A CRITICAL REVIEW OF THE PRACTICE OF EQUATING THE REACTIVITY OF SPENT FUEL TO FRESH FUEL IN BURNUP CREDIT CRITICALITY SAFETY ANALYSES FOR PWR SPENT-FUEL POOL STORAGE

RADIOACTIVE WASTE MANAGEMENT AND DISPOSAL

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This research examines the practice of equating the reactivity of spent fuel to that of fresh fuel for the purpose of performing burnup credit criticality safety analyses for pressurized water reactor (PWR) spent-fuel pool (SFP) storage conditions. The investigation consists of comparing k_{eff} estimates based on reactivity "equivalent" fresh fuel enrichment (REFFE) to k_{eff} estimates using the calculated spent-fuel isotopics. Analyses of selected storage configurations common in PWR SFPs show that this practice yields nonconservative results (on the order of a few tenths of a percent) in configurations in which the spent fuel is adjacent to higher-reactivity assemblies (e.g., fresh or lower-burned assemblies) and yields conservative results in configurations in which spent fuel is adjacent to lower-reactivity assemblies (e.g., higher-burned fuel or empty cells). When the REFFE is determined based on unborated water moderation, analyses for storage conditions with soluble boron present reveal significant nonconservative results associated with the use of the REFFE. Finally, it is shown that the practice of equating the reactivity of spent fuel to fresh fuel is acceptable, provided the conditions for which the REFFE was determined remain unchanged. Determination of the REFFE for a reference configuration and subsequent use of the REFFE for different configurations violates the basis used for the determination of the REFFE and, thus, may lead to inaccurate, and possibly, nonconservative estimates of reactivity.

A significant concentration (~2000 ppm) of soluble boron is typically (but not necessarily required to be) present in PWR SFPs, of which only a portion ($\lesssim$500 ppm) may be credited in safety analyses. Thus, a large subcritical margin currently exists that more than accounts for errors or uncertainties associated with the use of the REFFE. Consequently, the findings presented here do not represent a significant safety concern unless/until the subcritical margin associated with the soluble boron (that is not currently explicitly credited) is offset by the uncertainties associated with burnup credit and/or the expanded allowance of credit for the soluble boron.

I. INTRODUCTION

Storage of spent fuel in underwater racks at reactors has been standard practice in the United States since the start of the nuclear industry. Spent-fuel pools (SFPs) at reactors are licensed under Title 10 Part 50 of the Code of Federal Regulations (10 CFR 50) and represent a controlled facility operated in conjunction with the reactor operation. In lieu of credit for soluble boron in the water, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation has licensed the use of burnup credit for many years in borated SFPs at pressurized-water reactor (PWR) plants.[1] The regulatory allowance of burnup credit in SFPs, including credit for fission products, seems to be partly justified by the presence of soluble boron in the SFPs. The reactivity margin associated with soluble boron is inherently credited in SFP burnup credit analyses to account for uncertainties

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associated with the utilization of burnup credit. This approach is justified on the basis that in most U.S. PWR SFPs there is sufficient soluble boron present (soluble boron concentrations of ~2000 ppm are common) to maintain subcriticality even if an entire storage rack intended to accommodate burned fuel were misloaded with fresh fuel assemblies of the highest allowable enrichment. Note that the recent allowance of partial soluble boron credit reduces this associated margin.

Guidance on the regulatory requirements for the criticality safety analysis of fuel storage at reactors is documented in Ref. 1. The spent nuclear fuel (SNF) inventory subsequent to the decay of the short-lived ^{135}Xe isotope is typically used within a two-dimensional representation of a storage rack to determine a fresh fuel enrichment that provides the same neutron multiplication factor as the SNF inventory. The process of equating the neutron multiplication factor of low-enriched fresh fuel to that of high-enriched spent fuel is referred to as "reactivity equivalencing" (Ref. 2). Upon determination of the reactivity "equivalent" fresh fuel enrichment (REFFE), it is typically used within a three-dimensional Monte Carlo code to perform the actual criticality safety analysis.

This type of approach to burnup credit hinges on the adequacy of the process to determine the REFFE corresponding to SNF, as well as the proper use of the REFFE within environments that provide similar neutronic characteristics. Until recently, this general process had been used to obtain burnup credit in PWR SFPs where credit for the soluble boron is taken only for postulated accident events. However, as mentioned, the NRC has recently approved credit for soluble boron up to 5% in Δk (Ref. 1).

The practice of equating reactivity, whether equating reactivity of fuel at a particular initial enrichment and burnup combination to fuel with a different initial enrichment and burnup combination or equating reactivity of spent fuel to fresh fuel, is referred to as *reactivity equivalencing*. Throughout this paper, reactivity equivalencing refers to equating the reactivity of spent fuel to that of fresh fuel. The determination of the REFFE involves (a) calculating k_{eff} as a function of burnup $k(B)$ and (b) calculating k_{eff} as a function of initial enrichment $k(E)$. All calculations are performed for the same geometric configuration. Based on the calculated functions, the reactivity at a particular burnup (with the calculated spent-fuel isotopics) is compared to the reactivity as a function of initial enrichment to determine the initial enrichment value (fresh fuel isotopics) that yields the same reactivity (i.e., the REFFE). In other words, a fresh fuel enrichment is determined that yields the same reactivity as the burned fuel (i.e., calculated spent-fuel isotopics).

The acceptability of this practice can be demonstrated, provided the environment in which the REFFE is determined remains unchanged. However, it is often the case that the REFFE is determined for a reference configuration (e.g., an infinite array of storage rack cells in unborated water) and then utilized in various similar, but not identical, configurations. This practice violates the basis used for the determination of the REFFE and, thus, may lead to inaccurate, and possibly, nonconservative estimates of reactivity. This latter possibility has motivated this review of the practice of equating the reactivity of spent fuel to fresh fuel.

Recent work by Neuber[3] has raised criticism of the practice of applying reactivity equivalence relations between spent fuel and fresh fuel for boiling water reactor (BWR) spent-fuel storage and identified the potential for nonconservative results. Although this recent work considered the application of reactivity equivalence in storage configuration variations that are not considered to be representative of U.S. BWR SFP analyses, it raises serious and valid concerns regarding the practice of reactivity equivalencing. Hence, Neuber's work,[3] along with the recent acceptance of partial credit for soluble boron,[1] provides additional motivation for this examination of reactivity equivalencing for analyses of realistic PWR SFP conditions in which the practice of reactivity equivalencing is routinely employed. Note that soluble boron is not present in BWR SFPs.

II. SFP STORAGE

Depending on storage needs and rack designs, criticality safety evaluations for PWR SFPs may include analyses for a number of different storage conditions and configurations. These conditions and configurations may include the following:

1. reference configuration—an infinite array of storage rack cells containing spent-fuel assemblies
2. checkerboard configurations [e.g., alternating patterns of either (a) empty cells and fresh or spent fuel or (b) highly burned fuel and low-burned fuel]
3. optimal configurations, which may involve various combinations of spent and fresh fuel (e.g., configurations in which 3 out of every 4 cells contain spent fuel, but the remaining cell contains either fresh fuel, low-burnup fuel, or no fuel)
4. soluble boron in the SFP water
5. accident conditions (e.g., a misplaced fresh fuel assembly in a storage cell intended for spent fuel)
6. periphery rack configurations.

If the REFFE is determined based on a reference configuration and employed in the analysis of any of the other possible conditions, erroneous estimations of reactivity may result. Therefore, in the sections that follow, the practice of reactivity equivalencing will be evaluated

for a number of the aforementioned *realistic* storage conditions and configurations. The evaluation will consist of comparing k_{eff} estimates based on reactivity equivalencing to k_{eff} estimates using the calculated spent-fuel isotopics in configurations other than the reference.

III. CALCULATIONAL METHODS

The calculational methods necessary for this analysis include codes for depletion and criticality simulation. Fuel depletion analyses were performed with the SAS2H sequence of SCALE (Ref. 4). All SAS2H calculations utilized the SCALE 44-group (ENDF/B-V) library and were performed on a DEC AlphaStation 500. The depletion calculations were performed using time steps of 1 GWd/tonne U and conservative operational parameters for fuel temperature (1000 K), moderator temperature (600 K), soluble boron concentration (650 ppm) and specific power (continuous operation at 60 MW/tonne U). The sensitivity of k_{eff} to variations in these parameters is discussed in Ref. 5. A Westinghouse 17 × 17 optimized fuel assembly (OFA) with initial enrichment of 4.5 wt% ^{235}U was used in the depletion calculations.

The criticality calculations were performed with the CSAS25 sequence of SCALE (Ref. 4), which executes the KENO V.a Monte Carlo code. These calculations utilized the SCALE 238-group cross-section library, which is based on ENDF/B-V data. For calculations involving depleted fuel, atom densities were extracted from SAS2H output for use in CSAS25. Except for the intentional exclusion of ^{135}Xe per regulatory guidance (Ref. 1), all nuclides for which cross-section data are available in the SCALE 238-group library (some 233 nuclides) were included in the calculations. Although SAS2H has been validated against measured chemical assay data,[6–9] isotopic correction factors or biases (used to "correct" predicted isotopic compositions to that determined with measured assay data) were not used in this analysis, which is consistent with typical practice for this type of analysis.

IV. ANALYSES

IV.A. Reference Storage Cell

IV.A.1. Geometric Description

In the United States, high-density storage rack cells designed to accommodate spent fuel are generally composed of stainless steel walls with a single fixed neutron absorber panel (e.g., Boral) on each side.[10] The neutron absorber panel is held in place by a thin stainless steel sheath that is attached to the cell walls. Stainless steel boxes are arranged in an alternating pattern such that the connection of the box corners form storage cells between those of the stainless steel boxes. For the purpose of this analysis, the reference storage cell geometry has been defined with the following dimensions:

Cell inside dimension = 22.225 cm (8.750 in.)

Cell pitch = 22.784 cm (8.970 in.)

Cell wall thickness = 0.1905 cm (0.075 in.)

Sheath thickness = 0.0889 cm (0.035 in.)

Boral panel thickness = 0.2564 cm (0.101 in.)

^{10}B loading in Boral = 0.030 g ^{10}B/cm^2

Boral width = 19.05 cm (7.500 in.)

The reference storage configuration consists of an infinite radial array of storage cells in unborated water, which is modeled as a single storage cell with reflective boundary conditions through the centerline of the composite materials between the cells. The KENO V.a models included axial leakage by modeling 30 cm of water above and below the active fuel. The reference storage cell contains a Westinghouse 17 × 17 OFA assembly. A cross-sectional view of the calculational model, as generated by KENO V.a, is shown in Fig. 1. For the sake of simplicity and clarity (in terms of comparing results), uniform axial burnup was assumed, and thus the results of this analysis are not dependent on any particular axial burnup profile.

IV.A.2. Determination of the REFFE

The first step in determining the REFFE is to calculate k_{eff} as a function of burnup for the reference storage rack configuration with the calculated spent-fuel isotopics. Consistent with the guidance in Ref. 1, ^{135}Xe was excluded from the spent-fuel isotopics to ensure maximum reactivity. The calculated k_{eff} as a function of burnup is plotted in Fig. 2. Assuming the criticality safety criterion is defined as k_{eff} less than or equal to 0.93, the burnup required to meet this criterion may be directly determined from Fig. 2 to be 33 GWd/tonne U.

The second step involves calculating k_{eff} as a function of initial enrichment for the reference storage rack configuration with fresh fuel isotopics. The calculated k_{eff} as a function of initial enrichment is shown in Fig. 3. Based on these results, the fresh fuel enrichment that produces the same k_{eff} value as the calculated spent nuclear fuel (SNF) inventory (i.e., the REFFE) for a burnup of 33 GWd/tonne U may be determined to be 1.8086 wt% ^{235}U. For use in later analyses of alternative storage configurations, the REFFEs corresponding to burnups of 25 and 50 GWd/tonne U were also determined.

Specific criticality calculations may be performed with the REFFE values and with the calculated SNF inventories to verify the reactivity equivalence. Table I lists the results of the verification calculations and shows that the calculated k_{eff} values from the two approaches are statistically equal. The uncertainties listed in Table I

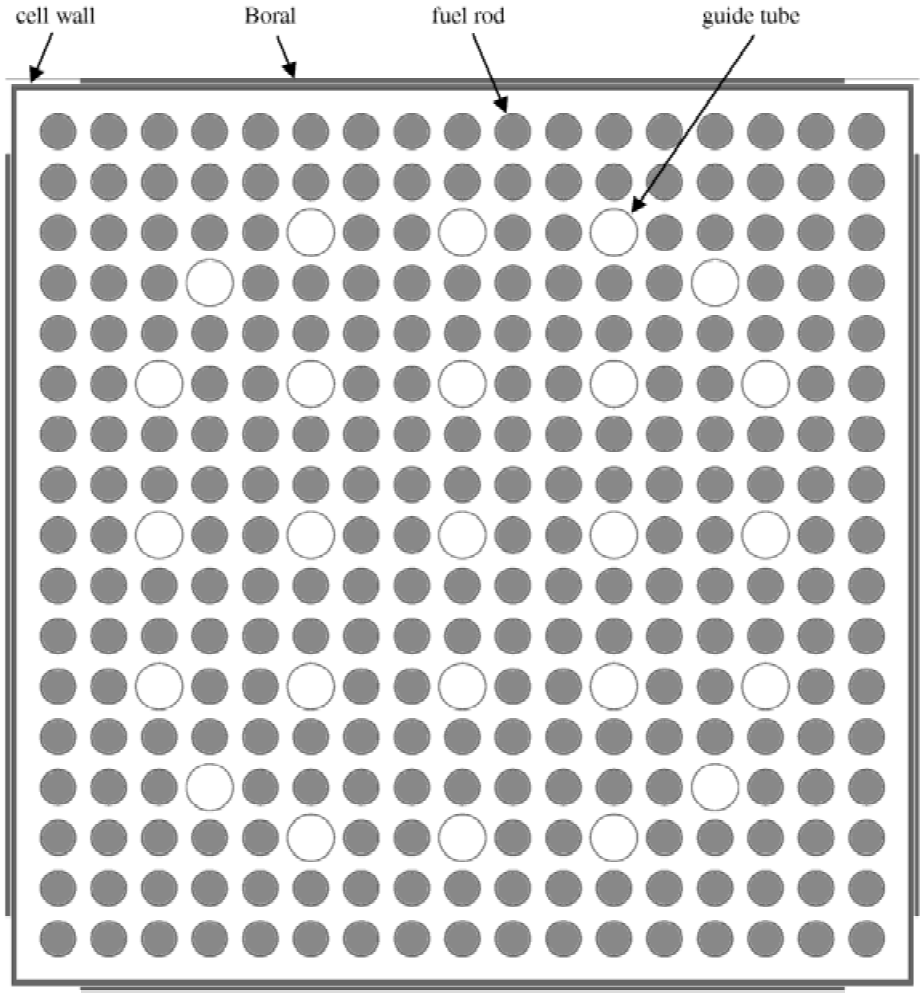

Fig. 1. KENO V.a calculational model of the reference storage rack configuration loaded with Westinghouse 17 × 17 OFA assemblies. Reflective boundary conditions are employed on all sides to simulate an infinite radial array of storage cells.

correspond to 1 σ. Considering that the REFFE values were determined by equating reactivity, the verification calculations should not be necessary. Nevertheless, they do provide confirmation of the determination of the REFFE values.

The following sections will use the REFFE values in a variety of different realistic storage conditions.

IV.B. Calculations with Soluble Boron Present

The double contingency principle specifies that it shall require at least two unlikely independent and concurrent events to produce a criticality accident. This principle precludes the necessity of considering the simultaneous occurrence of multiple accident conditions. Therefore, if soluble boron is present and controlled in the SFP water, the loss of soluble boron may be considered as one accident condition and a second concurrent accident condition need not be evaluated.[1] Consequently, the single-accident condition—loss of soluble boron—is typically assumed to be the *normal condition* for the reference analyses. Direct credit for the presence of soluble boron may be taken for other postulated accident conditions[1] (e.g., dropped or misplaced assembly).

Soluble boron is maintained in the water in PWR SFPs and, although concentrations vary from plant to plant, concentrations in the range of 1500 to 2000 ppm are considered typical.[10] In the past, credit for the soluble boron present in the SFP water was taken only for postulated accident conditions. Recently, however, the NRC has allowed credit for soluble boron up to 5% in Δk (Ref. 1) for *normal conditions*. Therefore, in this section, the impact of using the REFFE based on the reference configuration (unborated water) for calculations involving soluble boron is reviewed for normal conditions, as well as a typical accident condition.

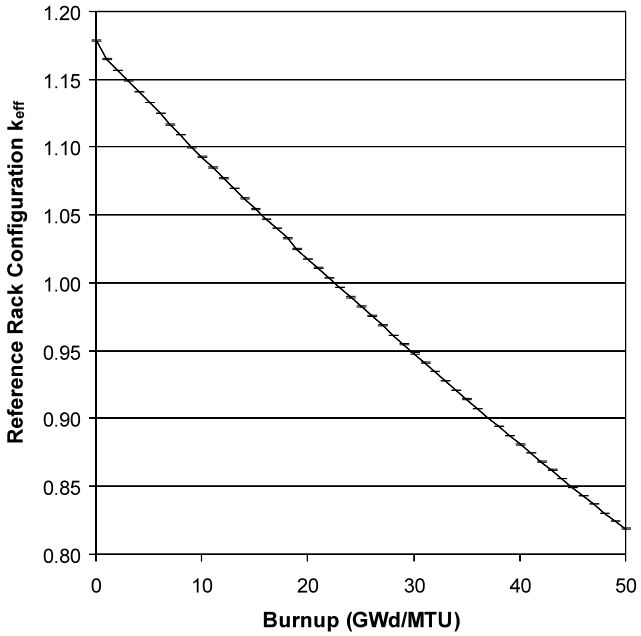

Fig. 2. Calculated k_{eff} as a function of burnup in the reference storage rack configuration (Westinghouse 17 × 17 OFA assembly with 4.5 wt% ^{235}U initial enrichment). Error bars represent 1 σ statistical uncertainties.

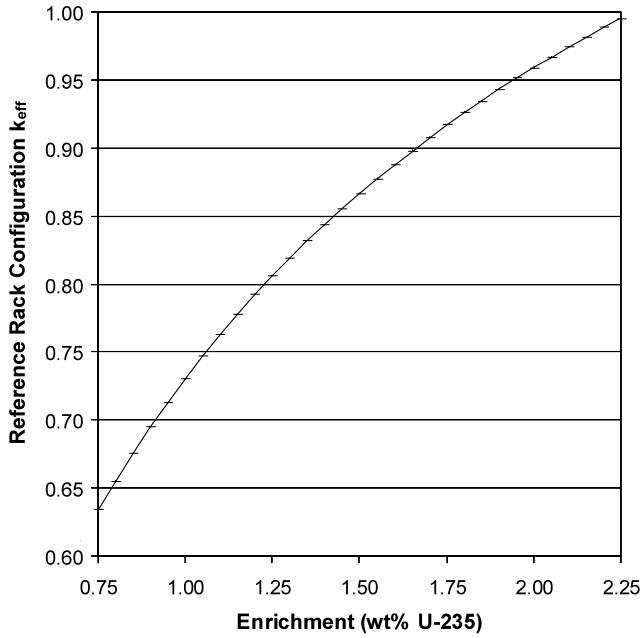

Fig. 3. Calculated k_{eff} as a function of enrichment in the reference storage rack configuration (Westinghouse 17 × 17 OFA assembly). Error bars represent 1 σ statistical uncertainties.

IV.B.1. Normal Conditions

Using the determined REFFE and the calculated SNF inventory (for a burnup of 33 GWd/tonne U), calculations were performed for an infinite radial array of storage cells (the reference geometric configuration) with increasing quantities of soluble boron (a departure from the reference configuration). The resulting k_{eff} values are listed in Table II and plotted in Fig. 4. The use of the REFFE is shown to produce nonconservative results when used in the presence of soluble boron. To demonstrate the effect as a function of burnup, Table III compares k_{eff} values for burnups of 25 and 50 GWd/tonne U. The Δk values between using the calculated SNF inventory and the REFFE, which are listed in the right columns of Tables II and III, and plotted in Fig. 5, clearly show the magnitude of the nonconservatism associated with using the REFFE (based on unborated water) for analyses with soluble boron. Additionally, these results show increasing nonconservatism with increasing soluble boron concentration and increasing burnup. This observation is considered to be important considering the recent allowance of credit for soluble boron up to 5% in Δk.

The soluble boron dissolved in the pool water is an effective thermal neutron absorber that competes for

TABLE I

Comparison of k_{eff} Results for the Reference Storage Configuration with Various Burnups

Configuration	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE	
Reference, B = 33 GWd/tonne U REFFE = 1.8086 wt% ^{235}U	0.92770 ± 0.00021	0.92760 ± 0.00023	0.00010 ± 0.00031
Reference, B = 25 GWd/tonne U REFFE = 2.1594 wt% ^{235}U	0.98303 ± 0.00022	0.98345 ± 0.00021	−0.00042 ± 0.00030
Reference, B = 50 GWd/tonne U REFFE = 1.2991 wt% ^{235}U	0.81910 ± 0.00019	0.81906 ± 0.00019	0.00004 ± 0.00027

TABLE II

Comparison of k_{eff} Results for the Reference Storage Configuration with Soluble Boron Present (Burnup = 33 GWd/tonne U)

Soluble Boron Concentration (ppm)	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE = 1.8086 wt% ^{235}U	
0 (Reference)	0.92770 ± 0.00021	0.92760 ± 0.00023	0.00010 ± 0.00031
200	0.90232 ± 0.00020	0.88678 ± 0.00020	0.01554 ± 0.00028
500	0.86619 ± 0.00020	0.83126 ± 0.00019	0.03493 ± 0.00028
1000	0.81364 ± 0.00019	0.75482 ± 0.00018	0.05882 ± 0.00026
1500	0.76904 ± 0.00019	0.69285 ± 0.00016	0.07619 ± 0.00025
2000	0.73034 ± 0.00017	0.64171 ± 0.00015	0.08863 ± 0.00023

neutrons with the boron in the fixed absorber panels and the fission product and actinide absorbers in the SNF, thereby reducing the reactivity worth of the fixed absorber panels and the fission product and actinide absorbers. In other words, the fixed absorber panels and fission product and actinide absorbers have greater negative reactivity worth in the reference (no soluble boron present) condition in which the REFFE was determined, resulting in a lower prediction of the REFFE value. This explanation is supported by the increased differences in k_{eff} with increasing concentrations of soluble boron and increasing burnup. Further, this observation is consistent with previous findings[11] that have shown that the presence of nonfuel absorbers (e.g., external fixed absorber panels) reduce the relative worth of fission products and actinide absorbers. Thus, similar nonconservative results may be expected for other conditions in which the reactivity worth of the absorbers is reduced with respect to the reference condition.

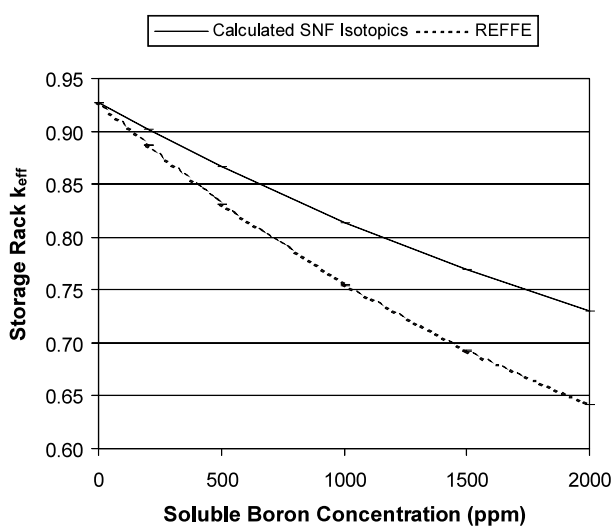

Fig. 4. Comparison of k_{eff} values with the calculated SNF isotopics and the REFFE as a function of soluble boron concentration in the reference storage configuration. Results correspond to fuel with 4.5 wt% ^{235}U initial enrichment that has accumulated 33 GWd/tonne U burnup. Error bars represent 1 σ statistical uncertainties.

IV.B.2. Accident Conditions

The misplacement of a fresh fuel assembly in a storage cell intended for spent fuel is an accident condition that must typically be considered in the criticality safety evaluation of an SFP. Naturally, this accident condition results in a higher reactivity than the reference configuration of spent fuel. Therefore, credit for soluble boron is used to offset the increased reactivity associated with the accident condition.

Using the determined REFFE and the calculated SNF inventory (for a burnup of 33 GWd/tonne U), calculations were performed for this accident condition. The calculational model assumed a 7 × 7 array of storage cells with reflective boundary conditions and a fresh 4.5 wt% ^{235}U assembly in the center cell of the array. Calculations were performed with increasing quantities of soluble boron to establish the necessary concentration to offset the increased reactivity associated with the misplaced fresh fuel assembly. The resulting k_{eff} values are listed in Table IV. For the condition with no soluble boron present, a small underestimation (nonconservative) is observed with the REFFE case. As soluble boron is added, the REFFE approach is shown to produce increasingly nonconservative results. If the goal of this particular evaluation was to determine the concentration of soluble boron necessary to offset the reactivity of the misplaced fresh fuel assembly (i.e., to maintain k_{eff} below 0.93), the REFFE approach would incorrectly suggest that 200 ppm is more than sufficient when in actuality a slightly higher soluble boron concentration is needed.

TABLE III

Comparison of k_{eff} Results for the Reference Storage Configuration with Soluble Boron Present for Burnups of 25 and 50 GWd/tonne U

Soluble Boron Concentration (ppm)	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE	
Burnup = 25 GWd/tonne U, REFFE = 2.1594 wt% ^{235}U			
0 (Reference)	0.98303 ± 0.00022	0.98345 ± 0.00021	−0.00042 ± 0.00030
200	0.95644 ± 0.00020	0.94355 ± 0.00021	0.01289 ± 0.00029
500	0.91902 ± 0.00019	0.88974 ± 0.00021	0.02928 ± 0.00028
1000	0.86549 ± 0.00020	0.81380 ± 0.00018	0.05169 ± 0.00027
1500	0.81829 ± 0.00018	0.75148 ± 0.00018	0.06681 ± 0.00025
2000	0.77744 ± 0.00018	0.69921 ± 0.00018	0.07823 ± 0.00025
Burnup = 50 GWd/tonne U, REFFE = 1.2991 wt% ^{235}U			
0 (Reference)	0.81910 ± 0.00019	0.81906 ± 0.00019	0.00004 ± 0.00027
200	0.79532 ± 0.00018	0.77630 ± 0.00019	0.01902 ± 0.00026
500	0.76180 ± 0.00017	0.72052 ± 0.00016	0.04128 ± 0.00023
1000	0.71352 ± 0.00017	0.64563 ± 0.00016	0.06789 ± 0.00023
1500	0.67288 ± 0.00016	0.58654 ± 0.00014	0.08634 ± 0.00021
2000	0.63826 ± 0.00015	0.53839 ± 0.00013	0.09987 ± 0.00020

IV.C. Calculations for Alternative Storage Configurations

Depending on storage needs and rack designs, criticality safety evaluations may include analyses for a number of different storage configurations. These alternative storage configurations are typically employed to either accommodate fuel assemblies that do not meet the normal storage requirements or to maximize storage capacity.

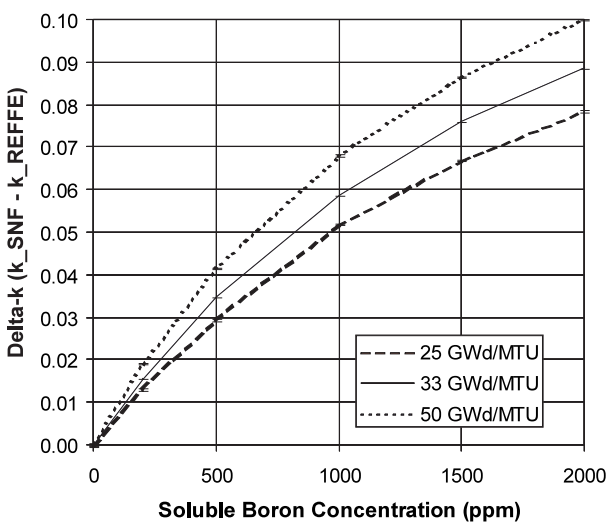

Fig. 5. Reactivity effect associated with the use of REFFE with soluble boron present. Results correspond to fuel with 4.5 wt% ^{235}U initial enrichment that has accumulated burnups of 25, 33, and 50 GWd/tonne U. Error bars represent 1 σ statistical uncertainties.

IV.C.1. Checkerboard Configurations

Although it is not an efficient use of valuable storage space, and thus is not desirable, fuel assemblies are often stored in a checkerboard configuration with empty cells (i.e., an alternating pattern of assemblies and empty cells). Examples where this type of checkerboarding may be employed include (a) temporary storage of fresh fuel in racks designed for burned fuel and (b) storage of assemblies that cannot meet the burnup requirements for normal storage. Alternatively, a checkerboard configuration may be used to expand the storage capacity through alternating storage of high-burnup fuel with low-burnup fuel that would not, by itself, be acceptable for storage in a normal infinite configuration. An illustration of these two storage configurations is provided in Fig. 6.

Table V compares calculated k_{eff} values based on calculated SNF isotopics and REFFE for several possible checkerboard configurations. Review of the results listed in Table V reveals a clear trend for when the use of REFFE produces conservative and nonconservative results. When a REFFE assembly is placed in a checkerboard configuration with a less reactive assembly (or an empty cell), the REFFE approach yields conservative

TABLE IV

Comparison of k_{eff} Results for the Misplaced Fresh Fuel Assembly Accident Configuration with Soluble Boron Present (Burnup = 33 GWd/tonne U)

Soluble Boron Concentration (ppm)	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE = 1.8086 wt% ^{235}U	
0	0.95800 ± 0.00029	0.95604 ± 0.00029	0.00196 ± 0.00041
200	0.93173 ± 0.00026	0.92106 ± 0.00028	0.01067 ± 0.00038
500	0.89566 ± 0.00029	0.87447 ± 0.00028	0.02119 ± 0.00040

TABLE V

Comparison of k_{eff} Results for Various Checkerboard-Type Configurations

Assemblies in Checkerboard Configuration	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE	
SNF (33 GWd/tonne U) and empty cells	0.64982 ± 0.00022	0.65599 ± 0.00023	−0.00617 ± 0.00032
SNF (33 GWd/tonne U) and fresh fuel (1.0 wt% ^{235}U)	0.83726 ± 0.00020	0.83819 ± 0.00020	−0.00093 ± 0.00028
SNF (33 GWd/tonne U) and fresh fuel (2.5 wt% ^{235}U)	0.97979 ± 0.00021	0.97860 ± 0.00021	0.00119 ± 0.00030
SNF (50 GWd/tonne U) and fresh fuel (3.5 wt% ^{235}U)	0.98774 ± 0.00024	0.98658 ± 0.00023	0.00116 ± 0.00033
SNF (50 GWd/tonne U) and SNF (25 GWd/tonne U)	0.90686 ± 0.00020	0.90664 ± 0.00020	0.00022 ± 0.00028

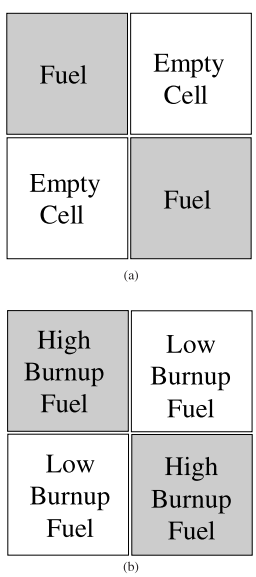

Fig. 6. Examples of checkerboard storage configurations: (a) checkerboard configuration with empty cells and (b) checkerboard configuration with alternating storage of burned fuel. Periodic boundary conditions are employed on all sides to simulate an infinite array of checkerboard configurations.

results. In contrast, when an REFFE assembly is placed in a checkerboard configuration with a more reactive assembly (e.g., fresh fuel) the REFFE approach yields nonconservative results.

When comparing the reference infinite configuration to a configuration in which the reference assembly is stored with higher-reactivity fuel, the reactivity of the latter configuration is controlled by the higher-reactivity fuel. Physically, the maximum reactivity or fission density for this latter configuration occurs in the higher-reactivity fuel, with the lower-reactivity (reference) fuel acting in a supplementary manner. Therefore, the fission products and actinide absorbers have less relative negative reactivity worth in this configuration (as compared to the reference configuration) because they are not physically located where the fission density is maximum. In contrast, the reactivity of the reference infinite configuration is controlled by the reference spent fuel and does not vary from storage cell to storage cell. Thus, the fission products and actinide absorbers have greater negative reactivity worth in the reference (infinite) condition because they are physically located throughout the system and the fission density is uniform (no spatial disadvantage). Consequently, a lower REFFE value is predicted in the

reference configuration, which leads to nonconservative results. However, the nonconservative differences in reactivity for the representative cases considered are small (<0.2%).

When comparing the reference infinite configuration to a configuration in which the reference assembly is stored with alternating empty cells or lower-reactivity fuel, the reactivity of the latter configurations are controlled by the reference spent fuel in lower-reactivity configurations. For the case with empty cells, it is postulated that spectral softening due to the empty cells enhances thermal neutron absorption in the fixed absorber panels and fission product and actinide absorbers, as well as thermal fission in the REFFE. Therefore, the absorbers have greater negative reactivity worth in these configurations (as compared to the reference configuration). Conversely, the absorbers have less relative negative reactivity worth in the reference configuration in which the REFFE was determined, and thus, the REFFE approach yields conservative results for these types of configurations.

IV.C.2. The 3-out-of-4 Storage Configurations

Another common storage practice involves storing fuel in a 3-out-of-4-storage pattern in which the contents of 1 out of every 4 storage cells differs from the remaining 3. Similar to checkerboarding, this storage approach may be used to either accommodate assemblies that do not meet the normal storage requirements or to expand the storage capacity through separation of higher-reactivity assemblies with lower-reactivity assemblies. Examples of this approach are illustrated in Fig. 7 for two possible configurations in which 3 out of every 4 cells contain spent fuel, while the remaining cell contains either no fuel or fresh fuel (possibly low-burnup fuel).

Table VI compares calculated k_{eff} values based on calculated SNF isotopics and REFFE for two possible 3-out-of-4 configurations. Review of the results listed in Table VI reveals the same basic trend observed in the previous subsection for checkerboard configurations. When a REFFE assembly is placed in storage with an empty cell (or a less reactive assembly), the REFFE approach yields conservative results. When placed in storage with a more reactive assembly (e.g., fresh fuel) the REFFE approach yields nonconservative results. The explanation for this behavior is the same as that given in Sec. IV.C.1. Similar to the results for checkerboard configurations, the differences appear to be on the order of a few tenths of a percent.

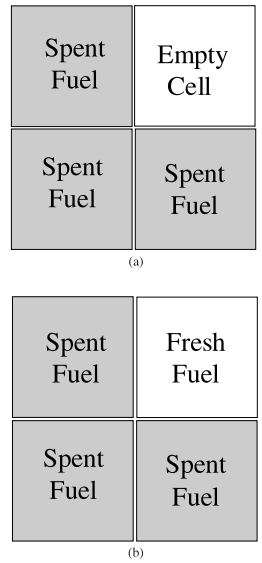

Fig. 7. Examples of 3-out-of-4 storage configurations: (a) 3-out-of-4 configuration with an empty cell and (b) 3-out-of-4 configuration to enable storage of low-burned fuel or fresh fuel with spent fuel. Periodic boundary conditions are employed on all sides to simulate an infinite array of 3-out-of-4 configurations.

V. CONCLUSIONS

The practice of equating the reactivity of spent fuel to the reactivity of fresh fuel, referred to as *reactivity equivalencing*, has been examined for analyses of realistic PWR SFP conditions. The practice is demonstrated to be acceptable, provided the geometric configuration and conditions on which the REFFE was determined remain unchanged. However, because it is often the case that the REFFE is determined for a reference configuration (e.g., infinite radial array of storage rack cells in unborated water) and then utilized in various similar but not identical configurations, the practice has been evaluated for a number of *realistic* conditions. The evaluation consisted of comparing k_{eff} estimates based on reactivity equivalencing to k_{eff} estimates using calculated spent-fuel isotopics in configurations other than the reference.

Analyses of selected storage configurations that are common in PWR SFPs support the following conclusions:

1. equivalencing yields nonconservative results (on the order of a few tenths of a percent) in configurations in which the spent fuel is placed in storage with higher reactivity assemblies (e.g., fresh or lower-burned assemblies)
2. equivalencing yields conservative results in configurations in which spent fuel is stored with lower-reactivity assemblies (e.g., higher-burned fuel or empty cells).

Analyses for storage conditions with soluble boron present reveal significant nonconservative results associated with the use of the REFFE. An underestimation of

TABLE VI

Comparison of k_{eff} Results for Various 3-out-of-4-Type Configurations

Assemblies in 3-out-of-4 Configuration	Calculational Approach		Difference (k_SNF − k_REFFE)
	Calculated SNF Inventory	REFFE	
3 SNF (33 GWd/tonne U) and 1 empty cell	0.82314 ± 0.00022	0.82562 ± 0.00024	−0.00248 ± 0.00033
3 SNF (33 GWd/tonne U) and 1 fresh fuel (1.0 wt% ^{235}U)	0.88791 ± 0.00020	0.88834 ± 0.00021	−0.00043 ± 0.00029
3 SNF (50 GWd/tonne U) and 1 fresh fuel (3.5 wt% ^{235}U)	0.94170 ± 0.00024	0.93992 ± 0.00025	0.00178 ± 0.00035

k_{eff} of more than 3% is shown for a soluble boron concentration of 500 ppm, and the underestimation is shown to increase with increasing soluble boron concentration. For accident conditions involving fresh fuel, such as the misplacement of a fresh fuel assembly in a rack cell designed for spent fuel, the reactivity is dominated by the fresh fuel assembly, and thus, the underestimation associated with using the REFFE with soluble boron present is less than that shown for the radially infinite spent-fuel storage configuration. However, an underestimation of k_{eff} of >2% is shown with a soluble boron concentration of 500 ppm for a misplaced fresh fuel assembly accident condition. The results demonstrate that the practice of equating spent fuel reactivity to fresh fuel (*analyzed at 0 ppm*) should not be employed for conditions crediting soluble boron.

Finally, note that the practice of equating the reactivity of spent fuel to fresh fuel is acceptable, provided the conditions for which the REFFE was determined remain unchanged. In fact, when employing two-dimensional depletion methods, the REFFE approach will include the radial depletion effects. However, determination of the REFFE for a reference configuration and subsequent use of the REFFE for different configurations violates the basis used for the determination of the REFFE and has been shown to produce inaccurate and nonconservative estimates of reactivity.

A significant concentration (~2000 ppm) of soluble boron is typically (but not necessarily required to be) present in PWR SFPs, of which only a portion (≲500 ppm) may be credited in safety analyses. Thus, a large subcritical margin currently exists that more than accounts for errors or uncertainties associated with the use of the REFFE. Consequently, the findings presented in this paper do not represent a significant safety concern unless/until the subcritical margin associated with the soluble boron (that is not currently explicitly credited) is offset by the uncertainties associated with burnup credit and/or the expanded allowance of credit for the soluble boron.

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