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UPDATED EVALUATION OF BURNUP CREDIT FOR ACCOMMODATING PWR SPENT NUCLEAR FUEL IN HIGH-CAPACITY CASK DESIGNS

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ABSTRACT

This paper presents an updated evaluation of the amount of burnup credit needed for high-capacity rail-type 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 recently released 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 shows 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. Therefore, ORNL is leading an effort to obtain data for the purpose of establishing the technical basis for crediting FPs in burnup credit licensing.

Key Words: 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

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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 inclusion 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 efforts [4] to evaluate the use of burnup credit to accommodate SNF in high-capacity storage and transportation casks. The evaluation is based on comparisons of recently released 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 cask [5] 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 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).

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 STARBUCS sequence [6], which automates burnup-credit analyses by coupling the depletion and criticality modules of SCALE [7], was used for these analyses. STARBUCS utilizes ARP and ORIGEN-S to perform the depletion analysis phase of the calculations. The ARP code prepares cross sections for each burnup step based on interpolation for fuel enrichment and mid-cycle burnup

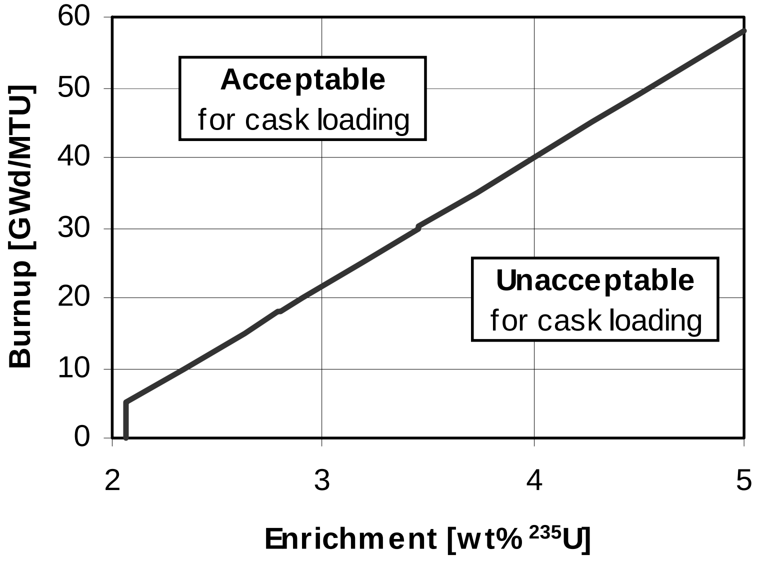


Figure 1. Illustrative burnup-credit loading curve. The vertical portion of the loading curve at low burnup corresponds to a region in which the reduction in reactivity due to burnup is smaller than the increase in reactivity associated with the conservatism in the burnup-credit evaluation. Hence, no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

from a user-specified ARP library that contains problem-dependent cross sections. ARP libraries can be specified from those distributed with the SCALE package or prepared by the user using one of the SCALE depletion sequences. The ORIGEN-ARP methodology offers a faster alternative to the SAS2H or TRITON depletion analysis sequences in SCALE, while maintaining computational accuracy [8].

Using the cross-section data prepared by ARP, ORIGEN-S performs depletion calculations to generate fuel compositions for all unique fuel regions (e.g., different axial- and/or horizontal-burnup regions). STARBUCS then creates and executes a CSAS25 (or CSAS26) input file that includes the depleted fuel compositions and utilizes the three-dimensional (3-D) KENO V.a (or KENO-VI) Monte Carlo criticality code. The KENO V.a calculations performed in support of the work reported in this paper 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. Unless stated otherwise, all loading curves shown in this paper correspond to k_{eff} = 0.940 ± 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 of 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 can be 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, CE 16 × 16, Babcock & Wilcox (B&W) 15 × 15, Westinghouse (WE) 17 × 17, WE 15 × 15, and WE 14 × 14. 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 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.

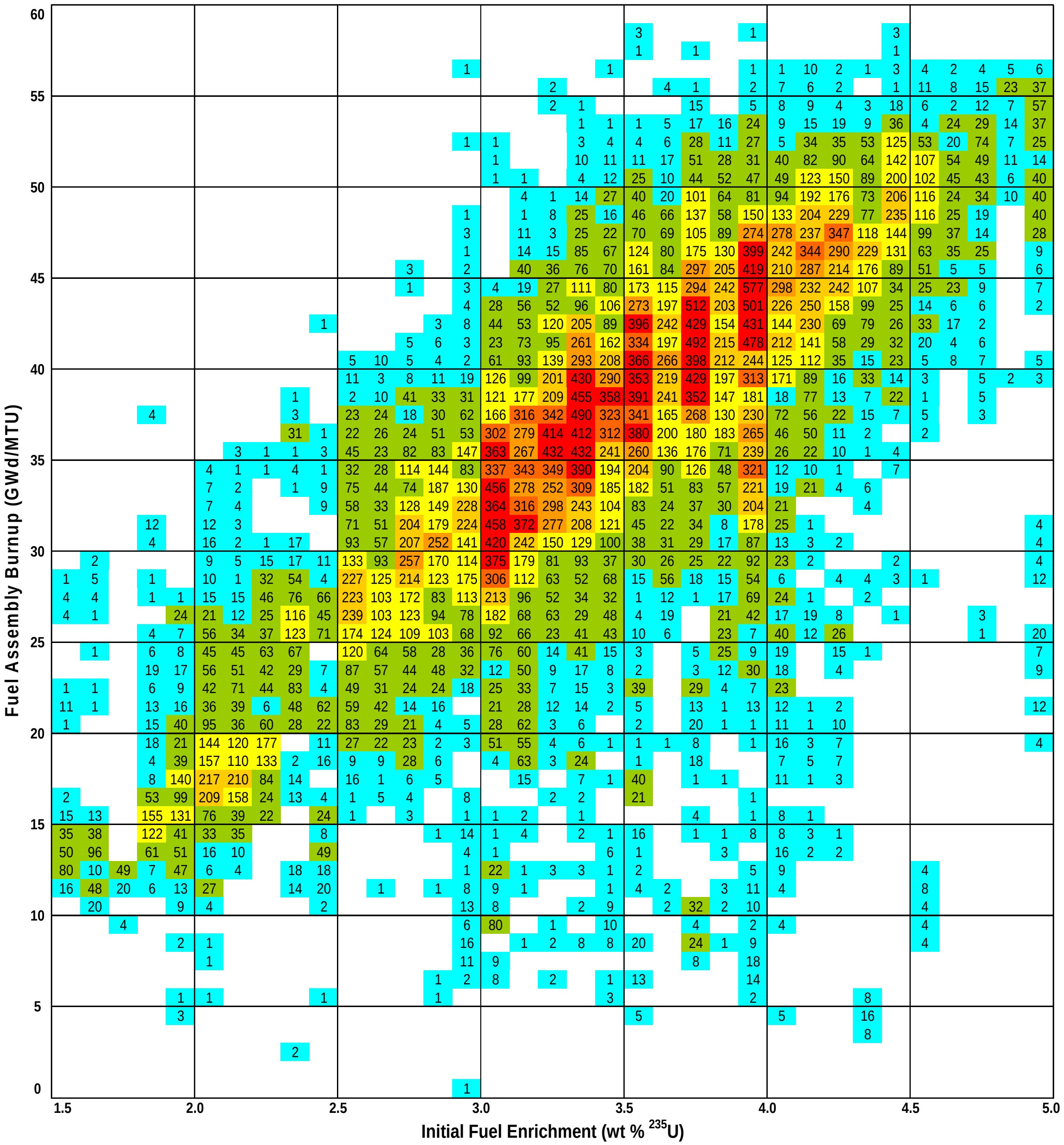
Because B&W and WE reactors have used burnable poison rods (BPRs), those cases assumed BPR exposure for the first 20 GWd/MTU of burnup. The effect of fixed absorbers, including BPRs, on the reactivity of PWR SNF is discussed in Ref. 12. Additional calculational details are available in Ref. 4.

4 U.S. COMMERCIAL SPENT NUCLEAR FUEL INVENTORY

The recently released discharge data [13] used for this evaluation correspond to SNF assemblies discharged from U.S. PWRs through the end of 2002 (see Figure 2) and were obtained from the Energy Information Administration (EIA) of the U. S. Department of Energy as a Microsoft Access™ database. The EIA obtained these data from form RW-859 data submitted by commercial nuclear power plant licensees. The 2002 RW-859 nuclear fuel data files include assembly-specific information for approximately 163,000 individual spent fuel assemblies. Of this number, 70,290 are PWR fuel assemblies. The six fuel assembly types—WE 17 × 17, WE 15 × 15, WE 14 × 14, B&W 15 × 15, CE 16 × 16, and CE 14 × 14—explicitly evaluated for this study comprise about 94% of the spent PWR fuel assemblies described in the database.

A review of the RW-859 (2002) data reveals that the average burnup of discharged PWR fuel assemblies has risen from around 20 GWd/MTU in 1975 to 45.7 GWd/MTU in 2002. This increase in assembly average burnup represents a significant increase in the amount of criticality safety margin available through burnup credit. Through 2002, 18.1 % of the 70,290 discharged PWR fuel assemblies had burnups greater than 45 GWd/MTU. The average initial ^{235}U enrichment of discharged PWR assemblies has risen from about 2.7 wt% in 1975 to 4.2 wt% in 2002. This trend of increasing initial enrichment has also made the fresh fuel assumption, historically used in criticality safety analyses, less practical. Figure 3 illustrates assembly average burnup and initial ^{235}U enrichment trends as a function of fuel assembly discharge per year. The total PWR spent fuel inventory is currently growing by about 3,300 fuel assemblies per year.

The 2002 RW-859 nuclear data files include some projected data showing that the number of assemblies to be discharged is forecast to be around 3,000 PWR assemblies per year through 2009, falling off significantly after 2009. These forecast data likely do not include the impact of plant license extensions. Combining historical and forecast data, about 95,000 PWR fuel assemblies will be discharged by 2014; of these, about 31,000 will have burnups exceeding 45 GWd/MTU. Figure 4 shows the historical and forecast data for the spent commercial PWR fuel assembly inventory. The RW-859 (2002) forecast fuel discharge data falls off drastically after 2009. Nuclear plant license extension activities will postpone the closure of many commercial nuclear power plants, pushing the reduction in the number of fuel assemblies discharged each year off a little farther into the future.



Number of Assy in Group			Total Assy	% of All	Cum. Assy
0	to	20	3,385	4.8	70,128
21	to	100	14,937	21.3	66,743
101	to	200	15,082	21.5	51,806
201	to	250	10,891	15.5	36,724
251	to	300	6,354	9.1	25,833
301	to	350	5,555	7.9	19,479
351	to	577	13,924	19.9	13,924

Figure 2. PWR spent fuel inventory from RW-859 (2002) nuclear data files.

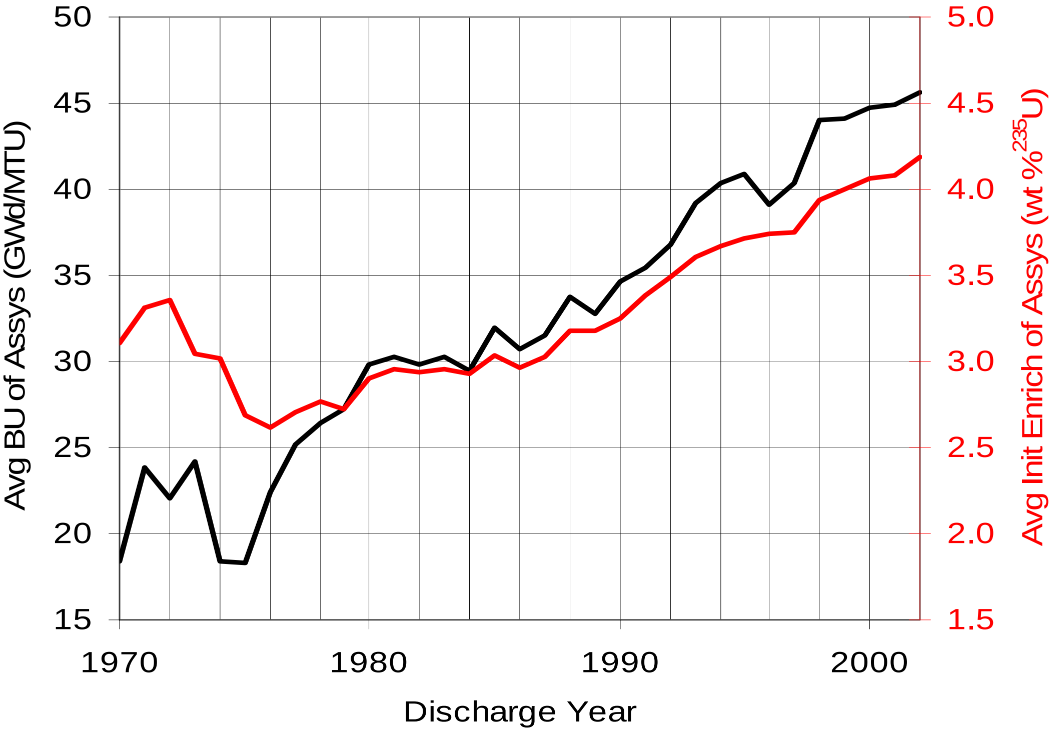


Figure 3. Historical trends of initial ^{235}U enrichment and fuel assembly burnup for discharged PWR fuel assemblies.

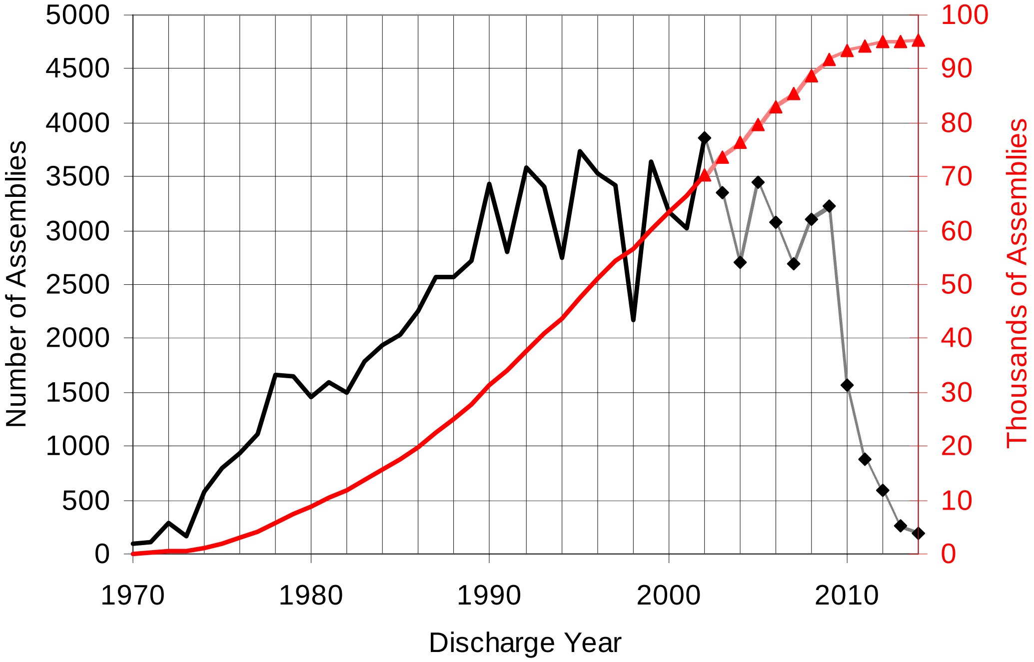


Figure 4. Historical trend of the number of PWR fuel assemblies discharged each year.

5 RESULTS

Loading curves, consistent with the ISG-8r2 guidance, for two of the six assembly types are provided in Figures 5 and 6, and the acceptability of the SNF assemblies for each fuel type is summarized in Table I. 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 acceptable assemblies. The results indicate that while burnup credit can enable loading a large percentage of the CE 14 × 14 and WE 14 × 14 assemblies in a high-capacity cask, its effectiveness under the current regulatory guidance is minimal for the other assembly designs considered.

Table I. 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	6,972	4,518 (65%)	2,454 (35%)
CE 16×16	6,828	1,731 (25%)	5,097 (75%)
B&W 15×15	7,519	166 (2%)	7,353 (98%)
WE 17×17	28,704	2,448 (9%)	26,256 (91%)
WE 15×15	10,365	475 (5%)	9,890 (95%)
WE 14×14	5,448	4,686 (86%)	762 (14%)
Total	65,836	14,024 (21%)	51,812 (79%)

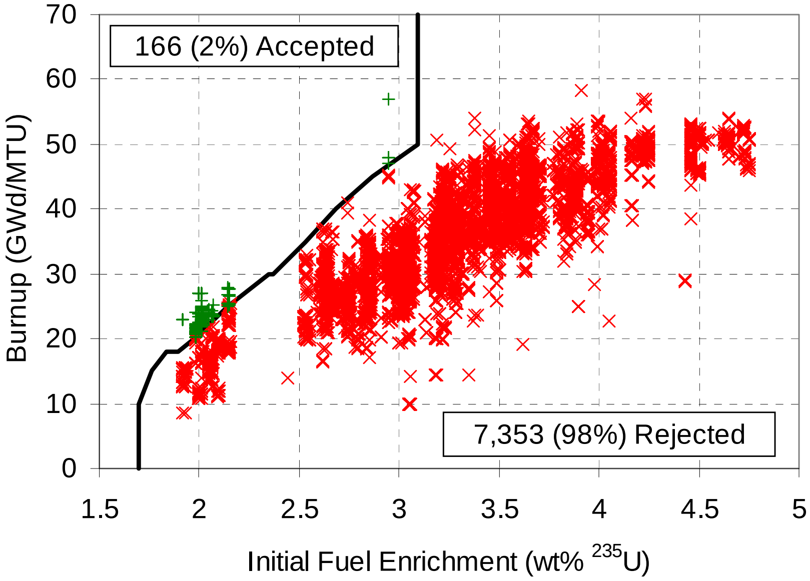


Figure 5. B&W 15 × 15 inventory shown with ISG-8r2-based burnup credit loading curve.

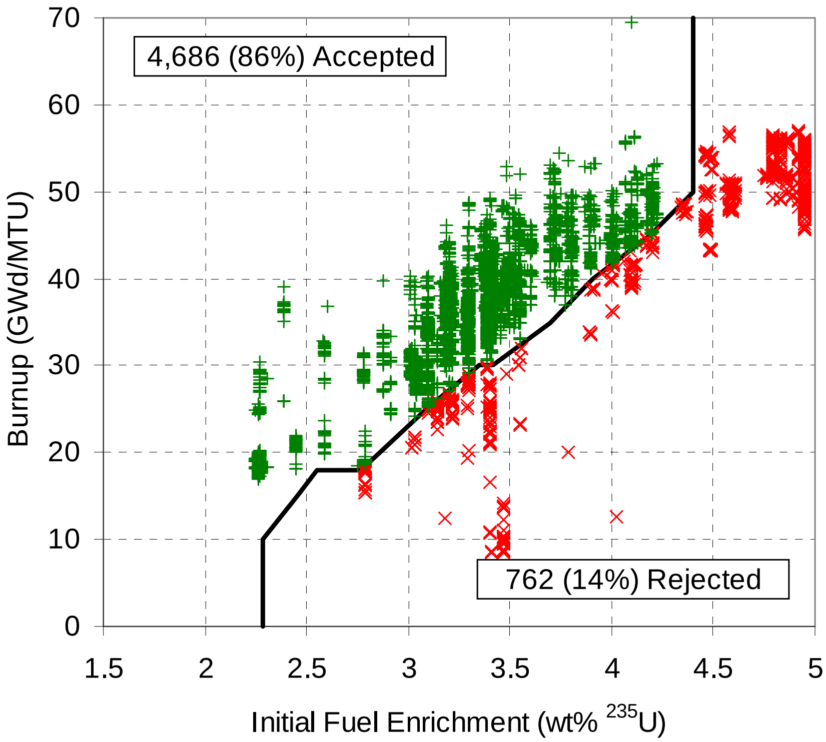


Figure 6. WE 14 × 14 inventory shown with ISG-8r2-based burnup credit loading curve.

To evaluate the effect of selected calculational assumptions, Figure 7 compares the ISG-8r2-based (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 minor actinides (^{236}U, ^{237}Np, ^{243}Am) and five of the primary six FPs (^{149}Sm, ^{143}Nd, ^{151}Sm, ^{133}Cs, and ^{155}Gd) with ICFs based on comparisons [11] with available assay data (^{103}Rh, also an important FP, is excluded because of insufficient measured assay data);

(3) inclusion of minor actinides and five primary FPs with spent fuel composition bias and uncertainty based on a best-estimate approach [11] for bounding isotopic validation;

(4) 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 spent fuel composition bias and uncertainty based on a best-estimate approach [11] for bounding isotopic validation; and

(5) inclusion of the principal FPs and minor actinides without any correction for isotopic validation.

Note that for a few of the relevant FPs (e.g., ^{103}Rh), insufficient measured assay data are available to estimate bias and uncertainty. Thus, with the exception of the final case, no credit was taken for their presence in the SNF.

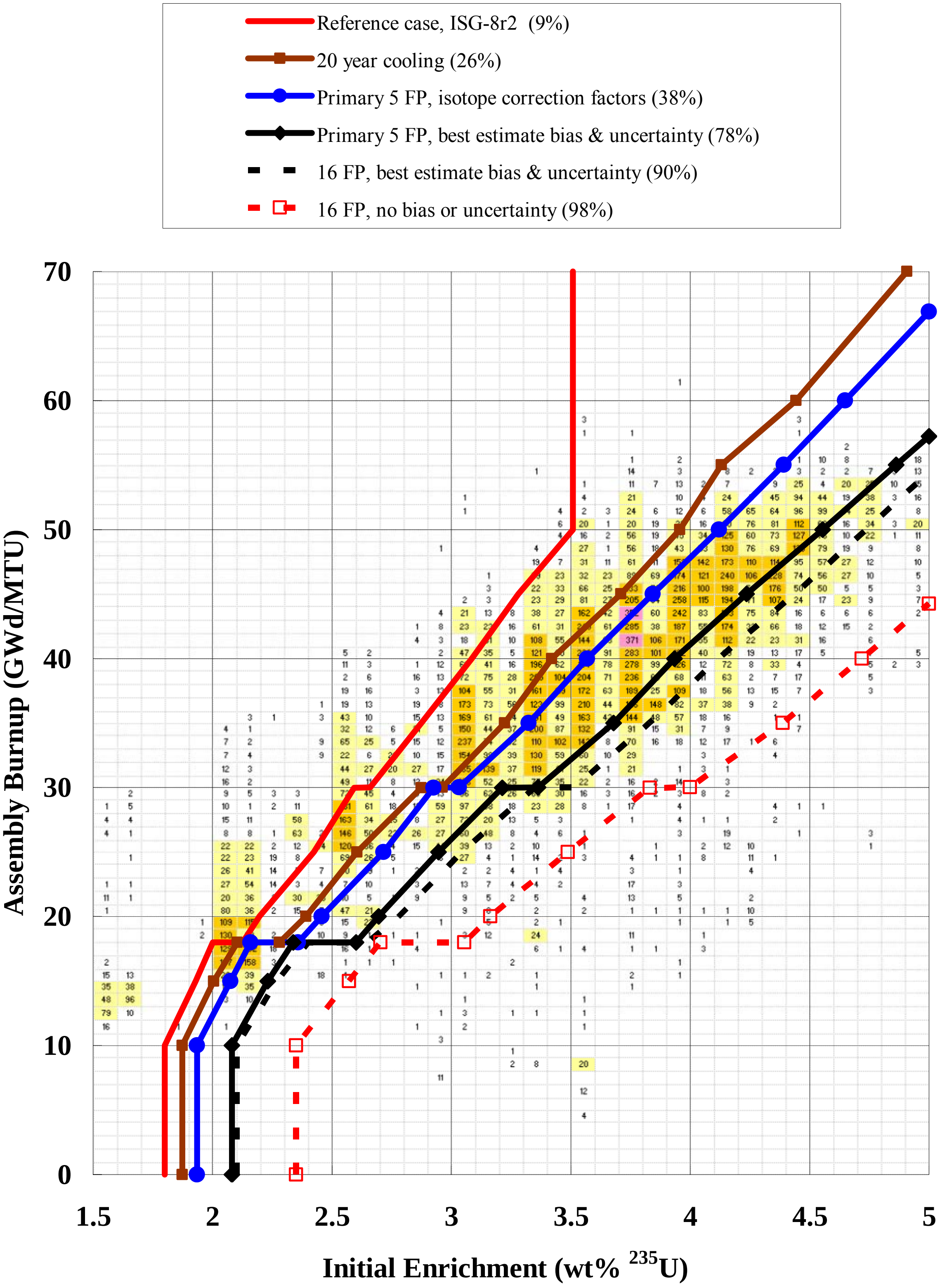


Figure 7. Comparison of calculational assumptions for WE 17 × 17 fuel assemblies. Percentages of inventory acceptable for the GBC-32 cask are shown in parentheses.

From Figure 7, it is apparent that extending cooling time beyond 5 years can 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 9 to 38% with the inclusion of the primary five FPs and minor actinides, and from 38 to 78% with the use of a bounding best-estimate approach for isotopic validation (both cases at 5-year cooling), as described in Ref. 11. Including the remainder of the principal FPs and using a best-estimate isotopic validation approach, the percentage of acceptable assemblies increases to 90%. The final case shown in Figure 7 corresponds to full credit for the calculated actinide and principal FP compositions and, given the conditions considered, represents an unattainable 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, for the purpose of this study, the loading curves are all based on an upper subcritical limit of 0.94 which, after the NRC-recommended administrative margin of 5%, inherently allows 1% Δk for criticality calculational bias and uncertainty.

While variations in cask design and computational approaches will impact the specific estimates of loading percentages, the authors believe that the GBC-32 cask is representative of high-capacity (i.e., ≥32 assembly) rail-type casks being considered by vendors, and thus the findings of this evaluation are expected to be representative.

6 CONCLUSIONS

Comparison of actinide-only-based loading curves for the GBC-32 cask with PWR SNF discharge data (through the end of 2002) 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 PWR SNF assemblies in high-capacity rail-type 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 proportion of SNF acceptable for loading in high-capacity casks will increase. Therefore, current work is focused 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. Therefore, ORNL is leading an effort to obtain data for the purpose of establishing the technical basis for crediting FPs in burnup credit licensing. The goal of this effort is to develop and/or obtain the scientific and technical information (e.g., chemical assay and critical experiment data) that can be publicly distributed to assist cask vendors in cask certification with burnup credit, including credit for the principal FPs.

Because the WE 14 × 14 and CE 14 × 14 assemblies are considerably less reactive than the other assembly designs considered herein, loading curves for these assemblies are notably lower than for the other fuel assembly types. 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 of up to 5 wt % ^{235}U are acceptable. Also, loading curves developed for the GBC-32 cask with selected modifications in design (increased poison loading) and utilization (rods inserted into the assembly guide tubes) [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.

7 ACKNOWLEDGMENTS

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