Evaluation of Burnup Credit for Accommodating PWR Spent Nuclear Fuel in High-capacity Cask Designs

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This paper presents an evaluation of the amount of burnup credit needed for high-density casks to transport the current U.S. inventory of commercial spent nuclear fuel (SNF) assemblies. A prototypic 32-assembly cask and the current regulatory guidance were used as bases for this evaluation. By comparing actual pressurized-water-reactor (PWR) discharge data (i.e., fuel burnup and initial enrichment specifications for fuel assemblies discharged from U.S. PWRs) with actinide-only-based loading curves, this evaluation finds that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of SNF assemblies in high-capacity storage and transportation casks. The impact of varying selected calculational assumptions is also investigated, and considerable improvement in effectiveness is shown with the inclusion of the principal fission products (FPs) and minor actinides and the use of a bounding best-estimate approach for isotopic validation. Given sufficient data for validation, the most significant component that would improve accuracy, and subsequently enhance the utilization of burnup credit, is the inclusion of FPs.

KEYWORDS: burnup credit, criticality safety, spent nuclear fuel, transportation

1. Introduction

Historically, criticality safety analyses for commercial light water reactor (LWR) spent fuel storage and transportation casks have assumed the spent fuel to be fresh (unirradiated) with uniform isotopic compositions corresponding to the maximum allowable enrichment. This *fresh-fuel assumption* provides a simple bounding approach to the criticality analysis and eliminates concerns related to the fuel operating history. However, because this assumption ignores the decrease in reactivity as a result of irradiation, it is very conservative and can result in a significant reduction in spent nuclear fuel (SNF) capacity for a given cask volume. Numerous publications have demonstrated that increases in SNF cask capacities from the use of burnup credit can enable a reduction in the number of casks and shipments, and thus have notable financial benefits while providing a risk-based approach to improving safety. The concept of taking credit for the reduction in reactivity due to irradiation of nuclear fuel (i.e., fuel burnup) is commonly referred to as *burnup credit*. 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 parasitic neutron-absorbing nuclides [non-fissile actinides and fission products (FPs)].

The utilization of credit for fuel burnup in an away-from-reactor criticality safety evaluation necessitates careful consideration of the fuel operating history, additional validation of calculational methods (for prediction and use of SNF isotopic compositions), consideration of new conditions and configurations for the licensing basis, and additional measures to ensure proper cask loading. For pressurized-water-reactor (PWR) fuel, each of these areas has been studied in some detail and considerable progress has been made in understanding the issues and developing approaches for a safety evaluation. Based on these studies, the U.S. Nuclear Regulatory Commission (NRC) issued Interim Staff Guidance 8 revision 1 (ISG-8r1) in July 1999.1) A discussion of the technical considerations that helped form the development of ISG-8 can be found in Ref. 2. Subsequently, ISG-8 revision 2 (ISG-8r2), which eliminated or lessened several of the limitations in ISG-8r1, was issued in September 2002.3)

The initial issuance and subsequent revisions of ISG-8 have provided the impetus for industry to proceed with a new generation of high-capacity cask designs using burnup credit. However, concerns have been raised that additional credit for fuel burnup, beyond that currently recommended in ISG-8, will be necessary to accommodate the majority of SNF assemblies in high-capacity (i.e., ≥ 32 assembly) casks.

This paper summarizes recent efforts4) to evaluate the use of burnup credit to accommodate SNF in high-capacity storage and transportation casks. The evaluation is based on comparisons of PWR discharge data (i.e., fuel burnup and initial enrichment specifications for fuel assemblies discharged from U.S. PWRs) with burnup-credit loading curves for the prototypical high-capacity GBC-32 cask5) and determinations of the percentage of assemblies that meet the loading criteria. Subsequently, variations in the principal analysis assumptions are considered to assess the potential for expanding the percentage of assemblies that may be accommodated in high-capacity casks.

Burnup-credit loading curves (see Figure 1) define assembly acceptability in terms of minimum required burnup as a function of initial assembly enrichment. Each burnup

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and enrichment combination on the loading curve corresponds to a limiting value of the effective neutron multiplication factor (k_{eff}) for a given configuration (e.g., a cask).

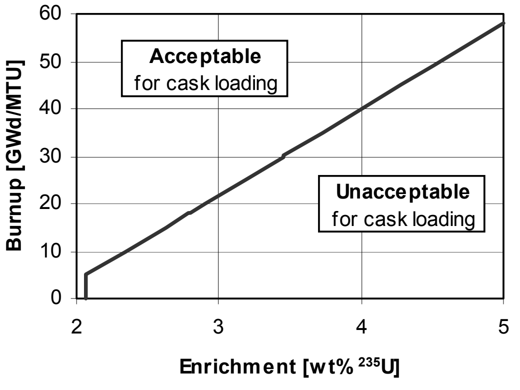


Fig.1 Illustrative burnup-credit loading curve. The vertical portion of the loading curve at low burnup corresponds to a region in which the reduction in reactivity due to burnup is smaller than the increase in reactivity associated with the conservatism in the burnup-credit evaluation. Hence, no credit is taken for burnup in this region.

2. Computational Methods

Burnup-credit analyses involve depletion calculations to determine the SNF isotopic compositions, extraction of SNF isotopic compositions from the depletion output for use in a criticality model, and a criticality calculation to determine the k_{eff} value. The recently developed STARBUCS sequence,[6] which automates burnup-credit analyses by coupling the depletion and criticality modules of SCALE,[7] 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 V.a. 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. The ORIGEN-ARP methodology offers a faster alternative to the SAS2H depletion analysis sequence in SCALE, while maintaining calculational accuracy.[8]

Using an ARP-generated cross-section library, ORIGEN-S performs the depletion calculations to generate fuel compositions for all unique fuel regions (e.g., different axial- and/or horizontal-burnup regions). The CSASI module is used to automate resonance self-shielding calculations and prepare macroscopic cross sections for each unique fuel region. Sequentially with CSASI, the WAX module is executed to append the cross sections into a single cross-section library. Finally, the STARBUCS module executes the three-dimensional (3-D) KENO V.a (or KENO-VI) Monte Carlo criticality code using the generated cross sections. 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 KENO V.a calculations utilized the SCALE 238-group cross-section library.

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[9] 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 0.94 and convergence criterion of ± 0.002. Thus, all loading curves shown in this paper correspond to $k_{eff} = 0.940 \pm 0.002$.

3. Burnup-Credit Analyses

In a separate effort related to burnup credit, a generic high-capacity (32-assembly) cask, designated GBC-32, was defined as a computational benchmark to provide a reference configuration for the estimation of reactivity margin available from FPs and minor actinides.[5] The GBC-32 cask is representative of burnup-credit casks currently being considered by U.S. industry and is therefore a relevant and appropriate configuration for this evaluation.

The regulatory guidance for burnup credit (ISG-8r2) recommends limiting the amount of burnup credit to that available from actinide compositions in SNF with an assembly-averaged burnup up to 50 GWd/MTU and cooled out-of-reactor for a time period between 1 and 40 years. The computational methodologies used for predicting the actinide compositions and determining the k_{eff} value are to be properly validated. Calculated isotopic predictions are typically validated against destructive chemical assay measurements from SNF samples, while criticality analysis methods are validated against applicable critical experiments. Thus, the nuclides in a safety analysis are limited primarily by the availability of measured/experimental data for validation. Regarding modeling assumptions, it is recommended that the applicant ensure that the actinide compositions used in analyzing the licensing safety basis are calculated using fuel design and in-reactor operating parameters selected to provide conservative estimates of the k_{eff} value under cask conditions. Furthermore, it is recommended that the calculation of the k_{eff} value be performed using cask models, appropriate analysis assumptions, and code inputs that allow adequate representation of the physics of the spent fuel cask environment.

Following the recommendations embodied in the regulatory guidance,[3] loading curves were generated for the GBC-32 cask for each of the following assembly types: Combustion Engineering (CE) 14 × 14, Babcock & Wilcox (B&W) 15 × 15, CE 16 × 16, and Westinghouse (WE) 17 × 17. Unless specifically stated otherwise, the following calculational assumptions were used:

- principal actinides only (i.e., ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am);

- conservative operating parameters for fuel temperature (1100 K), moderator temperature/density (610 K/ 0.63 g/cc), specific power (continuous operation at 60 MW/MTU), and soluble boron concentration (cycle-average value of 1000 ppm);[4)]
- burnup-dependent axial and horizontal burnup distributions suggested in Ref. 10;
- 5-year cooling time; and
- isotopic correction factors (ICFs), used to adjust predicted compositions for individual nuclides for bias and uncertainty (to a 95%/95% confidence level), as determined from comparisons of calculated and measured isotopic compositions from Ref. 11.

Because B&W and WE assemblies have used burnable poison rods (BPRs), those cases assumed BPR exposure for the first 20 GWd/MTU of burnup. The effect of fixed absorbers, including BPRs, on the reactivity of PWR SNF is discussed in Ref. 12. Additional calculational details are available in Ref. 4. The discharge data[13)] used for this evaluation corresponds to SNF assemblies discharged from U.S. PWRs through the end of 1998 (see Figure 2).

4. Results

The loading curves for the four assembly types are provided in Figure 3, and the acceptability of the SNF assemblies for each fuel type is summarized in Table 1. Consistent with the regulatory guidance, assemblies that require burnup > 50 GWd/MTU are classified as unacceptable. Also, the determination of acceptability does not account for burnup uncertainty, which would reduce the percentage of

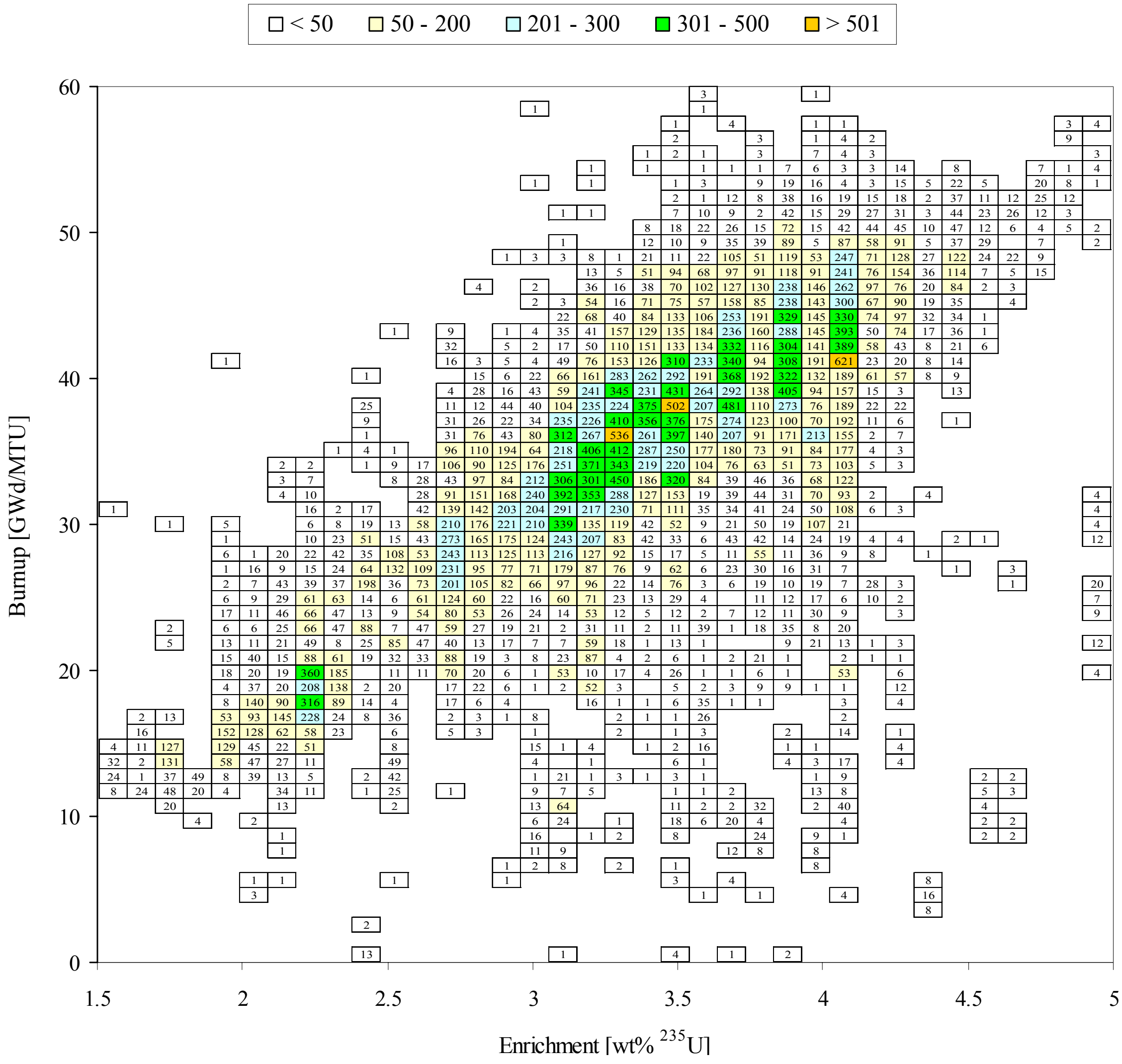
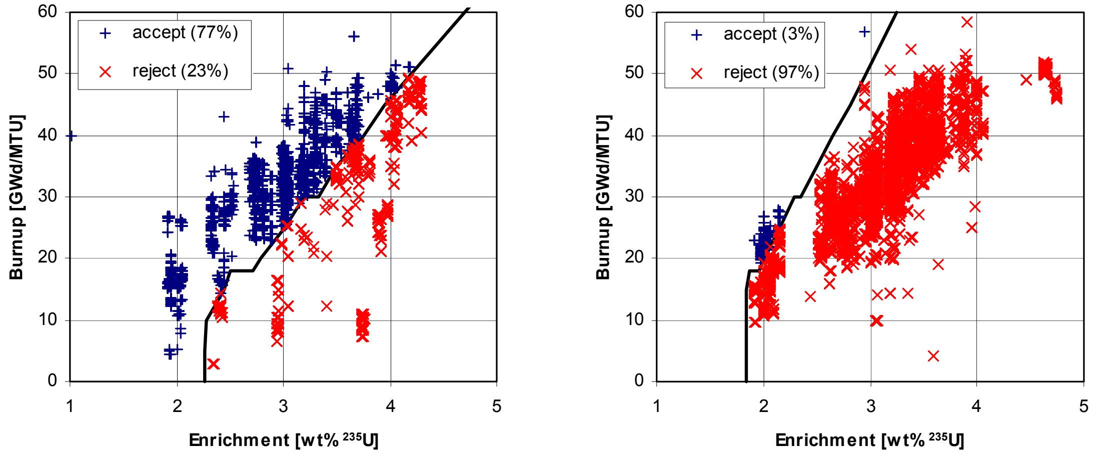
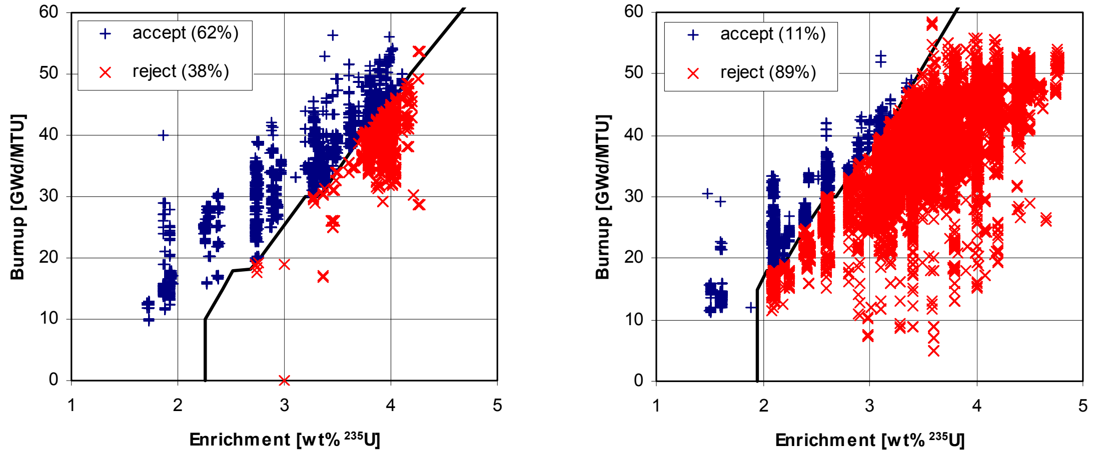


Fig. 2 U.S. PWR SNF discharge data through 1998 (numerical values correspond to the number of assemblies).



(a) CE14×14 **(b)** B&W 15×15



(c) CE 16×16 **(d)** WE 17×17

Fig. 3 Comparison of discharged SNF assemblies to actinide-only-based loading curves for the GBC-32 cask

Table 1 Summary of SNF acceptability in the GBC-32 cask with actinide-only burnup credit for the four assembly types considered

Assembly type	Total in discharge data	Number acceptable for loading	Number unacceptable for loading
CE 14×14	5453	4194 (77%)	1259 (23%)
B&W 15×15	6439	190 (3%)	6249 (97%)
CE 16×16	5809	3618 (62%)	2191 (38%)
WE 17×17	21569	2437 (11%)	19132 (89%)
Total	39270	10439 (27%)	28831 (73%)

acceptable assemblies. The results indicate that while burnup credit can enable loading a large percentage of the CE assemblies in a high-capacity cask, its effectiveness under the current regulatory guidance is minimal for the B&W and WE assembly designs considered.

To evaluate the effect of selected calculational assumptions, Figure 4 compares the reference case loading curve for the WE 17 × 17 assembly with loading curves for the following individual variations: (1) extended cooling time (20 years); (2) inclusion of the principal FPs (^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{143}Nd, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{155}Gd) and minor actinides (^{236}U, ^{237}Np, ^{243}Am) with ICFs based on comparisons11) with available assay data; (3) inclusion of the principal FPs and minor actinides based on a best-estimate approach11) for bounding isotopic validation; and (4) inclusion of the principal FPs and minor actinides without any correction for isotopic validation. Note that for a few of the relevant FPs, no measured assay data are available.

Thus, with the exception of the final case, no credit was taken for their presence in the SNF.

From Figure 4, it is apparent that extended cooling time can be used effectively to incrementally increase the percentage of acceptable assemblies. (A more detailed discussion of the effects of cooling time is available in Ref. 14.) However, inclusion of FPs and/or the use of more realistic approaches for isotopic validation offers significantly larger potential benefits. For the GBC-32 cask, the percentage of acceptable assemblies increases from 11 to 58% with the inclusion of the principal FPs and minor actinides (both cases at 5-year cooling), and from 58 to 94% with the use of a bounding best-estimate approach for isotopic validation, as described in Ref. 11. The final case shown in Figure 4 corresponds to full credit for the calculated actinide and principal FP compositions and represents a limit in terms of the potentially available negative reactivity. For the cases with FPs included no explicit consideration of criticality validation with FPs is included. However, the loading curves are all based on an upper subcritical limit of 0.94 (as opposed to 0.95), which inherently allows 1% Δ*k* for criticality calculational bias and uncertainty.

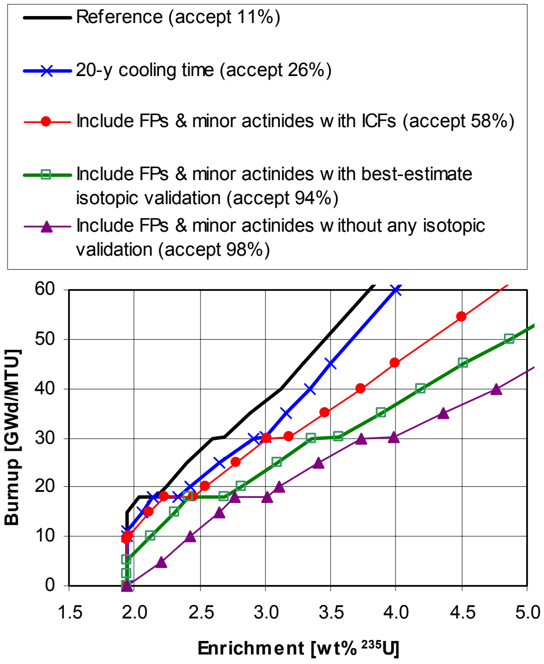


Fig. 4 Effect of calculational assumptions on loading curves for the GBC-32 and WE 17 × 17 assemblies.

5. Conclusions

Comparison of actinide-only-based loading curves for the GBC-32 cask with PWR SNF discharge data (through the end of 1998) leads to the conclusion that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of SNF assemblies in high-capacity casks. The loading curves presented in this paper are such that a notable portion of the SNF inventory would be unacceptable for loading because the burnup value is too low for the initial enrichment. Relatively small shifts in a cask loading curve, which increase or decrease the minimum required burnup for a given enrichment, can have a significant impact on the number of SNF assemblies that are acceptable for loading. Thus, as the uncertainties and corresponding conservatisms in burnup credit analyses are better understood and reduced, the population of SNF acceptable for loading in high-capacity casks will increase. Therefore, future work should focus on improving the accuracy associated with estimates of subcritical margin with burnup credit. Given appropriate data for validation, the most significant component that would improve accuracy, and subsequently enhance the utilization of burnup credit, is the inclusion of FPs. Consequently, an effective approach for validation of FPs is a key element necessary for the expansion of burnup credit.

Because the CE assemblies are considerably less reactive than the WE and B&W assemblies considered herein, loading curves for the CE assemblies are notably lower than those for WE and B&W assemblies. Assemblies that are not qualified for loading in a given high-capacity cask (i.e., do not meet the minimum burnup requirement for its initial enrichment value) must be stored or transported by other means. These include (1) high-capacity casks with design/utilization modifications and (2) lower-capacity (e.g., 24-assembly) casks that utilize flux traps and/or increased fixed-poison concentrations. In previous work,[4)] loading curves developed for actinide-only burnup credit with an established 24-assembly cask design are such that all or very nearly all assemblies with initial enrichments up to 5 wt% ^{235}U are acceptable. Also, loading curves developed for the GBC-32 cask with selected design (increased poison loading) and utilization (rods inserted into the assembly guide tubes) modifications[4)] illustrate alternative means for increasing the number of assemblies acceptable for loading in high-capacity cask designs. Although the use of rod inserts impacts operational procedures, the approach (coupled with burnup credit consistent with current regulatory guidance) offers a great deal of flexibility to achieve needed reductions in reactivity in an existing high-capacity cask design.

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