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Regulatory Status of Burnup Credit for Dry Storage and Transport of Spent Nuclear Fuel in the United States

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Abstract

During 1999, the Spent Fuel Project Office of the U.S. Nuclear Regulatory Commission (NRC) introduced technical guidance for allowing burnup credit in the criticality safety analysis of casks for transporting or storing spent fuel from pressurized water reactors. This paper presents the recommendations embodied by the current NRC guidance, discusses associated technical issues, and reviews information needs and industry priorities for expanding the scope and content of the guidance. Allowable analysis approaches for burnup credit must account for the fuel irradiation variables that affect spent fuel reactivity, including the axial and horizontal variation of burnup within fuel assemblies. Consistent with international transport regulations, the burnup of each fuel assembly must be verified by pre-loading measurements. The current guidance limits the credited burnup to no more than 40 GWd/MTU and the credited cooling time to five years, imposes a burnup offset for fuels with initial enrichments between 4 and 5 wt% ^{235}U, does not include credit for fission products, and excludes burnup credit for damaged fuels and fuels that have used burnable absorbers. Burnup credit outside these limits may be considered when adequately supported by technical information beyond that reviewed to-date by the NRC staff. The guidance further recommends that residual subcritical margins from the neglect of fission products, and any other nuclides not credited in the licensing-basis analysis, be estimated for each cask design and compared against estimates of the maximum reactivity effects associated with remaining computational uncertainties and potentially nonconservative modeling assumptions. The NRC's Office of Nuclear Regulatory Research is conducting a research program to help develop the technical information needed for refining and expanding the evolving guidance. Cask vendors have announced plans to submit the first NRC license applications for burnup credit later this year.

1. Background and Introduction

Historically, the NRC's approval of criticality safety evaluations for commercial spent fuel in casks has been based on analyzing the irradiated fuel as though it were unirradiated and without burnable poisons. This "fresh-fuel" assumption has provided a straightforward and bounding approach for showing that spent fuel packages will remain subcritical under analyzed normal and accident conditions with assumed water ingress. However, the extreme conservatism inherent in the fresh-fuel assumption can lead to excessive and costly design requirements for neutron absorbers and/or spacing of the spent fuel. The term burnup credit refers to allowing the criticality safety of spent fuel systems to be evaluated using analyses that consider the reduced reactivity of irradiated fuel. In commercial power-reactor fuels that have achieved most of their intended burnup, the major actinides (i.e., isotopes of uranium, plutonium, and americium) generally account for well over half of the change in reactivity relative to the fresh fuel assumption, with fission products accounting for most of the remainder.

In the U.S., interest in burnup credit for spent fuel casks has focused mainly on fuel from pressurized water reactors (PWRs) rather than from boiling water reactors (BWRs). The primary reason for this is that the smaller size and correspondingly lower reactivity of individual BWR assemblies, in relation to PWR assemblies, leads to relatively small economic penalties in cask design and capacity when analyzed under the fresh-fuel assumption. Burnup credit for PWR spent fuel, on the other hand, is expected to significantly increase the allowed capacity of large casks. For example, a rail cask design approved to hold 24 PWR fuel assemblies under the fresh-fuel assumption may eventually be modified to hold 32 assemblies when analyzed with burnup credit.

The NRC and the U.S. nuclear industry have been discussing the issues of applying burnup credit to single-purpose transport casks and dual-purpose storage-and-transport casks for over a decade. The U.S. Department of Energy (DOE) directed considerable resources toward the study of burnup credit and produced a topical report that proposed a method for crediting actinide burnup effects in the analysis of casks for PWR spent fuel [1]. During the 1995-98 time frame, the DOE topical report was revised twice [2, 3] in response to the NRC's review and comments.

Based in part on technical information provided in the DOE topical report, and supplemented by information available from other sources, the NRC's Spent Fuel Project Office (SFPO) issued in May 1999 the initial version of its interim staff guidance document, ISG-8 [4], which described an interim basis for allowing partial burnup credit in PWR spent fuel casks. At about the same time, the NRC's Office of Nuclear Regulatory Research initiated a burnup credit research program to support the staff's phased efforts in this area. In July 1999, early results from the NRC research program enabled SFPO's issuance of Revision 1 of ISG-8, which introduced the currently accepted recommendations for cask-specific approval of limited burnup credit for PWR fuel [5]. These recommendations were discussed at public meetings with stakeholders [6, 7] and have been recently incorporated into the updated standard review plans for spent fuel dry storage and transport [8, 9]. SFPO expects to issue further technical guidance on burnup credit as more information becomes available from ongoing research efforts and the application review process. Cask vendors have announced plans to submit the first NRC license applications for burnup credit later this year.

The following sections present the recommendations embodied by the current NRC guidance, discuss associated technical issues, and review information needs and industry priorities for expanding the scope and content of the evolving guidance.

2. Recommendations for Burnup Credit in PWR Spent Fuel Casks

The NRC technical guidance introduced in Revision 1 of ISG-8, and subsequently incorporated into the applicable standard review plans, provides recommendations under the following six headings: (1) Limits for the Licensing Basis, (2) Code Validation, (3) Licensing-Basis Model Assumptions, (4) Loading Curve, (5) Assigned Burnup Loading Value, and (6) Estimate of Additional Reactivity Margin. Except as specified in these recommendations, the application of burnup credit does not alter the current guidance and recommendations provided by the NRC staff for the criticality safety analysis of transport and storage casks. Each recommendation is cited below in *italics* and is followed by comments on associated technical issues.

(1) ***Limits for the Licensing Basis:*** *The licensing-basis analysis performed to demonstrate criticality safety should limit the amount of burnup credit to that available from actinide compositions associated with PWR irradiation of UO_2 fuel to an assembly-average burnup value of 40 GWd/MTU or less. This licensing-basis analysis should assume an out-of-reactor cooling time of five years and should be restricted to intact assemblies that have not used burnable absorbers. The initial enrichment of the fuel assumed for the licensing-basis analysis should be no more than 4.0 wt% ^{235}U unless a loading offset is applied. The loading offset is defined as the minimum amount by which the assigned burnup loading value (see Recommendation 5) must exceed the burnup value used in the licensing safety basis analysis. The loading offset should be at least 1 GWd/MTU for every 0.1 wt% increase in initial enrichment above 4.0 wt%. In any case, the initial enrichment shall not exceed 5.0 wt%. For example, if the applicant performs a safety analysis that demonstrates an appropriate subcritical margin for 4.5 wt% fuel burned to the limit of 40 GWd/MTU, then the loading curve (see Recommendation 4) should be developed to ensure that the assigned burnup loading value is at least 45 GWd/MTU (i.e., a 5 GWd/MTU loading offset resulting from the 0.5 wt% excess enrichment over 4.0 wt%). Applicants requesting use of actinide compositions associated with fuel assemblies, burnup values, or cooling times outside these specifications, or applicants requesting a relaxation of the loading offset for initial enrichments between 4.0 and 5.0 wt%, should provide the measurement data and/or justify extrapolation techniques necessary to adequately extend the isotopic validation and quantify or bound the bias and uncertainty.*

Comments

Credit for fission product effects is not included in the current guidance because of large uncertainties arising from the lack of readily available radiochemical assay data and measured reactivity data for neutron absorbing fission products. In addition, the neglect of fission products provides additional reactivity margin that is used in compensating for the remaining uncertainty and modeling issues in actinide-only burnup credit (see Recommendation 6). The restriction of credited burnup levels to no more than 40 GWd/MTU reflects the lack of readily available actinide assay data for fuels burned beyond that level. The loading offset permits limited burnup credit in the absence of actinide assay data from spent fuels with initial enrichments beyond 4 wt%. The loading offset is an example of how conservative modeling adjustments can be judiciously used to compensate for validation uncertainties that arise from moderate extrapolations beyond the measured data. NRC calculations show that applying the offset to fuel with an initial enrichment of 4.5 wt% and an assigned burnup of 45 GWd/MTU (i.e., credited as only 40 GWd/MTU) would typically correspond to a k-effective penalty on the order of 1.5%.

In justifying the loading offset approach, it is noted that, with other factors being equal, an increase in initial enrichment lowers the contribution from actinides to the reduced reactivity of spent fuel, thereby increasing the relative contribution from fission products. Thus, the neglect of fission products in actinide-only burnup credit is especially helpful in further offsetting the uncertainties from this limited extrapolation to initial enrichments above 4 wt%. The neglect of fission products is less helpful for extrapolating to burnups beyond 40 GWd/MTU because the actinide contribution to reducing the reactivity of irradiated fuel increases much more rapidly with burnup than does the contribution from fission products. Extrapolation of the isotopic validation to burnups beyond 40 GWd/MTU is further hindered by the expectation of greater computational challenges in modeling the increased neutronic heterogeneity of high-burnup fuel designs and core loadings.

The exclusion of fuels that have used burnable absorbers is due in part to the lack of readily available, comprehensive information on the range of burnable absorber designs and their past and present uses. It is well known that the use of burnable absorbers generally leads to more fissile plutonium production per burnup increment. Extending burnup credit to include fuels that have used burnable absorbers will therefore necessitate a compilation of basic information on burnable absorber designs, supplemented by technical studies to establish appropriate modeling practices for the various design categories. Recommended modeling practices will need to incorporate added conservatism to account for the computational uncertainties arising from the present lack of isotopic validation data for fuels with burnable absorbers.

(2) ***Code Validation:*** *The applicant should ensure that the analysis methodologies used for predicting the actinide compositions and determining the neutron multiplication factor (k-effective) are properly validated. Bias and uncertainties associated with predicting the actinide compositions should be determined from benchmarks of applicable fuel assay measurements. Bias and uncertainties associated with the calculation of k-effective should be derived from benchmark experiments that represent important features of the cask design and spent fuel contents. The particular set of nuclides used to determine the k-effective value should be limited to that established in the validation process. The bias and uncertainties should be applied in a way that ensures conservatism in the licensing safety analysis. Particular consideration should be given to bias uncertainties arising from the lack of critical experiments that are highly prototypical of spent fuel in a cask.*

Comments

The data presented to the NRC for validating actinide-only criticality calculations are based on a series of laboratory critical experiments with unirradiated fuel rods containing either low-enriched UO_2 or PuO_2 mixed with UO_2 (MOX). These benchmark experiments differ from spent fuel in casks with regard to material compositions and geometries and the resulting neutronic competition among non-fuel components and the major actinides present in the fuel rods. The experiments do not represent the effects of axial fuel composition gradients and the typical local peaking of the neutron importance near the ends of spent fuel assemblies. Furthermore, the reactivity worth of poison plates or other absorber components is typically much lower in the benchmark experiments (e.g., $|\Delta k/k| < 0.04$) than in a cask analysis (e.g., $|\Delta k/k| > 0.20$).

To the extent practical, important physical differences between the cask analysis and the validation benchmarks should be considered explicitly in deriving a conservative adjustment for the computational bias and uncertainty. The potential uncertainties associated with any remaining validation issues not explicitly factored into the applied bias adjustment should be estimated and evaluated against estimates of additional reactivity margins (see Recommendation 6). Additional isotopic and criticality validation data are of key importance to (a) extending burnup credit beyond 40 GWd/MTU, (b) reducing or removing the loading offset for initial fuel enrichments between 4 and 5 wt%, and (c) providing credit for fission products.

(3) ***Licensing-Basis Model Assumptions:*** *The applicant should ensure that the actinide compositions used in analyzing the licensing safety basis (as described in Recommendation 1) are calculated using fuel design and in-reactor operating parameters selected to provide conservative estimates of the k-effective value under cask conditions. The calculation of the k-effective value should be performed using cask models, appropriate analysis assumptions, and code inputs that allow adequate representation of the physics. Of particular concern should be the need to account for the axial and horizontal variation of the burnup within a spent fuel assembly (e.g., the assumed axial burnup profiles), the need to consider the more reactive actinide compositions of fuels burned with fixed absorbers or with control rods fully or partly inserted, and the need for a k-effective model that accurately accounts for local reactivity effects at the less-burned axial ends of the fuel region.*

Comments

In-core conditions during fuel depletion can strongly affect how the actinide composition changes with burnup. In particular, the production of fissile plutonium per burnup increment is enhanced by in-core conditions that harden the neutron energy spectrum seen by the fuel (e.g., high soluble boron concentration, use of solid absorbers, low moderator density) or that otherwise increase resonant neutron capture (i.e., high fuel temperature). The specific-power history further influences the actinide mix by affecting the competition between radioactive decay and neutron absorption in the intermediate transition actinides.

The in-core neutron energy spectrum can also be affected by cladding creep-down and hydrogen absorption into the cladding. Both of these phenomena lead to increased moderation and can therefore be safely neglected in the fuel depletion models used for actinide-only burnup credit. However, in modeling the isotopic validation benchmarks, these and related effects on in-core fuel geometry (e.g., thermal expansion, pellet swelling, cladding oxidation) may warrant further consideration in order to avoid the masking of any tendency to underpredict the fissile plutonium production. For cask criticality models, the increased moderation caused by such changes in the fuel rod can be safely approximated by assuming unirradiated fuel rod dimensions with water in the pellet-clad gap.

The first and second revisions of the DOE topical report have described a set of modeling assumptions that adequately bounds the effects of horizontal burnup gradients within spent fuel assemblies. Significant uncertainties remain, however, regarding the analysis of reactivity effects associated with axial burnup profiles, often referred to as “end effects.” Some of the largest axial effects occur when the top of the fuel assembly is underburned as a result of partial insertion of control rods at power. In these cases, the increased k-effective is governed by two important phenomena: (1) the lower burnup at the top of the fuel, and (2) the increased production of fissile plutonium caused by the in-core spectral hardening effects of the control rods (i.e., thermal neutron absorption and moderator displacement). In many instances, the second phenomenon can be more important than the first. Studies reviewed to-date have considered only the first phenomenon, reduced local burnup, in the identification and recommended noding of bounding axial burnup profiles.

A closely related aspect of the axial profile issue concerns the use of part-length absorber rods for axial power shaping. Some of the axial burnup profiles in the data base evaluated for the DOE topical report featured strong local burnup depressions caused by the use of part-length absorbers near the fuel midplane. The neutron importance in fuels with this type of burnup profile and absorber-rod history is highest near the middle of the fuel rather than near the top. Such "saddle shaped" burnup profiles therefore represent a potential departure from the more widely studied end-effect profiles. To help resolve the remaining issues and uncertainties of axial profile effects, additional analytical studies are needed on both types of profiles to correctly evaluate the combined absorber-rod effects of depressed local burnup and increased fissile plutonium production and to determine which, if any, of the two profile types is generally more reactive in representative cask designs. Further work is also needed to expand the data base of calculated or measured axial burnup profiles, with emphasis on the bounding shapes arising from the historical uses of full-length and part-length control rods.

It is noted that the higher k-effective of fuel burned in the presence of absorber rods is a strong function of initial fuel enrichment, with lower enrichments showing larger effects from the absorber-rod-induced spectral hardening. This is partially explained by noting that, with less ^{235}U initially present, the depletion of ^{235}U provides less offset for the increase in fissile plutonium production. The current data base of readily available isotopic assay benchmarks has only limited applicability for validating the computed effects of absorber rods on the actinide composition of spent fuel.

(4) ***Loading Curve:*** *The applicant should prepare one or more loading curves that plot, as a function of initial enrichment, the assigned burnup loading value above which fuel assemblies may be loaded in the cask. Loading curves should be established based on a 5-year cooling time and only fuel cooled at least five years should be loaded in a cask approved for burnup credit.*

Comments

A burnup credit loading curve is derived from a series of k-effective calculations performed on a licensing-basis cask model. The resulting points on the loading curve give, for each value of initial enrichment, the fuel burnup value at which the computed k-effective equals the upper subcritical limit, i.e., where the bias-adjusted k-effective equals the recommended acceptance criterion of 0.95. Each calculation generally models a cask loaded with identical fuel assemblies (i.e., assemblies identical in design, initial enrichment, average burnup, assumed burnup profiles, and assumed in-core depletion parameters). To assess the effects of mixed fuel loadings, supplemental calculations may needed on cask models containing fuels from two or more points on the loading curve. Any increase in k-effective resulting from mixed loadings may necessitate an adjustment to the derived loading curve.

The 5-year cooling time has been chosen in large part because the burnup credit modeling studies in the U.S. have been based largely on fuel cooled for five years. Another consideration has been that the use of a single cooling time helps limit the added complexity of fuel loading specifications, which may be further governed by thermal and radiation shielding criteria. There is currently little need in the U.S. to load fuels cooled less than five years. It is well known that the reactivity of spent fuel decreases with time for all cooling times between 100 hours and 100 years. This effect is governed mainly by the decay of fissile ^{241}Pu to nonfissile ^{241}Am but, as discussed below, is reduced by the amplification of axial profile effects with cooling time. Basing the loading curves on a 5-year cooling time provides added conservatism for fuel with longer cooling times.

(5) ***Assigned Burnup Loading Value:*** *The applicant should describe administrative procedures that should be used by licensees to ensure that the cask will be loaded with fuel that is within the specifications of the approved contents. The administrative procedures should include an assembly measurement that confirms the reactor record assembly burnup. The measurement technique may be calibrated to the reactor records for a representative set of assemblies. For an assembly reactor burnup record to be confirmed, the measurement should provide agreement within a 95 percent confidence interval based on the measurement uncertainty. The assembly burnup value to be used for loading acceptance (termed the assigned burnup loading value) should be the confirmed reactor record value as adjusted by reducing the record value by the combined uncertainties in the records and the measurement.*

<u>Comments</u>

The NRC considered whether to accept the burnup values of record solely as determined by in-core physics calculations. However, reactor records have been known to contain errors and criticality safety is usually based on measured values rather than estimated values. In addition, the history of reported operating events in the fuel storage pools at reactors suggests that administrative and operational errors can be expected in the selection and handling of fuel assemblies for cask loading. Thus, it is desirable to have some measurement check of the record burnup values. The recommended use of pre-loading measurements is consistent with requirements in the international transport regulations [10] and with the applicable guidance in NRC Regulatory Guide 3.71 [11].

The measurement strategy used here will provide protection against internal inconsistencies in the records data. Because of energy balance checks and the shuffling of fuel assemblies between burn cycles, the uncertainty in the absolute record values is expected to be small but potentially variable from plant to plant. Reducing the record value by the uncertainties in the records and measurements encourages the operators to improve their core calculation methods and employ high quality measurement techniques. Initially, the measurement of all fuel assemblies is planned. A sampling plan for the measurements may be justified after positive experience is gained with administrative controls, loading operations, and the quality of records data.

Burnup verification techniques may be based on gamma-ray measurements or a combination of gamma-ray and neutron measurements and may include axial scans. It is noted that passive neutron measurements are sensitive to the greatly increased production of ^{242}Cm and ^{244}Cm caused by the spectral hardening effects of absorber rods and, because of this sensitivity, may find eventual use in addressing the effects of absorber-rodded burnup histories. (See also related comments under Recommendations 3 and 6 and in the subsequent discussion of information needs.)

(6) ***Estimate of Additional Reactivity Margin:*** *The applicant should provide design-specific analyses that estimate the additional reactivity margins available from fission product and actinide nuclides not included in the licensing safety basis (as described in Recommendation 1). The analysis methods used for determining these estimated reactivity margins should be verified using available experimental data (e.g., isotopic assay data) and computational benchmarks that demonstrate the performance of the applicant's methods in comparison with independent methods and analyses. The Organization for Economic Cooperation and Development Nuclear Energy Agency's Working Group on Burnup Credit provides a source of computational benchmarks that may be considered. The design-specific margins should be evaluated over the full range of initial enrichments and burnups on the burnup credit loading curve(s). The resulting estimated margins should then be assessed against estimates of: (a) any uncertainties not directly evaluated in the modeling or validation processes for actinide-only burnup credit (e.g., k-effective validation uncertainties caused by a lack of critical experiment benchmarks with either actinide compositions that match those in spent fuel or material geometries that represent the most reactive ends of spent fuel in casks); and (b) any potential nonconservatisms in the models for calculating the licensing-basis actinide inventories (e.g., any outlier assemblies with higher-than-modeled reactivity caused by the use of control rod insertion during burnup).*

<u>Comments</u>

This recommendation arises from the NRC staff's efforts at addressing the following question: Can the combined effects of uncertainties and approximations in actinide-only burnup credit outweigh the margins from the neglect of fission products? Table 1 summarizes the results of DOE's and NRC's initial analyses toward answering this question [12]. At three places in the second revision of DOE's topical report (Sections 3.2, 4.1.5, and 4.2.3.3), a portion of the large reactivity margin arising from the neglect of fission products and ^{236}U was used in attempting to bring closure to an issue. In response to requests from the NRC staff, the final revision of the topical report provided in its Table 7-4 a tally of the estimated effects of uncertainties in the proposed burnup credit methodology and how well they are offset by reactivity margins resulting from the neglect of fission products and ^{236}U. Specifically, for selected values of initial enrichment and burnup, the DOE tabulation (included in Table 1) subtracted three reactivity allowances from the estimated fission-product margins. The three reactivity allowances were to account for (a) the unmodeled higher reactivity of fuel assemblies in which control rods were inserted during part of the burnup and the uncertainties associated with (b) criticality validation issues (i.e., physical differences between the benchmarks and cask analyses) and (c) computer code adequacy issues (e.g., source sampling and convergence). The DOE results showed a net residual margin for all evaluated combinations of initial enrichment and burnup.

NRC calculations on representative cask models have demonstrated that the estimated fission-product margins can vary substantially between cask designs. For example, higher poison loadings in the basket reduce the margins by capturing neutrons otherwise absorbed by fission products. Estimated fission-product margins can be further reduced by the effects of nonuniform burnup within fuel assemblies. All fuel-in-cask models analyzed by the NRC yielded calculated fission-product margins significantly smaller than those given in DOE's topical report, which were based on a poison-free pin-cell model. As shown in Table 1, subtracting the topical report's three reactivity allowances from the NRC-calculated margins for fission products and ^{236}U leaves negative residual margins at certain values of low initial enrichment and low burnup. These results can be explained in part by noting that DOE's assumed reactivity allowances for the reactivity effects of burnup in the presence of control rods are greatest at low initial enrichments and constant beyond burnups of 15 GWD/MTU. It is possible, however, that such combinations of low burnup and low initial enrichment will fall below the burnup credit loading curve for a given cask design.

In response to NRC questions, section 7.4 of the final DOE topical report discussed several smaller margins, in addition to those resulting from the neglect of fission products and ^{236}U, that are associated with apparent modeling conservatisms in the proposed actinide-only methodology for burnup credit. Such additional margins would generally tend to offset some or all of the negative residual margins in Table 1. However, most of the additional margins are based on comparisons against the typical or mean case and therefore do not cover the full range of possible or credible fuel loadings that would be allowed under the proposed burnup credit methods. The NRC staff therefore concludes that it is not possible, based on information considered to-date, to ensure categorically that the aggregate of such additional margins is large enough to offset actinide-only uncertainties in all cask designs. The staff expects that further insights into the existence and magnitude of residual margins will emerge from NRC research efforts and the application review process.

3. Information Needs and Industry Priorities for Extended Burnup Credit

Industry stakeholders have expressed interests in (1) applying burnup credit to PWR fuels that have been exposed to burnable absorbers, (2) crediting cooling times beyond five years, (3) crediting burnups beyond 40 GWd/MTU, (4) reducing the burnup offset penalty for fuels with initial enrichments between 4 and 5 wt% ^{235}U, (5) seeking credit for fission products, and (6) establishing limited burnup credit for BWR spent fuel in casks. The NRC staff has in turn requested industry assistance in acquiring the technical information needed for developing NRC technical review guidance addressing each of these areas [6, 7]. These areas are the focus of ongoing and planned activities within the NRC's burnup credit research program [13, 14]. Observations on relevant technical issues and information needs are provided below.

Current NRC research activities include analytical studies toward establishing guidance on acceptable methods and modeling assumptions for computing the effects of burnable poisons on spent fuel isotopics. Consistent with industry priorities, the initial emphasis has been on two early design categories of removable burnable poison rods. However, progress to-date has been limited by difficulties in gathering comprehensive information on the configurations and uses of these and other categories of burnable absorber designs. As more design information becomes available, the analytical studies will be expanded to address the remaining categories of removable, fixed, and integral burnable poison designs. In general, the evolving NRC guidance will seek to identify appropriately conservative modeling assumptions to compensate for any uncertainties associated with incomplete design documentation and for shortages of isotopic validation data pertaining to burnable absorbers.

Research studies on the crediting of cooling times beyond five years are also in progress. An important phenomenon in this context is that, as cooling time increases, the computed k-effective of a loaded cask becomes more sensitive to variations in the assumed axial burnup profiles. Accordingly, the NRC's ongoing analytical studies seek to address (1) how the amplification of the axial profile effects (e.g., end effects) with cooling time slows the net decrease in k-effective and (2) whether and how the existence of stronger axial effects at cooling times beyond five years may necessitate reassessment of the bounding axial burnup profiles and the axial noding schemes used in modeling them. It is noted that the importance of axial-effect uncertainty grows with cooling time in proportion to the axial effect itself.

From the preceding comments on the estimation of additional reactivity margin (see Recommendation 6 and Table 1), it is clear that future credit for fission product effects will be limited by the uncertainties and potential nonconservatisms remaining in the analysis of actinide effects. In particular, fission product credit will necessitate a direct accounting for the potentially strong effects that absorber-rodded burnup histories can have on the reactivity of PWR spent fuel assemblies. It has been noted that at-power insertion of full-length or part-length control rods has seen only limited practice in the recent operating histories of U.S. PWRs. For example, present-day reactor operations generally restrict at-power control rod insertions to the "bite position," a position near the top of the active fuel that may vary from plant to plant and cycle to cycle. However, because the NRC licenses cask designs to accept the spent fuel from many or all plants, the safety analyses for casks must account for the worst-case rodded-burnup histories in the worst-case cycles at the worst-case plants. The NRC staff has therefore solicited industry assistance in compiling and summarizing comprehensive information on worst-case rodded burnup histories from all past and present operations at U.S. PWRs [7, 12].

The NRC research program is now engaging in international collaborations to acquire the additional isotopic and criticality validation data needed for extending burnup credit beyond 40 GWd/MTU, for reducing or eliminating the loading offset for initial enrichments between 4 and 5 wt% ^{235}U, and for adding credit for fission products. These and related NRC research efforts are described in another paper presented at this meeting [15]. The experimental data emerging from these international efforts will help in further reducing uncertainties within the current and evolving guidance limits for PWR burnup credit in casks and will find eventual use in establishing limited burnup credit in casks for BWR spent fuel.

4. References

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Table 1. Results from NRC's Independent Analysis of Table 7-4 in DOE Topical Report, DOE/RW-0472 Rev.2, Tally of the Use of Fission-Product and ^{236}U Margin for Addressing Uncertainties of Actinide-Only Burnup Credit

Enrichment (wt% ^{235}U) and Burnup (GWD/MTU)		EFPM = Estimated Fission Product and ^{236}U Margin (%Δk_{eff})		DOE's Reactivity Allowances for Uncertainty Issues and Approximations in Actinide-Only Burnup Credit (%Δk_{eff})			Estimated Remaining Margin (%Δk_{eff}) with EFPM from:	
		DOE TR Rev.2 (Pin Cell)	NRC Case A (OECD GBC-32 Cask)	Criticality Validation Issues	Effect if Control Rods were Inserted During Depletion	Computer Code Adequacy Issues	DOE TR Rev.2 (Pin Cell)	NRC Case A (OECD GBC-32 Cask)
3.0	15	8.4	4.4	2.0	3.3	1.0	2.1	**-1.9**
	30	13.0	5.9	2.0	3.3	1.0	6.7	**-0.4**
	45	16.0	6.9	2.0	3.3	1.0	9.7	0.6
3.6	15	8.2	4.3	2.0	2.1	1.0	3.1	**-0.8**
	30	12.8	5.6	2.0	2.1	1.0	7.7	0.5
	45	16.2	6.7	2.0	2.1	1.0	11.1	1.6
4.5	15	7.9	4.2	2.0	1.0	1.0	3.9	0.2
	30	12.4	5.6	2.0	1.0	1.0	8.4	1.6
	45	16.1	6.5	2.0	1.0	1.0	12.1	2.5