gad_pins: 23
n_unique_pins: 14

	0	1	2	3	4	5	6	7	8	9
0	2.00									
1	3.20	4.80								
2	4.00	5.60	9.00							
3	4.80	5.60	7.20	7.20						
4	5.60	9.00	9.00	9.00	9.00					
5	5.60	9.00	9.00	0.00	0.00	9.00				
6	3.60	9.00	7.20	0.00	0.00	9.00	9.00			
7	4.80	9.00	9.00	9.00	9.00	9.00	9.00	9.00		
8	4.00	7.20	9.00	9.00	9.00	9.00	9.00	9.00	9.00	
9	3.20	4.80	7.20	8.80	8.80	8.80	8.80	8.80	5.60	4.80

	0	1	2	3	4	5	6	7	8	9
0	0.00									
1	0.00	0.00								
2	0.00	8.00	0.00							
3	0.00	0.00	8.00	0.00						
4	0.00	8.00	0.00	8.00	0.00					
5	0.00	0.00	4.00	0.00	0.00	0.00				
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
7	0.00	8.00	0.00	8.00	0.00	6.00	0.00	0.00		
8	0.00	0.00	6.00	0.00	8.00	0.00	8.00	0.00	8.00	
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 4. LEU and LEU+ pin enrichment maps (**left**) and gadolinia loadings (**right**).

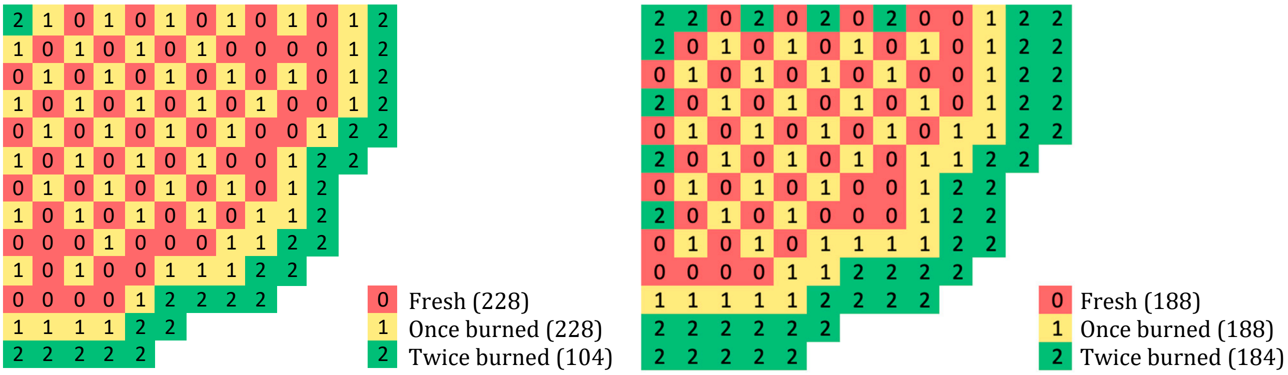
3.1.2. Core Design

The core maps available from the initial cycles of Hatch 1 and Peach Bottom 2 [11,12] reactors represent short-cycle LEU fuel based on checkerboard core maps that are not representative of modern core maps. Therefore, several equilibrium core cycles were designed in an attempt to provide a baseline design for a representative LEU and for LEU+ fuel cores that are anticipated under different loading strategies. The following objectives were established in the design of core and shuffle maps:

- Shuffle maps should sustain an equilibrium core.
- The number of feed assemblies should be close to a third of the total assemblies, and discharge burnup should be maximized.
- Batch average enrichment should be minimized while maintaining criticality for 24-month and 36-month cycles (for ARO).
- Assembly average discharge burnup should be less than 60 GWd/MTU for a 24-month cycle and less than 80 GWd/MTU for a 36-month cycle.

Several variations in core loading and shuffling patterns were tested because the same cycle length can be achieved by either increasing the average enrichment or increasing the number of fresh fuel (feed) assemblies. However, based on fuel cost, the discharge burnup, safety limits, and target cycle lengths for three different cores were designed. A "cold center" design approach [20], which has a twice-burned assembly in the center of the core surrounded with once-burned fuel assemblies, was adapted for the core2 design

(Figure 5). Although this core uses fewer fresh assemblies and is economically more viable compared to other 36-month cycle cores, the center assembly reaches the highest burnup and can be limiting. A 24-month cycle core design (core3) that was analyzed is also presented in Figure 5. This paper primarily presents LEU and LEU+ fuel comparisons for the core2 design.



2	1	0	1	0	1	0	1	0	1	0	1	2
1	0	1	0	1	0	1	0	0	0	0	1	2
0	1	0	1	0	1	0	1	0	1	0	1	2
1	0	1	0	1	0	1	0	1	0	0	1	2
0	1	0	1	0	1	0	1	0	0	1	2	2
1	0	1	0	1	0	1	0	0	1	2	2	
0	1	0	1	0	1	0	1	0	1	2		
1	0	1	0	1	0	1	0	1	1	2		
0	0	0	1	0	0	0	1	1	2	2		
1	0	1	0	0	1	1	1	2	2			
0	0	0	0	1	2	2	2	2				
1	1	1	1	2	2							
2	2	2	2	2								

0 Fresh (228)
1 Once burned (228)
2 Twice burned (104)

2	2	0	2	0	2	0	2	0	0	1	2	2
2	0	1	0	1	0	1	0	1	0	1	2	2
0	1	0	1	0	1	0	1	0	0	1	2	2
2	0	1	0	1	0	1	0	1	0	1	2	2
0	1	0	1	0	1	0	1	0	1	1	2	2
2	0	1	0	1	0	1	0	1	1	2	2	
0	1	0	1	0	1	0	0	1	2	2		
2	0	1	0	1	0	0	0	1	2	2		
0	1	0	1	0	1	1	1	1	2	2		
0	0	0	0	1	1	2	2	2	2			
1	1	1	1	1	2	2	2	2				
2	2	2	2	2	2							
2	2	2	2	2								

0 Fresh (188)
1 Once burned (188)
2 Twice burned (184)

Figure 5. Core2 (36-month) and Core3 (24-month) loading patterns.

3.2. Results

3.2.1. Burnup and Pin Peaking

Core maximum and average fuel discharge burnups are provided in Table 1 for LEU and LEU+ assemblies at different average enrichments. As expected, LEU+ cores have higher core average burnups at the beginning of cycle (BOC) and EOC. Core burnup increases linearly with cycle length, and the enrichment increase provides the required reactivity for the extended cycle length. Increasing enrichment decreases the core average burnup for the same cycle length. However, increased power peaking at the core center causes twice-burned center assemblies to have relatively higher burnup for Core 2. Although core loading with 8% max (6.63% average) assemblies becomes subcritical at the end of the 36-month cycle, core loading with 9% maximum (7.4% average) assemblies has excess reactivity. Therefore, a 36-month cycle is expected to be achieved with a core average enrichment of 7.1%. Pin peaking factors for the reference 24-month 5% maximum enrichment core are compared to pin peaking factors for the 36-month 9% maximum enrichment core: a conservative comparison is presented in Figure 6. Although the maximum Fq values remain the same for both cores, considering both cores are not optimized, a negligible difference is observed for FdH.

Table 1. Fuel discharge for different core designs and fuel enrichments.

Core Design	**Assembly Design (Maximum)**	**Cycle Length (Months)**	**Assembly Discharge Burnup (GWd/MTU)**		**Core Burnup (GWd/MTU)**
			Average	**Max**	**Average**
Core 2	5%	24	43.53	47.63	33.01
Core 2	8%	36	65.68	70.86	50.43
Core 2	9%	36	65.89	72.00	50.18

3.2.2. Doppler Temperature Coefficient

The DTC was calculated in a manner consistent with that used in the Phase 1 study. At hot full power (HFP), core fuel temperatures were uniformly set to 900 K and 1300 K, whereas the core-wide void fraction was set to 40%. Unlike the Phase I study, the fuel temperature and void fraction changes were instantaneous changes to each core's existing depletion history, as expected during a normal operation. Changes in DTC with cycle depletion for Core 2 LEU and LEU+ (9%) are shown in Figure 7. DTCs are compared between the reference 5% max core and the 9% max cores. DTC is 3% smaller in the LEU+ core at BOC, and this difference disappears at EOC with burnup. The magnitude of the DTC decreases with increasing enrichment. However, the difference diminishes with burnup. The maximum relative difference in DTC is observed at BOC between LEU+ and LEU cores (−2.8% and −1.6% for 9% and 6% maximum enrichment cores, respectively). This difference is considerably smaller than the 15% difference originally reported in the Phase 1 study. The drop in difference between the two studies is the result of a higher core average burnup in the LEU+ core than in the LEU core, increasing the magnitude of DTC with increasing burnup.

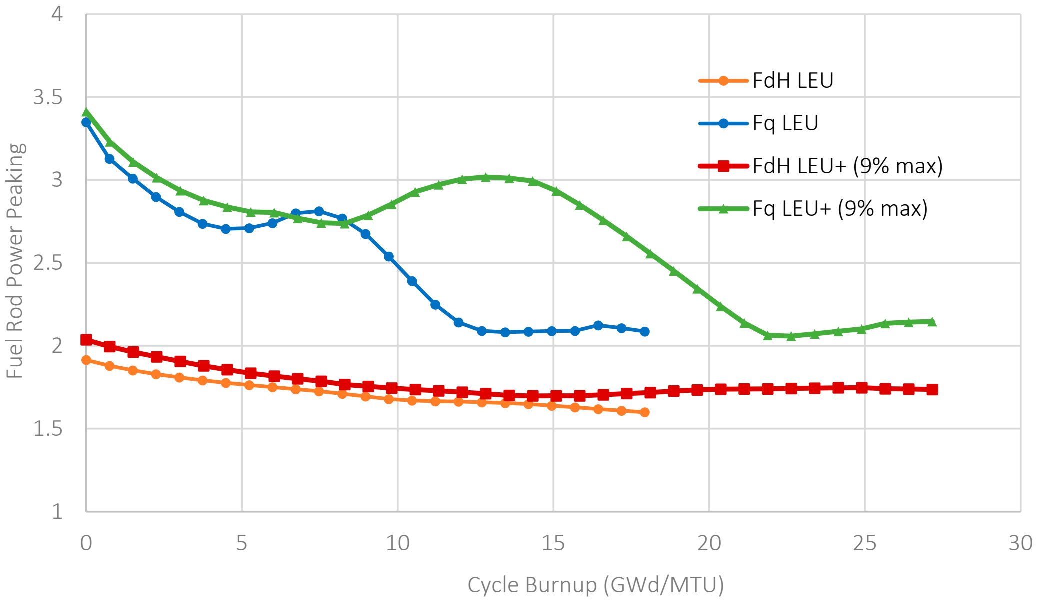


Figure 6. FdH and Fq pin power peaking factors for Core 2 LEU and Core 2 LEU+.

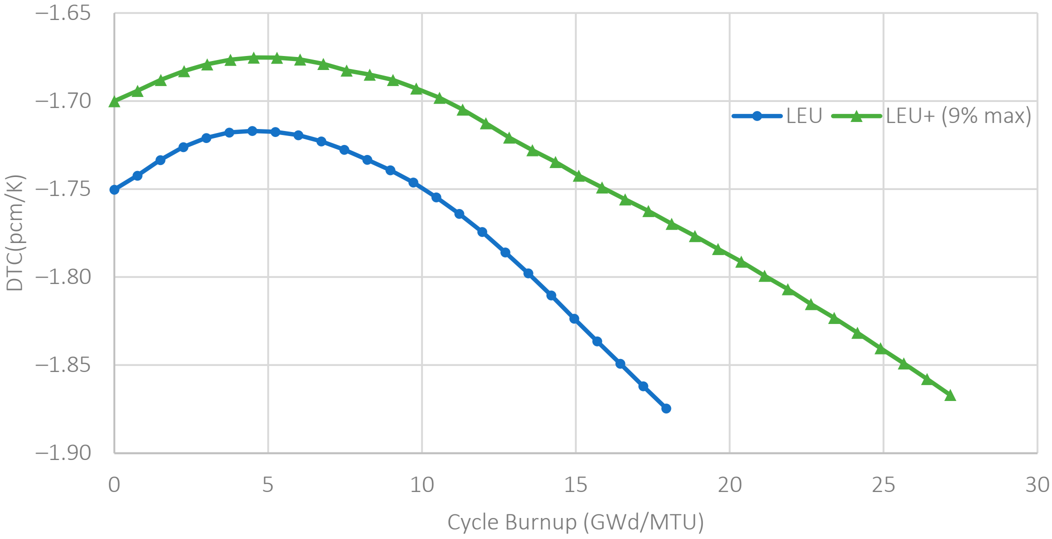


Figure 7. Doppler reactivity coefficient for LEU and LEU+ cores.

3.2.3. Moderator Void Fraction Reactivity Coefficient

The moderator void fraction reactivity coefficient (MVC) is an important parameter with respect to the safety of BWR operation, similar to DTC. Therefore, it is important for LEU+ core designs to have comparable MVCs throughout the cycle. One of the concerning findings of the Phase I report [1] was that the MVC of LEU+ fuel can approach 0 at BOC for a 10% enrichment VAN lattice and 15 pcm/% void for a 10% enrichment DOM lattice. The difference in MVC between LEU and LEU+ fuel was shown to be 40 pcm/% void at BOC.

The MVC for LEU and LEU+ cores (6% max and 7% max for 24-month-cycle Core 3 and 9% max for 36-month-cycle Core 2) is compared in Figures 8 and 9 for high-void (70–40%) and low-void (40–10%) regions. Both regions show similar trends during the cycle. Although differences between LEU and LEU+ (9%) cores can be as high as 35 pcm/%void at BOC for high-void regions (24 pcm/%void for low-void regions), at EOC, both cores have negligible differences (3 pcm/%void). As noted in the Phase I study, MVC decreases with increasing enrichment. The Phase I study also showed that MVC is close to 0 pcm/% void at BOC; however, at the core level, MVC does not drop below −85 pcm/void % for high-void conditions and −65 pcm/void% for low-void conditions throughout the cycle.

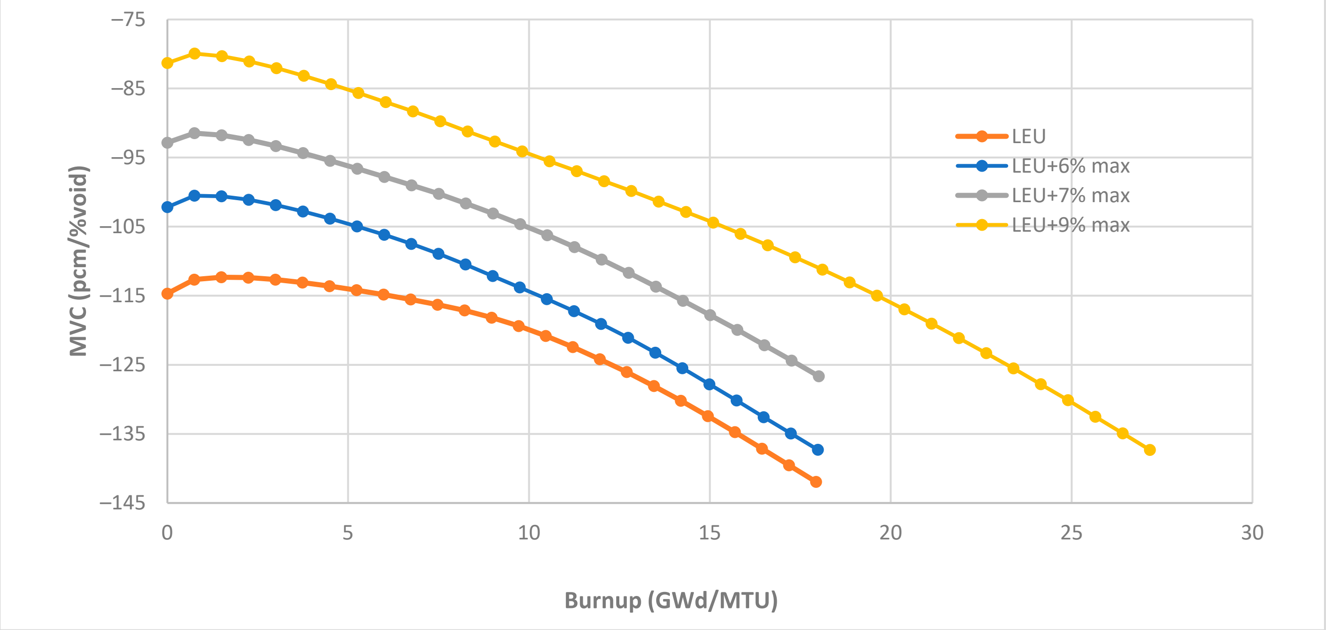


Figure 8. Moderator void reactivity coefficient for LEU and LEU+ cores at high void.

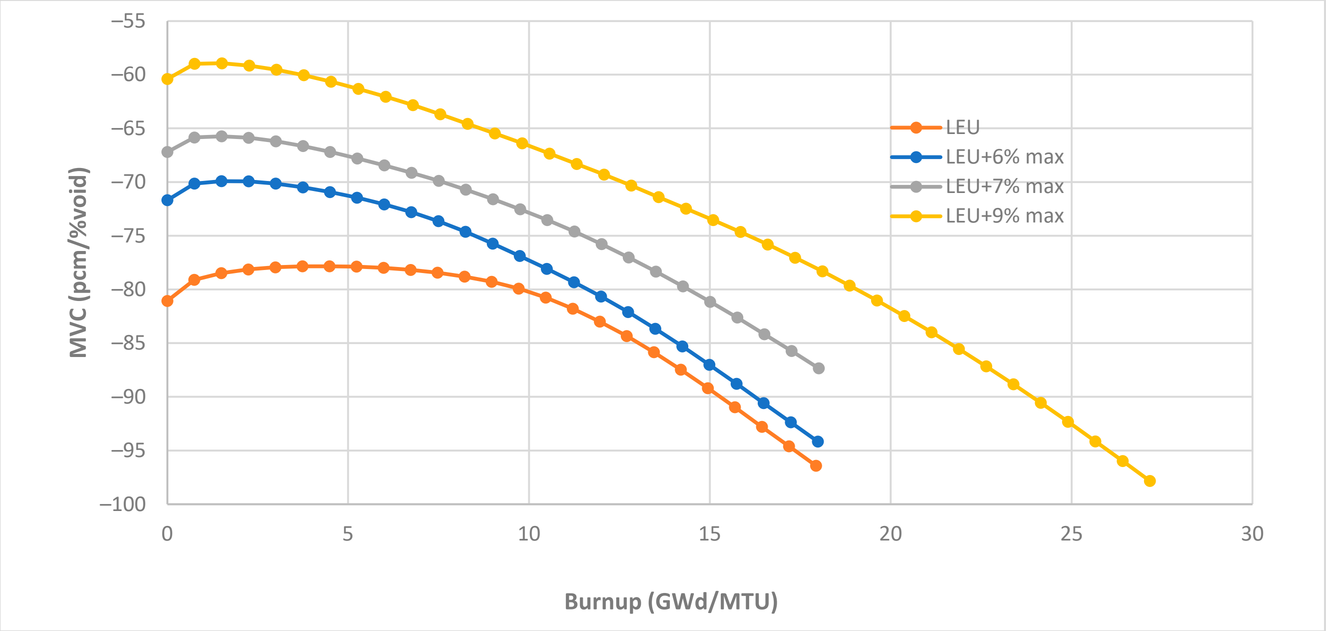


Figure 9. Moderator void reactivity coefficient for LEU and LEU+ cores at low void.

3.2.4. Shutdown Margin

Shutdown margin (SDM) calculations provide the amount of negative reactivity a core can have before the core could be shut down while the highest-worth control blade is stuck. In this report, instead of considering the highest-worth control blade, the highest-worth control bank is assumed to be stuck for SDM calculations. This assumption not only simplifies calculations, but it also provides a more generic, less core-dependent analysis in the comparison of LEU and LEU+ cores. Unlike the control blade worth calculations, SDM calculations are performed at two different reactor states with different assumptions to simulate the worst-case scenarios for a shutdown (Table 2). Therefore, the calculated SDM values are combinations of control blade bank, Xe-Sm concentration, and void fraction reactivity worths for each core at different burnups. It should be noted that using constant Xe-Sm concentrations after shutdown instead of zero concentrations as in typical SDM calculations is a conservative but more consistent approach when LEU and LEU+ cores are compared.

Table 2. Core state description for control bank worth calculations.

State Parameters	BOC		EOC	
	Before Shut-Down	**After Shut-Down**	**Before Shut-Down**	**After Shut-Down**
Fuel temperature	Calc. value [b]	Calc. value [b]	Calc. value [b]	Constant [a]
Coolant temperature	Saturation	Saturation	Saturation	Saturation
Void fraction	Calc. value [b]	0%	Calc. value [b]	0%
Xe-Sm concentration	0	0	Calc. value [b]	Constant

[a] Equal to the pre-shutdown value; [b] calculated value by PARCS/PATHS at full-power operation, varying core-wide.

As shown in Figure 10, both LEU+ cores have higher SDMs than the LEU core at BOC. The largest SDM increase is for core2 with 9% max fuel. The improvement in BOC SDM with increasing enrichments comes from the reduced reactivity contributions from DTC and MVC after shutdown, because both phenomena increase reactivity at shutdown. Despite the BOC trends, at EOC, SDM is reduced for an LEU+ (9% max) core by 750 pcm compared to that of the LEU core. However, a similar reduction is not observed for the 7% max core3 design. Core design and excess reactivity at EOC play important roles for the observed reduction in SDM.

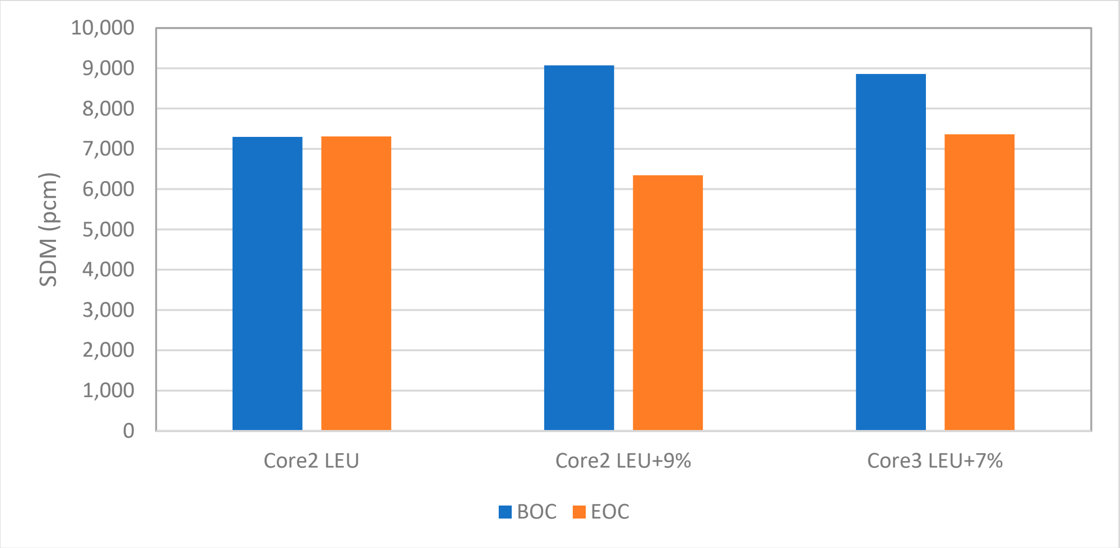


Figure 10. SDM for different core designs at BOC and EOC.

4. Conclusions

This paper presents highlights of Phase 1 and Phase 2 studies conducted at ORNL on BWR LEU+ HBU fuels. Phase 1 studies compared LEU and LEU+ fuels at different enrichments and burnup values to assess differences in reactivity coefficients, nuclear data uncertainties, decay heat, and isotopic inventory changes for shielding, storage, and transportation applications at the lattice physics level. Phase 2 studies focused on the reactor physics feasibility of an LEU+ core and provided data for detailed storage, shielding, and transportation calculations. Although limited optimization is allowed in core design to capture general design-independent core behavior, rigorous lattice design optimization enabled more realistic pin power comparisons. Although not presented here, as with DTC and MVC, control blade worths exhibit a decrease in magnitude that coincides with increasing enrichment and an increase in magnitude with burnup. However, SDM increases at BOC with increasing enrichment. The EOC value for SDM shows a strong dependency on core design and excess reactivity. Considering the higher core average burnup in LEU+ cores, the differences in reactivity coefficients and pin peaking factors between LEU and LEU+ cores are not significant and can be improved with core optimization.

Author Contributions: Conceptualization, U.M., W.A.W.; analysis, U.M., R.C.; writing—original draft preparation, U.M.; resource W.A.W.; funding acquisition W.A.W. All authors have read and agreed to the published version of the manuscript.

Funding: Support for this work was provided by the US Nuclear Regulatory Commission's Offices of Nuclear Regulatory Research, Nuclear Reactor Regulation, and Nuclear Material Safety and Safeguards.

Disclaimer: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan), accessed on 24 January 2025.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Diaz, M. DSFM Regulatory Conference, "Advanced Fuels Update on the Front End of the Fuel Cycle", 2019. Available online: https://www.nrc.gov/docs/ML1925/ML19255F598.pdf (accessed on 10 October 2024).
2. Pimental, F.; Smith, F. *The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors*; Nuclear Energy Institute: Washington, DC, USA, 2019.
3. Hall, R.; Cumberland, R.; Sweet, R.; Wieselquist, W. *Isotopic and Fuel Lattice Parameter Trends in Extended Enrichment and Higher Burnup LWR Fuel, Vol. 1: PWR Fuel*; ORNL/TM-2020/1833; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2021.
4. Cumberland, R.; Sweet, R.; Mertyurek, U.; Wieselquist, W.A. *Isotopic and Fuel Lattice Parameter Trends in Extended Enrichment and Higher Burnup LWR Fuel, Vol. II: BWR Fuel*; ORNL/TM-2020/1835; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2021.
5. Hall, R.; Sweet, R.; Belles, R.; Wieselquist, W.A. *Extended-Enrichment Accident-Tolerant LWR Fuel Isotopic and Lattice Parameter Trends*; ORNL/TM-2021/1961; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2021.
6. Mertyurek, U.; Wieselquist, W.A. *Assessment of Core Physics Characteristics of Extended Enrichment and Higher Burnup LWR Fuels Using the Polaris/PARCS Two-Step Approach, Vol. II: BWR Fuel*; ORNL/TM-2022/2444; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2022.
7. Bae, J.W.; Mertyurek, U.; Asgari, M. *Light Water Reactor LEU+ Lattice Optimization*; ORNL/TM-2021/2366; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2022.

8. Hu, J.; Mertyurek, U.; Wieselquist, W.A. *Assessment of Core Physics Characteristics of Extended Enrichment and Higher Burnup LWR Fuels Using the Polaris/PARCS Two-Step Approach. Vol. I: PWR Fuel*; ORNL/TM-2022/1831; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2022.
9. Mertyurek, U.; Cumberland, R.; Wieselquist, W.A. Core Physics Characteristics of Extended Enrichment and Higher Burnup Boiling Water Reactor Fuel. In Proceedings of the International Conference on Physics of Reactors (PHYSOR 2024), San Francisco, CA, USA, 21–24 April 2024.
10. Peakman, A.; Grove, C.; Fitzgerald, K.; Gregg, R. Development of an equilibrium loading pattern and whole-core fuel performance assessment in the Advanced Boiling Water Reactor (ABWR) with UO_2 and U_3Si_2 fuels. *Prog. Nucl. Energy* **2019**, *117*, 103053. [CrossRef]
11. Holloway, G.L.; Fawks, J.E.; Crawford, B.W. *Core Design and Operating Data for Cycles 2 and 3 of Hatch 1*; EPRI NP-2106; Electric Power Research Institute: San Jose, CA, USA, 1984.
12. Larsen, N.H. *Core Design and Operating Data for Cycles 1 and 2 of Peach Bottom 2*; EPRI NP-563; Electric Power Research Institute: San Jose, CA, USA, 1978.
13. Lawing, C.; Palmtag, S.; Asgari, M. BWR Progression Problems. 2021. Available online: https://info.ornl.gov/sites/publications/Files/Pub148107.pdf (accessed on 28 January 2025).
14. Downar, T.; Ward, A.; Seker, V. *PARCS v3.3.0, Volume II: User's Guide*; Technical Report; University of Michigan: Ann Arbor, MI, USA, 2017.
15. Collins, B.; Li, L.; Wang, D.; Stimpson, S.; Jabaay, D.; Ward, A.; Xu, Y.; Downar, T. PATHS: A steady-state two-phase thermal hydraulic solver for PARCS depletion. In Proceedings of the NURETH, Toronto, OM, Canada, September 2011.
16. Yarsky, P.; Ward, A.M.; Xu, Y.; Downar, T.J.; Hudson, N. The Application of PARCS/PATHS to Depletion of HATCH Cycles 1–3. In Proceedings of the NURETH-15, Pisa, Italy, 2013.
17. Mertyurek, U.; Jessee, M.; Betzler, B. Lattice physics calculations using the embedded self-shielding method in Polaris, Part II: Benchmark assessment. *Ann. Nucl. Energy* **2021**, *150*, 107829. [CrossRef]
18. Ward, A.; Xu, Y.; Downar, T. *GenPMAXS—v6.3.1 Release Code for Generating the PARCS Cross Section Interface File PMAXS*; University of Michigan: Ann Arbor, MI, USA, 2021.
19. Fensin, M.L. Optimum Boiling Water Reactor Fuel Design Strategies to Enhance Reactor Shutdown by the Standby Liquid Control System. Master's Thesis, University of Florida, Gainesville, FL, USA, 2004.
20. Maag, E.M.; Knott, D. BWR reload strategy based on fixing once-burnt fuel between cycles. *Nucl. Technol.* **2017**, *136*, 278–291. [CrossRef]