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DEVELOPMENT OF TECHNICAL BASIS FOR BURNUP CREDIT REGULATORY GUIDANCE IN THE UNITED STATES

C. V. Parks
Oak Ridge National Laboratory

J. C. Wagner
Oak Ridge National Laboratory

D. E. Mueller
Oak Ridge National Laboratory

I. C. Gauld
Oak Ridge National Laboratory

ABSTRACT

In the United States there has been and continues to be considerable interest in the increased use of burnup credit as part of the safety basis for spent nuclear fuel (SNF) systems, and this interest has motivated numerous technical studies related to the application of burnup credit for assuring subcriticality limits are met. Responding to industry requests and needs, the U.S. Nuclear Regulatory Commission initiated a burnup credit research program, with support from the Oak Ridge National Laboratory, to develop regulatory guidance and the supporting technical bases for allowing and expanding the use of burnup credit in pressurized-water reactor SNF storage and transport applications. The objective of this paper is to summarize the work and significant accomplishments, with references to the technical reports and publications for complete details.

INTRODUCTION

Historically, criticality safety analyses for transport and dry cask storage of spent nuclear fuel (SNF) in the United States assumed the fuel contents to be unirradiated (i.e., “fresh”) fuel compositions. However, it is well understood that taking credit for the reduction in reactivity associated with fuel depletion can enable more cost-effective, higher-density storage and transport of SNF while maintaining a sufficient subcritical margin to establish an adequate safety basis. In recent decades, increasing SNF inventories have necessitated expanding and optimizing SNF storage and transport capacity. Consequently, there has been, and continues to be, considerable interest in the United States in the increased use of burnup credit in SNF operations, particularly related to storage and transport of commercial pressurized-water reactor (PWR) SNF.

In July 1999, the U.S. Nuclear Regulatory Commission (NRC) Spent Fuel Project Office (SFPO) issued Interim Staff Guidance 8, Revision 1 (ISG8R1), to provide recommendations for the use of burnup credit in storage and transport of PWR SNF.[1] A discussion of the technical considerations that helped form the development of ISG8R1 is available in Ref. 2. ISG8R1 is specific to PWR fuel; no such similar guidance permitting burnup credit for boiling-water reactor fuel in storage and transport has been developed. ISG8R1 recommendations were subsequently included in the standard review plans for transportation casks and dry storage cask facilities.[3,4] Subsequent to the issuance of ISG8R1, the NRC Office of Nuclear Regulatory Research (RES) initiated an effort at the Oak Ridge National Laboratory (ORNL) to investigate the technical basis for extending the criteria and recommendations of ISG8R1 with the goal of improved implementation of burnup credit. The work sponsored by NRC RES provided reference material for NRC SFPO to use in its preparation of Revision 2 of ISG8 (ISG8R2),[5] which was released in September 2002. Reference 6 discusses each of the six recommendations within ISG8R2 with specific emphasis on the changes implemented with ISG8R2. More recently, work sponsored by NRC RES has been focused on resolution of issues related to burnup credit license applications and extension of burnup credit to include credit for fission products.

The following sections provide a brief review of the numerous technical studies performed by ORNL for the U.S. NRC burnup credit research program.

REVIEW OF TECHNICAL STUDIES

The NRC research program was initiated using a baseline report[7] developed to document the current status of burnup credit and to provide a straw man prioritization for areas where additional guidance, information, and/or improved understanding were judged beneficial to the effective implementation of burnup credit in transport and dry storage casks. The baseline report was used to initiate and facilitate a Phenomena Identification and Ranking Table (PIRT) process, which was used by the NRC RES to help prioritize a coordinated program of research and, via expert and public meetings, obtain input/feedback from industry and other interested parties. The results of the PIRT panel's findings are documented in Ref. 8. Focus areas for the NRC research program were established.[9] The activities and accomplishments within each of the focus areas are reviewed briefly in this section.

Enhancements to the Guidance

The initial research activity was to develop a comprehensive reference report that used current cask designs (rail and truck) to provide a consistent basis for demonstrating the magnitude of the various negative reactivity components as a function of burnup, initial enrichment, and cooling time.[10] A reference configuration consisting of a cask with 32 PWR assembly locations (referred to as the GBC-32) was developed, and the Standardized Computer Analyses for Licensing Evaluation (SCALE) code system[11] was used to calculate the reactivity components as a function of initial enrichment (2–5 wt % ^{235}U), burnup (0–60 GWd/MTU), and cooling time (0–40 years). The ISG8R1 recommended that applicants prepare an estimation of the additional reactivity margin available from fission products and minor actinides relative to SNF compositions containing only the major actinides. The values in Reference 10 can provide an indication of the validity of design-specific estimates of fission-product margin. Figure 1 shows the range of predicted fission product margin and shows the minimum margins increase with burnup from ~0.03 Δk at 10 GWd/MTU to ~0.08 Δk at 60 GWd/MTU.

To assist the research effort and to provide NRC staff with a tool to readily investigate and quantify the effects of the various burnup credit input assumptions, a new computational analysis sequence, the Standardized Analysis of Reactivity for Burnup Credit using SCALE (STARBUCS), was developed.[12] The sequence automates coupling of the depletion/decay analysis for each spatial zone to the 3-D criticality analysis, allowing the user to easily model the axial and horizontal burnup gradients in a spent fuel assembly, select the specific actinides and/or fission products to be included in the criticality analysis, apply isotopic correction factors to the predicted spent fuel nuclide inventory to account for computational bias and uncertainties, and automatically generate loading curves.[13]

Neutron spectrum hardening may cause a fuel assembly burned in conjunction with burnable absorbers to have a higher reactivity for a given burnup than an assembly that has not used burnable absorbers. Thus, ISG8R1 did not recommend use of burnup credit for fuel containing burnable

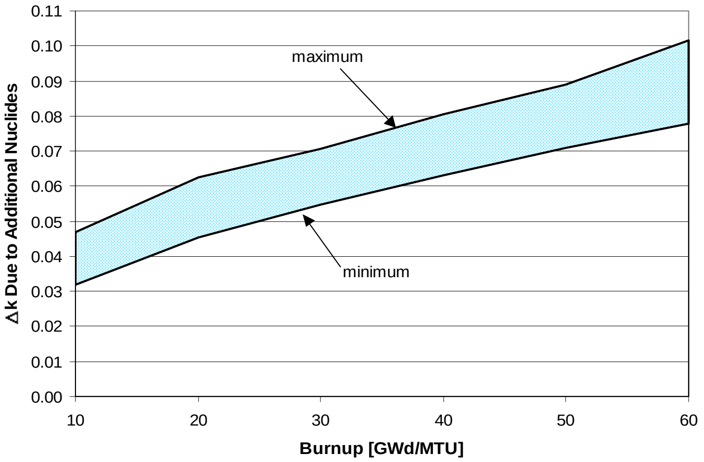

Figure 1. Range of Δk values in the GBC-32 cask due to the additional nuclides (minor actinides and fission products) as a function of burnup for all cooling times and initial enrichments considered. *Source*: Ref. 10.

poison rods (BPRs) and/or integral burnable absorbers (IBAs) or for assemblies exposed to control rods (CRs)—limitations that the PIRT panel saw as significant because of the large inventory of assemblies affected. Hence, the research program performed investigations[14- 16] to quantify how the k_{eff} value of a discharged assembly would change due to irradiation with BPRs and IBAs included in the assembly. References 14–16 provide a characterization of the effect of burnable absorbers (e.g., see Figure 2) on SNF and indicate that a depletion analysis with a maximum realistic loading of BPRs (i.e., maximum neutron poison loading) and maximum realistic burnup for the exposure should provide an adequate bounding safety basis for fuel with or without burnable absorbers. This result led to the recommendation included in ISG8R2 allowing assemblies exposed to burnable absorbers to be loaded in a burnup-credit cask provided a bounding approach was utilized in the depletion analysis. The varying effects of CR insertion as a function of burnup and CR design were also quantified and typical operating conditions were reviewed, enabling an increased understanding of the effect of CR exposure on the reactivity of discharged SNF.[16,17] The study showed that full CR insertion for burnup values up to 5–10 GWd/MTU (a conservative value for PWRs operating in the U.S.) results in an increase in cask k_{eff} values on the same order as seen for BPRs. Thus, since BPRs and CRs cannot be inserted in an assembly at the same time, it follows that the inclusion of BPRs in the assembly irradiation model (up to burnup values that encompass realistic operating conditions) should adequately account for the potential increase in k_{eff} that may occur for SNF exposed to CRs during irradiation.

Another restriction within ISG8R1 that was deemed significant by the PIRT panel was that credit for only 5 years of cooling time was recommended. This recommendation eliminated assemblies with shorter cooling times from cask loading and limited the allowable credit for reactivity reduction associated with cooling time. A comprehensive study[18] of the reactivity behavior as a function of cooling time for various cask designs and SNF compositions was performed. Figure 3 illustrates the expected reactivity behavior for SNF in the GBC-32 cask for different SNF composition assumptions, including actinides only, actinides plus fission products, and all available nuclides. The fact that the reactivity begins to increase around 100 years after discharge necessitates consideration of the time frame for interim SNF storage and transport in the evaluation of acceptable cooling times. The curve indicates that the reactivity of the SNF at 40 years after discharge is approximately the same as that of the SNF cooled for 200 years. At the time of this study, the probability that SNF in a storage or transportation cask would remain in place for more than 200 years was judged to be low, which led to the recommended limiting cooling-time criterion in ISG8R2 of 40 years (i.e., no credit for cooling time beyond 40 years should be taken).

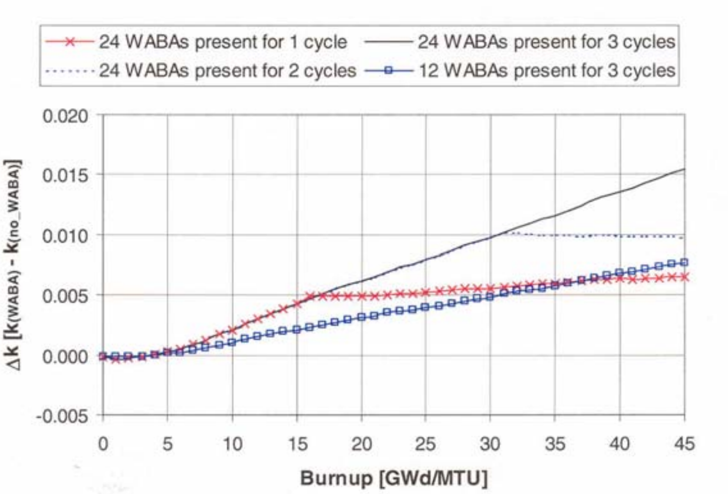

Figure 2. Comparison of Δk values, as a function of burnup, for assemblies exposed to wet annular burnable assembly rods. Results correspond to Westinghouse 17 × 17 assemblies with 4.0 wt % ^{235}U initial enrichment. *Source*: Ref. 14

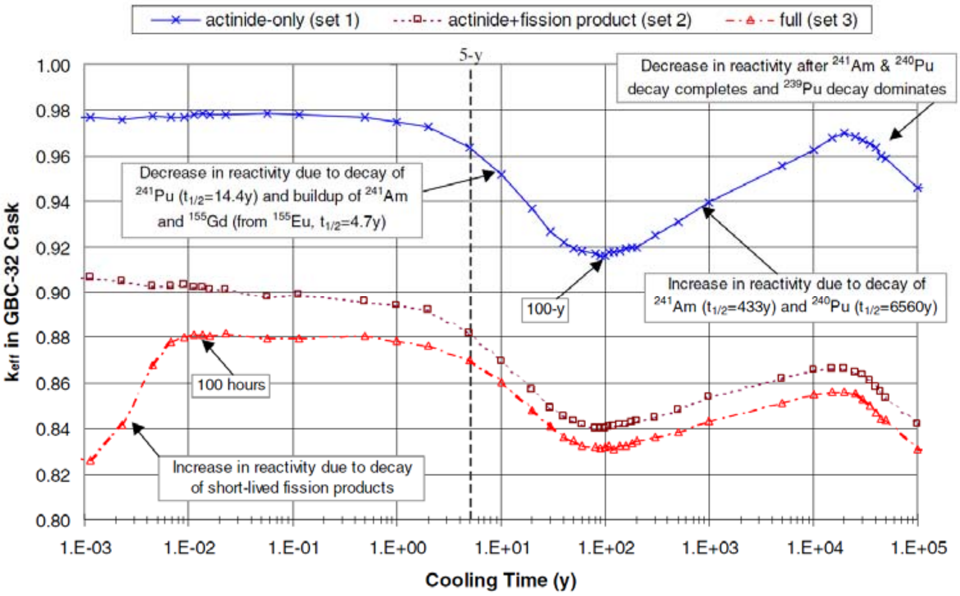

Figure 3. Reactivity behavior in the GBC-32 cask as a function of cooling time for different nuclide sets. The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup. *Source*: Ref. 18.

An ISG8R1 deficiency noted by the PIRT panel was the lack of criteria and guidance for the selection of an appropriate axial burnup profile for use in a safety assessment. The axial-burnup profile has a significant impact on reactivity (> 8% Δk for high burnup SNF with actinides and fission product compositions) and therefore the assumed profile(s) is an important component of a burnup-credit safety analysis.[19] The U.S. database of profiles was examined in detail to identify profiles that maximize the k_{eff}, assess its adequacy for PWR burnup credit analyses, and investigate the existence of trends with fuel type and/or reactor operations.[20,21] The U.S. database provides a good representation of discharged assemblies in terms of fuel vendor, reactor design, types of operation; however, it was deficient in the number of profiles associated with assembly burnup values greater than 40 GWd/MTU and initial enrichment values greater than 4.0 wt %. The work of Reference 21 indicates that a high probability exists that profiles providing the highest reactivity in intermediate burnup ranges will also provide the highest reactivity at higher burnups. Consequently, by using risk-informed judgment along with the margin presented by isotopes not included in the safety analysis, the existing database was judged adequate for burnup values beyond 40 GWd/MTU and initial enrichments above 4 wt%. However, it was recommended that care be taken to select profiles that include a margin for the potential added uncertainty in moving to higher burnups and initial enrichments.

Another goal of the research program was to provide guidance to regulators and industry on the technical areas where improved information could most enhance the estimation of accurate subcritical margins and identify areas where future work would provide the most benefit.[22] The report also included an evaluation of the degree of burnup credit needed for high-density casks to transport the current discharged U.S. inventory of SNF. Loading curves (one for each assembly design) for the GBC-32 package based on credit for actinides only and the recommendations of ISG8R2 showed that only 27% of the total U.S. inventory of SNF could be loaded.[23] These results demonstrated that additional negative reactivity (through either increased credit for fuel burnup or cask design/utilization modifications) is necessary to accommodate the majority of the discharged SNF assemblies in high-capacity casks. However, relatively small shifts in the actinide-only-based cask loading curves can have a significant impact on the number of SNF assemblies that are acceptable for loading (see Figure 4). Reference 22 demonstrated that the most significant component that could effectively impact a shift of the loading curve is the accurate inclusion of fission products. Consequently, experimental data and an effective approach for validation of fission products were confirmed to be key elements necessary for the expanded utilization of burnup credit.

Experiments and Methods to Reduce Subcritical Margin

Uncertainties in the predicted isotopic concentrations in SNF represent one of the largest sources of overall uncertainty in criticality calculations that use burnup credit. As shown in Ref. 22, the uncertainties in the calculated nuclide concentrations can have a significant effect on the uncertainty in the safety margin in criticality calculations and ultimately can affect the potential capacity of spent fuel transport and storage casks employing burnup credit. Therefore, efforts were initiated to investigate, compare, and document[24] approaches for considering the effects of nuclide uncertainties in burnup-credit analyses. The subcritical margin estimated using best-estimate methods was compared with the margin estimated using conventional bounding methods of uncertainty propagation. To quantify the comparison, each of the strategies for estimating uncertainty was performed using a common database of spent fuel isotopic assay measurements (i.e., destructive measurements of isotopic compositions) for PWR fuels and predicted nuclide concentrations obtained using the SCALE code system. The experimental database applied in the study was expanded, from that used in previous studies, to include 56 spent fuel assay samples that included the important burnup-credit actinides and some limited fission product measurements. The study demonstrated that the bounding method, while easy to implement and clearly easy to defend as conservative, results in unrealistically large margins that were at least twice that predicted using best-estimate methods. The work described in Ref. 24 has led to renewed focus on the acquisition, evaluation, and analysis of additional destructive radiochemical assay measurement data, with emphasis on recently available high-enrichment and high-burnup data that include fission product measurements.[25-27]

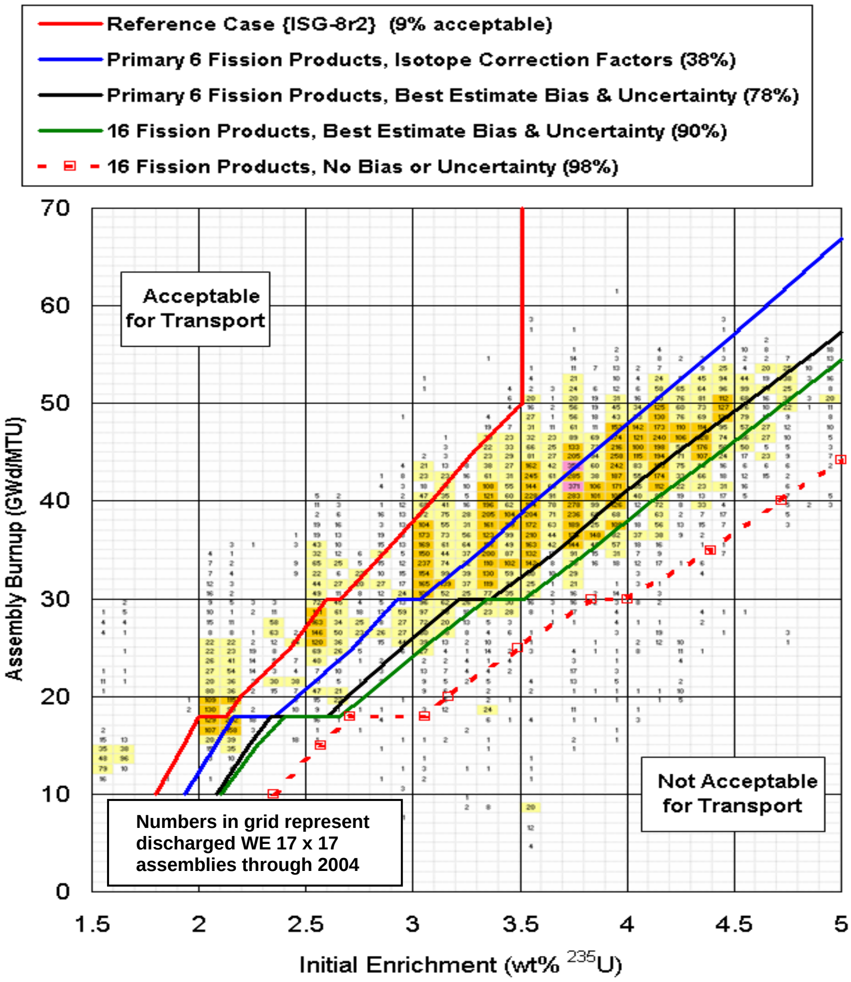

Figure 4. Comparison of loading curve calculational assumptions for WE 17 × 17 fuel assemblies. Percentages of inventory acceptable for the GBC-32 cask are shown in parentheses. “Primary 6 Fission Products” are ^{103}Ru, ^{133}Cs, ^{149}Sm, ^{143}Nd, ^{151}Sm, and ^{155}Gd . “16 Fission Products” are ^{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, and ^{155}Gd. *Source*: Ref. 28.

NRC staff have noted that the rationale for restricting ISG8R2 to actinide-only is based largely on the lack of clear, definitive experiments that can be used (even for actinide-only SNF compositions) to estimate the bias and uncertainty for computational analyses associated with a burnup credit safety case. To address the issue of criticality validation, ORNL directed its efforts at obtaining, and making available to industry, a well-qualified experimental database. Rather than an *a priori* decision on suitability of candidate experiments, ORNL sought to obtain and assess critical experiment data from the following sources:

1. critical experiments within the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (IHECSBE),
2. proprietary critical experiment data,
3. commercial reactor critical state points (CRCs) (i.e., critical state points from operating reactors), and
4. proposed new critical experiments.

The experiments either do not contain the same set of nuclides and/or relative compositions present in SNF or they have other aspects that might impair their use in validation (e.g., the CRCs). As part of this effort, ORNL negotiated to gain access to a series of proprietary critical experiments, referred to as the Haut Taux de Combustion (HTC) experiments, performed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) at their Valduc critical experiment facility. These experiments were of interest because the plutonium-to-uranium ratio and the isotopic compositions of both the uranium and plutonium used in the simulated fuel rods were designed to be similar to those of a typical PWR fuel assembly with an initial enrichment of 4.5 wt % ^{235}U and burnup of 37.5 GWd/MTU. The HTC experiments include configurations designed to simulate fuel-handling activities, pool storage, and transport in casks constructed of thick lead or steel. Reports[29,30] were prepared that discuss existing relevant experiments from the IHECSBE, the evaluation of the four HTC experimental data reports and ORNL analysis of the experiments, applicability of the experiments to PWR SNF applications as determined by sensitivity/uncertainty methods,[31] and conclusions and recommendations concerning their use for burnup credit applications. The HTC experiments substantially strengthen the technical basis for validation by adding to the previously small number of applicable experiments against which to compare burnup credit applications.

To address questions that arose related to the use of CRC state points for criticality validation, studies[32,33] were performed to assess the neutronic similarities that may exist between a generic cask containing typical SNF assemblies and CRC state points. The results indicated that the CRC state points at or near the end of a reactor cycle are highly similar to the GBC-32 cask containing SNF assemblies. However, the report also notes that the uncertainties in the complex CRC configurations (e.g., fuel isotopic compositions, physical characteristics of reactor core components, and reactor operating history information) are not known and that an evaluation and quantification of the uncertainties in the CRC configurations is needed prior to the use of CRCs for code validation (i.e., quantifying code bias and bias uncertainty).

A principal challenge for crediting fission products in a burnup credit safety evaluation is the limited availability of relevant fission product critical experiments for bias and bias uncertainty determination. A recent paper[34] provides an evaluation of the available critical experiments that include fission products, along with bounding, burnup-dependent estimates of fission product biases generated by combining energy-dependent sensitivity data for a typical burnup credit application with the nuclear data uncertainty information distributed with SCALE 6. Using the methods described in Ref. 34, the bias determined for the GBC-32 cask using the 16 most important stable or near-stable fission products is predicted to be no greater than 2% of the total worth of the 16 fission products, or <1.3% in k_{eff}.

Burnup Measurements

ISG8R2 recommends a burnup measurement for each assembly to confirm the reactor record and compliance with the assembly burnup value used for loading acceptance. To understand the significance of a misload, and the corresponding diligence with which such misloadings should be prevented, it is necessary to understand the consequences of potential assembly misloading on the system k_{eff} value and to evaluate the associated increases in k_{eff} against inherent margins (e.g., an administrative margin), where present. To support this understanding, a study[35] was performed to determine the changes in k_{eff} that can result from a wide variety of postulated fuel misloading events in the GBC-32 cask. A large variety of misload scenarios were postulated and analyzed (e.g., misloading one or more assemblies with lower burnup than allowed, misleading one or more fresh fuel assemblies). The report did not address the likelihood of occurrence for any of the misload configurations considered. In summary, the consequences to k_{eff} of loading assemblies that have slightly reduced burnup (e.g., 5% due to uncertainties in the burnup verification process), as compared with the required burnup, were fairly small (≤1% Δk). On the other hand, loading one or more highly enriched (i.e., >4 wt %) fresh fuel assemblies has a significant consequence on criticality safety. These findings suggest that while it may not be necessary to precisely verify the burnup value, it is necessary to ensure that fresh or very low burnup (nearly fresh) fuel assemblies are not misloaded into a cask.

NRC has initiated an effort to reevaluate the burnup measurement recommendation of ISG8R2 and to evaluate potential alternatives to confirmatory burnup measurements.[36] In support of that effort, a report[37] was prepared to review and summarize information and issues relevant to preshipment burnup measurements when using burnup credit in PWR SNF transport and storage casks. In particular, the report reviewed the role of burnup measurements for demonstrating compliance with burnup loading criteria, burnup measurement capabilities and experience, generation and accuracy of utility burnup records, fuel movement and misloading experience, and the consequences of misloading assemblies in casks designed for burnup credit.

RECENT ACTIVITIES AND FUTURE DIRECTIONS

Current research efforts are directed toward developing the technical basis and information for revising ISG8R2 to allow credit for fission products. As mentioned, these efforts are primarily focused on the acquisition, evaluation, and analysis of additional critical experiment and radiochemical assay data and on methods development related to the use of the data to support credit for fission products. The goal is to develop and establish a technically sound validation approach (both depletion and criticality) for SNF criticality safety evaluations based on best-available data and methods, to demonstrate the approach and applicability, and to provide reference bias results. Specifically, for isotopic validation, the planned approach is to use a best-estimate Monte Carlo-based method to determine burnup-dependent reactivity bias and bias uncertainty in isotopic predictions via comparisons of isotopic composition predictions and measured isotopic compositions from destructive radiochemical assay, utilizing as much assay data as is available. For criticality validation, the planned approach is to utilize available critical experiment data (e.g., the HTC data) for validation of principal actinides, utilize as much available fission-product critical experiment data as is practically possible, utilize calculated sensitivities and nuclear data uncertainties to predict individual biases for all relevant fission products as a function of burnup, and verify predictions of biases based on sensitivities and nuclear data uncertainties with calculated biases based on the limited available fission-product critical experiment data. These activities are ongoing and will be the subject of future papers.

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