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Criticality Analysis of Assembly Misload in a PWR Burnup Credit Cask

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ABSTRACT

The Interim Staff Guidance on burnup credit (ISG-8) for spent fuel in storage and transportation casks, issued by the Nuclear Regulatory Commission's Spent Fuel Project Office, recommends a burnup measurement for each assembly to confirm the reactor record and compliance with the assembly burnup value used for loading acceptance. This recommendation is intended to prevent unauthorized loading (misloading) of assemblies due to inaccuracies in reactor burnup records and/or improper assembly identification, thereby ensuring that the appropriate subcritical margin is maintained. This report presents a computational criticality safety analysis of the consequences of misloading fuel assemblies in a high-capacity cask that relies on burnup credit for criticality safety. The purpose of this report is to provide a quantitative understanding of the effects of fuel misloading events on safety margins. A wide variety of fuel-misloading configurations are investigated and results are provided for informational purposes. This report does not address the likelihood of occurrence for any of the misload configurations considered. For representative, qualified burnup-enrichment combinations, with and without fission products included, misloading two assemblies that are underburned by 75% results in an increase in k_{eff} of 0.025−0.045, while misloading four assemblies that are underburned by 50% also results in an increase in k_{eff} of 0.025−0.045. For the cask and conditions considered, a reduction in burnup of 20% in all assemblies results in an increase in k_{eff} of less than 0.035. Misloading a single fresh assembly with 3, 4, or 5 wt% ^{235}U enrichment results in an increase in k_{eff} of ~0.02, 0.04, or 0.06, respectively. The report concludes with a summary of these and other important findings, as well as a discussion of relevant issues that should be considered when assessing the appropriate role of burnup measurements.

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ABBREVIATIONS

BAA	burnable absorbers assemblies
BPRs	burnable poison rods
GBC-32	generic 32 PWR-assembly
ISG-8	Interim Staff Guidance on burnup credit
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
SNF	spent nuclear fuel
WE	Westinghouse Electric

1 INTRODUCTION

The reduction in reactivity that occurs with fuel burnup is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. The concept of taking credit for the reduction in reactivity due to fuel burnup in a criticality safety evaluation is commonly referred to as *burnup credit*. The final product of a burnup-credit safety evaluation is a loading curve, which specifies loading criteria in terms of the minimum required assembly burnup as a function of initial assembly enrichment. A loading curve represents combinations of burnup and initial enrichment that correspond to a limiting value of the effective neutron multiplication factor (k_{eff}) for a given configuration (e.g., a cask). Assemblies with insufficient burnup, as compared with the loading curve, are not acceptable for loading.

The Nuclear Regulatory Commission (NRC) Spent Fuel Project Office has issued Interim Staff Guidance[1] on burnup credit (ISG-8) for pressurized water reactor (PWR) spent nuclear fuel (SNF) in dry storage and transportation casks. This guidance recommends a measurement of assembly burnup for each assembly to confirm the reactor record and the assembly burnup value used for loading acceptance. This recommendation is intended to prevent unauthorized loading (misloading) of assemblies due to inaccuracies in reactor burnup records and/or improper assembly identification, thereby ensuring that the appropriate subcritical margin is maintained. The purpose of this report is to provide a better understanding of the effects of fuel-misloading events on criticality safety margins, which could aid in assessing the appropriate role for burnup measurements.

Misloading of an underburned fuel assembly causes an increase in reactivity. The extent of the increase is dependent on several factors, but is dominated by the amount by which the actual assembly burnup is less than the minimum burnup value for loading acceptance and the position of the assembly. Using a full cask model of a relevant high-capacity cask design, burnup-credit analyses are presented to investigate the effect of misloading both underburned (burnup below the minimum burnup value for loading acceptance) and fresh fuel assemblies. The analysis considers two representative burnup points on cask loading curves developed with and without the principal fission products present and includes an investigation of (1) the effect of misloading conditions involving underburned fuel (burnup values that are 90, 80, 50, 25, 10, and 0% of the minimum value required by the loading curve); (2) the effect of misloading conditions involving fresh fuel (2, 3, 4, and 5 wt% ^{235}U); and (3) for each scenario, the effect of misloading multiple (1, 2, 3, and 4) assemblies. The investigation of misloading underburned fuel assemblies provides estimates of the effect of misloading events involving inaccurate reactor records for assembly burnup, while the investigation of misloading fresh fuel with different enrichment values provides estimates for worst-case misloading events, potentially due to improper assembly identification. However, quantification of the probability of such misloading events is beyond the scope of this report.

Note that the analyses presented in this report may not be applicable to high-leakage cask designs like truck casks. Also, misloading events involving assemblies with more reactive axial burnup profiles than assumed in the safety analysis are not addressed in this study, but have been considered elsewhere.[2] The potential impact of such misloading events may be mitigated by careful selection of bounding axial burnup profiles for the safety analysis.

2 EFFECT OF MISLOAD ON REACTIVITY

2.1 COMPUTATIONAL METHODS AND MODELS

The computational methods necessary for this analysis include codes for depletion and criticality simulation. The recently developed STARBUCS sequence,[3] which automates burnup-credit analyses by coupling depletion and criticality modules of SCALE,[4] was used for this analysis. In particular, STARBUCS couples the following SCALE code modules to achieve the automation: ARP, ORIGEN-S, CSASI, WAX, and KENO. The ARP code prepares cross sections for each burnup step based on interpolation for fuel enrichment and midcycle burnup from a user-supplied ARP library that contains problem-dependent cross sections. For this analysis, problem-specific ARP libraries were generated with the SAS2H sequence of SCALE. All SAS2H calculations utilized the SCALE 44-group (ENDF/B-V) library. The depletion calculations were performed using the operational parameters summarized in Table 1, which result in a conservative prediction of k_{eff} (i.e., k_{eff} is overestimated with respect to typical SNF parameters). The sensitivity of k_{eff} to variations in these parameters is discussed in Refs. 5 and 6.

Table 1 Summary of parameters used for the depletion calculations

Parameter	Value/Representation
Fuel temperature (K)	1100
Moderator temperature (K)	610
Clad temperature (K)	620
Power density (MW/MTU)	60
Moderator boron concentration (ppm)	1000
Burnable poison rods (BPRs)	Maximum number (24) of Westinghouse Electric (WE) burnable absorbers assemblies (BAA) rods present during the entire depletion.*

* J. C. Wagner and C. V. Parks, *Parametric Study of the Effect of Burnable Poison Rods for PWR Burnup Credit*, NUREG/CR-6761 (ORNL/TM-2000/373), U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, March 2002.

Using an ARP-generated cross-section library, ORIGEN-S performs the depletion calculations to generate fuel compositions for the burnup and decay time associated with each axial fuel region. Subsequently, the CSASI module is called to automate resonance self-shielding and prepare macroscopic fuel cross sections for each axial region. Finally, the STARBUCS module executes the three-dimensional (3-D) KENO V.a Monte Carlo criticality code using the generated axially varying macroscopic cross-section library. To ensure proper convergence and reduce statistical uncertainty, the KENO V.a calculations simulated 1100 generations, with 2000 neutron histories per generation, and skipped the first 100 generations before averaging; thus, each calculated k_{eff} value is based on 2 million neutron histories. The criticality calculations utilized the SCALE 238-group cross-section library, which is primarily based on ENDF/B-V data.

The determination of burnup-enrichment combinations for a burnup-credit loading curve requires a series of depletion and criticality (STARBUCS) calculations associated with an iterative search and/or interpolation. This process is automated via an iterative search capability[7] that allows repeated STARBUCS calculations to be performed, using a least-squares analysis of the results to automatically adjust enrichment until a desired k_{eff} value is obtained within a desired tolerance for a user-supplied series of burnup steps. For this work, loading curves were generated for a target k_{eff} value of 0.940 and a convergence criterion of ±0.002. Thus, the loading curves shown in this report correspond to k_{eff} = 0.940 with a tolerance band of ±0.002. Selected burnup-enrichment combinations from the loading curves were used as reference conditions for the investigation of assembly misloading events.

A generic 32 PWR-assembly (GBC-32) cask[8] was used for this analysis. The GBC-32 design was previously developed to provide a reference cask configuration that is representative of typical high-capacity rail casks being considered by industry, and thus is considered to be a relevant and appropriate configuration for the analyses presented in this report. The boron loading in the Boral panels in the GBC-32 cask model is 0.0225 g $^{10}B/cm^2$. Detailed specifications for the GBC-32 cask are provided in Ref. 8. In all cases considered for this analysis, the GBC-32 cask is assumed to be fully flooded with full-density water.

The reference fuel design used in the GBC-32 cask is the WE 17 × 17 fuel assembly; dimensional specifications are available in Ref. 8. With the exception of the misloaded assemblies for the various misloading configurations considered, all of the assemblies in the cask model are the same (i.e., the same initial enrichment, burnup, and cooling time). For all assemblies in all cases, WE 17 × 17 fuel and a cooling period of 5 years are assumed. Cross-sectional views of the reference computational model (i.e., without any misloaded assemblies present), as generated by KENO V.a, are shown in Figures 1 and 2. Consistent with the specification in Ref. 8, the model represents the active fuel length as 18 equally spaced axial regions to enable representation of the variation in axial composition due to burnup. Although the axial burnup profile is known to be dependent on total accumulated burnup, a single axial burnup profile was used throughout this analysis. The bounding axial burnup suggested in Ref. 9 for PWR fuel with assembly-averaged discharge burnup greater than 30 GWd/MTU was used throughout this study. Because the effect of horizontal variations in burnup has been shown to be small, and thus is not expected to influence the findings of this study, uniform horizontal burnup was assumed.

As mentioned, misloading of an underburned fuel assembly causes an increase in reactivity. The exact magnitude of the increase may be dependent on several factors, including cask design, assembly design, assembly irradiation conditions, post-irradiation cooling time, assembly enrichment, assembly burnup, and assembly position within the cask. However, the magnitude of the increase is dominated by the amount by which the actual assembly burnup is less than the minimum burnup value for loading acceptance and the position of the assembly within the cask. Therefore, a variety of cases involving misloading of underburned assemblies, including cases involving misloading of assemblies with no burnup (i.e., with fresh fuel), are considered. For all cases involving misloading, the misloaded assemblies are assumed to be in the central position(s) to provide a bounding estimate of the effect. Figure 3 illustrates the misloaded assembly positions within the GBC-32 cask that were assumed for this analysis. To evaluate the potential dependency on the nuclides included in the criticality analysis, separate calculations were performed with the following sets of nuclides: (1) the principal actinides and (2) the principal actinides and fission products. The actinide and fission product nuclides considered are listed in Table 1 and are consistent with those identified in Ref. 10 as being the most important for criticality calculations. For all other potentially dependent factors, representative conditions were assumed (i.e., a representative high-capacity cask design, representative burnup credit depletion conditions, representative fuel assembly specifications, and a 5-year cooling time).

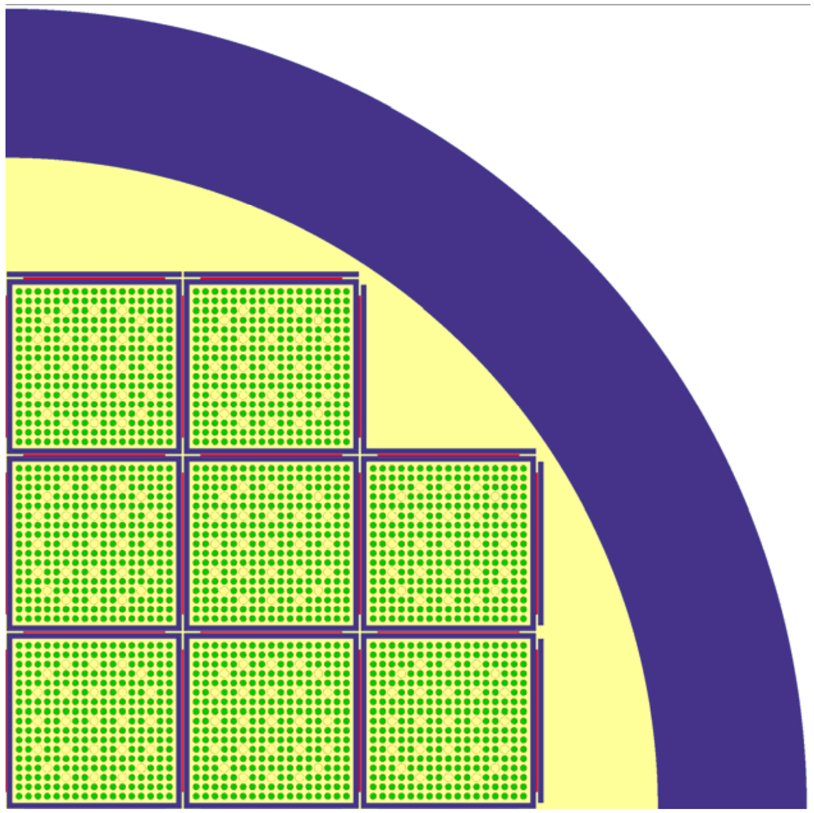


Figure 1. Radial cross section of one quarter of the KENO V.a model of the GBC-32 cask.

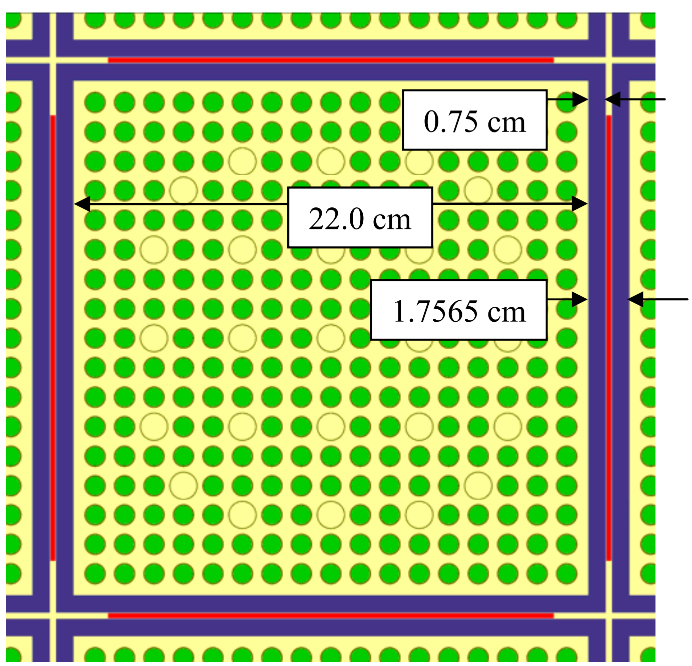
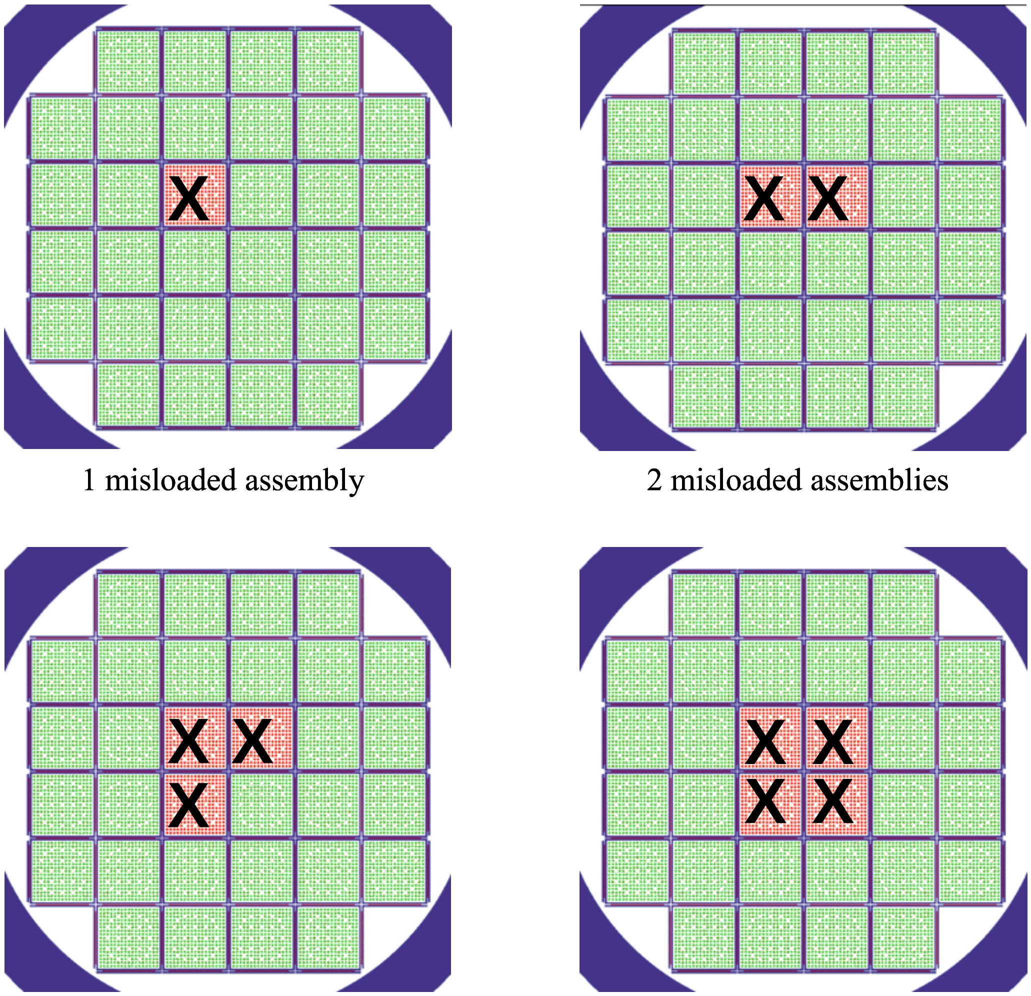


Figure 2. Cross-sectional view of assembly cell in KENO V.a model of the GBC-32 cask.



1 misloaded assembly | 2 misloaded assemblies | 3 misloaded assemblies | 4 misloaded assemblies

Figure 3. Illustration of the misloaded assembly positions (indicated by an "X") within the GBC-32 cask that were assumed for this analysis.

Table 2 Nuclide sets used for the analysis

Set 1: Principal actinides (10 total)									
U-234	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	O†
Set 2: Principal actinides and fission products (29 total)									
U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Am-243	Np-237	Mo-95	Tc-99	Ru-101	Rh-103	Ag-109	Cs-133	Sm-147	Sm-149
Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151	Eu-153	Gd-155	O†	

†Oxygen is neither an actinide nor a fission product, but is included in this list because it is an integral part of the fuel, and hence included in the calculations.

2.2 ANALYSIS AND RESULTS

The computational methods and models described in the previous subsection were used to quantify the effect of misloading on k_{eff}, and the analyses are presented in this subsection. The analysis considers two representative burnup points from cask loading curves based on the principal actinides with and without the principal fission products present, and includes an investigation of the effect of misloading conditions involving (1) underburned fuel (burnup values that are 90, 80, 50, 25, 10, and 0% of the minimum value required by the loading curve); (2) fresh fuel (2, 3, 4, and 5 wt% ^{235}U); and (3) multiple (1, 2, 3, and 4) assemblies.

The investigation of misloading underburned assemblies provides estimates of the effect of misloading events involving inaccurate reactor records for assembly burnup, while the investigation of misloading fresh fuel with different enrichment values provides estimates for worst-case misloading events, potentially due to improper assembly identification. Although no attempt is made herein to quantify the probability of such misloading events,[11] others have estimated that the probability of a single misloading can be as high as 10^{-3} and as low as 10^{-5} for a large cask. If it is valid to assume that multiple misloading events in a single cask are statistically independent, the probability of misloading *n* assemblies can be estimated by raising the probability of a single misloading to the power *n*.

The first step in this analysis was to determine fuel burnup and enrichment combinations that (1) yield a k_{eff} value consistent with regulatory recommendations[12,13] for a criticality safety evaluation and (2) are representative of discharged SNF. Based on a review of SNF discharge data,[14] burnup values of 30 and 45 GWd/MTU were selected for consideration. Subsequently, loading curves were generated for each of the two nuclide sets considered (see Table 2) to determine the corresponding enrichment values. The loading curves, which correspond to k_{eff} = 0.940 ± 0.002, are shown in Figure 4. The burnup-enrichment combinations used as reference conditions for investigating the potential effects of assembly misloading events are taken directly from the loading curves in Figure 4 and are listed in Table 3.

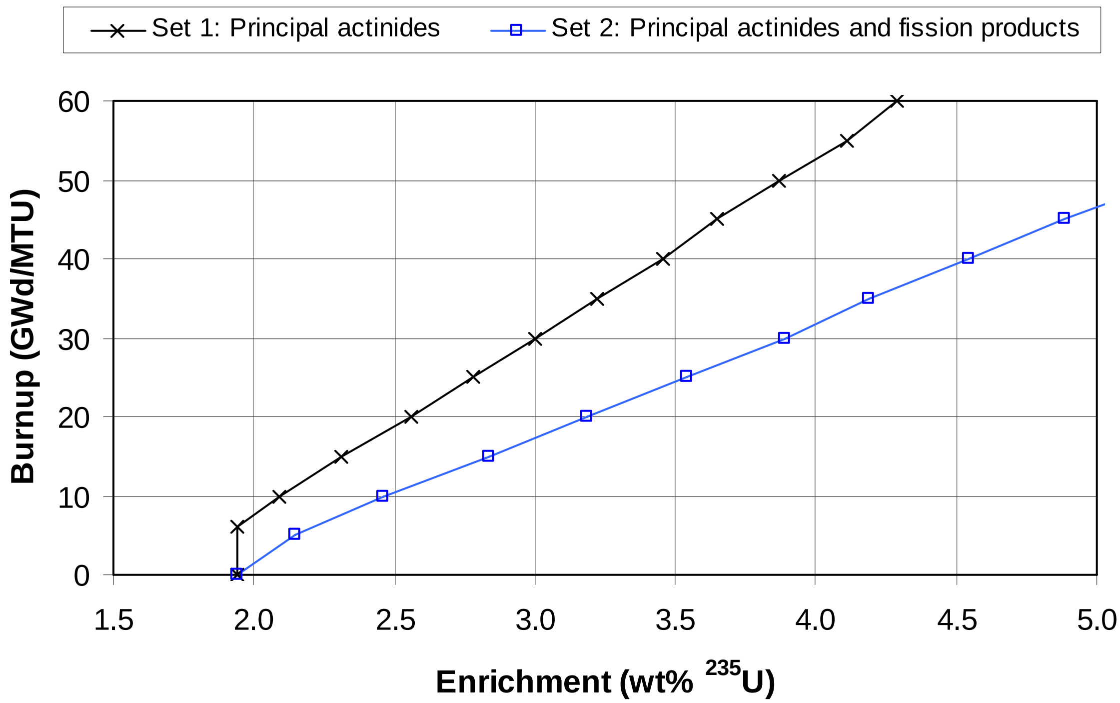


Figure 4. Loading curves for the two sets of nuclides considered.

Table 3 Reference burnup and enrichment combinations† used for evaluating the effects of assembly misloading events

Burnup (GWd/MTU)	Enrichment (wt% ^{235}U)	
	Set 1: Principal actinides	Set 2: Principal actinides and fission products
30	3.00	3.88
45	3.66	4.89

†The reference burnup and enrichment combinations correspond to a k_{eff} value of 0.940 ± 0.002 in the GBC-32 cask for the conditions described in Section 2.1.

2.2.1 Misloading Conditions Involving Underburned Fuel

To investigate the effect of misloading conditions involving underburned fuel, calculations were performed for misloads of 1−4 assemblies with burnup values that are 90, 80, 50, 25, 10, and 0% (fresh) of the minimum value required by the loading curve. The underburned assemblies that actually have some burnup were modeled with axially varying burnup. However, axially varying burnup is not applicable to assemblies without burnup, and hence, the fuel compositions are axially uniform for those cases. The large variation in burnup values and the number of misloaded assemblies is analyzed for informational purposes; a judgment has not been made as to whether the conditions considered here represent credible misloading events. The credibility of such events must be determined elsewhere.

Using the principal actinides (Set 1 nuclides from Table 2) and the corresponding reference burnup-enrichment combinations from Table 3, the effects of misloading assemblies with burnup values below the value required by the loading curve are shown in Figure 5. The results are presented in terms of the difference in k_{eff} values (Δk) between a given case involving fuel misloading and the reference conditions (without fuel misloading). For the same conditions, the results are plotted as a function of the burnup reduction in Figure 6 to enable estimates of the effect for other underburned values.

For a given percentage of the required burnup value (e.g., 50%), the effect is larger for the burnup-enrichment combination with higher burnup (i.e., the case for 45 GWd/MTU) because the actual burnup reduction is larger (in terms of GWd/MTU) and the initial enrichment is higher. For the two burnup-enrichment combinations considered, misloading one assembly with 0% of the required burnup (fresh) results in an increase in k_{eff} of 0.02−0.035. Misloading two assemblies that are underburned by 75% results in an increase in k_{eff} of 0.02−0.035. Likewise, misloading four assemblies that are underburned by 50% also results in an increase in k_{eff} of 0.025–0.035. Note that the conditions considered here involve the misloaded assemblies placed in the most reactive (central) positions within the cask (see Figure 3).

To investigate the effect of including the principal fission products, the above calculations were repeated using the principal actinides and fission products (Set 2 nuclides from Table 2) and the corresponding reference burnup-enrichment combinations from Table 3. The results are shown in Figures 7 and 8. Because the reactivity reduction due to burnup is increased with the inclusion of the principal fission products, the impact of burnup reductions is also larger, as compared to the cases without fission products present. For example, misloading one assembly with 0% of the required burnup (fresh) results in an increase in k_{eff} of 0.035–0.055, as compared to 0.02–0.035 for the actinide-only case. Misloading two assemblies underburned by 75% or four assemblies underburned by 50% results in an increase in k_{eff} of 0.035–0.045. For higher burnup values, which correspond to higher enrichment values, the increase in k_{eff} will be larger.

Finally, to evaluate the effect of a systematic, non-conservative error in burnup for all assemblies, calculations were performed for various burnup reductions in all 32 assemblies. The results plotted in Figure 9 quantify the increase in k_{eff} as a function of the percentage of the required minimum burnup. A notable conclusion from this figure is that for all variations considered, a reduction in burnup of 20% in all assemblies results in an increase in k_{eff} of less than 0.035.

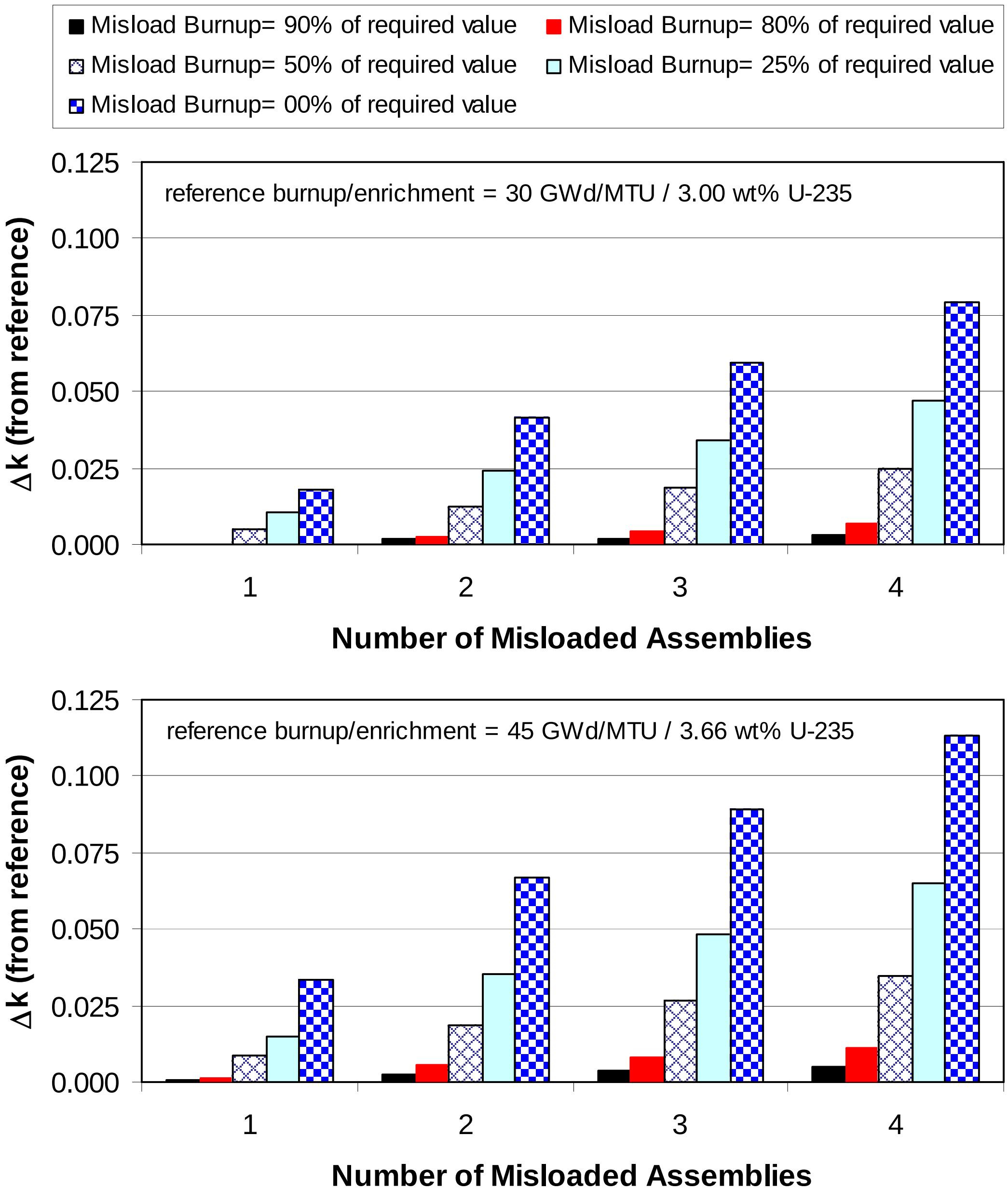


Figure 5. Δk effect as a function of the number of misloaded assemblies for various cases involving underburned fuel, using the Set 1 nuclides.

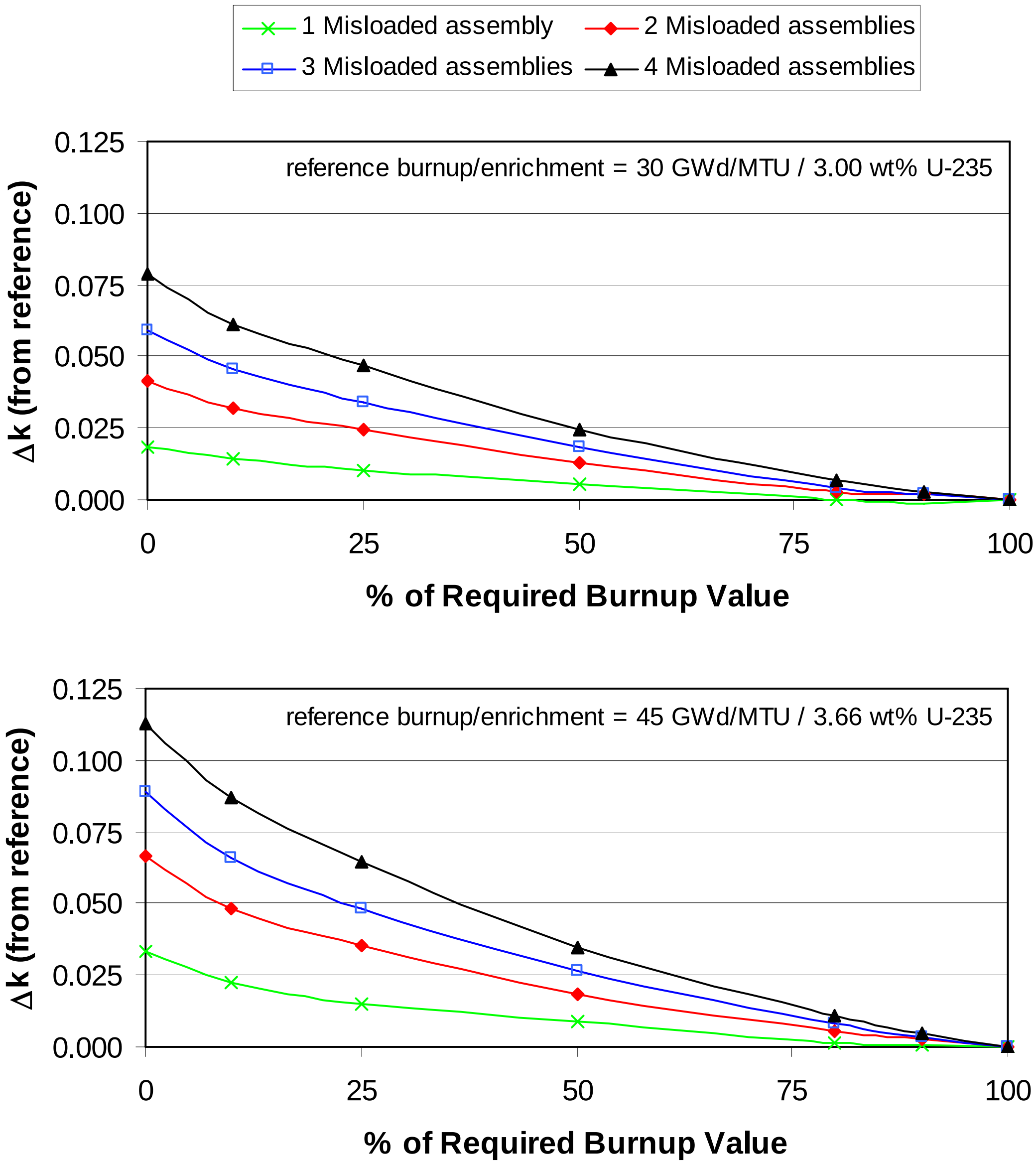


Figure 6. Δk effect as a function of the percentage of required burnup for cases involving 1–4 misloaded assemblies, using the Set 1 nuclides.

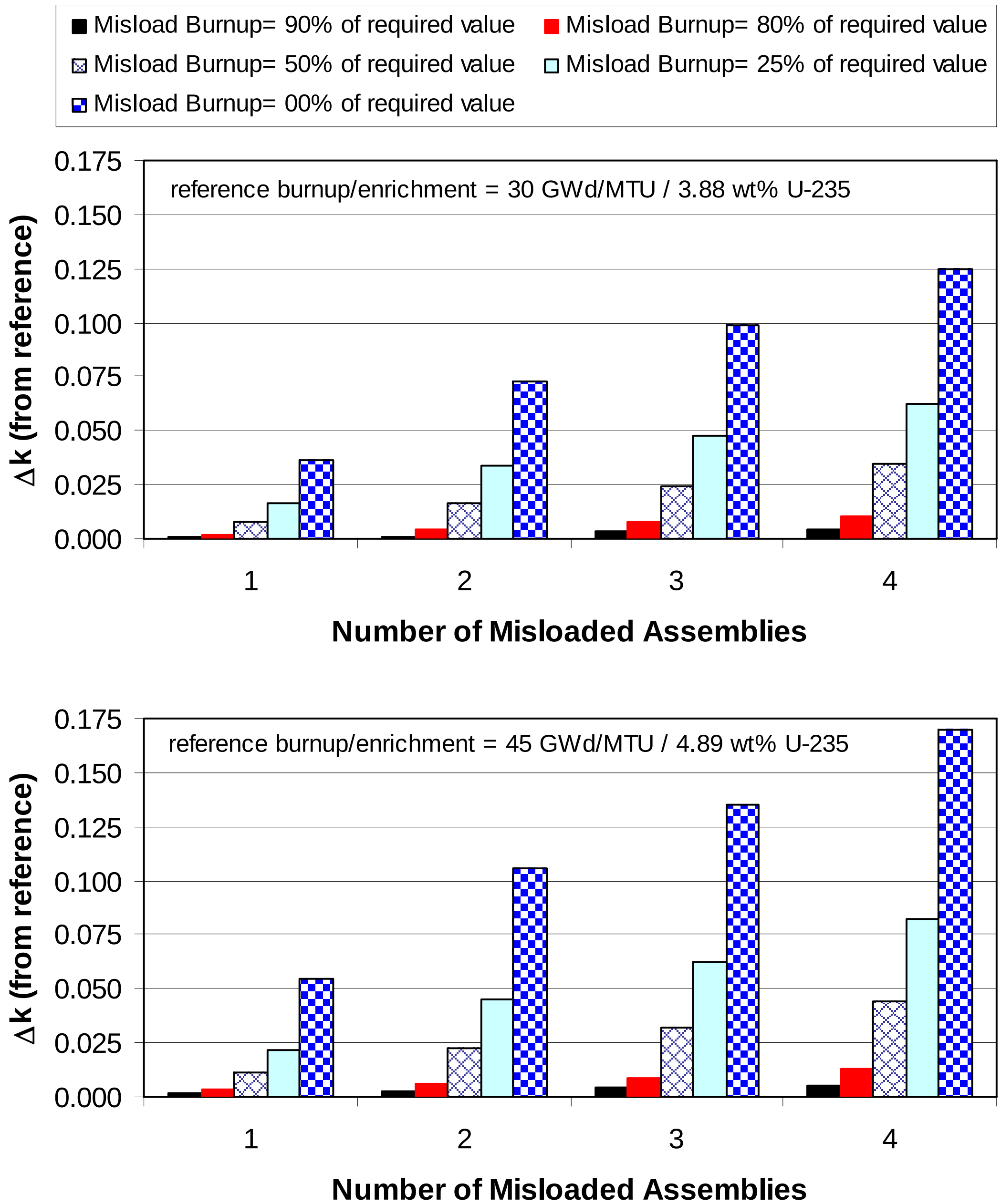


Figure 7. Δk effect as a function of the number of misloaded assemblies for various cases involving underburned fuel, using the Set 2 nuclides.

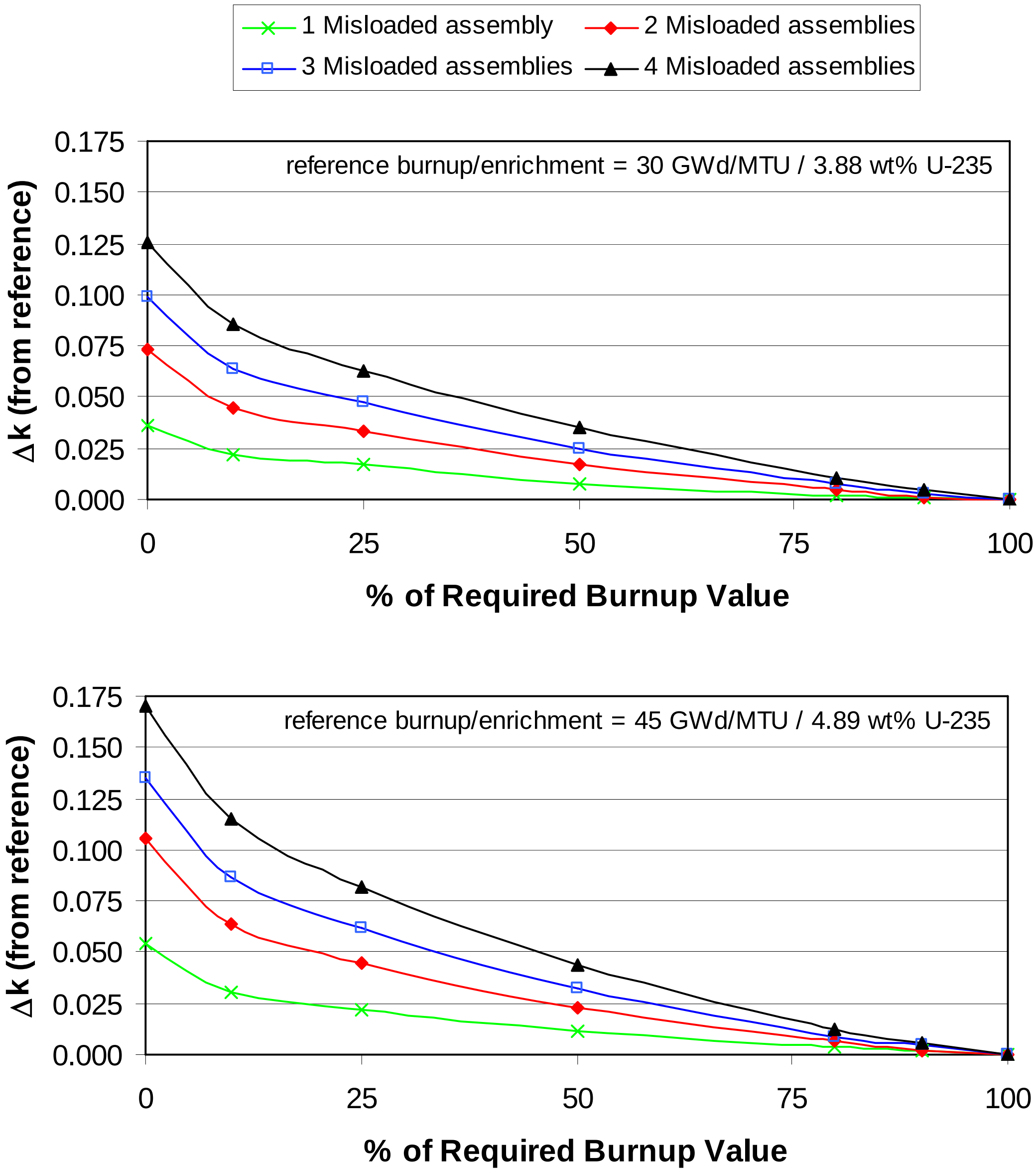


Figure 8. Δk effect as a function of the percentage of required burnup for cases involving 1–4 misloaded assemblies, using the Set 2 nuclides.

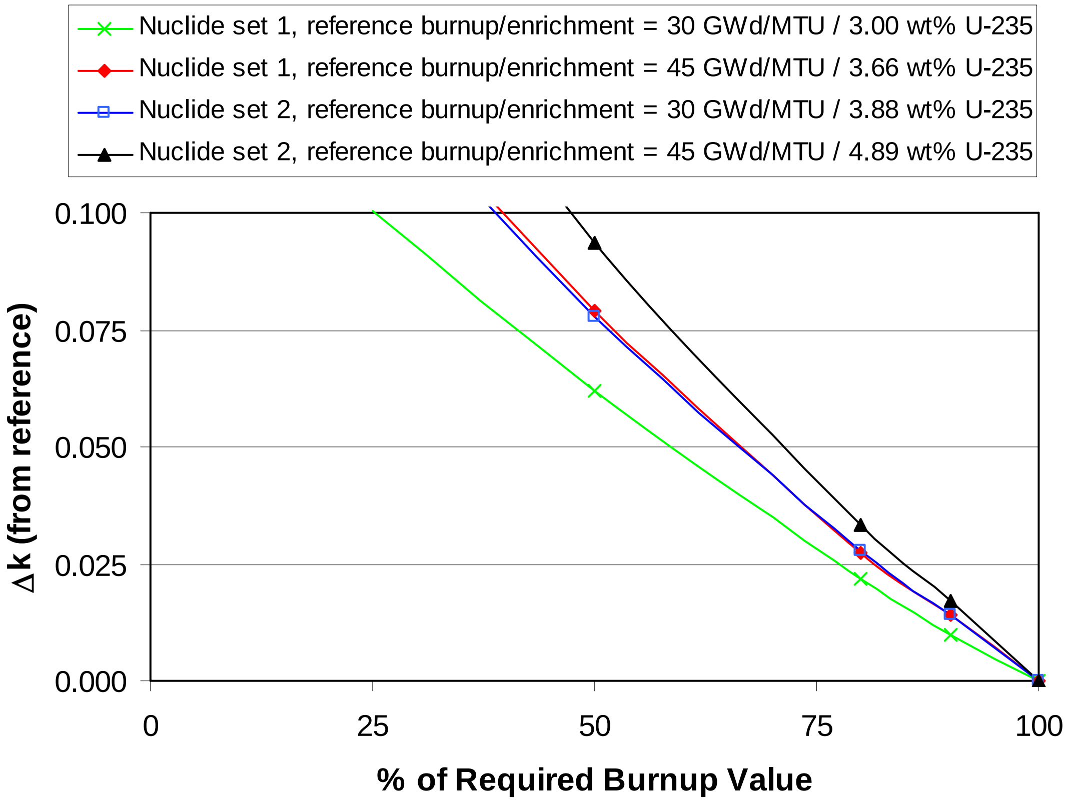


Figure 9. Δk effect as a function of the percentage of required burnup for cases involving a systematic error in burnup for all 32 assemblies.

2.2.2 Misloading Conditions Involving Fresh Fuel

To investigate the effect of misloading conditions involving fresh fuel assemblies, calculations were performed for misloads of 1–4 assemblies with enrichments between 2.0 and 5.0 wt% ^{235}U. The large variation in enrichment values and the number of misloaded assemblies were analyzed for informational purposes; one should not infer that the conditions considered here were assessed for their probability of occurrence. The credibility of such events must be determined elsewhere.

Using the principal actinides (Set 1 nuclides from Table 2) and the corresponding reference burnup-enrichment combinations from Table 3, the effects of misloading fresh fuel assemblies are shown in Figure 10. For the same conditions, the results are plotted as a function of fuel enrichment in Figure 11 to enable estimates of the effect on k_{eff} as a function of enrichment and the number of misloaded assemblies.

For the cases considered, the effects of misloading fresh fuel assemblies are not highly dependent on the burnup-enrichment combination, as each burnup-enrichment combination corresponds to the same value of k_{eff} and the misloaded fresh fuel assemblies are not dependent on the reference burnup-enrichment combination. The results indicate that misloading a single fresh assembly with 3, 4, or 5 wt% ^{235}U enrichment results in an increase in k_{eff} of ~0.02, 0.04, or 0.06, respectively. Misloading two fresh assemblies with 5 wt% ^{235}U enrichment results in an increase in k_{eff} of more than 0.10.

To investigate the effect of including the principal fission products, the above calculations were repeated using the principal actinides and fission products (Set 2 nuclides from Table 2) and the corresponding reference burnup-enrichment combinations from Table 3. The results are shown in Figures 12 and 13. Because the burnup-enrichment combinations correspond to the same value of k_{eff} and the misloaded fresh fuel assemblies are not dependent on the reference burnup-enrichment combination or the nuclides included in the spent fuel compositions, the results with the fission products present are nearly identical to the actinide-only results (i.e., the results are not dependent upon the presence of the fission products).

This analysis assumes that the misloaded assemblies are placed in the most reactive (central) positions within the cask (see Figure 3). The effect of misloading a single fresh assembly with 5 wt% ^{235}U enrichment in different locations within the GBC-32 cask is shown graphically in Figure 14. Although the results shown correspond to the reference actinide-only, burnup-enrichment combination of 45 GWd/MTU and 3.66 wt% ^{235}U, the Δk results were found to be insensitive to the burnup-enrichment combination considered or the presence of the principal fission products. Hence, the results in Figure 14 are representative of the other cases considered.

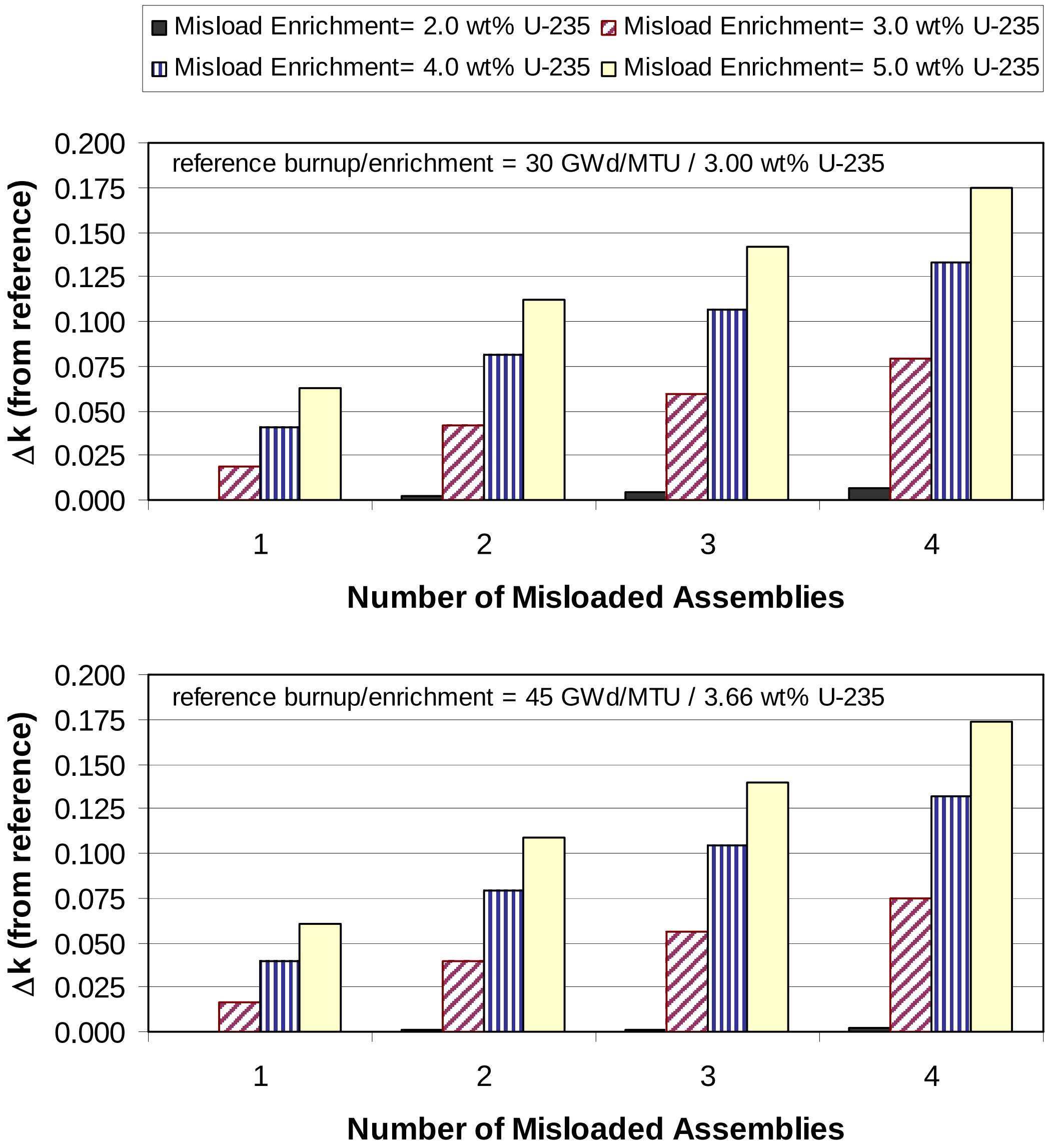


Figure 10. Δk effect as a function of the number of misloaded assemblies for various cases involving fresh fuel, using the Set 1 nuclides.

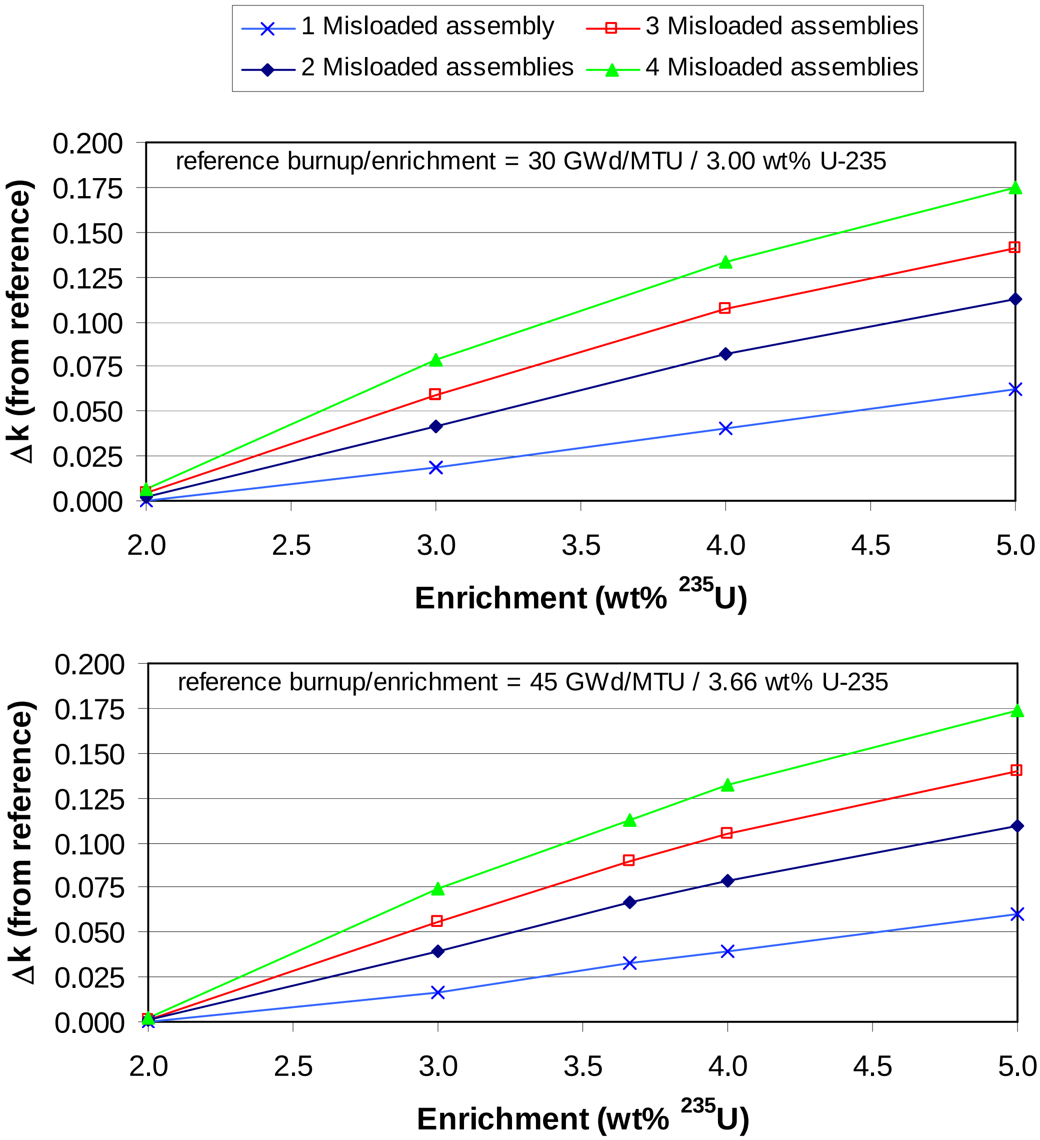


Figure 11. Δk effect as a function of enrichment for cases involving 1–4 misloaded fresh fuel assemblies, using the Set 1 nuclides.

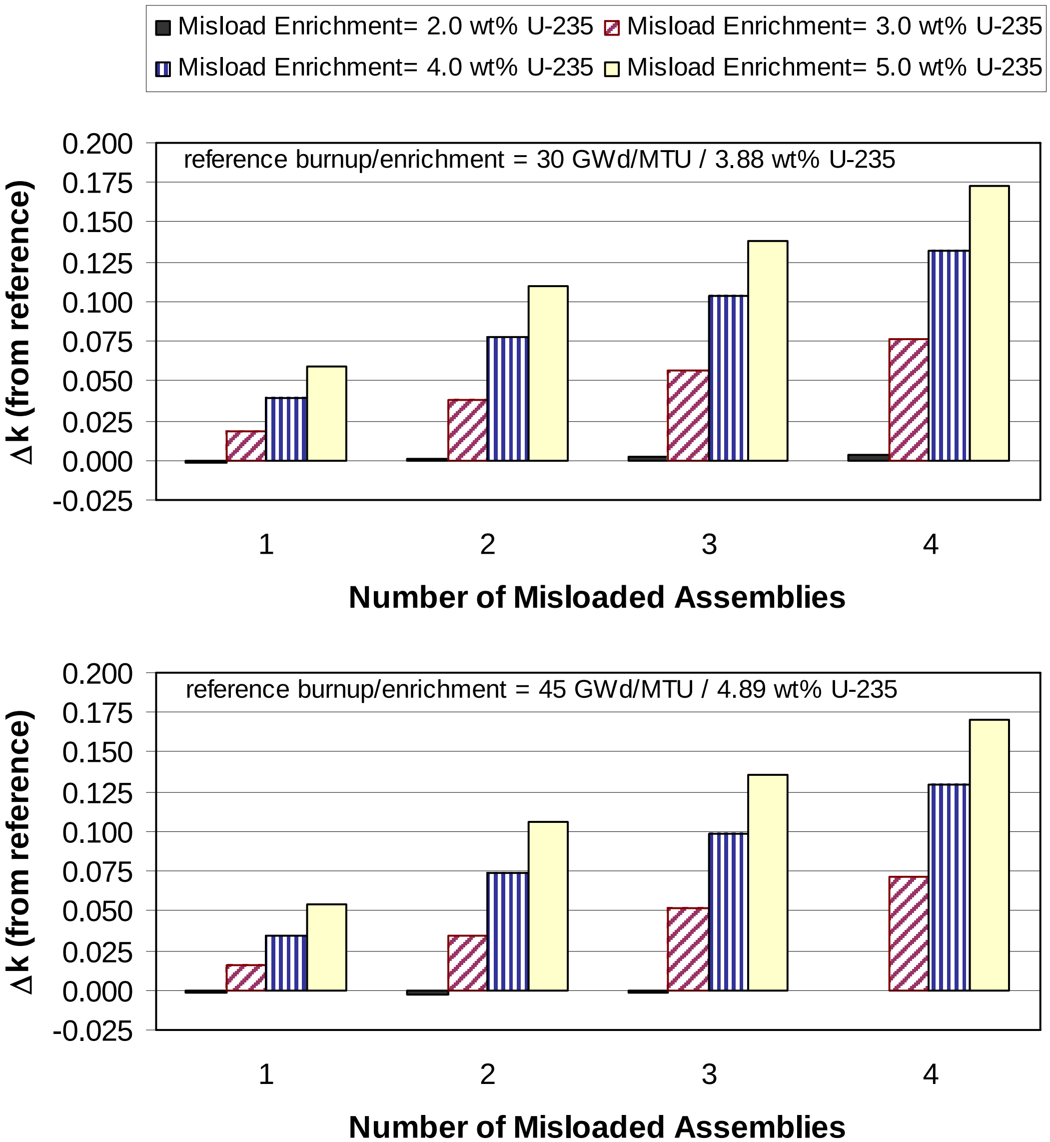


Figure 12. Δk effect as a function of the number of misloaded assemblies for various cases involving fresh fuel, using the Set 2 nuclides.

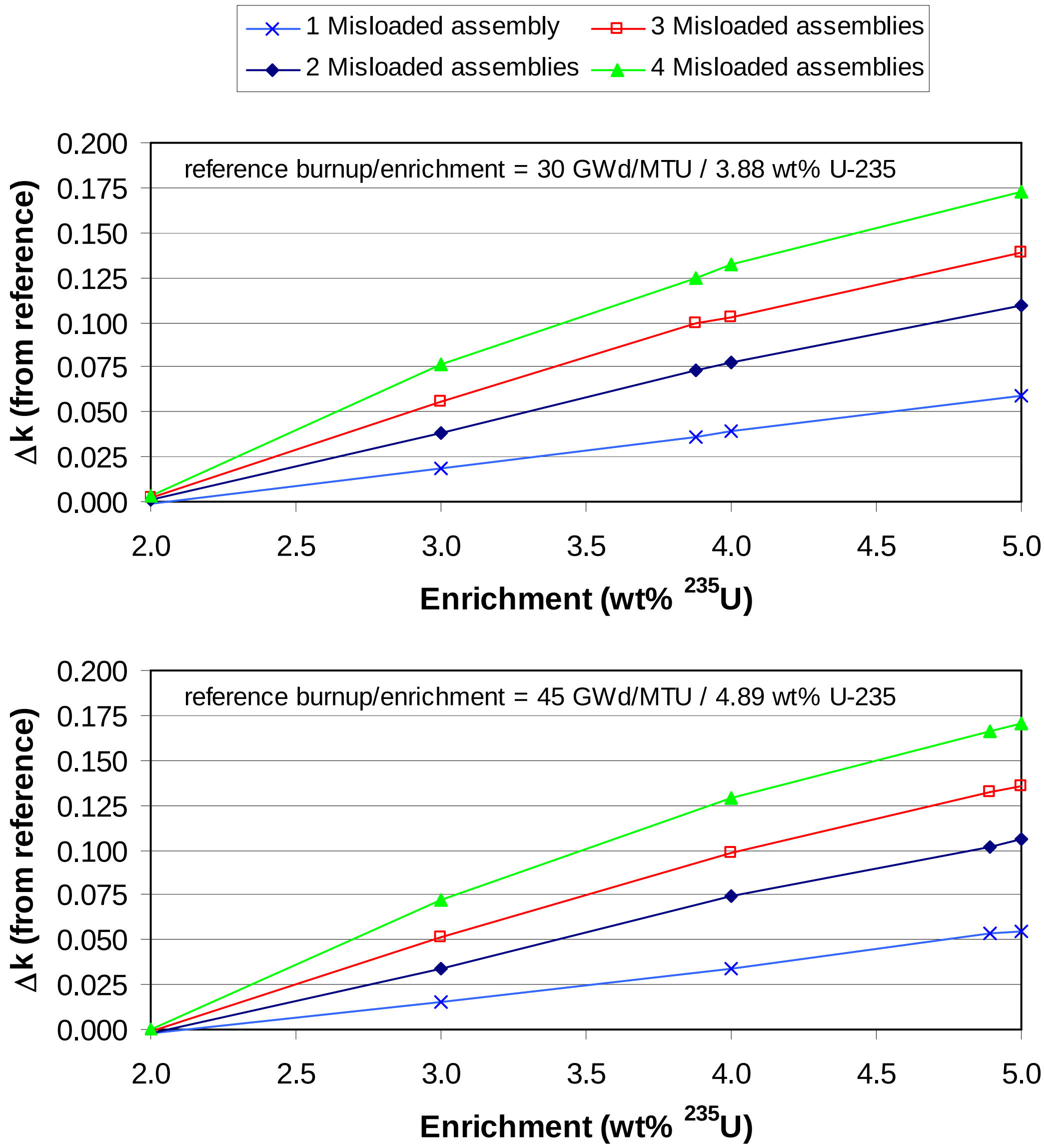


Figure 13. Δk effect as a function of enrichment for cases involving 1–4 misloaded fresh fuel assemblies, using the Set 2 nuclides.

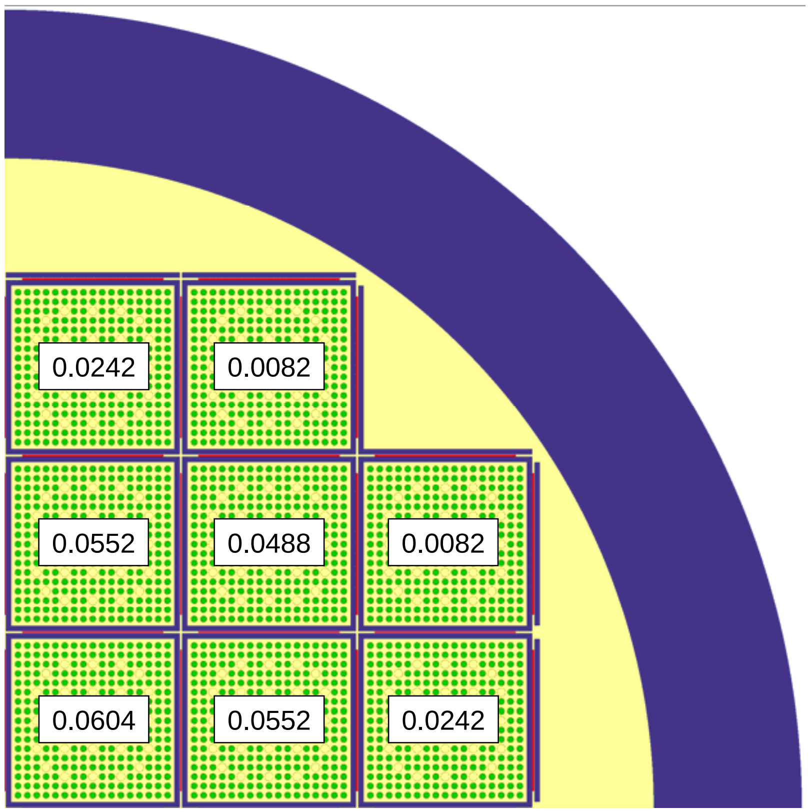


Figure 14. Δk effect of misloading a single fresh assembly with 5 wt% ^{235}U enrichment in different locations within the GBC-32 cask. The results correspond to the burnup-enrichment combination of 45 GWd/MTU and 3.66 wt% ^{235}U and the Set 1 nuclides.

3 DISCUSSION AND CONCLUSIONS

The analysis presented in the previous section investigated the effect of a wide variety of misloading conditions for a high-capacity cask that relies on burnup credit for criticality safety. In particular, the increases in k_{eff} and associated consequences to the subcritical safety margin were quantified for misloading events involving underburned and fresh fuel assemblies. The analyses are based on a high-capacity rail-type cask, and hence may not be applicable to high-leakage cask designs (e.g., truck casks). Also, misloading events involving assemblies with more reactive axial burnup profiles than assumed in the safety analysis were not addressed in this study, but have been considered elsewhere.

For representative, qualified burnup-enrichment combinations and actinide-only burnup credit analysis assumptions, it was found that misloading one assembly with 0% of the required burnup (fresh) results in an increase in k_{eff} of 0.02–0.035 over the range of burnup values considered. Likewise, misloading two assemblies that are underburned by 75% results in an increase in k_{eff} of 0.025–0.035, while misloading four assemblies that are underburned by 50% also results in an increase in k_{eff} of 0.025–0.035. Because the reactivity reduction due to burnup is increased with the inclusion of fission products, the impact of underburned fuel is also larger, as compared with corresponding cases without fission products present. Consequently, misloading one assembly with 0% of the required burnup (fresh) results in an increase in k_{eff} of 0.035-0.055, as compared with 0.02–0.035 for the actinide-only case. Misloading two assemblies underburned by 75% or four assemblies underburned by 50% results in an increase in k_{eff} of 0.035–0.045. For all cases considered, four simultaneous misloads involving 20% reduced burnup result in a maximum increase in k_{eff} of 0.0125. Another notable observation is that for the cask and conditions considered, a reduction in burnup of 20% in all assemblies results in an increase in k_{eff} of less than 0.035.

For misload conditions involving fresh fuel assemblies, the results indicate that misloading a single fresh assembly with 3, 4, or 5 wt% ^{235}U enrichment results in an increase in k_{eff} of ~2, 4, or 6%, respectively. Notably, a single fresh fuel assembly with 5.0 wt% ^{235}U enrichment loaded into the cask center will result in an increase in k_{eff} of more than 0.05, while misloading two fresh 5 wt% ^{235}U assemblies results in an increase in k_{eff} of more than 0.10. Because the burnup-enrichment combinations correspond to the same value of k_{eff} and the misloaded fresh fuel assemblies are not dependent on the reference burnup-enrichment combination or the nuclides included in the spent fuel compositions, these results were not dependent upon the presence of fission products. Throughout this analysis the misloaded assemblies were placed in the most reactive (central) positions within the cask (see Figure 3). Therefore, the impact of misloading assemblies into noncentral positions (e.g., nearer to the radial cask periphery) is bounded by the cases considered herein.

The results of this study could be used in a larger process to assess the role of burnup measurements in loading operations for high-capacity casks that rely on burnup credit for criticality safety. Such a process would likely also consider a number of other relevant factors, such as the accuracy of reactor assembly burnup data, the probability of various misloading events, the available understanding of the physics and operational process, the subcritical margin needed to assure safety, and the number and probability of concurrent events required to reach an unsafe condition. Information on the accuracy of utility spent fuel burnup records for a Westinghouse PWR is available in Ref. 15. Also note that for actinide-only burnup credit, consistent with ISG-8, there is an inherent but unquantified additional margin of safety due to the presence of fission products.

A number of principles and practices for addressing abnormal and/or unlikely events in the implementation of criticality safety for other applications may have relevance to this situation. The applicability of such principles and practices to the fuel misloading events should be reviewed.

4 RECOMMENDATIONS

This report provides the changes in k_{eff} that can result from a wide variety of postulated fuel misloading events in a high-capacity burnup credit rail cask. This quantitative information will help in understanding the impact of such events on the subcritical margin and aid in assessing the appropriate role for burnup measurements in assuring safety.

Ensuing activities seeking to assess the appropriate role of burnup measurements should consider the following factors:

- estimates of misloading probabilities and characteristics;
- the effect of misloading events on the subcritical margin (i.e., results of this investigation);
- the subcritical margin needed to assure safety;
- available understanding of the physics and the operation process;
- the accuracy of reactor records for assembly burnup; and
- relevant criticality safety practices and principles.

Assessing the role of burnup measurements for all types of burnup credit casks (e.g., truck casks) will require additional studies such as that presented here.

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