Addressing the Axial Burnup Distribution in PWR Burnup Credit Criticality Safety Analyses

J. C. Wagner
Oak Ridge National Laboratory,
P.O. Box 2008,
Oak Ridge, TN 37831-6370
wagnerjc@ornl.gov
(865) 241-3570

Executive Summary

This paper summarizes efforts related to developing a technically justifiable approach for addressing the axial burnup distribution in PWR burnup-credit criticality safety analyses. The paper reviews available data on the axial variation in burnup and the effect of axial burnup profiles on reactivity in a SNF cask. A publicly available database of profiles is examined to identify profiles that maximize the neutron multiplication factor, k_{eff}, assess its adequacy for general PWR burnup credit analyses, and investigate the existence of trends with fuel type and/or reactor operations. For this assessment, a statistical evaluation of the k_{eff} values associated with the profiles in the axial burnup profile database was performed that identifies the most reactive profiles as statistical outliers that are not representative of typical discharged SNF assemblies. The impact of these bounding profiles on the neutron multiplication factor for a high-density burnup credit cask is quantified. Finally, analyses are presented to quantify the potential reactivity consequence of assemblies with axial profiles that are not bounded by the existing database. The paper concludes with findings for addressing the axial burnup distribution in burnup credit analyses.

1. Introduction

The Interim Staff Guidance (ISG-8) on burnup credit [1] for pressurized water reactor (PWR) spent nuclear fuel (SNF), issued by the Nuclear Regulatory Commission's Spent Fuel Project Office, recommends the use of analyses that provide an "*adequate representation of the physics*" and notes particular concern with the axial and horizontal variation of burnup. Due to the relatively minor impact of the horizontal burnup gradient on the neutron multiplication factor, k_{eff}, in a typical rail-type burnup credit cask, further investigations related to horizontal burnup currently have low-priority, but may be considered in future work. In contrast, the axial burnup profile can have a significant impact on k_{eff} [2], and therefore is an important component of a burnup credit safety analysis [1, 3]. However, ISG-8 offers no guidance regarding an acceptable means to address the axial burnup distribution in a computational model. Therefore, efforts have been expended to review available axial burnup data and evaluate the effect of numerous axial profiles on k_{eff} in a SNF cask, with the goal of developing an acceptable approach to address the axial burnup distribution in general PWR burnup credit evaluations. A summary of these efforts is described in this paper.

2. Background

Axial variations in flux result in a non-uniform burnup distribution along the axial length of SNF. The axial distribution is typically characterized by end regions that are significantly under-burned with respect to the assembly-average burnup. The shape of the distribution is dependent upon the accumulated burnup, as well as other characteristics of the assembly operating history (e.g., partial-length absorbers, axial power shaping rods, control rods, and non-uniform axial fuel enrichments). For fuels of moderate-to-high burnup (i.e., burnups beyond ~20 GWd/MTU), these under-burned regions are dominant in terms of reactivity, and thus, must be properly represented to ensure subcritical margins.

The accumulated burnup for a spent fuel assembly is typically available (from plant data) in terms of the assembly-averaged burnup. To accurately calculate the reactivity of spent fuel, a calculational model must include the axial distribution, which is done by axially segmenting the model to approximate the axially varying burnup (isotopic concentrations). The most reactive region of the spent fuel is near the assembly ends, where there exists a balance between increased multiplication due to lower burnup and increased leakage due to closer proximity to the fuel ends. The difference in k_{eff} between a calculation with explicit representation of the axial burnup distribution and a calculation that assumes uniform axial burnup has become known as the "end effect." Although the assumption of uniform axial burnup has no physical validity for SNF, it has proven useful as a reference for comparison of the effect of the axial burnup distribution.

Numerous studies have been performed to quantify the reactivity effect associated with axial burnup distributions. A fairly comprehensive review of those studies is available in Ref. [2]. In general, these studies have shown that assuming uniform axial burnup is conservative for low burnups, but becomes increasingly nonconservative as burnup increases. The transition between conservative and nonconservative is dependent on numerous factors (including enrichment, cooling time, and the nuclides included in the criticality model), but generally occurs in the burnup range of 15–25 GWd/MTU.

For a given axial burnup profile, the end effect has been shown to be strongly dependent upon the cooling time and the presence of fission products in the criticality model. An example of this dependence is given in Fig. 1, which shows the end effect, for two cooling times, with and without fission products present, in a typical high capacity cask (GBC-32) [4] designed for burnup credit.

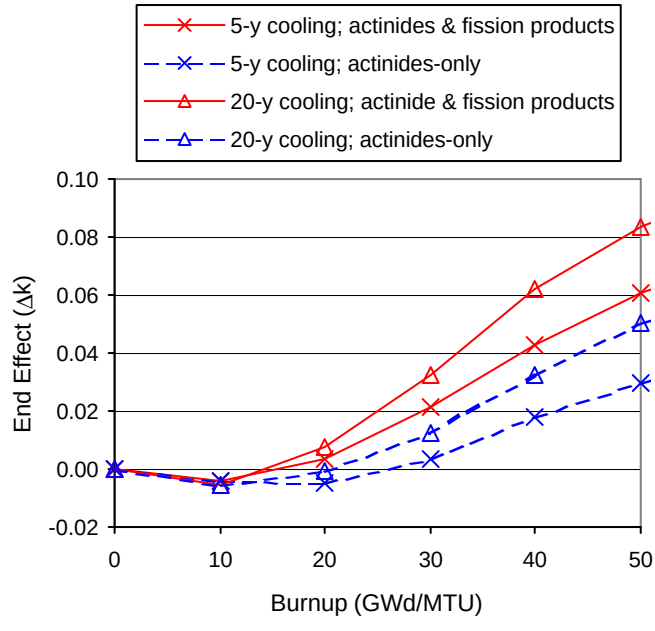


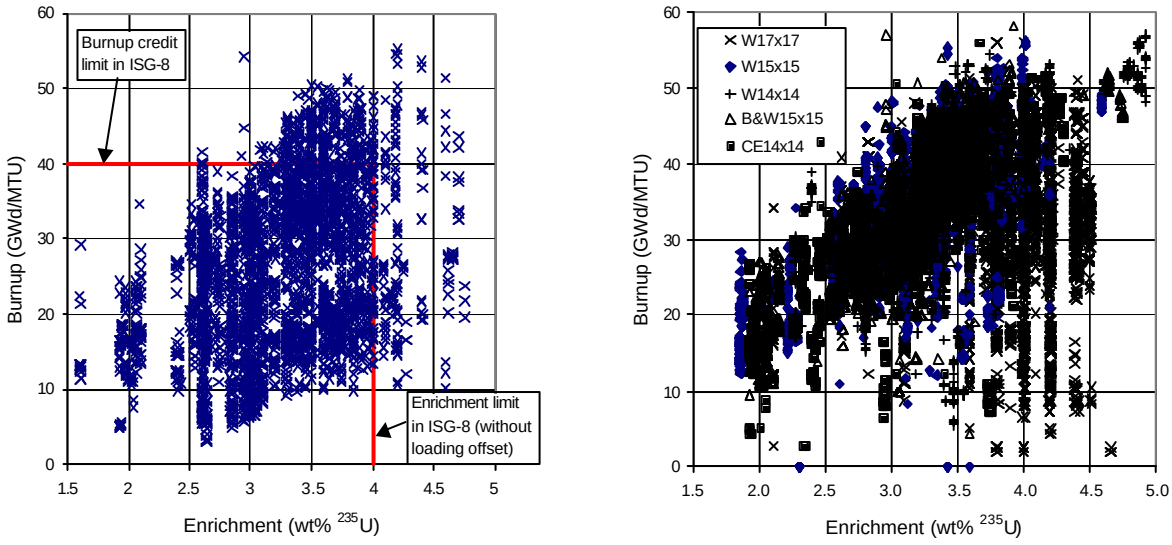
Figure 1. End effect in GBC-32 cask.

The results show that the end effect (1) increases with burnup, (2) becomes positive later in burnup when fission products are not included, (3) is reduced when fission products are neglected, and (4) increases with cooling time. These findings are consistent with those observed by the Organization for Economic Cooperation and Development's (OECD) Expert Group on Burnup Credit (EGBUC) [5,6]. Although the end effect has been shown to be dependent upon many factors, it is primarily dependent on the slope of the burnup profile near the ends of the fuel, which is dependent on the fuel assembly design, burnup, and operating environment.

3. Axial Burnup Profile Data

Recognizing the importance of the axial burnup profile, work sponsored by the Department of Energy (DOE) generated a database of more than 3000 PWR axial-burnup profiles. This publicly available database (YAEC-1937) [7], contains 3169 PWR axial burnup profiles from ~1700 different assemblies, which represent three fuel vendors through the mid-1990s, 20 different reactors, and 106 cycles of operation. The 106 cycles of operation include first cycles, out-in fuel management and low leakage fuel management [7]. The axial burnup profiles are specified in terms of 18 axial regions and were calculated with various three-dimensional (3-D) core physics codes that are the current methods used in fuel management, reload analysis, and core operational support. Although their accuracy is verified through safe reactor operation and industry history of operating within technical specifications, there has been interest in quantifying the uncertainties in the calculated burnups, particularly as a function of axial height. Responding to this interest, a study [8] was performed to evaluate the uncertainties utilizing in-core measurements and core neutronic calculations for a Westinghouse PWR. The uncertainty in burnup was determined by comparing calculated and measured reaction rates at the instrumented locations and using analytical methods and nearby measurements to infer "measurements" in the un-instrumented locations. The study [8] concluded that the uncertainty in burnup, evaluated over three cycles of operation, decreases with increasing burnup. For assemblies discharged after one cycle of burnup the uncertainty was estimated to be <2%; after two cycles of burnup the uncertainty was <1%; and after three cycles of burnup the uncertainty was ~1%. Particularly relevant to this discussion is the evaluation of the uncertainty in the axial distribution; uncertainties of <7% are quoted [8] for the top and bottom ends of the assemblies.

The breakdown of the 3169 profiles, in terms of fuel vendor/design, are as follows: 1334 Babcock & Wilcox (B&W) 15×15 profiles from eight reactors, 544 Combustion Engineering (CE) 14×14 profiles from one reactor, 228 CE 16×16 profiles from two reactors, 156 Westinghouse 15×15 profiles from two reactors, and 907 Westinghouse 17×17 profiles from eight different reactors. According to Ref. [9], 44,598 PWR assemblies have been discharged from commercial PWRs through 1994. Thus the YAEC-137 database represents ~4% of the total number of PWR assemblies discharged through 1994. The data covers a range of burnup from 3.086 to 55.289 GWd/MTU and an enrichment range of 1.24 to 4.75 wt % ^{235}U. To illustrate the range and depth of the database, in terms of burnup and enrichment, Fig. 2a plots the burnup and enrichment combination for each of the 3169 profiles in the database (solid lines are included on Fig. 2a to indicate the current ISG-8 limitations on maximum burnup and enrichment). Figure 2b plots the PWR SNF discharge data through 1998 [10] for comparison. The burnup and enrichment regime of ISG-8 appears to be well covered by the database. Also, in comparison to the discharge data, the lower burnup and enrichment regime appears to be well-covered; this is



(a) **(b)**

Figure 2. Burnup and enrichment combinations: (a) YAEC-1937 database and (b) discharge data through 1998.

partially due to the fact that the database includes first and second cycle profiles for many of the assemblies. For extension beyond the current burnup and enrichment limits, expansion of the database to include more profiles with higher burnup and enrichments would be desirable. However, in general, the axial burnup profile is relatively insensitive to enrichment and becomes flatter with burnup. Consequently, axial profiles for higher burnups will likely be bounded by profiles in the existing database.

The profiles in the YAEC-1937 database include fuel designs that used burnable absorbers with different poison absorber types such as: Burnable Poison Rods (BPRs) of borosilicate glass and B_4C; and Integral Burnable Absorbers (IBAs) of ZrB_2 (Integral Fuel Burnable Absorbers, IFBAs), B_4C, erbium and gadolinium. In addition, the profiles include assemblies exposed to control rods, including APSRs. Thus in terms of categories, the axial profile database appears to provide an excellent representation of discharged PWR SNF assemblies through the mid-1990s.

In addition to the YAEC-1937 database, more than 1200 measured (derived from measured power densities) axial profiles from two German reactors have become available [11]. Although these profiles are limited to two reactors that may not be representative of U.S. PWRs, they provide significantly more detailed axial burnup representation (e.g., the effect of grid spacers is readily apparent) than is available in the YAEC-1937 data. Additional axial burnup data has become available as a result of efforts performed under the Office of Civilian Radioactive Waste Management to analyze commercial reactor criticals for the Yucca Mountain Project [12].

4. Determination of Bounding Axial Profiles

To account for the axial burnup distribution in a burnup-credit evaluation, an approach must be developed to address the impact in a general manner. One such approach is to identify and use axial-burnup profiles that are limiting in terms of the value of k_{eff}, and yet sufficiently realistic as to not provide undue burden (i.e., excess conservatism). The approach to date has been to

determine “bounding” axial profiles from actual burnup profiles; either identifying specific profiles that are “bounding” or developing “artificial bounding” profiles based on the characteristics of actual “bounding” profiles.

Previous works [13, 14] in this area have employed a relatively straightforward approach – perform criticality calculations for each burnup shape to determine the shape that produces the greatest end effect. The most extensive published work is that of Parish and Chen [14], which used one-dimensional (1-D) diffusion calculations to determine bounding profiles based on the YAEC-1937 database. After excluding a number of burnup profiles for various reasons (e.g., non-uniform axial enrichment and incomplete data), the remaining 2988 burnup profiles were arranged into 12 burnup groups, each spanning a burnup range of ~4 GWd/MTU. Axially varying burnup was included by linear interpolation of 2-group assembly-averaged neutron cross sections, which were generated by CASMO-3. The axial burnup profile within each burnup group that yielded the largest end effect was identified. Based on the calculational results and physical arguments, “artificial” bounding axial profiles were developed for each of the twelve burnup-groups [14]. Although the purpose for developing these artificial profiles is not discussed, it is assumed they were developed to introduce additional conservatism. The burnup profile changes with burnup – tending to flatten with increasing burnup. Consequently, an axial burnup profile from a low burnup assembly generally yields a larger end effect than a profile from a higher burnup assembly. It is for this reason that the axial burnup profiles are separated into burnup ranges in analyses for bounding axial profiles.

Kang and Lancaster [15] expanded the work of Parish and Chen to determine bounding profiles over coarser burnup ranges for use with the DOE actinide-only burnup credit methodology [3]. Although not endorsed by ISG-8, the approach proposed in Ref. [3] represents the only known available guidance for treating the axial burnup distribution in burnup credit analyses.

In support of a more detailed assessment of the YAEC-1937 database, an independent bounding profile analysis was performed using 1-D discrete ordinates (XSDRNMPM [16]) calculations for each of the 2988 profiles considered in Ref. [14]. Unlike the work of Ref. [14], the profiles in each burnup group were evaluated consistently (i.e., at the same initial enrichment and burnup) and the profiles were ranked in terms of their corresponding k_{eff}. The criticality calculations for this evaluation corresponded to an infinite radial array of fuel pins in out-of-reactor conditions (i.e., unborated water at 20° C) and 5-year cooling. Fuel depletion calculations were performed with SAS2H. Despite the differences in approach, the independent calculations generally confirmed the bounding profiles determined in Ref. [14]. Where differences in bounding profiles were observed, the differences were due to more than one profile resulting in essentially the same k_{eff} value. In those particular cases, the difference between calculations with the bounding profile determined in this analysis and the bounding profile determined by Parish and Chen is less than 0.05% Δk.

To address questions regarding the applicability of 1-D ranking analyses to 3-D burnup credit casks, analyses were also performed with each of the profiles in the GBC-32 cask [4]. The criticality calculations were performed with the KENO V.a Monte Carlo code [16] using the SCALE 238-group cross-section library. The 3-D calculations confirmed the results of the 1-D ranking analysis.

The bounding profile analysis performed here included the major fission products. Studies to address the effect of the actinide-only assumption and cooling time on the determination of bounding axial profiles are currently being completed and documented. The preliminary results suggest the bounding profiles determined with fission products present are valid for actinide-only calculations and that within the timeframe of interest to storage and transport analyses (~5-40 years), the bounding profiles do not change with cooling time. However, these results are still being finalized.

5. Statistical Comparison of Profiles

Although the YAEC-1937 database is broad in scope, it is not exhaustive. An expressed concern has been the adequacy of this (or any) finite database to completely represent the infinite variety of possible profiles resulting from irradiation in U.S. PWRs. To address this concern, a statistical comparison has been performed on the k_{eff} values associated with each of the profiles in the database and the results have been used to (1) assess how representative the "bounding" profiles are to the rest of the profiles and (2) provide an indication of the probability that other axial profiles may exist that are more reactive than the "bounding" profiles (from the database).

The results have shown that the bounding profiles are not representative of the average. Figure 3 shows the spread of k_{eff} values that result from the set of profiles in one of the 12-burnup ranges considered, together with the bounding profile (from the database). Similar figures have also been generated for the other burnup ranges, but are not include here for brevity. In addition to the individual calculated k_{eff} values, Fig. 3 shows the mean k_{eff} value and indicators for 1, 2, and 3 standard deviations. An examination of the calculated k_{eff} values reveals that, for each of the 12 burnup ranges, the k_{eff} value associated with the bounding axial profile, is more than 3 standard deviations above the mean and, in most cases, is more than 5 standard deviations above the mean. In other words, the limiting profiles can be considered statistical outliers, as opposed to representative of typical SNF profiles. Consequently, one can infer that if the

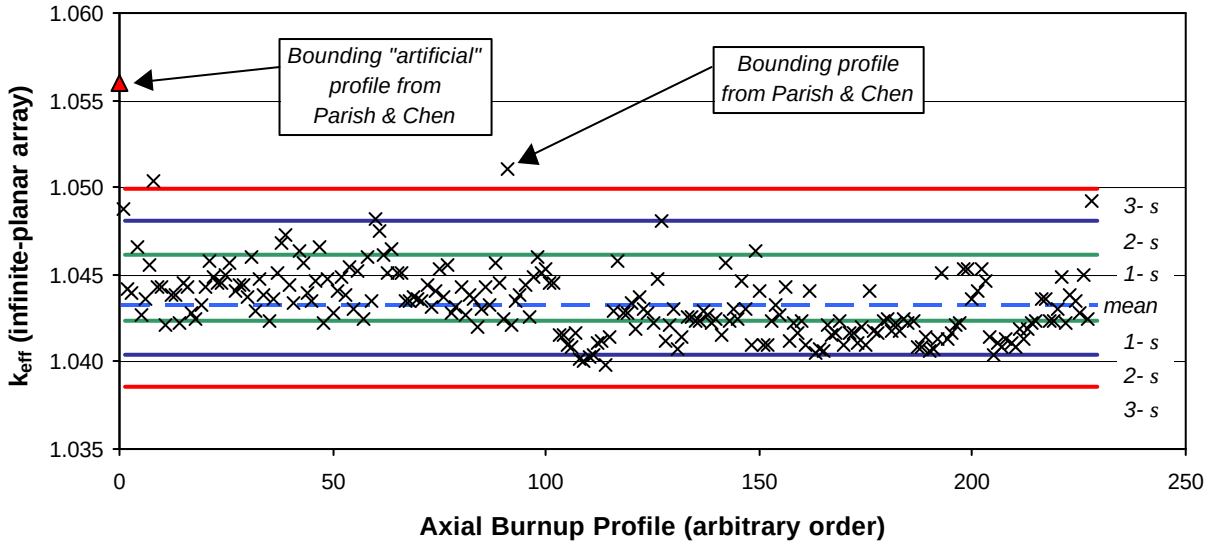


Figure 3. k_{eff} values based on the YAEC-1937 database profiles for 38-42 GWd/MTU

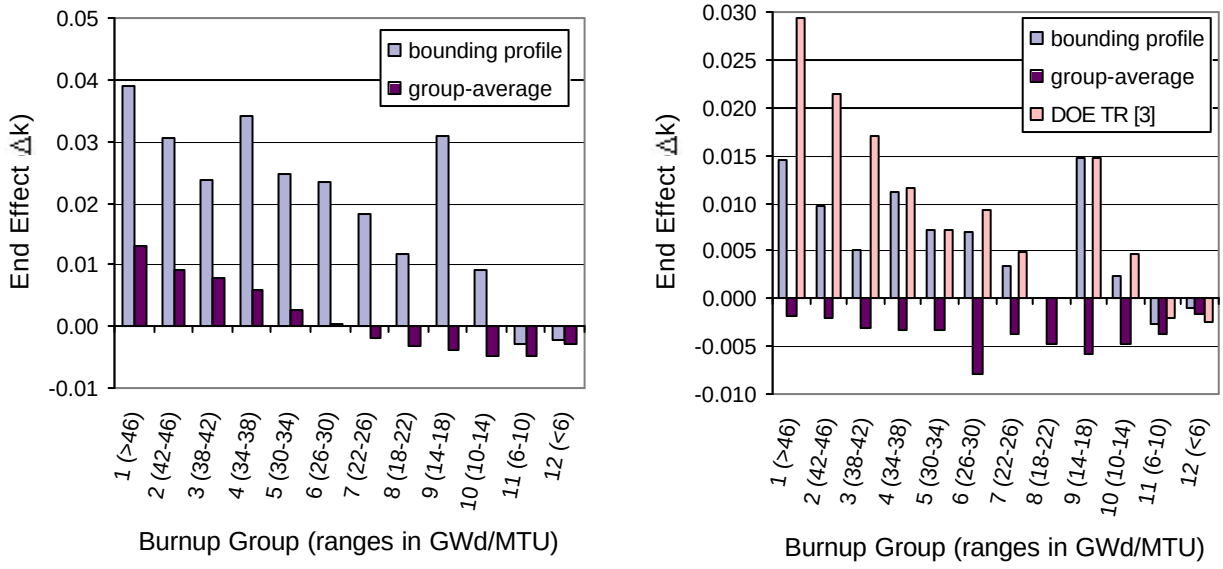
database adequately represents U.S. PWR SNF, the probability that other axial profiles exist that are notably more reactive than the limiting profile (determined from the database) is very small.

A concern with any data set is the possibility that the data set is biased by one or more data subsets. For the YAEC-1937 database, the concern is whether the conclusions reached by analysis of the database are dictated by data from a single reactor or fuel type. Although the spread in the results shown in Fig. 3 and the fact that the 12 bounding profiles include profiles from 7 different plants suggest that this is not the case, trends with fuel type and reactor were also investigated. The k_{eff} value associated with each profile was plotted in terms of fuel type and reactor to assess the existence of trends with fuel type and/or reactor operations. The results demonstrate that the most-reactive profile is often associated with the B&W 15×15 assembly; however, it is noted that this is by far the most prevalent fuel type in the database (1334 of the 3169 profiles; 42% of the total, representing 8 different reactors). The Δk values for each of the fuel types exhibit similar variability, which suggests an absence of any clear trends with fuel type. However, the CE fuel types were observed to generally exhibit smaller end effects. Comparison of Δk values for individual reactors show similar variability, which suggests an absence of any clear trends with reactor operations. However, the results of these comparisons suggest greater variability in the Δk values from reactors utilizing B&W 15×15 assemblies. This observation was confirmed by comparison of the standard deviations in k_{eff} values from the various fuel types. It is difficult to decipher whether the greater observed variability for the B&W 15×15 assemblies is real, or can be attributed to the greater representation within the database, relative to the other fuel types. Based on visual examination of the profiles and a review of past B&W operations, it is suspected that the variability is real and associated with the use of control rods and axial power shaping rods.

6. End Effect in a Burnup Credit Cask

Although the analyses in the previous sections were performed with 1-D calculations for an infinite radial array of fuel pins, the results have been confirmed with 3-D calculations with the GBC-32 cask, which is a high-density, 32-PWR-assembly conceptual cask design [4]. Figure 4a compares the end effect based on the bounding profiles from Ref. [14] to the group-average end-effect for each of the 12 burnup groups, where the "group-average end effect" refers to the average of the end effects corresponding to each of the profiles within a burnup group. The calculations for each burnup group, except for the highest and lowest burnup group, assumed the median burnup. For the highest and lowest burnup groups, burnups of 50 and 4 GWd/MTU, respectively, were assumed. The results in Fig. 4a demonstrate that the group-average end effect is less than ~1% Δk for these conditions (i.e., 5-year cooling, fission products present) and is negative for burnups below approximately 26 GWd/MTU. The use of the bounding profiles results in end effects that are generally between 1 and 4% Δk, and thus adds considerable margin as compared to the average.

For comparison of analyses without fission products, Fig. 4b shows the end effect in the GBC-32 cask with only the major actinides included (i.e., ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am). The results in Fig. 4b demonstrate that, on average, the end effect is negative for these conditions (i.e., 5-year cooling, actinide-only). However, the use of the bounding profiles results in end effects that are generally positive and <1.5% Δk. Note that the end effect is known



(a) **(b)**

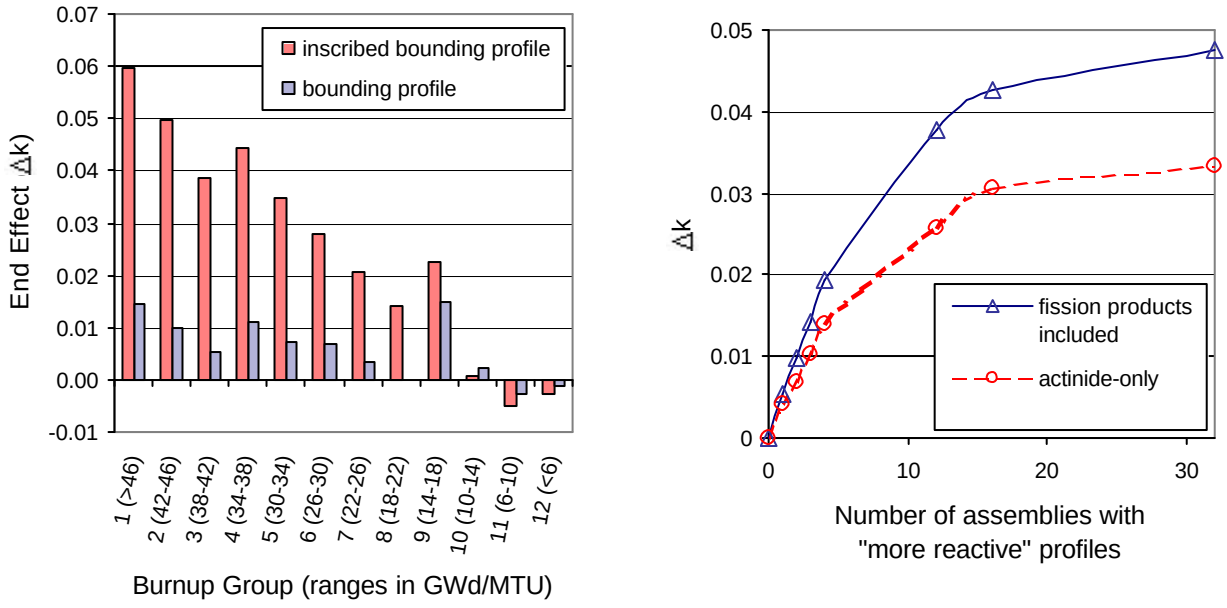
Figure 4. Comparison of end effects in the GBC-32 cask based on calculations with 5-year cooling: (a) actinides and fission products and (b) actinides-only.

to increase notably with increasing cooling time. Although less than when fission products are included, it is evident from Fig. 4b that the use of bounding profiles adds considerable margin (as much as 1.5% Δk), as compared to the actual average.

For comparison, Fig. 4b also shows the end effect resulting from the approach suggested in the DOE topical report on actinide-only burnup credit [3], which consists of using bounding profiles over coarser burnup ranges (i.e., a single profile in each of the following 3 burnup ranges: 0-18, 18-30, and >30 GWd/MTU). The 3 profiles suggested for use in the DOE topical report correspond to the bounding profiles from Ref. [14] for burnup groups 5, 8, and 9. Therefore, the end effect associated with the bounding profiles and the approach of Ref. [3] are equivalent for burnup groups 5, 8, and 9. For a given profile, the end effect increases with burnup, and thus the Ref. [3] approach of using bounding profiles associated with coarse burnup ranges results in larger end effects, as is apparent in Fig. 4b. However, the more conservative nature of the approach in Ref. [3] may be considered preferable to the use of 12 different bounding profiles. In any case, the approach in Ref. [3] is simpler from an analysis standpoint.

7. Impact of Significantly More Reactive Profiles

Finally, analyses were performed to assess the impact of loading an assembly into a burnup credit cask that has an axial profile that is not bounded by the exiting database. The more-reactive profiles used for the analysis were artificially developed profiles created by setting the average node burnup equal to the minimum node burnup for the actual bounding profiles. Although this approach, referred to as inscribing, yields axial profiles that result in significantly larger end effects (as shown in Fig. 5a), it is an effective means to define an **extremely more-reactive profile** that may be used for this evaluation. The analysis was performed for a burnup of 36 GWd/MTU, which corresponds to burnup group 4, and assumed that the assemblies with the more-reactive profile were loaded in the cask from the center outward; the bounding profile



(a) **(b)**

Figure 5. End effect comparisons in GBC-32 cask with 5-year cooling: (a) inscribed profiles and actinide-only conditions and (b) D*k* consequence of loading assemblies with a more-reactive profile (based on inscribing) for a burnup of 36 GWd/MTU.

was used for the other assemblies. The results are shown in Fig. 5b for calculations with and without fission products present and confirm the relatively small reactivity consequence associated with a single assembly with an extremely more reactive profile. Results are also shown in Fig. 5b for multiple loadings of assemblies with more-reactive profiles to demonstrate the associated impact on k_{eff}. The reactivity consequence of loading a single assembly with an extremely more reactive profile, as compared to the bounding profile, is shown to be less than ~0.5% Δk. Note that the reactivity consequence of loading an assembly with a more-reactive profile will depend on burnup and the definition of the more- reactive profile.

8. Summary

The analyses summarized in this paper are part of a larger study/effort to develop a technically justifiable approach for addressing the axial burnup distribution in burnup credit analyses. These studies suggest that the YAEC-1937 database is adequate for obtaining profiles for use with actinide-only burnup credit within the burnup and enrichment range of ISG-8 (≤40 GWd/MTU, ≤4.0 wt % ^{235}U). The rationale for this conclusion are: (1) the database appears to provide an adequate representation of discharged U.S. PWR SNF; (2) the bounding profiles, as determined from the database, are statistical outliers, and thus the probability that more reactive profiles exist is very small; (3) the bounding profiles will be applied to all assemblies in a burnup credit cask; and (4) the reactivity consequence of loading an assembly with an artificially-developed more-reactive profile is small. Note that use of the bounding profiles has been shown to add considerable margin (as much as 1.5% Δk) as compared to the actual average. Although there are more than 200 profiles for enrichments greater than 4.0 wt % ^{235}U and more than 350 profiles for burnups greater than 40 GWd/MTU, the finding is limited to the specified burnup and

enrichment range defined in ISG-8 at this time. Future work should address the adequacy of the database for higher burnups and enrichments, and expand the database as additional profiles become available. Additionally, future work should also evaluate the impact of the burnup uncertainty. Planned future work will seek to use risk-informed insights to relax conservatism by establishing criteria for the development and use of more realistic profiles. For example, if axial-profile measurements for each assembly were performed prior to loading, a profile deemed bounding for the "typical" profiles could be used in a safety analysis and the profile for the as-loaded assembly could be checked for adherence. Alternatively, approaches to allow the use of more realistic profiles (e.g., profiles that bound 95% of the actual profiles) without such axial measurements should also be investigated.

References

1. *Spent Fuel Project Office Interim Staff Guidance – 8, Rev. 1 – Limited Burnup Credit*, U.S. Nuclear Regulatory Commission, July 30, 1999.

2. J. C. WAGNER and M. D. DeHART, *Review of Axial Burnup Distribution Considerations for Burnup Credit Calculations*, ORNL/TM-1999/246, Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, February 2000.

3. *Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages*, DOE/RW-0472, Rev. 2, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, September 1998.

4. J. C. WAGNER, *Computational Benchmark for Estimation of Reactivity Margin from Fission Products and Minor Actinides in PWR Burnup Credit*, ORNL/TM-2000/306, Oak Ridge National Laboratory, in preparation.

5. M. TAKANO and H. OKUNO, *OECD/NEA Burnup Credit Criticality Benchmark - Result of Phase IIA*, JAERI-Research-96-003 (NEA/NSC/DOC(61)01), Japan Atomic Energy Research Institute, 1996.

6. A. NOURI, *OECD/NEA Burnup Credit Criticality Benchmark - Analysis of Phase II-B Results: Conceptual PWR Spent Fuel Transportation Cask*, IPSN/98-05 (NEA/NSC/DOC(98)1), Institut de Protection et de Surete Nucleaire, May 1998.

7. R. J. CACCIAPOUTI and S. VAN VOLKINBURG, *Axial Burnup Profile Database for Pressurized Water Reactors*, YAEC-1937, Yankee Atomic Electric Company (May 1997).

8. *Determination of the Accuracy of Utility Spent Fuel Burnup Records – Interim Report*, Electric Power Research Institute, EPRI TR-109929, May 1998.

9. *Spent Nuclear Fuel Discharges from U.S. Reactors 1994*, SR/CNEAF/96-01, Energy Information Administration, U.S. Department of Energy, February 1996.

10. RW-859 Nuclear Fuel Data, Energy Information Administration, draft.

11. J. C. NEUBER, *Measured Axial Burnup Shapes from Nuclear Power Plants Neckarwestheim 1 and Neckarwestheim 2*, Siemens AG Power Generation Group, NEA-1607, June, 1999.

12. *Disposal Criticality Analysis Methodology Topical Report*, YMP/TR-004Q, Rev. 1, DOE OCRWM (2000).

13. M. D. DeHART, *Sensitivity and Parametric Evaluations of Significant Aspects of Burnup Credit for PWR Spent Fuel Packages*, ORNL/TM-12973, Lockheed Martin Energy Research Corp., Oak Ridge National Laboratory, May 1996.

14. T. A. PARISH and C. H. CHEN, *Bounding Axial Profile Analysis for the Topical Report Database*, Nuclear Engineering Dept, Texas A&M University, May 1997.

15. C. H. KANG and D. B. LANCASTER, "Actinide-Only Burnup Credit for Pressurized Water Reactor Spent Nuclear Fuel – III: Bounding Treatment of Spatial Burnup Distributions," *Nucl. Technol.* **125**, 292 (1999).

16. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, III, May 2000. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.