

CRITICALITY SAFETY RECOMMENDATIONS FOR THE TREATMENT OF EXTENDED ENRICHMENT AND HIGH BURNUP FUEL FOR STORAGE AND TRANSPORTATION SYSTEMS**

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ABSTRACT

Current United States Nuclear Regulatory Commission (NRC) regulations for the safe operation, maintenance, storage, and transportation of low-enriched uranium (LEU) fuel in commercial power plants limit the fuel enrichment to 5.0 wt % ²³⁵U or less. With an increased industry push to use extended enrichment (EE) fuel for high-burnup (HBU) fuel cycles, the NRC must have a technical basis on which to assess regulations to account for fuel enrichments above the 5.0 wt % limit. This paper details findings to be delivered to the NRC regarding NUREG-2215 and NUREG-2216 (Standard Review Plans for Spent Fuel Dry Storage and Transportation Packages, respectively) to ensure the satisfaction of 10 CFR Parts 71 and 72 with EE and HBU fuels concerning burnup credit.

The basis of the findings given to the NRC will be developed from a review and analysis of current and hypothetical fuel and irradiation parameters. Whereas the full recommendations will detail criticality safety and shielding parameterizations and conclusions, this paper focuses on the criticality safety implications of EE and HBU fuel, examining conservative conditions of these systems as they relate to initial fuel enrichment, burnup, absorber exposure and other poison loadings, and moderator conditions expected in EE and HBU fuel cycles. EE and HBU fuels are very similar to fuel used in currently operating reactors; the primary motivation is to operate longer cycles with higher net power production per assembly lifetime without incorporating novel assembly or fuel designs.

For the analysis, the SCALE 6.3.0 package was used. The SCALE/Polaris module for lattice physics and depletion was used for the generation of fuel inventories across the various parameterizations—particularly enrichment, burnup, and depletion conditions—whereas the SCALE/ORIGAMI sequence interpolates between calculated state points to generate inventories reflecting variations due to axial burnup profiles and cooling times. With generated inventories at parameterized conditions, SCALE/CSAS calculates eigenvalue solutions for a generic burnup credit cask with 18 axial zones and 32 Westinghouse 17 × 17 optimized fuel assemblies—the GBC-32 representative storage and/or transport cask. This paper provides a summary of eigenvalue responses to examined parameters and presents the sensitivity of burnup credit to EE and HBU fuels.

KEYWORDS

Criticality Safety, Burnup Credit, Extended Enrichment, High Burnup, Spent Fuel Storage and Transportation

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1. INTRODUCTION

Title 10 CFR Part 71 and Part 72 establish license determination and approval of nuclear storage and transportation packages [0, 0]. To assist US Nuclear Regulatory Commission (NRC) staff in the technical review of these packages for safe and secure determination, NUREG-2215 and NUREG-2216 demonstrate general procedures for use by NRC staff as “Standard Review Plan[s]” [0, 0]. One component of the review process is the criticality evaluation of the packages to demonstrate the subcriticality of the package contents. For the treatment of spent fuel, the use of burnup credit (BUC) is an approved methodology for crediting the effects of fuel depletion through reactor operation. As fuel depletes, reactivity decreases due to a decrease in fissionable material and a buildup of fission products. BUC methodologies can include crediting actinides only (AO) or actinides-plus-fission products (AFPs), which emphasize longer-lived and chemically stable nuclides in spent fuel. BUC review recommendations are noted in Section 7.5.5 of NUREG-2215 and Section 6.4.7 and Attachment 6A of NUREG-2216 [0, 0]. To prepare for industry forays into fuel cycles implementing extended enrichment (EE) and high-burnup (HBU) management schemes, these sections addressing BUC must have supporting analysis to ensure the recommendations provided are consistent with the physics of the depletion of higher enrichment and burnup fuels. The NRC initiated a multipronged project with Oak Ridge National Laboratory (ORNL) to examine multiple aspects of incorporating EE and HBU fuel cycles into the recommendations provided by the Standard Review Plans to deliver supporting evidence.

This work focuses on the renewed analysis of various parametric effects of the depletion history of spent fuel on BUC at higher burnups and enrichments. BUC is still a demonstrably conservative estimate of reactivity while reducing the calculated reactivity of fuel for storage or transportation. Conservatism is ensured in part by using conservative depletion parameters when detailed histories are either unknown or variable. With increased enrichment and burnup, the behavior of standard review parameters is likely to change direction and/or magnitude. Multiple comprehensive reports have addressed specific aspects of depletion histories—NUREG/CR-6801 investigates bounding axial profiles to ensure axial variations in depletion are conservatively captured, NUREG/CR-6781 details cooling time sensitivity, and NUREG/CR-6665 and ORNL/TM-12973 provide parametric evaluations of various assembly and depletion parameters [0–0]. A consistent limitation in these studies is the range of enrichment and burnup examined, typically no higher than 5.0 wt % and 60 GWd/MTU. In addition to increased enrichments and burnups, fuel cycles with EE and HBU will have increased burnable absorber loadings and/or increased soluble boron content. Variations in specific power or burnup profiles may occur to accommodate longer cycle lengths. These parameterizations must be analyzed at increased enrichments and burnups of representative systems to develop an intuition of potential adjustments for implementation in BUC methodologies. At the conclusion of the project, a NUREG/CR document will be published detailing the studies summarized herein.

2. METHODOLOGY

This study used SCALE 6.3.0 in all aspects of analysis [0]. The ENDF/B-VII.1 [0] 252-group library was used in all aspects apart from a brief bias assessment of eigenvalues generated by the multigroup library relative to continuous energy. Depletion modeling used the Westinghouse 17×17 optimized fuel assembly (OFA) as the basis for analysis, which was carried into criticality safety analysis of the fuel within the storage cask [0]. The GBC-32 storage cask was modeled in criticality safety analysis with the spent Westinghouse (WE) 17×17 fuel compositions generated by depletion modeling [0].

The analysis sequence is as follows and is summarized in Figure 1. Fuel and depletion parameters described in Table I detail the WE 17×17 OFA assembly characteristics and operation histories used as inputs to the Polaris module. Polaris is a 2D lattice physics code for light-water reactors (LWRs) with ORIGEN embedded for depletion. One output of Polaris is an *.f33* file, which contains one-group reaction coefficients. When coupled with other *.f33* files from sister Polaris calculations at different but related conditions (e.g., burnup, moderator density, enrichment) into an ORIGEN library, interpolation can be performed with ORIGAMI to generate spent fuel compositions at the requested burnup,

moderator density, and enrichment. With the ability to interpolate burnups, ORIGAMI can generate axial zone compositions from a provided axial burnup profile, calculating the burnup at each node and interpolating upon that burnup. ORIGAMI was used to generate AFP compositions. The axial profile implemented is drawn from NUREG/CR-6801 and is meant to be bounding [0]. Thus, groupings of Polaris calculations can produce 18 axial zones of spent fuel compositions readable by the CSAS module with the use of ORIGAMI. The spent fuel is placed into the respective axial nodes of the CSAS model, and an eigenvalue calculation is performed to produce the final output of k_{eff} .

Table I details the examined parameters presented in this paper with the baseline parameters underlined. For simplicity and lack of information on true EE and HBU operation schemes, parameterizations were performed universally (e.g., constant soluble boron content throughout operation), as the intent is the resulting sensitivity to the parameter. Enrichments between 5.0 and 8.0 wt % were analyzed at burnups between 15 and 75 Gwd/MTU. Baseline parameters are the default other than when the parameter of interest is being analyzed.

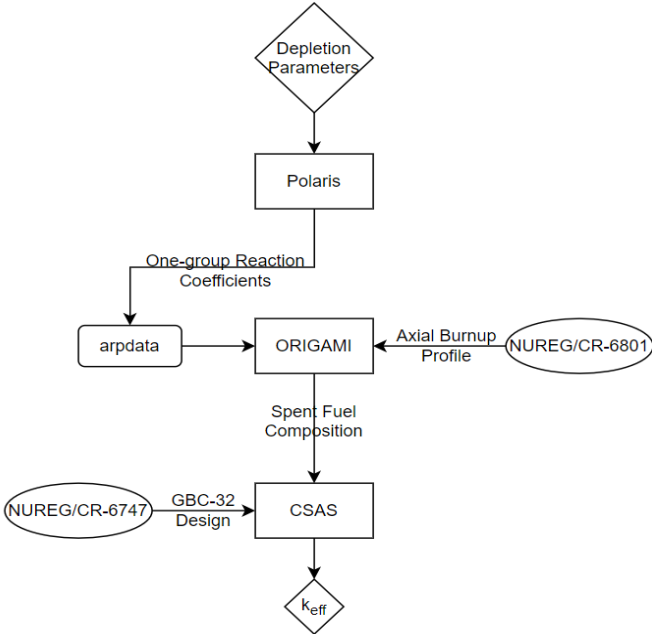


Figure 1. SCALE workflow for burnup credit analysis of the GBC-32 cask.

Table I. Fuel and operation parameters adjusted in depletion and storage.

Parameter	Value
Average assembly burnup values (Gwd/MTU)	15 25 35 45 55 65 75
Fuel initial enrichment values (²³⁵ U wt %)	5.0 5.5 <u>6.0</u> 6.5 7.0 7.5 8.0
Number of IFBA rods	0 <u>80</u> 104 128 156 200
Fuel specific power (MW/MTU)	15 20 30 <u>40</u> 50
Average soluble boron concentration (ppm)	0 600 <u>1000</u> 1800 2500
Moderator density and temperature (g/cm ³)/(K)	0.608/615 <u>0.630/610</u> 0.700/585 0.770/550
Fuel temperature (K)	560 800 <u>900</u> 1600
Fuel density (g/cm ³)	10 <u>10.26</u> 10.75
Number of WABA rods	<u>0</u> 8 20 24
Cooling time (years)	1 3 <u>5</u> 7 10 20 30 40 50 70 100

3. RESULTS

This section details the parametric effects for criticality safety analysis of spent fuel transportation and storage packages. As a parametric study, the intent is not to demonstrate the subcriticality of contents within the modeled GBC-32 cask. Parametric analyses investigate the variables defined in Table I with the baseline values unperturbed. Values were often examined over conservative ranges relative to true operational conditions. Unless otherwise noted, trend behavior between 5.0 and 6.5 wt % is similar for behaviors between 5.0 and 8.0 wt %: a greater effect than 5.0 wt % but less than 8.0 wt %. Uncertainties in k_{eff} are 10 pcm and uncertainties in Δk_{eff} are 14 pcm. Most plot uncertainties are the size of the marker. If shown, uncertainties will represent 95% (2σ) for improved visibility.

3.1. Burnup and enrichment

Figure 2 plots the variation in GBC-32 eigenvalue with burnup and enrichment. As expected, the eigenvalue response is positive with increased enrichment and negative with increased burnup. At this scale, differences in burnup behavior by enrichment appear identical. With increasing enrichment, the slope of depletion (at constant soluble boron loading, burnable absorber loading, etc.) decreases at a rate of approximately 10 pcm per GWd/MTU (600 pcm between 15 and 75 GWd/MTU) per 0.5 wt % increment. Further analysis of the differential k_{eff} as a function of burnup will be detailed in the final NUREG/CR document.

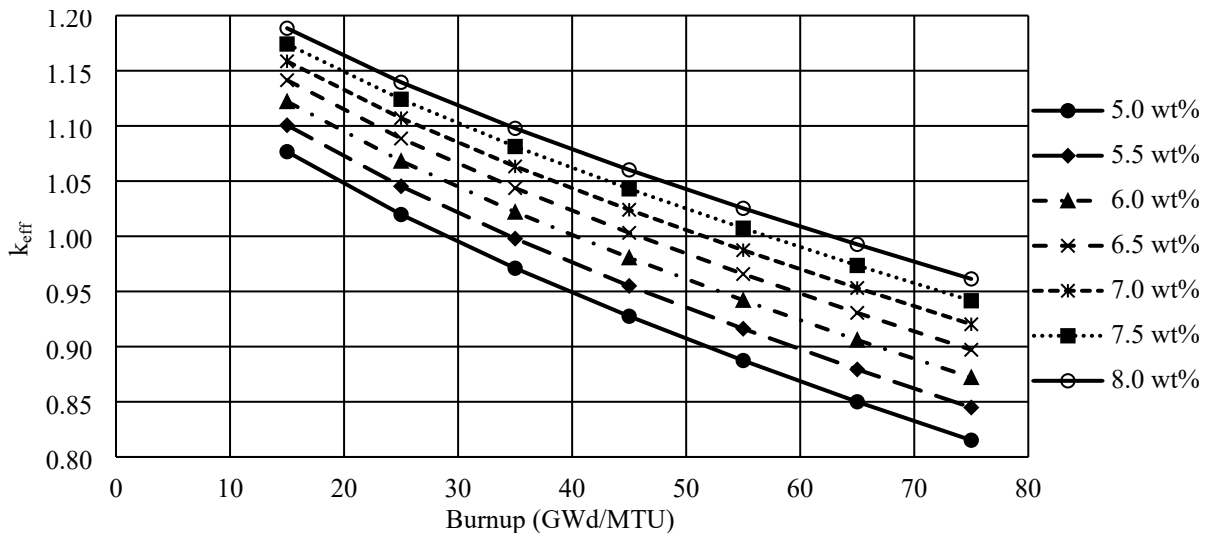


Figure 2. GBC-32 k_{eff} as a function of burnup and enrichment.

3.2. Cooling time

The effect of assembly cooldown post-irradiation on cask criticality was analyzed for 5.0, 6.5, and 8.0 wt % ^{235}U PWR fuel. Figure 3 displays the effect of cooling time on 5.0 and 8.0 wt % fuel at various burnups. With increased enrichment, the variation in k_{eff} is lessened as a function of cooling time relative to one year of cooling. The behavior while muted is generally the same. As shown in NUREG/CR-6781, reactivity develops a local minimum at ~ 100 years post-irradiation. This is consistent for all burnups and enrichments, as ^{241}Pu decays into ^{241}Am . With less ^{241}Pu production at higher enrichments, there is less of a decrease in reactivity in the first 100 years as less decay of ^{241}Pu to ^{241}Am occurs as demonstrated in NUREG/CR-6781. While not examined beyond 100 years, it would be expected that a resulting upswing in reactivity in the 100–1000-year timeframe would be similarly affected as less ^{241}Pu results in less ^{241}Am to decay, as well as less ^{240}Pu . ^{241}Pu inventory in the depleted fuel is less in the 8.0 wt % case for lower burnups, before reaching parity with 5.0 wt. % concentrations at 65 and 75 GWd/MTU. These slight increases are not enough to offset the reduction in the $^{241}\text{Pu}/^{235}\text{U}$ ratio- reducing

the relative reactivity impact of ^{241}Pu production and the resulting decay into ^{241}Am . As a function of burnup, the trend accrues more of an effect with increased burnup with no observed change in slope. This is found to be the case in most parameters analyzed.

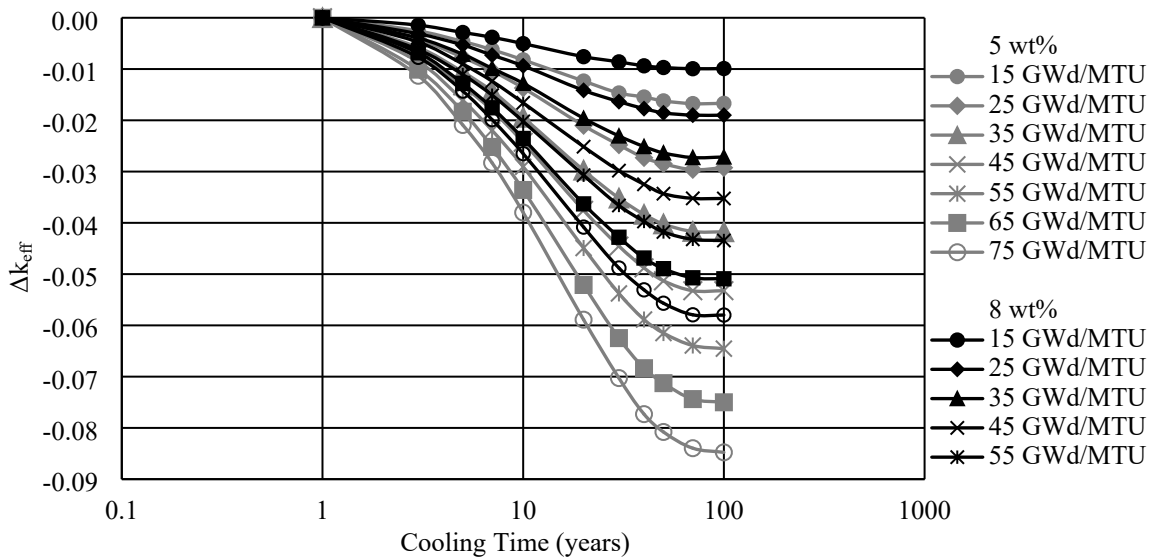


Figure 3. GBC-32 k_{eff} variation as a function of burnup and cooling time for 5.0 wt % (light gray) and 8.0 wt % (black).

3.3. Specific power

Figure 4 shows the effect of specific power on various burnups and enrichments. Here the uncertainty (2σ) in the eigenvalue differentials is visible, emphasizing the scale of the differences from specific power relative to cooling time and enrichment. As enrichment increases, the trend slightly tails out at lower burnups before increasing linearly with burnup. This may be due to Monte Carlo uncertainties.

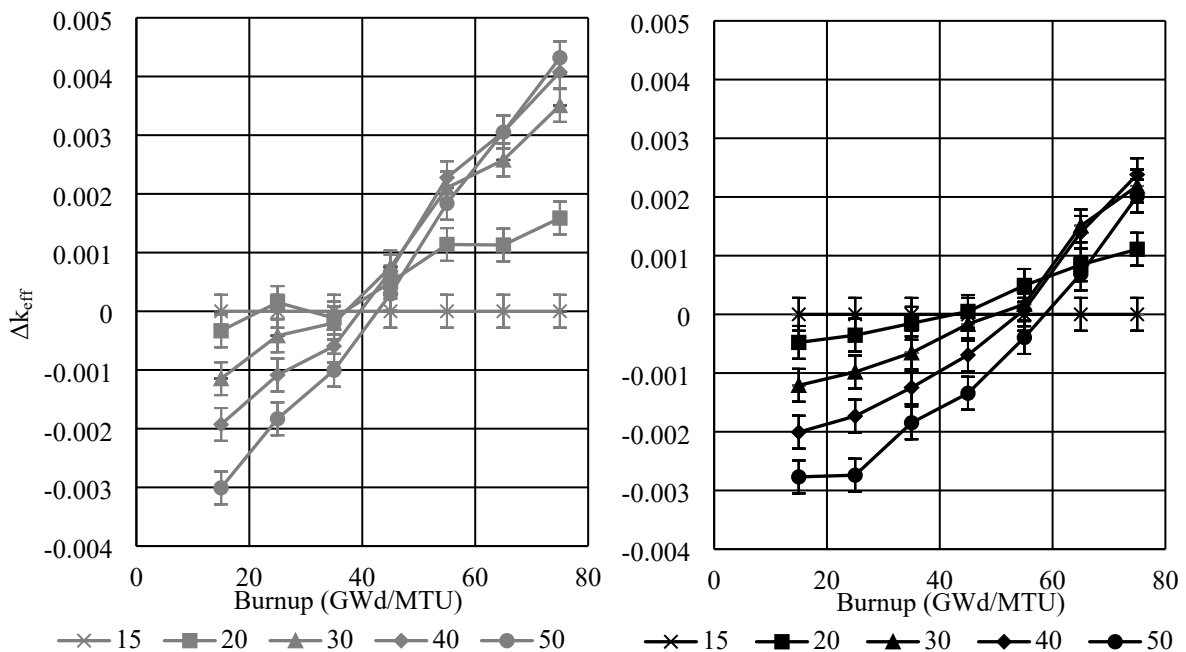


Figure 4. GBC-32 k_{eff} variation ($\pm 2\sigma$) versus burnup for various specific powers (MW/MTU) for 5.0 wt % (left) and 8.0 wt % (right).

At 5.0 wt %, the range of specific powers results in a -300 to an approximately +450 pcm shift in k_{eff} for 50 MW/MTU relative to 15 MW/MTU-specific power. At 8.0 wt %, the range is from -300 to about +250 pcm. At lower specific powers and burnups, each specific power has a distinct reactivity impact. At both 5.0 and 8.0 wt %, higher burnups show convergence in specific power behavior. Fission product worth is understood to be the driving factor for specific power conservatism because lower power operation of the same discharge burnup extends the operating cycle, allowing for slower production and additional decay of fission product poisons throughout operation. Previous studies examined AO and AFP differences [0]; however, they are not addressed by this work. Lower specific power is the more conservative approach for examined enrichments at lower burnup. As discharge burnup increases, the trend reverses: higher specific powers become the more reactive state as actinides build up.

3.4. Fuel temperature and density

Fuel temperature and density are both strongly impactful parameters on reactivity, which increases with fuel temperature and burnup. This is expected as the increase in fuel temperature increases Doppler broadening resonance absorption in ^{238}U for ^{239}Pu production. While increased enrichment reduces ^{238}U concentrations for the capture of neutrons for ^{239}Pu production, ^{239}Pu is higher in absolute concentrations at higher enrichments. At higher enrichments and burnups, ^{235}U is burned preferentially resulting in less ^{239}Pu depletion, allowing a higher buildup at lower production rates. However, the $^{239}\text{Pu}/^{235}\text{U}$ ratio is significantly lessened with increased initial fuel enrichment, and thus the excess ^{239}Pu production from increased $^{238}\text{U}(n,\gamma)$ reactions due to increased fuel temperature is muted in its reactivity impact. For 560 K relative to 900 K, the difference is 150–920 pcm at 5.0 wt % and 40–460 pcm at 8.0 wt % for burnups of 15 and 75 GWd/MTU. Figure 5 displays state points of enrichment and burnup at the varied temperatures, demonstrating that an increase in fuel temperature increases the reactivity of spent fuel. The magnitude of this effect increases with burnup but decreases with enrichment.

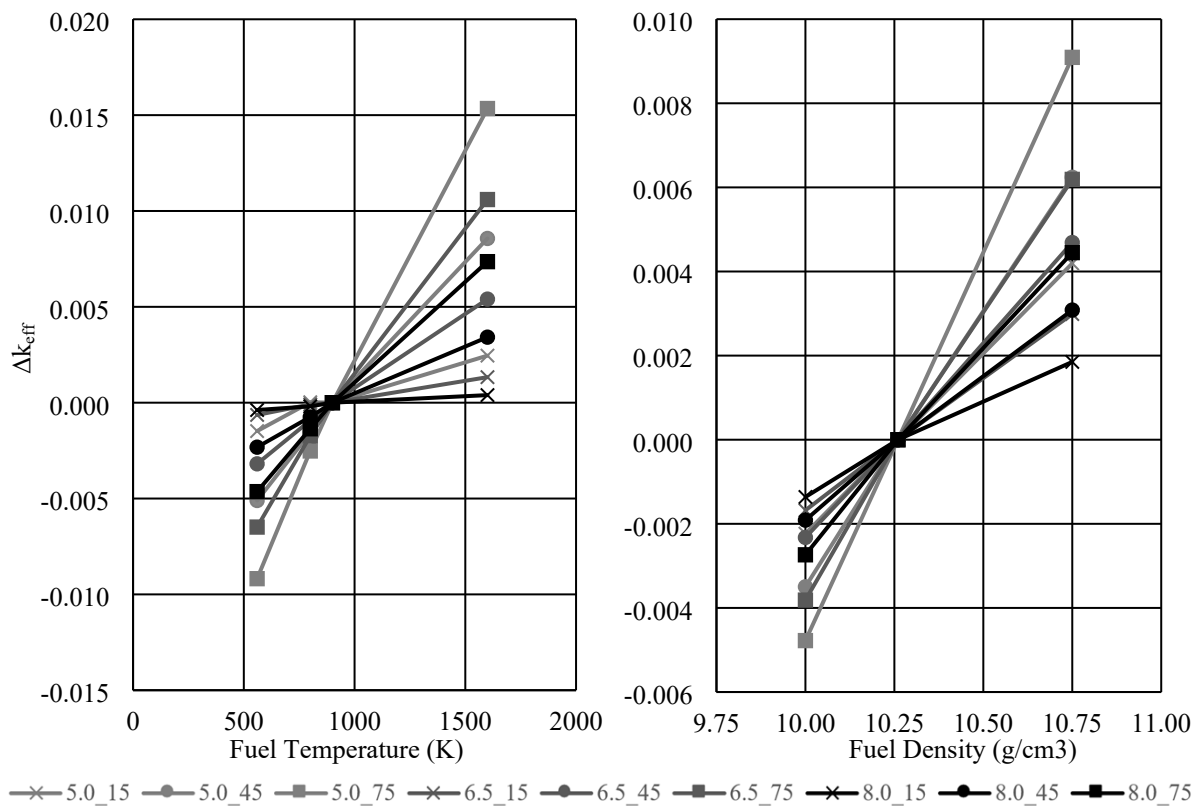


Figure 5. GBC-32 k_{eff} variation ($\pm 2\sigma$) versus fuel temperature (left) and density (right). Lines are for various enrichment and burnup pairs, shown in the legend as <enrichment>_<burnup>, with <enrichment> in wt % and <burnup> in GWd/MTU.

With a fuel density of 10.75 vs. 10.0 g/cm³, a 600–1400 pcm effect is seen in 5.0 wt % fuel at 15 and 75 GWd/MTU, respectively. With increasing enrichment, the same effect is substantially muted with a 350–750 pcm effect seen at 8.0 wt %—effectively halved. Fuel density is not a parameter typically analyzed (not detailed in NUREG-2216) and is left only to “ensure that the value ... is justified to be realistic or conservative” in NUREG-2215 [0]. It is a known and constant value with more fuel (higher density) being more conservative. There is still an observed variation of k_{eff} with burnup and enrichment, with higher burnups and densities having higher relative eigenvalues.

3.5. Moderator temperature and density

Whereas fuel density and temperature are treated independently to account for manufacturing sintering and core operations, respectively, moderator density and temperature are directly correlated. The exact pairs are noted in Table I and drawn from [13]. In most cases, an increase in moderator temperature (thus a reduction in density) results in less moderation and a hardened spectrum. The hardened neutron energy spectrum results in increased production of Pu, which leads to increased reactivity at discharge. Figure 6 demonstrates the increasing reactivity with increased moderator temperature for 5.0 wt % and 8.0 wt % fuel. At low burnups (15 GWd/MTU), 8.0 wt % fuel at moderator temperatures of 585–615 K exhibit a negative 80–120 pcm reactivity effect with increased moderator temperature relative to a moderator temperature of 550 K. At higher burnups for 8 wt% fuel, the trend behaves as expected with increased moderator temperature increasing spent fuel reactivity. As with other BUC effects involving ²³⁹Pu production, the magnitude of the trend is reduced at higher enrichments with a lowered ²³⁹Pu/²³⁵U ratio. At low burnups and increasing enrichment, however, conventional conservatism of increased moderator temperature does not hold—lower-temperature water is the most reactive. Further analysis will be provided in the final NUREG/CR document to determine the expected cause of this behavior.

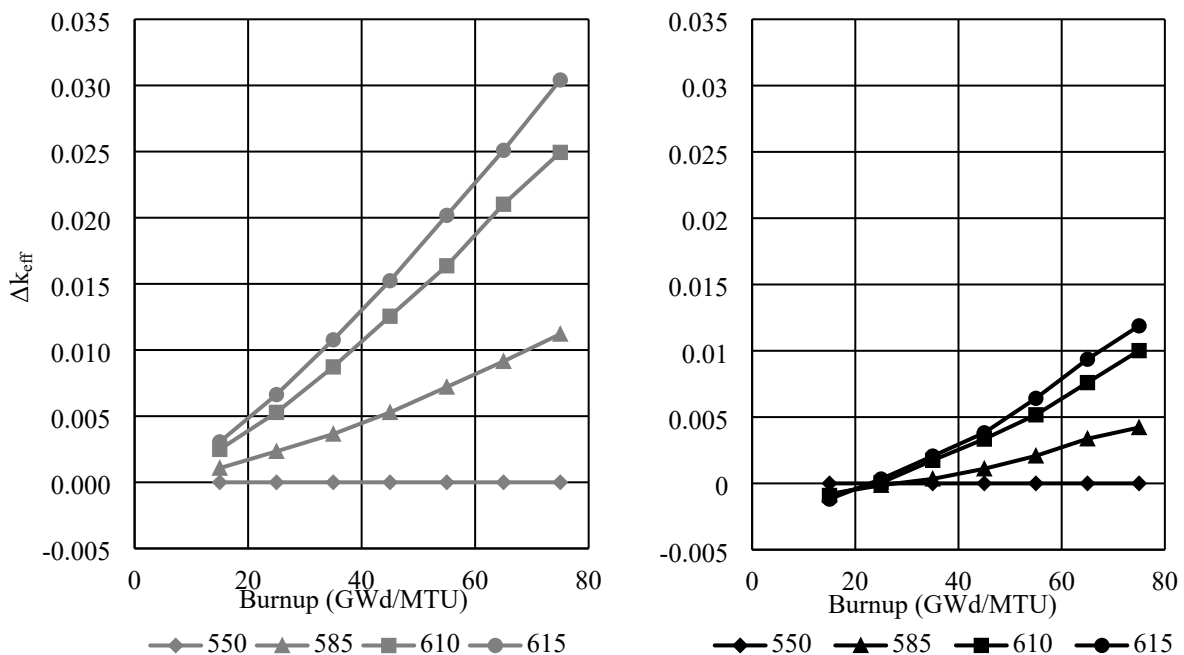


Figure 6. GBC-32 k_{eff} variation versus burnup for various moderator temperatures (K) for 5.0 wt % (left) and 8.0 wt % (right).

3.6. Soluble boron

Figure 7 shows the impact of soluble boron with increased enrichment and burnup. Another impactful parameter shows that an increase in soluble boron (boron—as with all other parameters—is held

constant throughout depletion) causes an increase in reactivity as the spectrum hardens. With increased enrichment, the effect of a spectral hardening parameter is reduced, as lower enrichments have more buildup of ^{239}Pu relative to total fissile material. The magnitude of increased boron at 8.0 wt % is approximately 20%–30% of the magnitude of increased boron at 5.0 wt %. Soluble boron exhibits a 1.19-1.31 pcm/ppm effect for 5.0 wt % fuel at 75 GWd/MTU, a 0.65-0.70 pcm/ppm effect for 6.5 wt % fuel at 75 GWd/MTU, and a 0.36-0.39 pcm/ppm effect for 8.0 wt % fuel at 75 GWd/MTU.

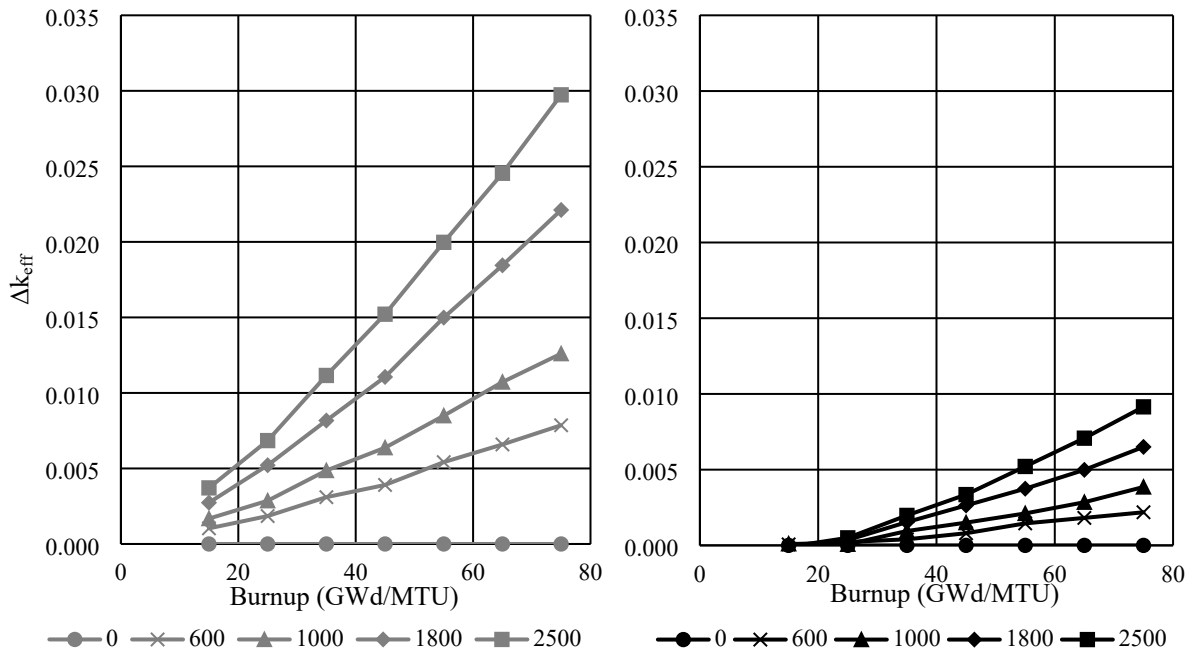


Figure 7. GBC-32 k_{eff} variation as a function of burnup and soluble boron (ppm) for 5.0 wt % (light gray) and 8.0 wt % (black).

3.7. Burnable absorbers

Residual burnable absorber material is not modeled in any CSAS criticality safety calculation. Two types of burnable absorbers were assessed: WE integral fuel burnable absorber (IFBA) and wet annular burnable absorber (WABA).

3.7.1 IFBA

Figure 8 shows various state points of enrichments and burnups at different IFBA loadings. In all cases, the increase in IFBA remains a positive effect on the eigenvalue. At lower burnups with increasing enrichment, there are minor fluctuations that approach no net effect and/or statistical insignificance. Apart from such cases, the increase in IFBA comes with a resulting increase in reactivity. As with soluble boron, integral burnable absorbers harden the spectrum, similarly leading to an increase in discharged fuel reactivity and the resulting decrease in magnitude with enrichment. Accounting for the maximum credible absorber loading would remain the more conservative approach to less effect.

3.7.2 IFBA + WABA

Figure 8 also shows various state points of enrichments and burnups at different WABA loadings in addition to 200 IFBA rods. As with IFBA, the increase in WABA largely remains a positive effect on the eigenvalue, with increased loading resulting in an increased eigenvalue. At lower burnups of higher enriched fuel (e.g., 8.0 wt % at 15 GWd/MTU), the reactivity effect becomes statistically indistinguishable from zero. In line with soluble boron and IFBA alone, increased loading with increased

enrichment decreases the relative k_{eff} . At low burnups, the addition of WABA to 200 IFBA becomes negligible. Although it would be an extreme loading of burnable absorbers, higher enrichments necessitate higher loadings, particularly with lower burnup and higher excess reactivity. Though the magnitude is small as to be effectively zero at this enrichment and burnup, the potential for convergence in excess reactivity at high absorber loadings, higher enrichments, and lower burnups should be noted.

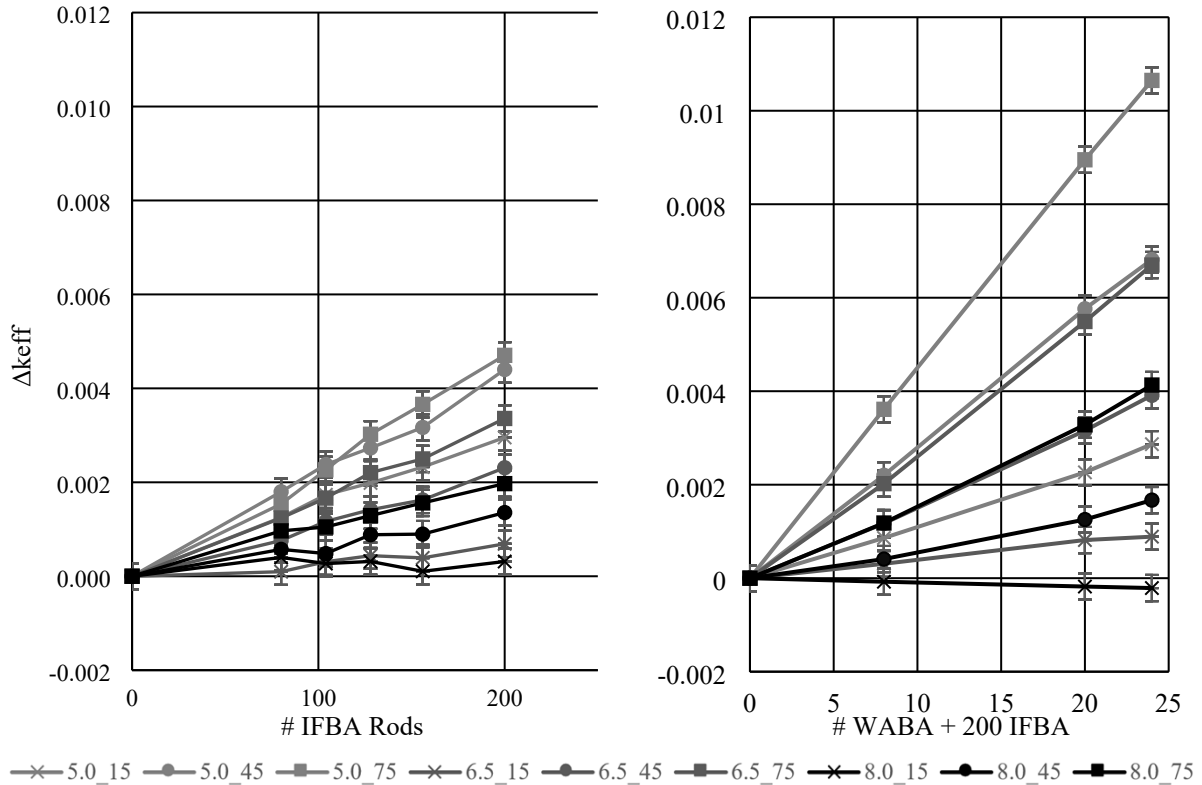


Figure 8. GBC-32 k_{eff} variation ($\pm 2\sigma$) as a function of burnup, enrichment, and burnable absorber loading.

3.8. Axial burnup profile

As operational schemes are unavailable, several hypothetical axial profiles were assessed to estimate the conservatism of the baseline axial profile. Two profiles were drawn from the Mertzyurek et al. assessment [13], whereas one was drawn from NUREG/CR-6801 [0]. All three profiles were shown to be bound by the baseline axial profile, chosen to be the “Group 5” profile of Table 5 in NUREG/CR-6801. End effects can be analyzed in greater detail upon the availability of public operating schemes.

4. CONCLUSIONS

Generally, most trends of reactivity behave as expected—increased enrichment increases reactivity, and increased burnup reduces reactivity. Trends that are a result of spectral hardening are muted with increased enrichment because of the lower $^{239}\text{Pu}/^{235}\text{U}$ ratio at higher enrichments. More detailed analysis and parametric variety will be provided in the final NUREG/CR document when it is published. In no instance did a trend become greater in significance with an increased enrichment, whereas in all instances trends continued the expected behavior with increased burnup. For specific power, an increase in enrichment may flatten the trend at lower burnups before returning to a linear relationship between reactivity and burnup. The inflection point evident in 5.0 wt % fuel at ~ 40 GWd/MTU burnup now appears at ~ 60 GWd/MTU at which higher specific power levels become more conservative—but also converge in their effect. The positive correlation between reactivity and fuel temperature and density is

maintained at a lower magnitude. Absorbers such as soluble boron, IFBA, and WABA demonstrate similar features hardening the spectrum through neutron absorption and, in the case of WABA, moderator displacement. Increasing enrichment reduces the effect of ^{239}Pu from a hardened spectrum such that the same soluble boron content produces a ~70% lower response in 8.0 wt % fuel than in 5.0 wt % fuel. A similar effect is observed with IFBA. The reduction continues with the accounting of WABA. The reduction becomes so severe that at low burnups and 8 wt % fuel, the inclusion of WABA in addition to 200 IFBA rods has no reactivity effect (i.e., modeling 200 IFBA and no WABA is statistically identical to 200 IFBA and 24 WABA). Moderator temperature at low burnups with increased enrichment demonstrates an unexpected decrease in reactivity with increased temperature, the cause of which will be presented in the final NUREG/CR. Axial profiles conservative for 5.0 wt% were bounding of 6.0 wt% fuel with hypothetical EE and HBU profiles from previous PWR analyses. End effects can be analyzed in a more detailed fashion once fuel management schemes are established for EE/HBU fuels.

ACKNOWLEDGMENTS

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