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U.S. Regulatory Recommendations for Actinide-Only Burnup Credit in Transport and Storage Casks

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Abstract. 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 pressurized-water reactor (PWR) spent fuel. Subsequent to the issuance of ISG8R1, the NRC Office of Regulatory Research (RES) has directed an effort to investigate the technical basis for extending the criteria and recommendations of ISG8R1 to allow improved implementation of burnup credit. This work sponsored by NRC/RES provided the reference material used by the NRC/SFPO to prepare Revision 2 of ISG8 (ISG8R2) that was released in September 2002. This paper discusses each of the six recommendations within ISG8R2 with specific emphasis on the changes implemented with ISG8R2 and the technical basis for the changes.

1. Introduction

The concept of taking credit for the reduction in reactivity due to irradiation of nuclear fuel (i.e., fuel burnup) is commonly referred to as burnup credit. The reduction in reactivity that occurs with fuel burnup is caused by the net reduction of fissile nuclides and the production of parasitic neutron-absorbing nuclides (nonfissile actinides and fission products). Historically, criticality safety analyses for transport and dry cask storage of spent nuclear fuel (SNF) assumed the fuel contents to be unirradiated (i.e., "fresh" fuel) compositions. 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 pressurized-water reactor (PWR) spent fuel [1]. These recommendations were subsequently included in the Standard Review Plan for transportation casks and dry storage cask facilities [2, 3]. Subsequent to the issuance of ISG8R1, the NRC Office of Nuclear Regulatory Research (RES) directed an effort to investigate the technical basis for extending the criteria and recommendations of ISG8R1 to allow improved implementation of burnup credit. The work sponsored by NRC/RES provided the reference material used by the NRC/SFPO to prepare Revision 2 of ISG8 (ISG8R2) [4], which was released in September 2002.

Similar to ISG8R1, the recommendations provided in ISG8R2 cover six areas:

(a) general information on limits for the licensing basis,
(b) guidance on code validation,
(c) guidance on licensing-basis model assumptions,
(d) guidance on preparation of loading curves,
(e) the process for assigning a burnup loading value to an assembly, and
(f) the benefit derived in demonstrating any additional reactivity margin beyond that which can be substantiated through the validation process.

The remainder of this paper discusses each of these six recommendations, with specific emphasis on the changes implemented with ISG8R2 and the technical basis for the changes.

2. Limits for licensing basis

Similar to ISG8R1, the recommendations of ISG8R2 restrict burnup credit to actinide compositions associated with UO_2 fuel irradiated in a PWR. However, ISG8R2 provides additional ranges for the burnup, initial enrichment, and cooling times that can be considered in the safety analysis performed for the licensing basis. ISG8R1 recommended that burnup credit should only be taken for assembly-averaged burnups up to a value of 40 GWd/MTU and that fuel with initial enrichments between 4.0 wt % and 5.0 wt % have an additional margin of burnup (1 GWd/MTU for every 0.1% enrichment above 4.0 wt %) beyond that for which credit is taken. Since the issuance of ISG8R1, additional radiochemical assay data for PWR fuel have become available. Figure 1 shows that the range of existing radiochemical data that are readily available for validation now extends up to 47.3 GWd/MTU and 4.1 wt % initial enrichment. Risk-informed technical judgement indicates that trends in the calculational bias and uncertainty derived from this database (see Sect. 3) can be extended for use with SNF having initial enrichments up to 5.0 wt % and average assembly burnups limited to 50 GWd/MTU. Fuel with an average assembly burnup greater than 50 GWd/MTU can be loaded into a burnup-credit cask; however, based on the limited assay data available for validation, credit should only be taken for the reactivity reduction up to 50 GWd/MTU.

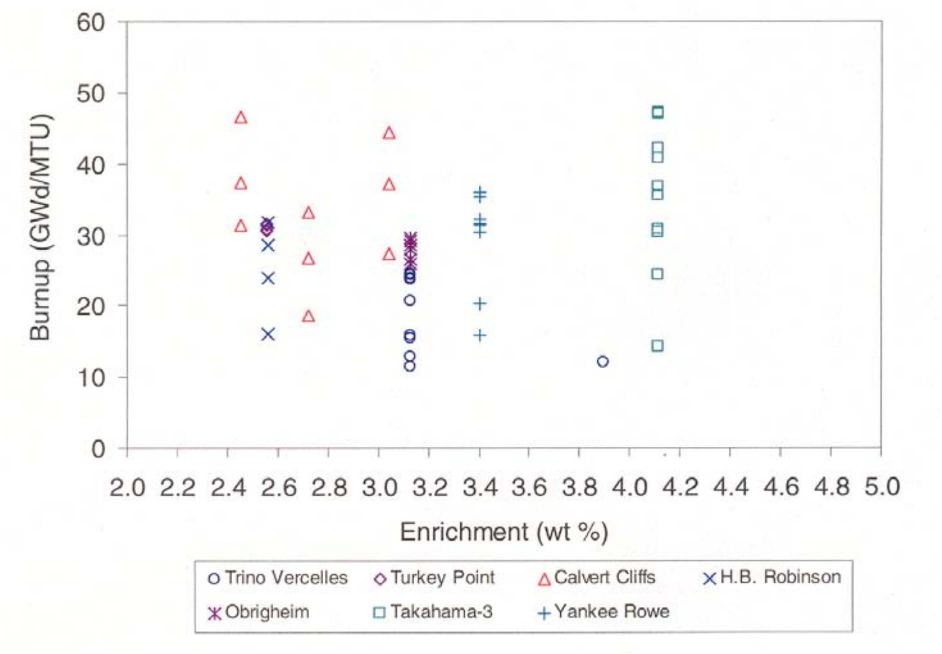

FIG. 1. Enrichment and burnup of 56 PWR assay samples available for burnup-credit isotopic validation.

Figure 2 illustrates the expected reactivity behavior for SNF in a hypothetical 32-element General Burnup Credit (GBC-32) cask, assuming use of major actinide concentrations in the calculation of k_{eff}. The fact that the reactivity begins to rise around 100 years after discharge means that the time frame for interim SNF storage should be considered in the evaluation of acceptable cooling times. The curve indicates that the reactivity of the fuel at 40 years is about the same as that of the fuel cooled for 200 years. The low probability that fuel in a storage or transportation cask would remain in place for more than 200 years led to the recommended limiting cooling-time criterion of 40 years (i.e., no credit for cooling time beyond 40 years should be taken). Approval of a cooling time longer than 5 years for burnup credit in dry storage or transportation casks does not automatically guarantee acceptance for disposal without repackaging. Reference [5] provides a comprehensive study of the effect of cooling time on burnup credit for various cask designs and SNF compositions.

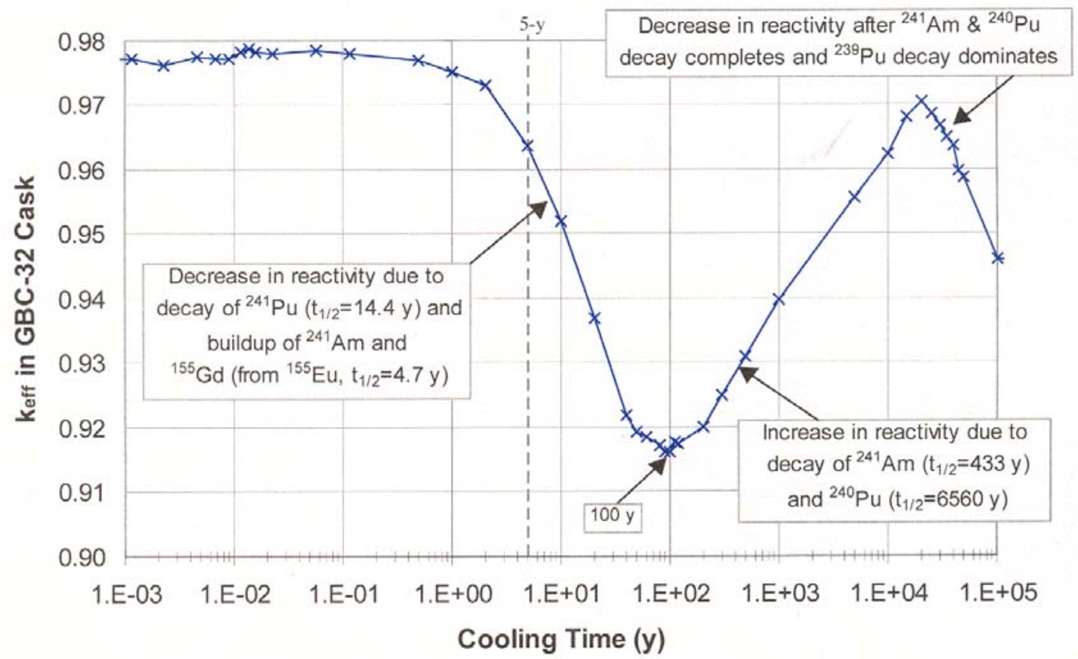

FIG. 2. Plot of k_{eff} in the prototypic GBC-32 cask using actinide-only assumptions for 40 GWd/MTU fuel with a 4.0 wt % initial enrichment.

The recommended acceptance criteria for burnup credit were set based on the characteristics of SNF discharged to date, the parameter space considered in the predominance of technical investigations, and the experimental data available to support development of a calculational bias and uncertainty. A safety analysis that uses parameter values outside those recommended by ISG8R2 will need to (a) demonstrate that the measurement or experimental data necessary for proper code validation have been included and/or (b) provide adequate justification that the analysis assumptions or the associated bias and uncertainty have been established in such a fashion as to bound the potential impacts of limited measurement or experimental data.

3. Code validation

ISG8R2 provides no substantive change in the guidance for code validation; the recommendation calls for validation of the analysis tools using measured data to determine appropriate bias and uncertainties. However, it was an examination of the available measured data and an evaluation of that data as it would apply to cask licensing that led to the extended burnup and enrichment limits of ISG8R2. The recommended credit for burnup is limited to 50 GWd/MTU because the assay data (e.g., Fig. 1) are not available to support development of a bias and uncertainty beyond this burnup without unwarranted extrapolation. From Fig. 1 it can be seen that the primary source of readily available assay data in the regime above 4.0 wt % and 40 GWd/MTU is from the Takahama PWR in Japan. Work reported in Ref. [6] has demonstrated that the standard deviations of the calculated-to-experimental nuclide ratios for the Takahama data are comparable with those observed for previous lower-enrichment and lower-burnup assay data. This lack of trending with burnup and enrichment was confirmed using different techniques for assessing the uncertainty and trends in the uncertainty. These findings are consistent with independent published results [7], in which use of French computational methods and JEF cross-section data to analyze assay data for PWR fuel with 4.5 wt % initial enrichment indicates a calculated-to-measured ratio comparable with that of lower-enriched fuel.

The methodology used to combine the biases and uncertainties for individual isotopes can have a significant impact on the final k_{eff} value and needs to be properly explained and justified.

Reference [6] contains a description of various approaches that can be used to obtain estimates of the bias and uncertainty in the SNF compositions. The simplest approach is to individually adjust the concentration of each nuclide based on the results of the validation against radiochemical assay data. This adjusted set of nuclides can then be used in the analysis of k_{eff} needed for the Safety Analysis Report (SAR). However, this process is conservative because each adjustment should be made so as to always create a more reactive system (e.g., fissile nuclides only adjusted to increase concentration and parasitic absorber nuclides only adjusted to decrease concentration).

A more realistic but more complex approach to incorporating bias and uncertainty from the SNF compositions is to use methods [6] that demonstrate how the uncertainty in the *combined* nuclide inventory propagates to an uncertainty in the k_{eff} value. The simplest way to implement this approach would be to first obtain the set of Δk values associated with separately changing the concentration of each SNF nuclide (only those used in the k_{eff} analysis) by the value of the bias and uncertainty in the prediction. Reference [6] indicates that a root-mean-square (RMS) summation of these individual Δk values provides an estimate of the uncertainty in the k_{eff} value due to the combined uncertainties in the inventory prediction. The impact on k_{eff} of the bias and uncertainty from the SNF concentrations is system dependent; thus, if a fixed Δk value (RMS-combined value of Δk for all nuclides) is used to account for the nuclide inventory uncertainties, the value must be obtained based on the cask design and contents specified. Propagation of the calculated inventory uncertainties into the criticality calculation representative of the cask configurations used in the SAR is the reason this approach is more complex and time-consuming to implement and review.

The RMS approach assumes the uncertainty for each nuclide is independent (i.e., random) and does not consider potential correlated uncertainties in transmutation and decay chains. However, the work of Ref. [6] shows that the use of several independent "best-estimate" approaches to predicting the uncertainty (e.g., use of RMS, use of Monte Carlo sampling from inventory calculated-to-measurement distributions, and direct use of measured and predicted assay data) provides similar estimates of the bias and uncertainty. This consistent estimation of the bias and uncertainty using various realistic approaches provides risk-informed confidence that the correlated uncertainties in the transmutation and decay chains have a minor impact.

The applicant is responsible for demonstrating that the experiments selected for the validation process are representative of the system (cask) of interest and that the code-to-experiment comparative information is utilized to estimate bounding values for the bias and uncertainty.

4. Licensing-basis model assumptions

This recommendation indicates that the actinide compositions used to determine a value of k_{eff} for the licensing safety basis should be calculated using fuel design and in-reactor operating parameter values that appropriately encompass the range of design and operating conditions for the proposed contents. Furthermore, the calculation of the k_{eff} value should be performed using cask models, appropriate analysis assumptions, and code inputs that allow adequate representation of the physics. This aspect is no different from the recommendation of ISG8R1. However, ISG8R2 goes further and provides additional guidance on selecting axial-burnup profiles and consideration of the impact of both burnable absorbers and control rods. In contrast, ISG8R1 included a restriction that assemblies exposed to burnable absorbers during irradiation not be considered eligible for loading in a cask designed for burnup credit.

4.1. Axial profiles

To support added guidance in ISG8R2, a review and evaluation of the publicly available U.S. database [8] of axial-burnup profiles were performed [9]. Although the database represents only 4% of the assemblies discharged through 1994, the review indicates that the database provides a good representation of discharged assemblies in terms of fuel vendor/reactor design, types of operation (i.e., first cycles, out–in fuel management, and low-leakage fuel management), burnup and enrichment ranges, and use of burnable absorbers. The primary deficiency in the database of Ref. [8] is the number of profiles associated with assembly burnup values greater than 40 GWd/MTU and initial enrichment values greater than 4.0 wt %. However, Ref. [9] 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 judgement along with the margin presented by isotopes not included in the analysis, the existing database should be adequate for burnups beyond 40 GWd/MTU and initial enrichments above 4%, if appropriate care is taken to select profiles that include a margin for the potential added uncertainty in moving to higher burnups and initial enrichments.

However, given the finite nature of the available database (4% of the inventory through 1994 discharge), a low probability likely exists that some discharged SNF would have a higher reactivity than the limiting profiles identified for the same burnup group. Using a generic burnup-credit cask model, Ref. [9] investigated the impact of loading single assemblies with a significantly more reactive profile and found the consequence to be small. Thus, the characterization of the limiting profiles from the database as statistical outliers, the use of a limiting profile for all assemblies loaded in the cask, and the low consequence associated with the loading of an assembly with a higher reactivity (beyond the selected limiting profile for that burnup group) have led to the recommendation that this publicly available database be accepted as an appropriate source for selecting axial-burnup profiles that will encompass the SNF anticipated for loading in a burnup-credit cask.

4.2. Burnable absorbers

Assemblies exposed to fixed neutron absorbers [integral burnable absorbers (IBAs)] and removable neutron absorbers [burnable poison rods (BPRs)] can have higher k_{eff} values than assemblies that are not so exposed, because the presence of the absorber will harden the spectrum and lead to increased ^{239}Pu production and reduced ^{235}U depletion. In addition, when removable neutron absorbers are inserted, the spectrum is further hardened due to displacement of the moderator. The lack of quantitative information on the effect of removable neutron absorbers caused the NRC to exclude assemblies irradiated with burnable absorbers as candidates for loading in a burnup credit cask.

Under the NRC/RES research program, investigations [10–12] have been performed to quantify how the k_{eff} value of a discharged assembly would change due to irradiation with BPRs and IBAs included in the assembly. A comprehensive range of assembly designs, absorber loadings, and exposure history was used to determine the impact on the k_{eff} value of SNF. The studies show that exposure to BPRs can cause the k_{eff} to increase up to 3% when the maximum absorber loading is assumed for the maximum exposure time. More typical absorber loadings and exposures (one cycle of 20 GWd/MTU) lead to increases of < 1% Δk (e.g., see Fig. 3). By comparison, except for one IBA type, where the increase was as much as 0.5% Δk, the IBAs actually provide a decrease in k_{eff} relative to assemblies not irradiated with IBAs. References [10–12] provide a general characterization of the effect of burnable absorbers on spent fuel 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.

4.3. Control rods

As with BPRs, control rods (CRs) fully or partially inserted during reactor operation can harden the spectrum in the vicinity of the insertion and lead to increased production of ^{239}Pu. In addition, CRs can alter the axial-burnup profile. In either case, the CR would have to be inserted for a reasonable fraction of the total irradiation time for these effects to be seen in terms of a positive Δk for the SNF cask. Domestic PWRs typically do not operate with CRs inserted, although the tips of the rods may rest at the fuel ends. However, some older domestic reactors and certain foreign reactors may have used control rods in a more extensive fashion such that the impact of CR insertion would be significant.

The results of a parametric study [12, 13] to quantify the effect of CR exposure are summarized in Fig. 4, where it can be seen that even for significant burnup exposures (up to 45 GWd/MTU), minor axial CR insertions (e.g., < 20 cm) result in an insignificant effect (less than 0.2% Δk) on the k_{eff} value of a burnup-credit cask. However, Ref. [13] shows that full insertion for burnups up to 5–10 GWd/MTU provided 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.

Insertion of CRs (or use of axial power-shaping rods, APSRs) during reactor operation can also lead to a distorted, or nontypical, axial-burnup profile. However, as noted in the discussion of axial profiles, the existing database of axial-burnup profiles [8] includes a representative sampling of assemblies exposed to CRs and APSRs. In fact, many of the limiting profiles that exist in the database are from assemblies exposed to CRs and APSRs. Thus, the appropriate selection of a limiting axial profile(s) from the available database (or a similar one) would, in a risk-informed fashion, adequately encompass the potential impact for axial-profile distortion caused by CRs and APSRs.

5. Loading curve

A loading curve is a plot that specifies, as a function of initial enrichment, the assigned burnup value above which fuel assemblies may be loaded in the cask. Typically the personnel responsible for loading an SNF cask have ready knowledge of the average assembly burnup and initial enrichment values. Thus, a loading curve that provides the burnup and initial enrichment combination associated with the upper subcritical limit for the cask will provide a rapid means to assess whether a specific assembly is acceptable for loading in the cask. Separate loading curves should be established for each set of applicable licensing conditions. For example, a separate loading curve should be provided for each minimum cooling time to be considered in the cask loading. The applicability of the loading curve to bound various fuel types or burnable absorber loadings should be justified. To limit the opportunity for misloading, only one loading curve should be used for each cask loading. Each loading curve should be clearly marked relative to key assembly characteristics (e.g., assembly design type, cooling time, etc.).

6. Assigned burnup loading value

In Regulatory Guide 3.71, NRC endorsed the recommendations of ANSI Standard 8.17-1997, with the exception that credit for fuel burnup may be taken only when the amount of burnup is confirmed by physical measurements. Like ISG8R1, the new guidance of ISG8R2 indicates that a measurement to confirm the average burnup recorded for an assembly is needed prior to or during cask-loading operations. The administrative procedures for cask loading should include such a measurement and note that the uncertainty in the measurement and the uncertainty in the reactor records should both be included in adjusting the reactor record burnup to an assigned burnup loading value. The burnup measurement approaches proposed to date use measurements of numerous assemblies and comparisons with reactor record values to self-calibrate the system. Thus, the measurement and record for these types of systems are not independent, and the uncertainty in both should be considered in order to mitigate the potential for a systematic error in the reactor records. An assessment of the uncertainty of the burnup values provided in reactor records has been performed [14], indicating that uncertainties should be less than 5% for PWR assemblies.

ISG8R2 does indicate that procedures confirming the reactor records using measurement of a sampling of the fuel assemblies will be considered if a database of measured data is provided to justify the adequacy of the procedure in comparison with procedures that measure each assembly.

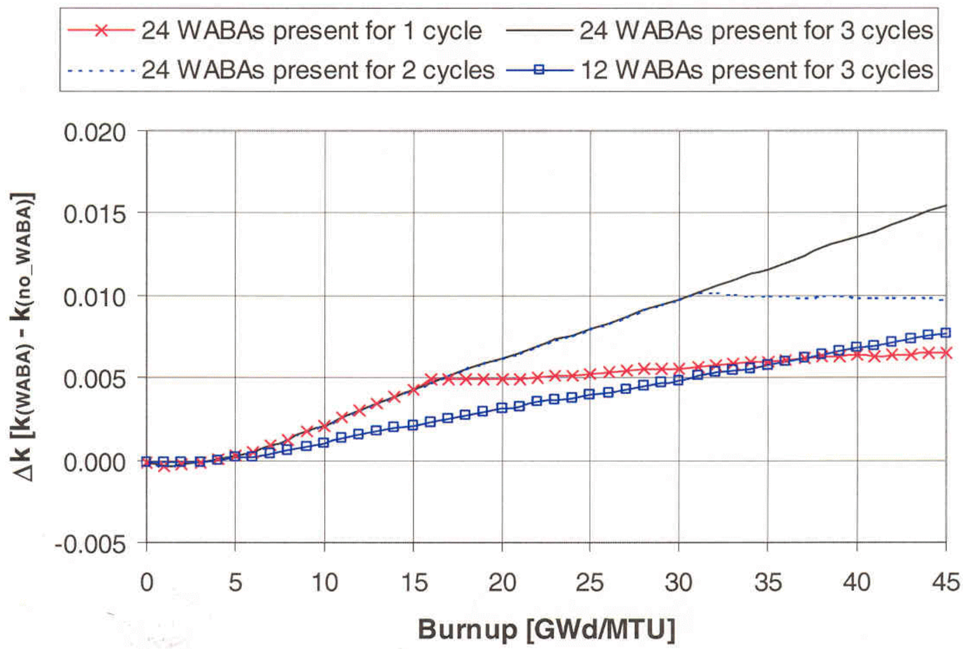

FIG. 3. Comparison of Δk values, as a function of burnup, for assemblies exposed to wet annular burnable assembly (WABA) rods. Results correspond to Westinghouse 17 × 17 assemblies with 4.0 wt % ^{235}U initial enrichment. Source: Ref. [11].

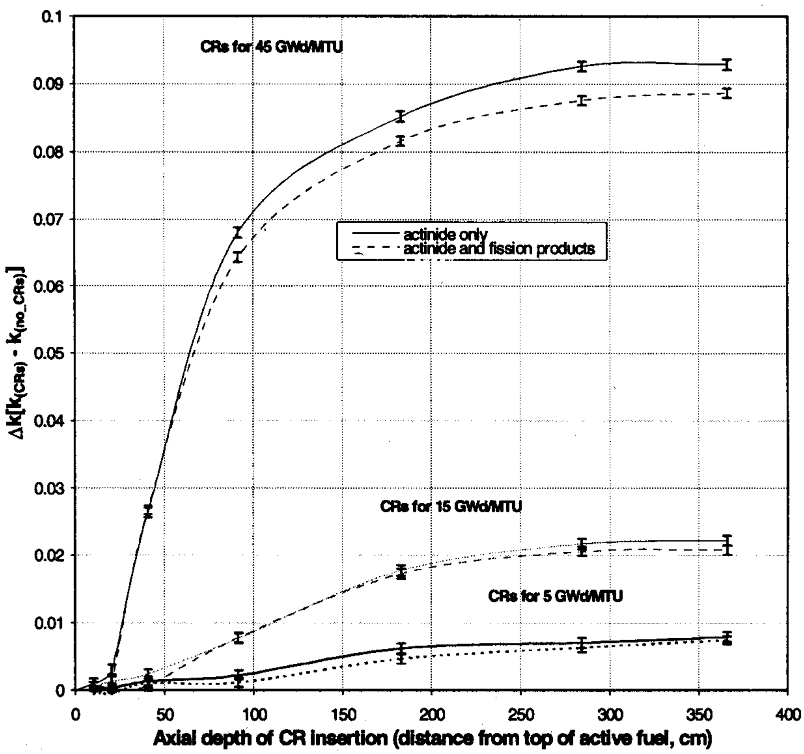

FIG. 4. Impact of CR insertion during irradiation on SNF in the GBC-32 cask. Source: Ref. [13].

7. Estimate of additional reactivity margin

As indicated in Ref. [6], the assay data available for fission-product nuclides are scarce relative to the data available for major actinides. In addition, the types of experiments (critical experiments, worth experiments, etc.) that may be needed to validate the reactivity effect from fission products are generally not publicly available and/or are difficult to use (e.g., reactor critical measurements and differential worth measurements). Thus, until additional data are available to validate the quantity of the fission-product worth for a specific cask, the NRC staff has not recommended that the fission-product inventory be considered in the licensing basis safety analysis for burnup credit.

The fact that the neutron-absorbing properties of fission products are known to reduce the k_{eff} value beyond the actinide-only assumption indicates that the actinide-only assumption is conservative. However, the quantity of the conservatism cannot be well substantiated given the existing experimental and measurement data. Until additional experience is gained with the uncertainties associated with actinide-only burnup credit, an estimate of the additional reactivity margin that is available from nuclides not considered in the safety analysis may be used to compensate for uncertainties not readily understood or quantified in the safety analysis using only actinides. The estimate should be specific to the cask design because the margin will vary depending on the external absorbers in the cask basket. The estimation of additional reactivity margin should not be used to reduce the level of validation or realistic bounding assumptions used as a basis for safety. However, the information can be used to help justify that difficult-to-quantify uncertainties are adequately covered within the safety envelope of the cask design. Other easily identified conservative assumptions that may have been used in the licensing basis model can also be considered.

8. Summary

Revision 2 of the Interim Staff Guidance 8 expands the ranges of SNF parameters that can be considered in the safety analysis of a burnup-credit cask. Fuel with average assembly burnups to 50 GWd/MTU and initial enrichments to 5.0 wt % can be considered for loading in a burnup-credit cask. Cooling times from 1 to 40 years can be considered. In addition, ISG8R2 allows assemblies exposed to burnable absorbers to be considered for loading and recommends a methodology for accounting for CR insertions.

The six recommendations provided in ISG8R2 were developed with intact PWR fuel as the basis. An extension to damaged fuel may be warranted if the applicant can demonstrate that any additional uncertainties associated with the irradiation history and structural integrity (both during and subsequent to irradiation) of the fuel assembly (or parts thereof) have been adequately addressed. In particular, an appropriate model that bounds the uncertainties associated with the allowed fuel inventory and fuel configuration in the cask must be applied. Such a model should include the selection of appropriate burnup distributions and any potential rearrangement of the damaged fuel during normal and accident conditions. The applicant should also strive to apply each of the recommendations provided in ISG8R2 and discuss or justify any exceptions taken due to the nature of the fuel (e.g., the use of the recommended axial-profile database may not be appropriate).

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