

Criticality Safety Implications of Extended-Enrichment and Accident-Tolerant Fuel for Fresh Fuel Storage

A.M. Shaw and J.B. Clarity
Oak Ridge National Laboratory
One Bethel Valley Road
Oak Ridge, TN 37831-6170
shawam@ornl.gov; clarityjb@ornl.gov

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ABSTRACT

Presently, there is increased industry interest in extended enrichments (LEU+). This work investigated the effect of LEU+ in fresh fuel storage environments by modeling a representative pressurized water reactor (PWR) new fuel vault (NFV), boiling water reactor (BWR) NFV, and two PWR spent fuel pools (SFP). Nominal enrichments were increased to 6.5 and 8 wt % using SCALE 6.2.4 CSAS based on publicly available details of NFV and SFP dimensions and compositions. Additionally, several accident-tolerant fuel (ATF) concepts inspired by publicly demonstrated industry implementations allowed the examination of chromium-coated cladding, chromia-doped UO₂, and FeCrAl cladding. Following 10 CFR § 50.68, the PWR NFV model was flooded to calculate the reactivity response to hydrogenous moderation at variable densities. As allowed by regulation, publicly available BWR NFVs were found to consistently implement “administrative controls and/or design features [to] prevent such flooding,” and therefore the BWR NFV, along with both PWR SFPs, modeled only fully flooded conditions. To counter increases in reactivity, absorber crediting was investigated with the addition of integral fuel burnable absorber, gadolinia rods, or reduced loading. In all cases, the use of standard UO₂ fuel and zirconium cladding was the bounding reactivity condition relative to ATF concepts. Crediting 64 or fewer IFBA rods in PWR storage spaces was sufficient to meet 10 CFR § 50.68 requirements, as was removing ~1 in 4 assemblies for the BWR NFV.

Key Words: Fresh Fuel, LEU+, ATF

1 INTRODUCTION

Enrichment increases to support high burnup and increased cycle length will significantly impact safety analyses made throughout the fuel cycle. Before fuel can be utilized in a reactor to produce power, it must safely arrive onsite and be unpacked and staged for operation. Criticality safety is a concern at most points in the fuel cycle, with fresh fuel storage areas holding dozens, if not hundreds, of fresh fuel assemblies in one location with relative proximity. Additionally, the fresh fuel must be available for core loading, being stored in spent fuel pools before transitioning to the core. Thus, there are two primary storage points for fresh fuel in a light-water reactor (LWR) plant that require supporting criticality safety analysis: the new fuel vault (NFV) and the spent fuel pool (SFP). This paper investigates the sensitivity of several example storage points to potential enrichment and fuel form changes.

NFVs normally consist of racks designed to allow for fuel recently unloaded from shipping packages to be inspected before being loaded into the SFP. The NFV racks are dry under normal conditions, generally composed of a metal support structure intended to designate an assembly's location for storage and prevent

movement that could damage the assembly or allow unintended clustering. The racks are often within a recessed concrete area, which provides structure for the rack and fuel mechanical safety but results in reflection back into the stored fuel. The most obvious criticality concern for dry fresh fuel stored in an array is ingress of water to the vault. In an industrial environment, steam, fire suppressant, or other voluminous hydrogenous material may encroach the NFV, albeit at lower density. To account for this filling of the vault by hydrogenous material of unknown density, criticality analyses of the vault model the system with (1) variable-density water to find an optimum point of moderator density, as well as (2) full flooding with nominal-density water.

SFPs normally consist of racks designed to allow for fresh fuel that has recently been transferred from the NFV and spent fuel from the core. PWR SFP racks are typically constructed in high- and low-density configurations, based on the burnup of the fuel, the presence of burnable absorbers (BA) incorporated into the fuel assemblies, etc. They consist of a metal support structure and are often modeled as periodically reflected 2×2 arrays of storage cells. Typically, high-density loading is reserved for spent fuel and low density for fresh fuel. As this study examined unburnt fuel, only low-density PWR SFPs were included as a class of investigation. BWR SFP racks use a uniform loading; thus, the maximum reactivity of the assembly throughout its life must be accounted for, requiring the analysis of burnup. This study intended to examine only fresh unburnt fuel, and for that reason BWR SFPs were not included as a class of investigation. SFPs in normal operation are fully flooded and often contain soluble boron. Because SFPs are flooded in normal operations, only the flooded condition is analyzed, as events causing variable density moderation are not credible.

Accident-tolerant fuels (ATFs) are a class of technologies intended both to avert and alleviate accidents and the conditions leading to their instigation. At a high level, these technologies are intended to ease thermomechanical stresses, improve thermal performance, and mitigate corrosion, among other issues encountered at accident conditions. ATF concepts chosen for this work include Cr coating of the conventional Zirc-4 cladding (Cr-coated), Cr₂O₃ (chromia) doping of the UO₂ fuel (Cr-doped), and the substitution of iron-chromium-aluminum (FeCrAl) cladding [1]. Chromium-coated cladding is of interest for reducing zirconium-water reactions at high temperatures, significantly reducing hydrogen production and risk of fission product release. Introducing metal oxide dopant increases fuel grain size and density, reducing fission product release. FeCrAl cladding exhibits improved high-temperature performance in reducing hydrogen generation and shows improved mechanical strength.

2 METHODOLOGY

2.1 Governing Regulation

The primary regulation relevant to this study investigating reactivity in a fresh fuel storage environment is 10 CFR 50.68, *Criticality Accident Requirements* [2]. Of relevance are 10 CFR 50.68 (2–4). The 10 CFR 50.68 (2) regulation requires that the k_{eff} of an NFV be less than 0.95 at a 95% probability and 95% confidence level when fully flooded with unborated water. The 10 CFR 50.68 (3) regulation requires that the k_{eff} of an NFV be less than 0.98 when filled with a low-density hydrogenous material. NFV requirements may be alleviated if appropriate administrative controls are implemented to prevent hydrogenous material ingress. Regarding SFPs, 10 CFR 50.68 (4) establishes two limits: that k_{eff} be less than 1.0 for normal conditions without crediting soluble boron and less than 0.95 for normal and accident conditions when crediting the soluble boron in the SFP water.

2.2 Models

To determine NFV and SFP sensitivities to LEU+ and ATF fuels, representative models were required. The US Nuclear Regulatory Commission's Agencywide Documents Access and Management System (ADAMS) public database was used to identify safety analysis documentation on operational or proposed NFV and SFP configurations and material compositions. Documentation for a representative PWR NFV,

BWR NFV, and two PWR SFPs were discovered. One SFP was a fully loaded 2×2 array, with intact poison panels between assemblies (the intact absorber, IA, SFP), whereas the other was a 2×2 array loaded in a checkerboard configuration, with two empty cells and no poison panels (the degraded absorber, DA, SFP). Credited in the BWR model were eight gadolinia rods. Nominal enrichments were 4.7 wt % for the BWR case and 5.0 wt % for the PWR cases. Fuel assemblies were Westinghouse (W) 17 × 17 STD PWR assembly and the ATRIUM 10 BWR assembly; a summary of assembly parameters is given in Table I. Assemblies were placed in the respective rack design for each storage site, summarized in Table II. The PWR NFV rack was fully encompassing, with gaps on each face forming four L-shaped corner braces with the given dimensions. Each tail length was 5.08 cm.

Table I. Fuel assembly parameters

Specification	W 17 × 17 STD [3]	ATRIUM 10 [4]
Fuel radius	0.410 cm	0.433 cm
Gap radius (clad IR)	0.418 cm	0.442 cm
Clad outer radius	0.475 cm	0.503 cm
Fuel rod pitch	1.260 cm	1.295 cm
Fuel rod height	365.760 cm	381.000 cm
Fuel enrichment	5.0 wt % ²³⁵ U	4.7 wt % ²³⁵ U
Fuel density	10.41 g/cm ³	10.55 g/cm ³

Table II. Storage rack parameters

Specification	PWR NFV	PWR IA SFP	PWR DA SFP	BWR NFV
Assembly pitch	55.880 cm	27.762 cm	27.305 cm	16.764 × 20.764 cm
Rack inner width	11.430 cm	22.352 cm	22.606 cm	16.120 cm
Rack thickness	0.635 cm	0.191 cm	0.305 cm	0.644 cm
Rack height	518.160 cm	506.730 cm	518.160 cm	381.000 cm

Nominal models were constructed with SCALE 6.2.4 CSAS5 utilizing the KENO V.a Monte Carlo code and the ENDF/B-VII.1 252-group cross section library with square pitched lattice cell data to account for effects of resonance self-shielding [5]. The uncertainty in each calculation is 0.00010 Δk_{eff} , resulting in an uncertainty on the deviation between two points of 0.00014 Δk_{eff} . However, final k_{eff} values must account for code uncertainty, bias, and hardware tolerances. Therefore, a sum of biases and uncertainties of 0.02 Δk_{eff} was applied to best estimate calculation results for PWRs and 0.03 Δk_{eff} for the BWR case; both margins have a rounded increase over reference values, as such an analysis cannot be performed here.

After nominal model construction, composition perturbations were introduced to account for increased enrichments and ATF concepts. LEU+ enrichments examined were 6.5 and 8 wt % ²³⁵U. For the Cr-coated condition, the Cr coating on the fuel rod was 20 μm of elemental chromium. The thickness was chosen to fall within the potential ranges of both Westinghouse and Framatome implementations, as reported in Hall et al. [1]. Only the fuel cladding—not the fuel or water channels made of zirconium—had this extra layer of chromium. Fuel doping options are diverse, but 1,000 ppm of chromia dopant was selected given a history of reactor operation[1]. This was modeled as a fuel volume fraction of 0.001 at full density. Chromia is not included in the SCALE standard composition library of materials, so it was modeled as 680 ppm Cr by weight and 320 ppm O. FeCrAl, too, has a variety of alloy compositions that fall under the FeCrAl class, but a FeCrAl variant named C26M had significant reactor operation [1]. The C26M variant and its composition of 12% by weight Cr, 6% Al, 2% Mo, 0.2% Si, 0.003% Y, and the remainder Fe were modeled,

replacing only fuel cladding. Because of the use of less neutronically transparent iron but with stronger mechanical properties, the cladding was thinner, reducing the neutronic penalty. Thinner cladding also allowed for larger fuel pellets. The fuel pellet and cladding inner radius increased by 0.018925 cm, whereas the cladding outer radius stayed constant.

With three enrichments and four fuel pin technologies, 12 perturbations were performed for each point of interest to determine the limiting conditions. To analyze points of interest to meet regulation, the PWR SFPs were modeled fully flooded, with water at nominal density (1.0 g/cm^3). The PWR NFV was modeled fully flooded, with water at variable densities: every 0.1 step between 0 and 1 g/cm^3 nominal density, with 0.01 sub steps between 0.05 and 0.10 to identify the point of optimum moderation. In a search of available BWR NFVs, all discovered documentation utilized administrative controls to prevent variable density moderation in the vault, nullifying the requirement for the analysis of optimum moderation for the BWR NFV. Thus, the BWR NFV was modeled fully flooded only.

2.3 Modeling Considerations

Beyond considering the conditions directly expressed in regulation, credible issues that would arise with licensing of LEU+ and ATF fuel were examined. This includes issues such as poison panel degradation, neutronic decoupling, soluble boron credit for misload offset, the eccentric positioning of assemblies within their racks, and BWR radial enrichment averaging [6]. Additionally, in instances where LEU+ would conflict with current regulation, BA crediting was examined with integral fuel burnable absorber (IFBA) or gadolinia rods to examine whether tolerable crediting would make hardware modifications unnecessary.

The IA and DA SFP models reflect the initial and final stages of boron degradation, which has been observed in legacy poison panels. In addition to modeling these two approaches taken in safety analyses, the IA SFP was modeled with variable poison panel densities to reflect its decomposition. Increments were taken in 10% steps, with 2% sub-steps in the final 10% to better express the removal of absorber. To investigate the potential neutronic decoupling dependence on enrichment, two bare identical assemblies were modeled in water, with an interval distance between the two. Assembly pitches were varied from 20 to 100 cm. This was done for both the W 17×17 and the ATRIUM 10 assembly.

Typically, the accident in which a fuel assembly is misloaded into a designated empty storage location results in the greatest reactivity increase. A series of misload calculations were performed to investigate the sensitivity of this reactivity increase to LEU+ using the DA SFP. This storage pattern utilizes the checkerboard loading pattern, wherein every other cell is empty, with a slightly higher reactivity relative to the IA SFP. The 2×2 array was expanded to 10×10 to reduce periodic boundary condition effects, with extraneous assemblies incrementally introduced. Up to 11 misloaded assemblies were investigated; one, five, and 11 were subsequently modeled with soluble boron credit (SBC) to calculate the required SBC concentration to offset the misload reactivity.

NFV and SFP racks are designed to maintain the separation of fuel assemblies and are nominally modeled with the assemblies in the center of cells. Off-center positioning or eccentric positioning of the assemblies could cause clustering of assemblies among nearby cells, resulting in a more reactive state. Each storage area had assemblies offset within their respective racks to a more centralized state, which varied by rack design. SFP designs were expanded to 4×4 arrays. Although many perturbations exist, the chosen centralization was expected to provide a reasonable estimate of enrichment-dependent effects.

BWR radial enrichment averaging is sometimes done to simplify the multiple radial enrichments used in an assembly. A specified enrichment scheme was not provided in the publicly available documents used in modeling, so an alternate publicly available distribution was used to investigate LEU+ impacts on radial averaging. This utilized an example GE 14 BWR lattice stored in the BWR NFV [7]. Dominant lattice enrichments were nominally an average of 4.3 wt %. Both the pin-wise detailed and lattice-averaged enrichments were modeled. Enrichments were scaled up to 6.5 and 8 wt % averages.

In some instances shown in this paper, current configurations were unable to comply with 10 CFR 50.68. However, the margin of failure was at times on the order of the sum of biases and uncertainties, or even within the rounding utilized in this study. It would follow that minor BA credit would allow compliance with regulation in many if not all instances. Therefore, models were altered to include representative IFBA and gadolinia loadings. For PWRs, 32 and 64 IFBA rods were investigated, as well as four gadolinia rods. For the BWR, in addition to the nominal eight gadolinia rods, 12, 16, and 20 rods were investigated. For both NFVs and the IA SFP, assembly removal resulting in empty cells was also investigated as an alternative to BA credit. This alternative explored the removal of approximately one in four assemblies.

3 RESULTS

3.1 LEU+ and ATF Results

Fully flooded LEU+ and ATF perturbation effects are noted in Figure 1. Each subfigure consists of Δk_{eff} relative to the nominal condition (zirconium clad, ~5 wt %), with the nominal margin to regulatory limits (0.95 for NFVs and 1.0 for SFPs) exhibited by a black bar. Notably, NFVs examined were more restrictive for LEU+ enrichments: all LEU+ and ATF variants except the PWR FeCrAl 6.5 wt % exceeded regulatory limits. Alternatively, most SFP perturbations managed to remain sufficiently subcritical. The DA SFP bypassed limits at 8 wt %. Across all storage types, several ATF trends were noticed. Primarily, the effect of chromia doping had negligible neutronic impact. Cladding variations of Cr coating and FeCrAl substitution resulted in neutronic penalties, on the order of 0.004 and 0.02–0.03 Δk_{eff} respectively. Cladding penalties were slightly lower for the BWR NFV. Additionally, the FeCrAl penalty showed an enrichment dependance, with the penalty in the 8 wt % cases showing 70–80% the magnitude of that in the 5 wt % case.

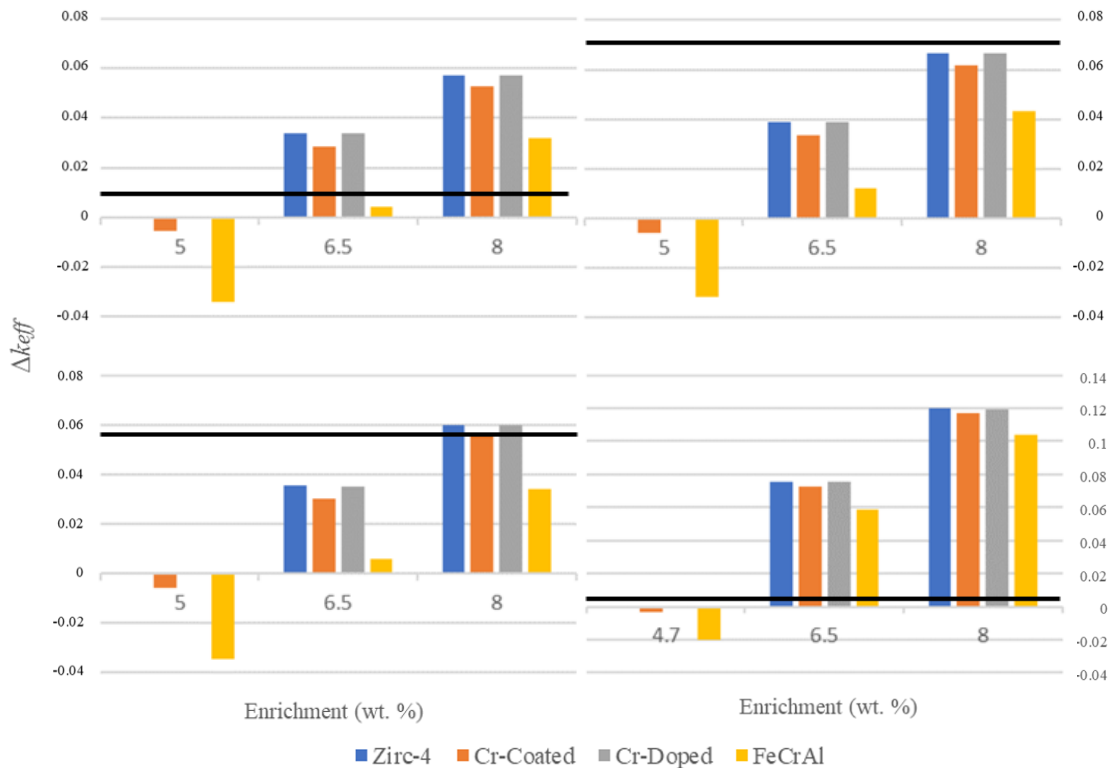


Figure 1. Changes from the fully flooded baseline of the LEU+ and ATF changes for (clockwise from top left) the PWR NFV, PWR IA SFP, BWR NFV, and PWR DA SFP model.

Optimum moderation of the PWR NFV is accounted for in Figure 2. Optimum moderation at all perturbations is within the required margin of 0.98 and occurs at 8% moderator density. Neutronic penalties from Cr coating and FeCrAl were at a slightly lower magnitude than that when fully flooded.

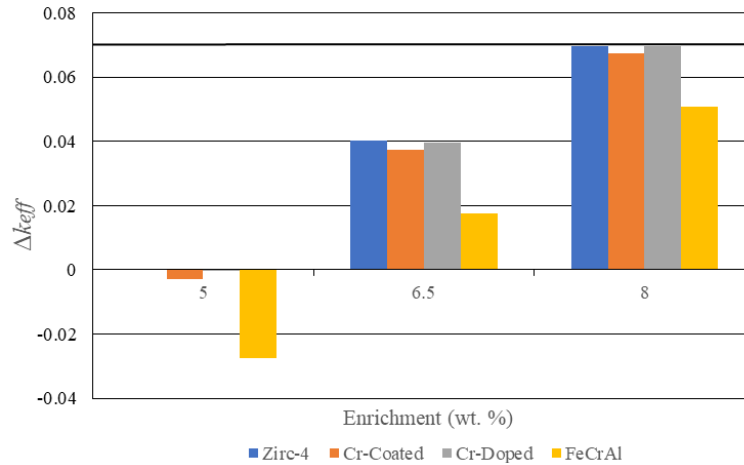


Figure 2. Changes from the optimum moderation baseline of the LEU+ and ATF changes for the PWR NFV.

3.2 Modeling Consideration Results

Table III illustrates the observed conservatism in using the average BWR radial enrichment as opposed to the pin-wise radial zoning. With increasing enrichment, the conservatism in enrichment averaging was shown to significantly decrease, though the effect remains a positive bias. Specific designs will impact the magnitude of these results, but are unlikely to change the conclusions based on the power distribution enrichment zoning is used to achieve. As noted in Section 2.3, the IA SFP model examined decreasing poison panel densities to reflect degradation. Densities were converted to ^{10}B areal densities, with the response plotted in Figure 3. The introduction of an absorber heavily impacts k_{eff} : the final 10% of absorber degradation represent approximately two-thirds of the total suppressive effect. To maintain a maximum reactivity below 1.0, 20% (0.0059 g/cm²), 40% (0.0117 g/cm²), and 90% (0.0264 g/cm²) of the intact absorber is required for the nominal, 6.5, and 8 wt % cases, respectively. With respect to LEU+, the poison panel worth is increased with enrichment, but as the figure shows, the behavior is otherwise identical. To investigate the neutronic decoupling sensitivity to LEU+ enrichments, bare PWR and BWR assemblies were incrementally brought together, with the responses shown in Figure 3. Results demonstrate the lack of enrichment-dependent variation in decoupling distance for both BWR and PWR assemblies. Centered and eccentrically positioned assembly k_{eff} values are shown in Table IV, with PWR enrichment-dependent effects between enrichments remaining at 50 pcm or less. The BWR NFV shows the greatest impact on k_{eff} from eccentricity, with increasing magnitude at LEU+ enrichments. The effect of 8 wt % fuel in the BWR NFV resulted in a 0.0035 Δk_{eff} over the nominal enrichment eccentricity effect.

Table III. BWR radial enrichment averaging

Fuel enrichment	Pin-wise	Lattice-averaged	Δk_{eff}
4.3 wt %	0.7492	0.7551	0.0059
6.5 wt %	0.8596	0.8638	0.0042
8 wt %	0.9117	0.9151	0.0034

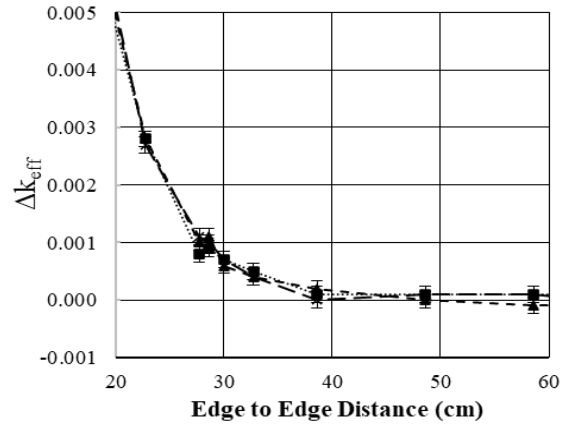
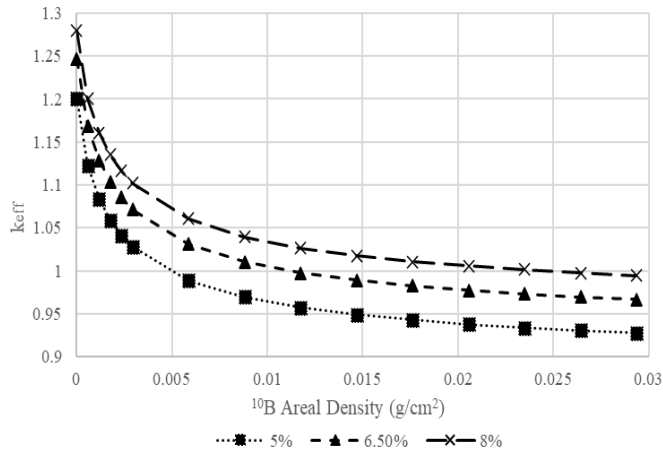


Figure 3. Clockwise from left: IA SFP poison panel degradation, PWR assembly decoupling, BWR assembly decoupling.

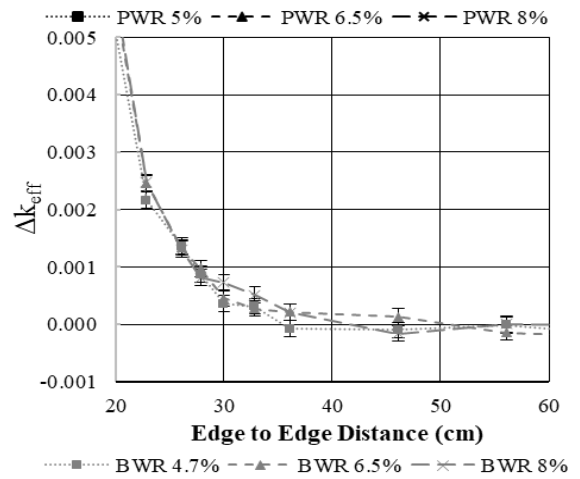


Table IV. Eccentric positioning effect

Storage area	k_{eff}	Fuel enrichment (wt %)		
		Nominal	6.5	8
Fully Flooded PWR NFV	Centered	0.9229	0.9567	0.9803
	Eccentric	0.9231	0.9572	0.9806
	Eccentricity Δk_{eff}	0.0002	0.0005	0.0003
Optimum Moderation PWR NFV	Centered	0.8901	0.9302	0.9598
	Eccentric	0.8924	0.9324	0.9623
	Eccentricity Δk_{eff}	0.0023	0.0022	0.0025
Fully Flooded BWR NFV	Centered	0.9151	0.9909	1.0351
	Eccentric	0.9351	1.0132	1.0586
	Eccentricity Δk_{eff}	0.0200	0.0223	0.0235
Fully Flooded IA SFP	Centered	0.9078	0.9467	0.9745
	Eccentric	0.9070	0.9464	0.9745
	Eccentricity Δk_{eff}	-0.0008	-0.0003	0.0000
Fully Flooded DA SFP	Centered	0.9212	0.9566	0.9812
	Eccentric	0.9231	0.9585	0.9836
	Eccentricity Δk_{eff}	0.0019	0.0019	0.0024

Misload effects are shown in Figure 4, which displays boron curves for the nominal condition and those for one, five, and 11 misloaded assemblies. Table V summarizes the considered boron concentrations at which k_{eff} is below 0.95. In many cases, the noted concentration results in k_{eff} are several percent lower than necessary simply because of calculation intervals and cutoffs.

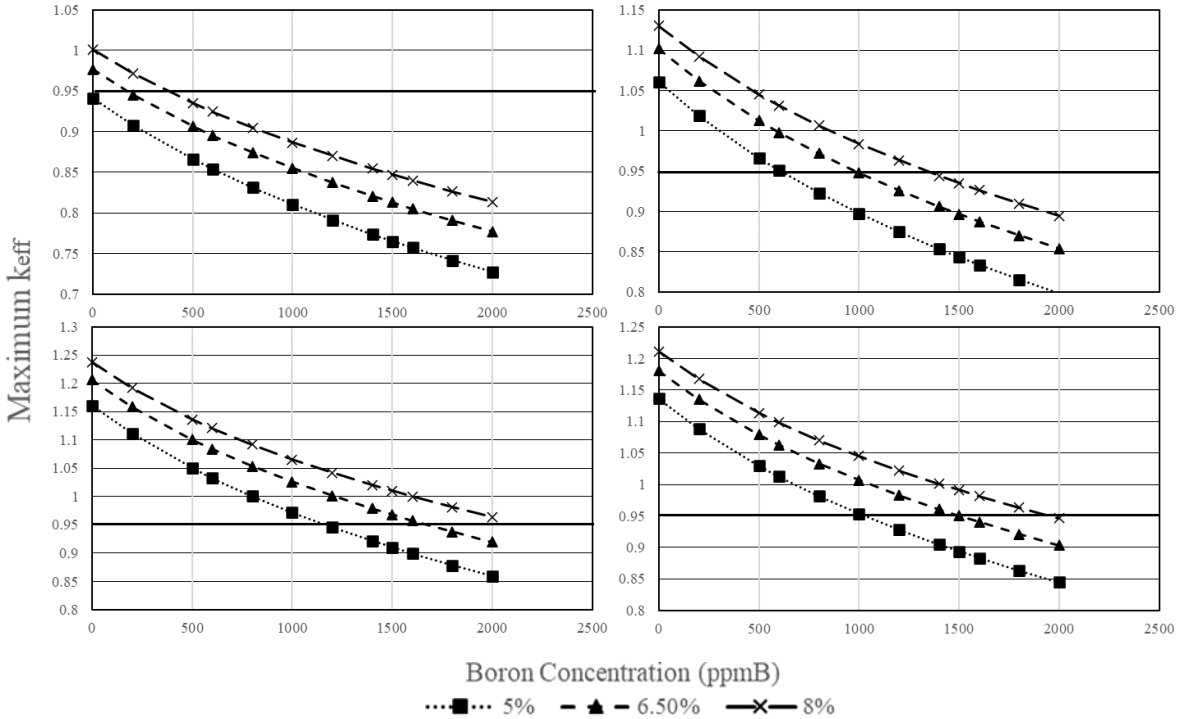


Figure 4. Clockwise from top left: Zero, one, five, and eleven misloads in the DA SFP model.

Table V. Soluble boron concentration (ppmB) required to offset misload reactivity

Fuel enrichment	Number of misloaded assemblies			
	0	1	5	11
5 wt %	0	800	1,200	1,200
6.5 wt %	200	1,000	1,600	1,800
8 wt %	500	1,400	2,000	2,000+

3.3 Burnable Absorber Credit

As noted in Section 2.3, several analyzed configurations resulted in k_{eff} values surpassing regulatory limits. Table VI presents results of calculations designed to offset these effects, with Δk_{eff} of zero occurring for the base condition (nominal with LEU+). Conditions in which k_{eff} is greater than regulatory limits are bolded and italicized in the table. Values of Δk_{eff} are consistent within configuration and enrichments—values in the 6.5% column and BWR NFV row are relative to the base BWR NFV model at 6.5%, values in the 8% column and BWR NFV row are relative to the base BWR NFV model at 8%, etc. Gadolinium at different concentrations was investigated, though the perturbations involved were shown to be less meaningful

relative to increased loading. PWR NFV optimum moderation was shown to be less limiting but was still verified to be within regulatory requirements; this is not presented here. Although no condition in the IA SFP was above regulatory requirements, credit was still investigated for comparison. For PWR storage, crediting 64 or fewer IFBA was sufficient in all cases up to the maximum enrichment investigated in this study. Reduced array loading in the BWR NFV and IA SFP were successful in reducing k_{eff} : the PWR NFV assemblies were effectively decoupled and the DA SFP was not investigated for its initial low loading scheme. The particularly enrichment-sensitive BWR NFV required 20 gadolinia rods for the 8 wt % condition, or the quarter reduction in loading.

Table VI. Reactivity crediting of burnable absorber and reduced assembly loading

Configuration	Total Assemblies	Gd rods	IFBA rods	Maximum reactivity (k_{eff})		Δk_{eff}	
				6.5 %	8 %	6.5 %	8 %
BWR NFV	210	8	0	1.0209	1.0651	0.0000	0.0000
	210	12	0	0.9754	1.0236	-0.0455	-0.0415
	210	16	0	0.9212	0.9729	-0.0997	-0.0922
	210	20	0	0.8891	0.9433	-0.1318	-0.1218
	160	8	0	0.9043	0.9435	-0.1166	-0.1216
PWR NFV	70	0	0	0.9767	1.0003	0.0000	0.0000
	70	0	32	0.9437	0.9713	-0.0330	-0.0290
	70	0	64	0.9047	0.9366	-0.0720	-0.0637
	58	0	0	0.9764	1.0000	-0.0003	-0.0003
	58	0	32	0.9432	0.9708	-0.0335	-0.0295
	58	0	64	0.9043	0.9362	-0.0724	-0.0641
	70	4	0	0.9572	0.9829	-0.0195	-0.0174
PWR IA SFP	4	0	0	0.9667	0.9945	0.0000	0.0000
	4	0	32	0.9332	0.9647	-0.0335	-0.0298
	4	0	64	0.8904	0.9269	-0.0763	-0.0676
	3	0	0	0.9249	0.9511	-0.0418	-0.0434
	3	0	32	0.8934	0.9230	-0.0733	-0.0715
	3	0	64	0.8514	0.8859	-0.1153	-0.1086
	4	4	0	0.9447	0.9753	-0.0220	-0.0192
PWR DA SFP	2	0	0	0.9766	1.0012	0.0000	0.0000
	2	0	32	0.9436	0.9722	-0.0330	-0.0290
	2	0	64	0.9049	0.9374	-0.0717	-0.0638
	2	0	80	0.8919	0.9256	-0.0847	-0.0756
	2	4	0	0.9568	0.9837	-0.0198	-0.0175

4 CONCLUSIONS

This study examined the sensitivity of LWR fresh fuel storage areas to LEU+ enrichments up to 8.0 wt % and ATF concepts. SCALE calculations were performed to calculate best-estimate k_{eff} values for four representative classes of fuel storage systems. Each model's baseline LEU enrichment of ~5 wt % UO₂ was increased to reflect potential LEU+ enrichment levels of 6.5 and 8.0 wt %. For cases in which maximum k_{eff} values exceed regulatory limits, crediting of integral burnable absorber credit and storage reduction were investigated to determine representative requirements. The examined PWR NFV configuration had an

insufficient margin to support LEU+ enrichments when fully flooded and a reactivity impact of $\sim 0.035 \Delta k_{eff}$ at 6.5 wt % fuel and $\sim 0.06 \Delta k_{eff}$ at 8 wt %. This reactivity impact was consistent with other W 17×17 STD assembly storage. Reasonable integral absorber credit successfully maintained compliance with regulatory limits for PWR sites. The examined BWR NFV configuration also had an insufficient margin for LEU+ fuel, becoming supercritical at all LEU+ conditions examined, with Δk_{eff} of ~ 0.08 at 6.5 wt % fuel and 0.12 at 8 wt %. A reduced loading of the vault was successful in reducing reactivity, as was crediting additional gadolinium. Whether this LEU+ sensitivity applies to other BWR storage will be addressed by considering burnup in the next phase of the analysis, which will address BWR SFPs.

Cr-coated cladding resulted in neutronic penalties of $0.003\text{--}0.005 \Delta k_{eff}$ in all models. Chromia-doped UO_2 had negligible neutronic impact. FeCrAl exhibited an enrichment-dependent heavy neutronic penalty. The penalty is $\sim 0.03 \Delta k_{eff}$ for examined PWRs and $\sim 0.02 \Delta k_{eff}$ for examined BWRs at nominal enrichments. This enrichment dependent penalty is shown to be greater in PWRs, with the penalty decreasing in magnitude by $\sim 0.008 \Delta k_{eff}$ at 8 wt % fuel and the BWR penalty decreasing $\sim 0.004 \Delta k_{eff}$ at 8 wt %.

Regarding the sensitivity of other modeling considerations to enrichment, decoupling assumptions based on the 12 in. (30.48 cm) convention are as true for LEU+ as LEU. Poison panel degradation, though it has a higher worth at increased enrichment, is otherwise identical to LEU fuel under the same conditions. PWR eccentric positioning is largely static. Conversely, BWR eccentric positioning increases with enrichment for a further increase of $0.0035 \Delta k_{eff}$ between 8 and 5 wt %. Additionally, BWR radial enrichment averaging has reduced conservatism with increasing enrichment. Although a full class of BWR storage areas has yet to be investigated, the general finding of the examined BWR in this study shows greater enrichment sensitivity than PWR counterparts and SFPs. This is illustrated by a near doubling of the Δk_{eff} observed in PWR assemblies due to LEU+, an illustrated increase in the eccentric positioning effect not observed in PWR assemblies, and though not replicated in PWRs, reduced conservatism in radial enrichment zoning averaging. Alternatively, the chosen representative case may be a potential outlier in its sensitivity, as the nominal model required a substantial credit at 4.7 wt %. However, given the Δk_{eff} observed in the GE 14, the observed BWR NFV LEU+ Δk_{eff} may be common in BWRs.

5 REFERENCES

1. R. Hall et al. *Extended-Enrichment Accident-Tolerant LWR Fuel Isotopic and Lattice Parameter Trends*. ORNL/TM-2021/1961. Oak Ridge: Oak Ridge National Laboratory (2021).
2. 10 CFR Part 50.68. “Criticality Accident Requirements.” *Code of Federal Regulations*, Title 10, Energy, Part 50, “Domestic Licensing of Production and Utilization Facilities.” (2006).
3. O. Ozer et al. *Optimum Cycle Length and Discharge Burnup for Nuclear Fuel Phase 1: Results Achievable Within the 5% Enrichment Limit*. EPRI Report 1003133 (2001).
4. O. C. Brown et al. *Brunswick Nuclear Plant New Fuel Storage Vault Criticality Safety Analysis for ATRIUM™-10 Fuel*. AREVA Report ANP-2661 (NP), Revision 0 (2007).
5. W. A. Wieselquist, R. A. Lefebvre, and M. A. Jessee, Eds., *SCALE Code System*, ORNL/TM-2005/39, Version 6.2.4, Oak Ridge National Laboratory, Oak Ridge, TN (2020).
6. *Guidance for Performing Criticality Analyses of Fuel Storage at Light Water Reactor Power Plants*. NEI-12-16, Rev. 4. Nuclear Energy Institute (2019).
7. M. L. Fensin. *Optimum Boiling Water Reactor Fuel Design Strategies to Enhance Reactor Shutdown by the Standby Liquid Control System*, Master of Engineering Thesis, University of Florida (2004).