Current Status and Potential Benefits of Burnup Credit for Spent Fuel Transportation

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Abstract—*Taking credit for the reduction in reactivity associated with fuel depletion can enable more cost-effective, higher-density storage, transportation, and disposal of spent nuclear fuel (SNF) while maintaining a subcritical margin sufficient to establish an adequate safety basis. This paper will review the current status of burnup credit applied to the design and transport of SNF casks in the United States. The effectiveness of burnup credit for accommodating pressurized-water-reactor SNF in high-capacity casks will be demonstrated by comparing loading curves with actual SNF discharge data. The potential benefits that can be realized using the current regulatory guidance for actinide-only burnup credit will be illustrated in terms of the inventory allowed in high-capacity casks and the concurrent reduction in SNF shipments. The additional benefits that might be realized by extending burnup credit to take credit for select fission products are also illustrated together with a discussion of the type of technical information needed to support a safety basis for full burnup credit (i.e., actinide and fission product credit).*

I. INTRODUCTION

Historically, criticality safety analyses for commercial light water reactor (LWR) spent fuel storage and transport 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. 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; i.e. non-fissile actinides and fission products (FPs).

For storage and transportation of pressurized-water-reactor (PWR) SNF, burnup credit allows a reduction in the assembly separation space needed for criticality control. For a typical rail-type cask, the reduction in assembly spacing enables an ~30% increase in cask capacity from ~24 to ~32 PWR assemblies. Hence, the potential benefit of using 32-assembly casks with burnup credit is a maximum reduction of 25% in the number of required shipments for PWR SNF, as compared to using 24-assembly casks. Note that due to the smaller cross-sectional area of some PWR assemblies (e.g., 14 × 14), assembly-specific canisters could be designed with capacities exceeding 32. However, for simplicity in this paper a value of 32 is used for the maximum capacity of PWR burnup credit casks.

In September 2002, the U.S. Nuclear Regulatory Commission (NRC) issued Interim Staff Guidance 8, Revision 2 (ISG-8r2), "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks."[1] This ISG provides guidance on (1) the criteria to determine whether SNF is eligible for burnup credit consideration, (2) the experimental data needed and the general approach to take for establishing the bias and uncertainty in the analysis codes, (3) modeling assumptions to consider in performing analyses for the safety basis, and (4) loading operations (e.g., use of a burnup vs. initial enrichment curve and burnup measurements). The ISG-8r2 provided enhanced guidance and recommendations in a number of areas where it was determined that the previous ISG revision (ISG-8r1)[2] was incomplete (e.g., recommendations to handle axial profile modeling), potentially confusing (e.g., criteria for SNF irradiated in presence of control rods), or unnecessarily restrictive (e.g., SNF with no exposure to burnable absorbers and burnup values less than 40 GWd/MTU). These and other issues were addressed in ISG-8r2 using technical bases established by a research program sponsored by the NRC Office of Regulatory Research.

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The acceptance of the NRC to consider the safety case for burnup credit cask designs is evidenced by issuance of ISG-8. However, the guidance endorses negative reactivity credit due to change in only the actinide compositions. Although actinide compositions provide the major contribution to reactivity reduction in SNF, this paper will illustrate that a significant proportion of the SNF inventory in the United States cannot be loaded in high-capacity (i.e., ≥ 32 assembly) casks unless the safety basis can take into account additional negative credit beyond that provided by major actinides.

This paper will review the effectiveness of ISG-8r2 relative to the potential SNF inventory that can be accommodated in high-capacity storage and transportation casks.[3-4] The paper will also review the additional potential benefits that might be achieved if adequate technical information is available to support a safety basis that includes the negative reactivity from FPs. The evaluations are 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 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). For this work, loading curves were generated using the SCALE code system[6] 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 $k_{eff} = 0.940 \pm 0.002$. The use of 0.94, as opposed to 0.95, inherently allows 1%)k for criticality calculational bias and uncertainty.

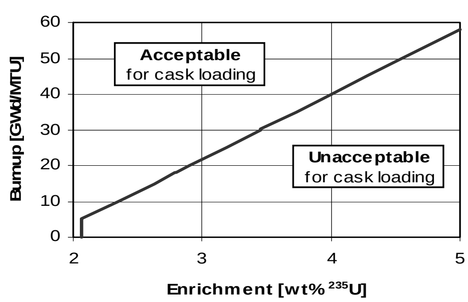


Fig.1 Illustrative burnup-credit loading curve. The vertical portion of the loading curve at low burnup corresponds to a region in which the reduction in reactivity due to burnup is smaller than the increase in reactivity associated with the conservatism in the burnup-credit evaluation. Hence, no credit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

II. BURNUP-CREDIT ANALYZED

A conceptual high-capacity (32-assembly) cask, designated GBC-32,[5] has been developed to provide a reference burnup credit cask design for use in establishing the effectiveness of ISG-8r2 and demonstrating potential benefits that might be gained with negative reactivity credit from actinides and FPs.

The regulatory guidance for burnup credit (ISG-8r2) recommends limiting the amount of burnup credit to that available from actinide compositions in SNF with 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, ISG-8r2 recommends 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 bounding 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,[1] 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:

- credit for 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);[3]
- burnup-dependent axial and horizontal burnup distributions suggested in Ref. 7;
- five-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. 8.

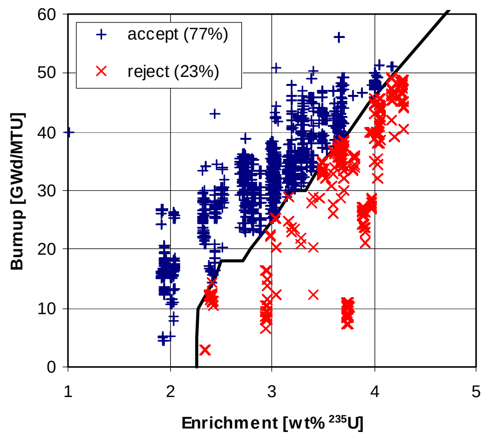
Because B&W and WE assemblies have used burnable poison rods (BPRs), those cases assumed BPR exposure for the first 20 GWd/MTU of burnup. The effect of fixed absorbers, including BPRs, on the reactivity of PWR SNF is discussed in Ref. 9. Additional calculational details are available in Ref. 3. The discharge data[10] used for this evaluation corresponds to SNF assemblies discharged from U.S. PWRs through the end of 1998.

III. INVENTORY OF SNF IN HIGH-CAPACITY CASKS

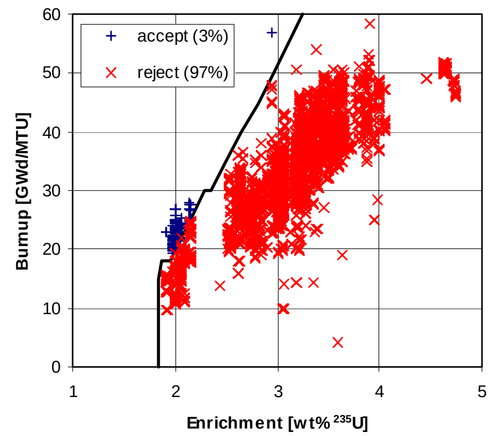
The loading curves for the four PWR assembly types noted above are provided in Figure 2, and the acceptability of the SNF assemblies for each fuel type is summarized in Table I.

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

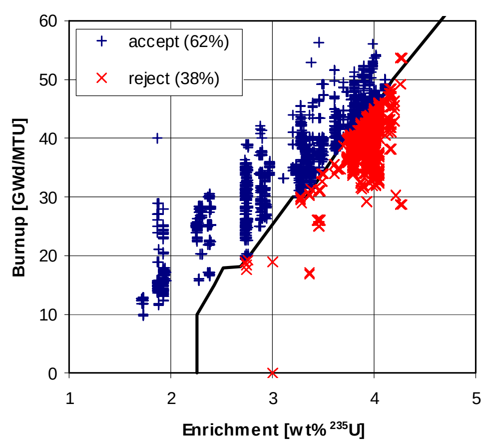
Assembly type	Total in discharge data	Number acceptable for loading	Number unacceptable for loading
CE 14×14	5453	4194 (77%)	1259 (23%)
B&W 15×15	6439	190 (3%)	6249 (97%)
CE 16×16	5809	3618 (62%)	2191 (38%)
WE 17×17	21569	2437 (11%)	19132 (89%)
Total	39270	10439 (27%)	28831 (73%)



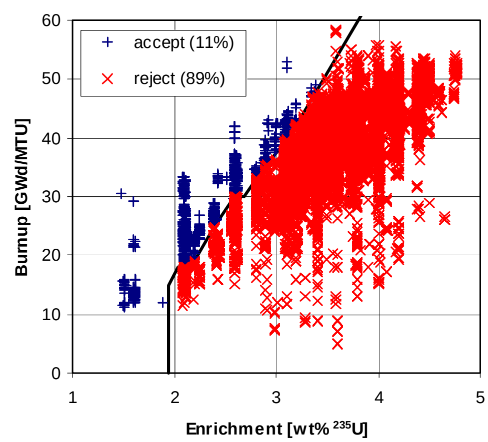
(a) CE14×14



(b) B&W 15×15



(c) CE 16×16



(d) WE 17×17

Fig. 2 Comparison of discharged SNF assemblies to actinide-only-based loading curves for the GBC-32 cask.

Consistent with the regulatory guidance of ISG-8r2, 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 assemblies in a high-capacity cask, the effectiveness of ISG-8r2 is minimal for the B&W and WE assembly designs considered.

To evaluate the effect of different calculational assumptions Figure 3 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 comparisons[8] with available assay data; (3) inclusion of the principal FPs and minor actinides based on a best-estimate isotopic uncertainty approach[8] 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.

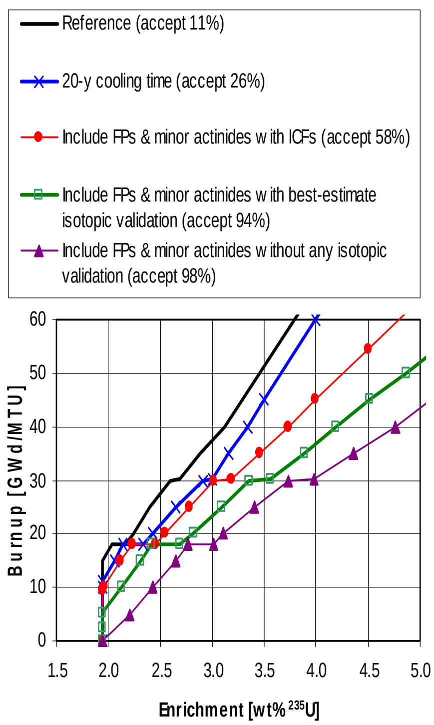


Fig. 3 Effect of calculational assumptions on loading curves for the GBC-32 and WE 17 × 17 assemblies.

From Figure 3, 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. 11.) However, inclusion of FPs and/or the use of more realistic approaches for isotopic validation offer potential benefits that are significantly larger. 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 five-year cooling), and from 58 to 94% with the use of a bounding best-estimate approach for isotopic validation, described in Ref. 8. The final case shown in Figure 3 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 specific consideration was given to the bias and uncertainty in k_{eff} caused by considering the FPs in the criticality analysis. However, the loading curves are all based on an upper subcritical limit of 0.94 (as opposed to 0.95), which inherently allows 1% Δk for criticality calculational bias and uncertainty.

IV. SIGNIFICANCE OF RESULTS

The results shown above demonstrate that additional negative reactivity is necessary to accommodate the majority of SNF assemblies in high-capacity casks and that the most significant way to improve the effectiveness of burnup credit is the inclusion of FPs in the burnup credit safety analysis. These studies show that burnup credit based on the recommendations embodied in ISG-8 (actinide-only) will enable ~30% of the PWR SNF assemblies to be loaded into high-capacity casks, and that, given appropriate data for validation, the inclusion of FPs can enable loading of ~90% of the SNF assemblies into high-capacity casks. This situation is depicted in Figure 4, which shows illustrative loading curves, based on the GBC-32 cask, plotted on top of the SNF discharge SNF (through the end of 1998). The blue curve (furthest to the left, labeled "Actinide-only five-year cooling") corresponds to current analysis assumptions consistent with ISG-8, Rev. 2. The black curve (furthest to the right, labeled "Principal Actinides & Fission Products five-year cooling") corresponds to the inclusion of the principal actinides and FPs.

Assuming assemblies that cannot be accommodated in a 32-assembly cask are transported in a 24-assembly cask, additional efforts to enable credit for FPs could potentially reduce the number of shipments by about 22%, as compared to a reduction of about 8% for actinide-only based burnup credit. This situation is illustrated graphically in Figure 5. Of course the potential reduction in the actual number of SNF shipments is dependent on the number of assemblies that will be transported, which at this time is not accurately known. However, given the current 70,000 Metric Ton Heavy Metal (MTHM) capacity limit established in the Nuclear Waste

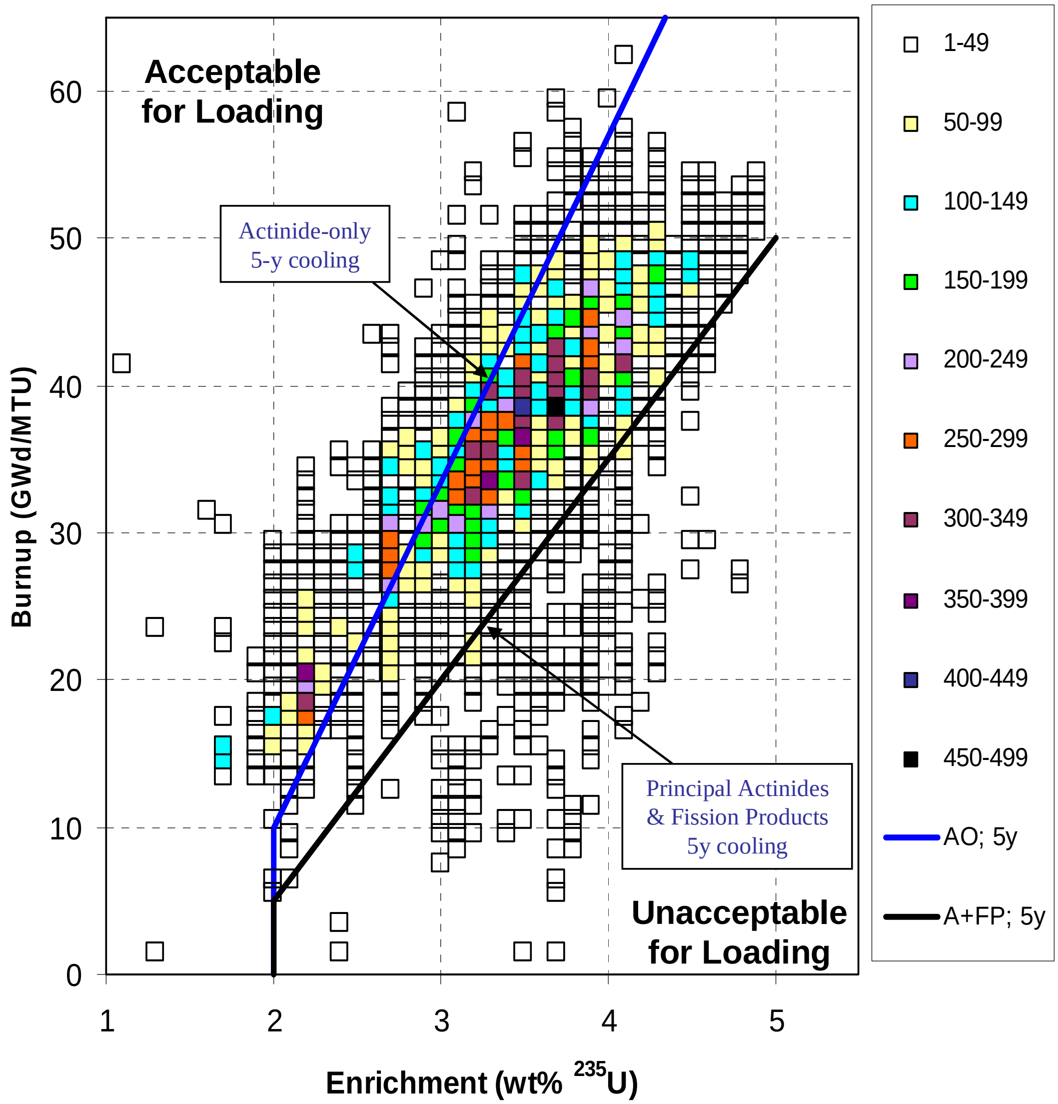


Fig. 4 PWR SNF discharge data through 1998 (numbers in legend indicate number of assemblies) shown with illustrative loading curves for the GBC-32 cask.

Policy Act, the percentage of total MTHM from PWRs as of the end of 1998 (64%), and the average number of PWR assemblies per MTHM (about 2.33 PWR assemblies/MTHM), it can be estimated that about 100,000 PWR assemblies will be transported to the repository. For this number of assemblies, it is estimated that about 315 shipments will be eliminated using actinide-only burnup credit in comparison to full use of the fresh fuel assumption. However, if a safety basis can be established to allow credit for FPs, there is a potential to further reduce the number of shipments by about 625. Thus, the estimated potential to be gained from use of full burnup credit is a reduction of ~940 shipments from interim storage sites to the repository.

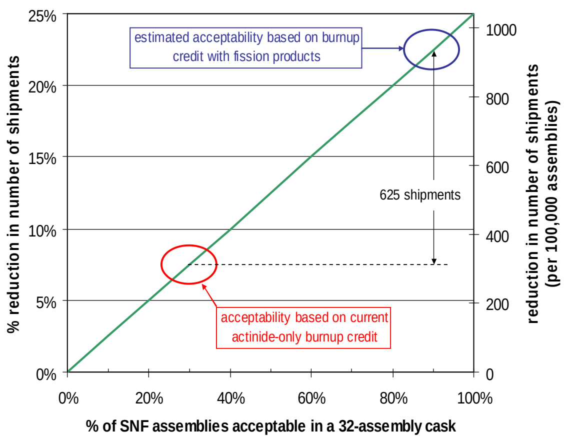


Fig. 5 Graphical representation of the potential reduction in the number of SNF shipments associated with the use of 32-assembly casks, as opposed to the use of 24-assembly casks. (Note that 100,000 assemblies in 24-assembly casks require 4167 shipments.)

Although use of FP credit reduces the number of potential shipments by nearly twice that provided with actinide-only burnup credit, one should not forget that the actinides are producing approximately 2/3 of the negative reactivity difference between fresh fuel and SNF. The dramatic benefits that can potentially be realized by FP credit are an artifact of the actinide-only loading curve(s) lying very near or within the burnup/enrichment band that represents the highest density region of the SNF inventory (see Figure 4). Thus, relatively small advances that enable additional negative reactivity credit may only shift the loading curve slightly, but will provide magnified benefits in terms of the SNF inventory that is acceptable for cask loading.

In preparing this paper, an informal survey of industry experts who have been looking at cost estimates for future cask shipments suggested single shipment costs (including freight and operational costs) to range from $200,000 to $500,000. These same experts judged the costs of manufacturing, loading, and shipping a 32-assembly cask to be roughly equivalent to that of a 24-assembly cask. Consequently, the actual cost savings associated with burnup credit will be dictated by the reduction in the number of shipments and the cost/shipment. For the number of assemblies assumed in Figure 5 (i.e., 100,000) and a single cask loading and transport cost of $250,000, it can be estimated that the economic benefit to be gained from using actinide-only burnup credit is a cost savings of about $79 million. Similarly, the additional economic benefit that can be realized if FP credit is obtained is a cost savings of $156 million, for a total cost savings of $235 million. Such economic savings, coupled with the reduction in potential dose exposure and non-radiological safety risk that comes with fewer shipments, will be a motivation to develop high-capacity casks that have loading criteria based on full burnup credit.

V. RECOMMENDATIONS

The ISG-8r2 restriction to actinide-only burnup credit is based on the lack of clear, definitive experiments that can be used to estimate the uncertainty associated with best-estimate analyses needed to obtain full burnup credit. Two types of experimental data are needed in order to provide a technical basis for extending the guidance of ISG-8r2 to include FPs. These two types of data are: (1) critical experiments that can be used to estimate the bias and uncertainty caused by FPs in the prediction of k_{eff} and (2) measured FP assay data that can estimate the bias and uncertainty in the prediction of the FPs within the SNF inventory.

Short term solutions to the lack of experimental data for FP credit are not apparent. For several years it has been recognized that the French company Cogema has developed experiments and measurements that address these data needs.[12] However, data from the Cogema program is largely proprietary, thus restricting its ability to address the current domestic needs.

Perhaps a better solution is to view the situation in the long term and work domestically to obtain the needed scientific and technical basis for establishing the uncertainties associated with predicting FP concentrations and performing a best-estimate criticality analysis of a SNF cask that includes FPs. Through a project funded by the DOE Nuclear Energy Research Initiative (NERI), Sandia National Laboratories has designed, and obtained a safety authorization to perform, critical experiments that consist of a lattice of unirradiated UO_2 fuel rods with foils of selected FP nuclides inserted between the pellets. A single experiment using ^{103}Rh foils has been completed under the NERI funding. Additional sponsorship is needed to prepare the foils and perform similar benchmark experiments with the other FPs that contribute significantly to reducing the reactivity.

The situation for measured FP assay data is also bleak in the United States. Of the samples for which assay data are now publicly available, many important FPs currently have four or fewer measurements, and the results exhibit high variability compared to actinide measurements. Therefore a concerted effort is needed to increase the number of assay measurements available for the key FP nuclides and to assure the additional measurements are performed with the accuracy needed to reduce the large variability in measurements. A number of domestic and international experimental programs designed to acquire additional high-burnup assay data for modern assembly designs are underway. Such programs are attempting to measure a much more comprehensive list of nuclides compared to earlier programs and are including consideration of the nuclides of importance to burnup credit, including the FP nuclides. If there are large uncertainties in this measured data and/or the number of samples acceptable for use is small, then the uncertainty associated with FP inventory prediction will be high, such that the identified benefit from the full burnup credit loading curve shift of Figure 3 would not be totally achieved. It would seem prudent to gather and assess data from current programs while planning future measurement programs that will provide for the type of fuel needed and with the accuracy that will enable future reductions in the uncertainties associated with predicting concentrations of actinides and FPs.

For boiling-water-reactor (BWR) SNF, current storage and transport cask designs (without water gaps) are capable of accepting ~68 assemblies with assembly-averaged initial enrichments up to ~4.0 wt % ^{235}U. Although the majority of BWR assemblies currently in storage meet this criterion, current BWR fuel designs feature assembly-averaged initial enrichments that exceed 4.0 wt % ^{235}U and future designs are expected to approach 5.0 wt % ^{235}U. Therefore, the benefits of burnup credit for BWR fuel include: (1) increase in allowable enrichments to safely accommodate all current and foreseeable assemblies and (2) reduction in costly fixed neutron poison loading in the canisters. Unlike PWR burnup credit, recognized benefits do not include increased cask capacity. However, without burnup credit, current BWR cask capacities would need to be decreased to accommodate discharged fuel with enrichments greater than ~4.0 wt % ^{235}U.

There has been little study of burnup credit for transportation of BWR fuel and so it is not clear what the best approach will be to achieve the quantity of burnup credit needed to achieve inventory loading for fuel up to 5 wt % enriched. Investigations similar to those of Ref. 3 are needed to determine the combination of acceptable modeling assumptions and experimental data that will be able to achieve the desired amount of burnup credit required for assuring future discharges of BWR assemblies can be loaded at full capacity into high density casks.

VI. 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. Because the CE assemblies are considerably less reactive than the WE and B&W assemblies considered herein, loading curves for the CE assemblies allow a much larger percentage of their inventory to be loaded in a burnup credit cask.

No matter the assembly type, Figure 2 demonstrates that 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. Given appropriate experimental data, a realistic best-estimate analysis of burnup credit that includes validated credit for FPs is the enhancement that will yield the most significant impact on future transportation plans. Therefore, future work should focus on obtaining the experimental data needed to obtain reliable (for FPs) and improved (for actinides) estimation of analysis uncertainties associated with burnup credit.

In general, 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,[3] 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[3] 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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