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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

Oak Ridge National Laboratory

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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

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ABSTRACT

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 PWR spent fuel pool (SFP) storage conditions. The investigation consists of comparing k_{inf} estimates based on reactivity "equivalent" fresh fuel enrichment (REFFE) to k_{inf} estimates using the actual 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. This observation is considered to be important, especially considering the recent allowance of credit for soluble boron up to 5% in reactivity. 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 (≤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.

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1 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 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 associated with the utilization of burnup credit. This approach is justified on the basis that there is typically sufficient soluble boron present in PWR SFPs (soluble boron concentrations of ~2000 ppm are common) to maintain sub-criticality 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 the storage pool geometry to determine a fresh fuel enrichment that provides the same reactivity (neutron multiplication factor, k_{inf}) as the SNF inventory. This reactivity "equivalent" fresh fuel enrichment (REFFE) is then used within a criticality safety analysis code to perform the actual 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 reactivity.[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 equival*encing refers to equating the reactivity of spent fuel to that of fresh fuel. The determination of the REFFE involves (1) calculating k_{inf} as a function of burnup $k(B)$ and (2) calculating k_{inf} as a function of initial enrichment $k(E)$. All calculations are performed for the same geometric configuration (e.g., an infinite array of storage rack cells in unborated water). Based on the calculated functions, the reactivity at a particular burnup (with the actual 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 actual burned fuel (i.e., 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[2] 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,[2] 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.

2 SPENT FUEL 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: (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); and (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 above *realistic* conditions. The evaluation will consist of comparing k_{inf} estimates based on reactivity equivalencing to k_{inf} estimates using the actual spent fuel isotopics in configurations other than the reference.

3 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.[3] 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 conservative operational parameters for fuel temperature (1000.0 K), moderator temperature (600.0 K), soluble boron concentration (650 ppm) and specific power (continuous operation at 60 MW/MTU). A Westinghouse 17×17 OFA assembly 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,[3] 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.

4 ANALYSES

4.1 Reference Storage Cell

4.1.1 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.[4] 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.)	Boral panel thickness:	0.2564 cm (0.101 in.)
Cell pitch:	22.784 cm (8.970 in.)	B-10 loading in Boral:	0.030 g B-10/cm^2
Cell wall thickness:	0.1905 cm (0.075 in.)	Boral width:	19.05 cm (7.500 in.)
Sheath thickness:	0.0889 cm (0.035 in.)		

The reference storage configuration consists of an infinite 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 Figure 1.

4.1.2 Determination of the Reactivity Equivalent Fresh Fuel Enrichment (REFFE)

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

The second step involves calculating k_{inf} as a function of initial enrichment for the reference storage rack configuration with fresh fuel isotopics. The calculated k_{inf} as a function of initial enrichment is shown in Figure 3. Based on these results, the fresh fuel enrichment that produces the same reactivity (k_{inf}) as the actual spent nuclear fuel (SNF) inventory (i.e., the REFFE) for a burnup of 33 GWd/MTU 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/MTU were also determined.

Specific criticality calculations may be performed with the REFFE values and with the actual SNF inventories to verify the reactivity equivalence. Table 1 lists the results of the verification calculations and shows that the calculated k_{inf} values from the two approaches are statistically equal. The uncertainties listed in Table 1 correspond to 1σ. 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.

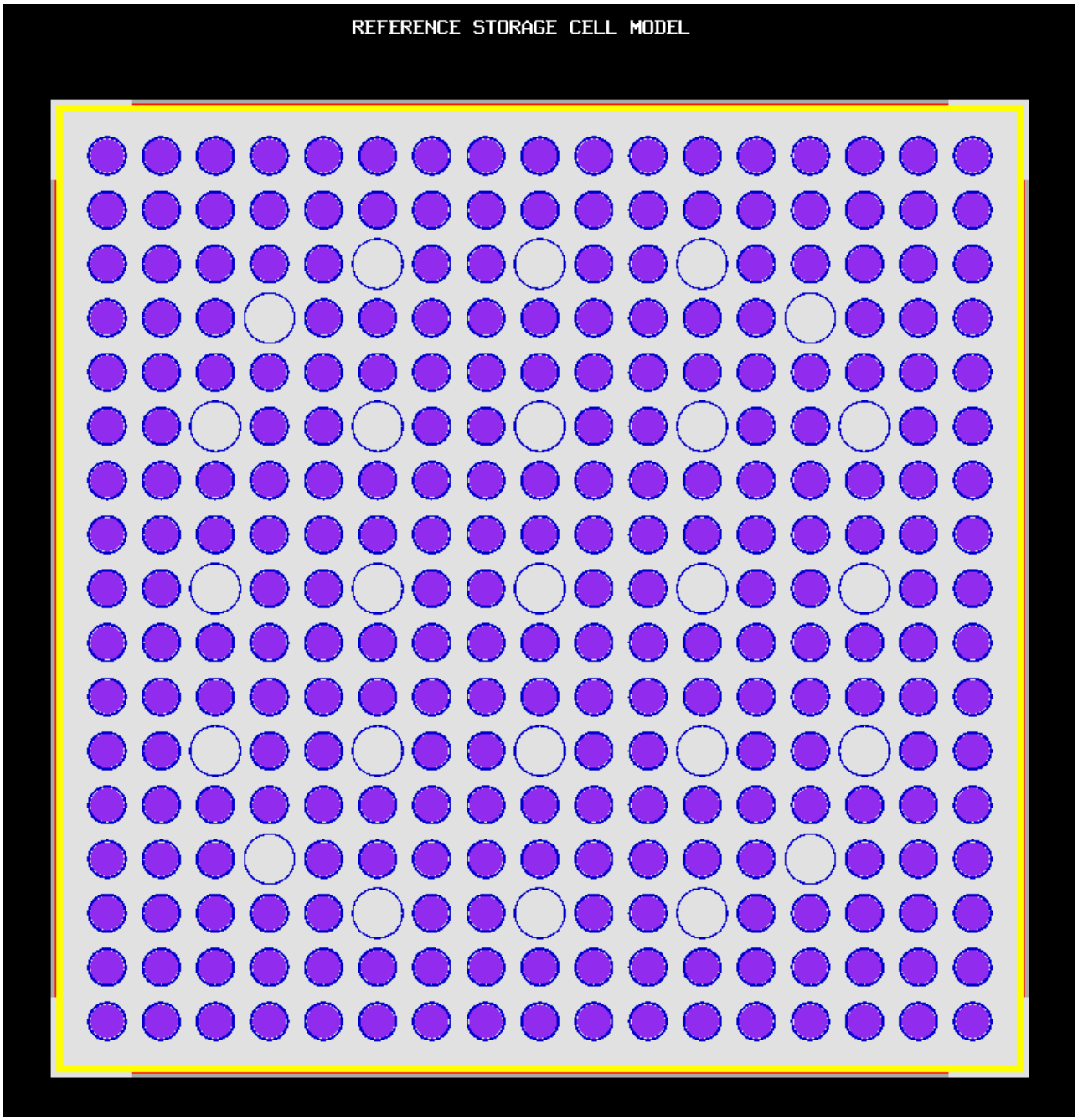


Figure 1 KENO V.a calculational model of the reference storage rack configuration loaded with Westinghouse 17 OFA assemblies. Reflective boundary conditions are employed on all sides to simulate an infinite array of storage cells.

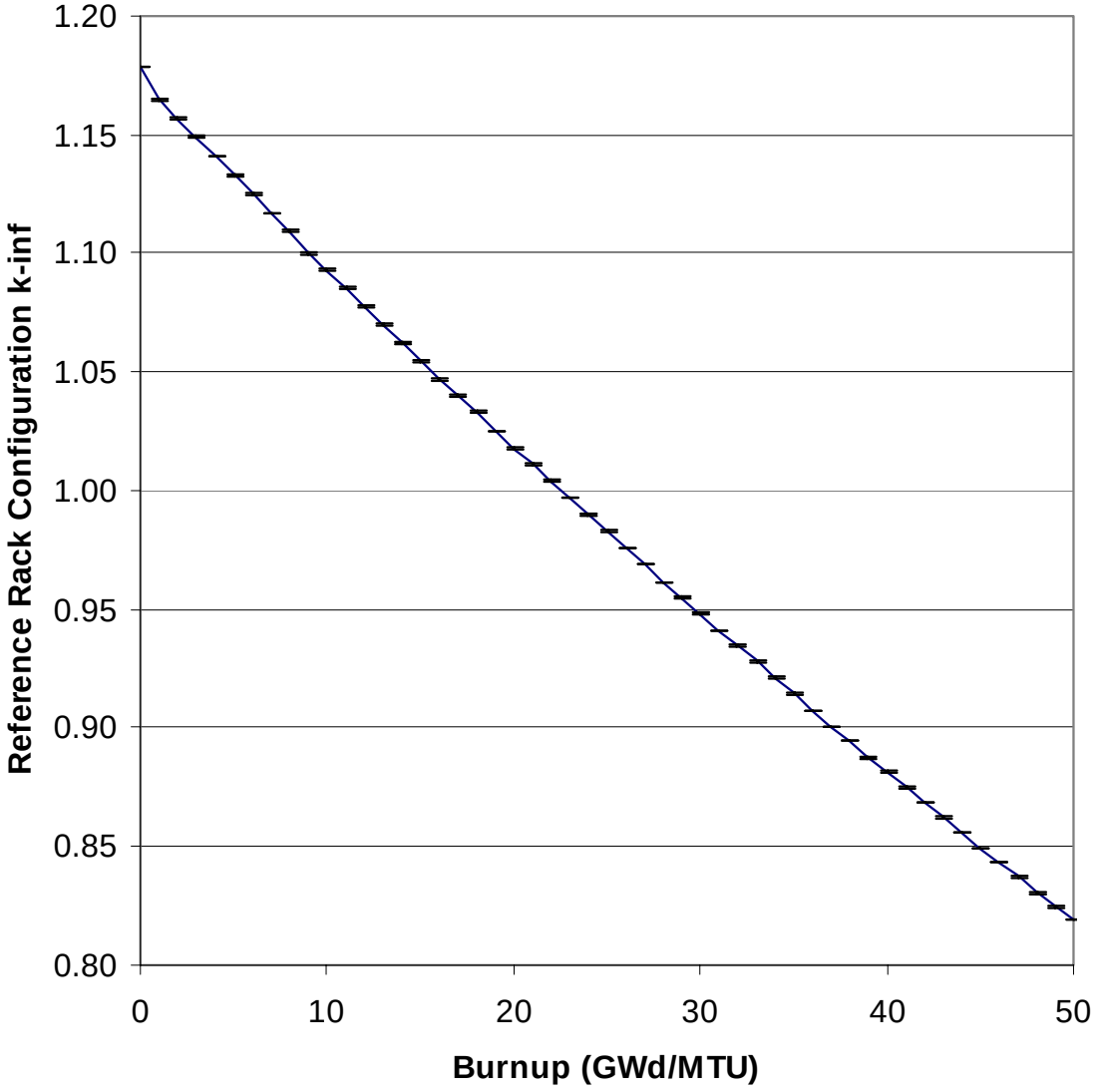


Figure 2 Calculated k_{inf} as a function of burnup in the reference storage rack configuration (Westinghouse 17 17 OFA assembly with 4.5 wt % ^{235}U initial enrichment). Error bars represent 1 statistical uncertainties.

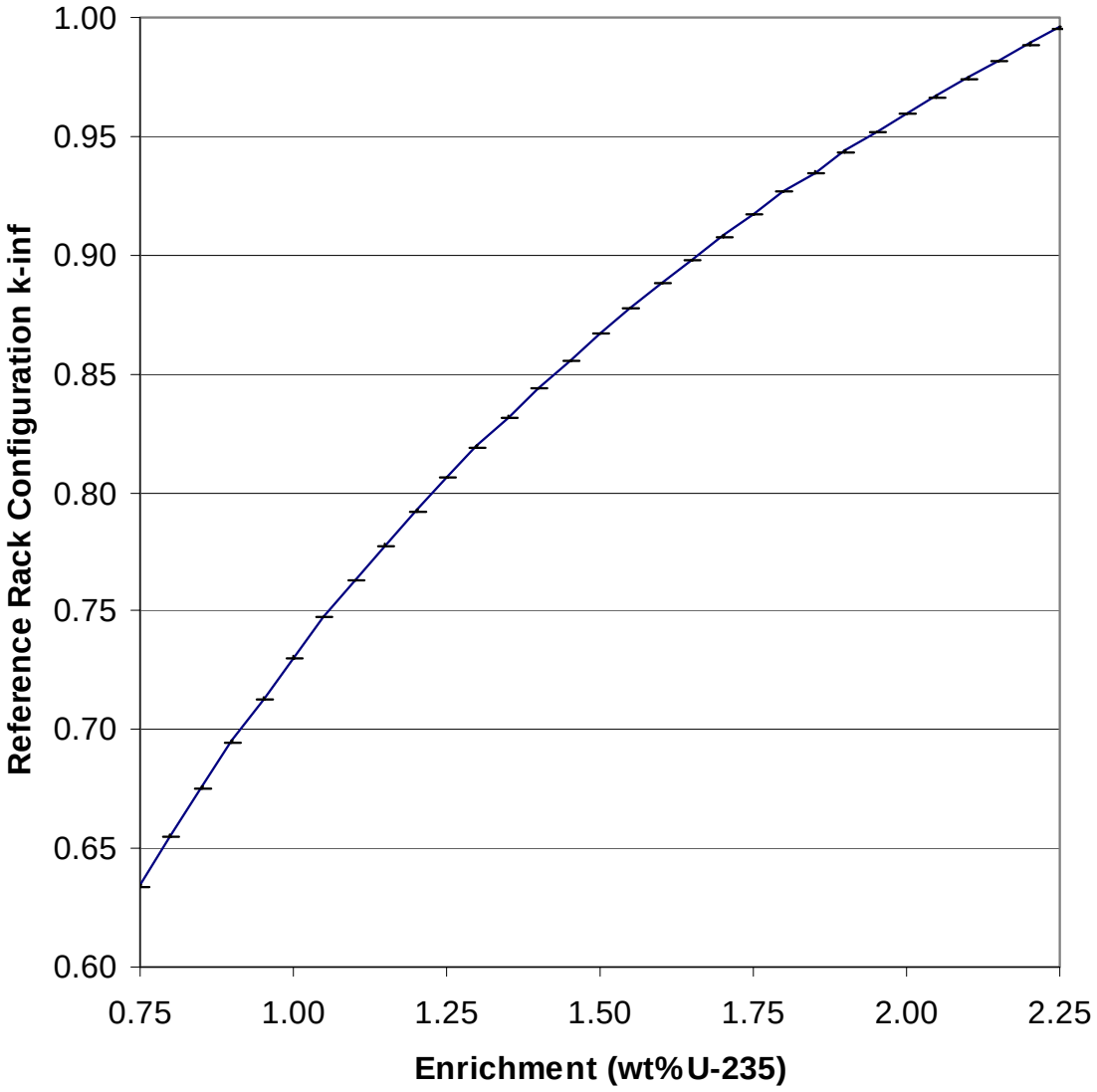


Figure 3 Calculated k_{inf} as a function of enrichment in the reference storage rack configuration (Westinghouse 17 × 17 OFA assembly). Error bars represent 1σ statistical uncertainties.

Table 1 Comparison of k_{inf} results for the reference storage configuration with various burnups

Configuration	Calculational approach		Difference (k_actual – k_REFFE)
	Actual SNF inventory	REFFE	
Reference, B = 33 GWd/MTU REFFE = 1.8086 wt % ^{235}U	0.92770 ± 0.00021	0.92760 ± 0.00023	0.00010 ± 0.00031
Reference, B = 25 GWd/MTU REFFE = 2.1594 wt % ^{235}U	0.98303 ± 0.00022	0.98345 ± 0.00021	-0.00042 ± 0.00030
Reference, B = 50 GWd/MTU REFFE = 1.2991 wt % ^{235}U	0.81910 ± 0.00019	0.81906 ± 0.00019	0.00004 ± 0.00027

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

4.2 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.[4] 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 reactivity[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.

4.2.1 Normal Conditions

Using the determined REFFE and the actual SNF inventory (for a burnup of 33 GWd/MTU), calculations were performed for an infinite array of storage cells (the reference geometric configuration) with increasing quantities of soluble boron (a departure from the reference configuration). The resulting k_{inf} values are listed in Table 2 and plotted in Figure 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 3 compares k_{inf} values for burnups of 25 and 50 GWd/MTU. The Δk values between using the actual SNF inventory and the REFFE, which are listed in the right-hand column of Tables 2 and 3, and plotted in Figure 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, especially considering the recent allowance of credit for soluble boron up to 5% in reactivity.

Table 2 Comparison of k_{inf} results for the reference storage configuration with soluble boron present (Burnup = 33 GWd/MTU)

Soluble boron concentration (ppm)	Calculational approach		Difference (k_actual – k_REFFE)
	Actual 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

The soluble boron in the water is an effective thermal neutron absorber. Because of its negative reactivity worth, the presence of soluble boron reduces the relative reactivity worth of the fission products and actinide absorbers. In other words, the fission products 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_{inf} with increasing concentrations of soluble boron and increasing burnup. Further, this observation is consistent with previous findings[5] 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 fission products is reduced with respect to the reference condition.

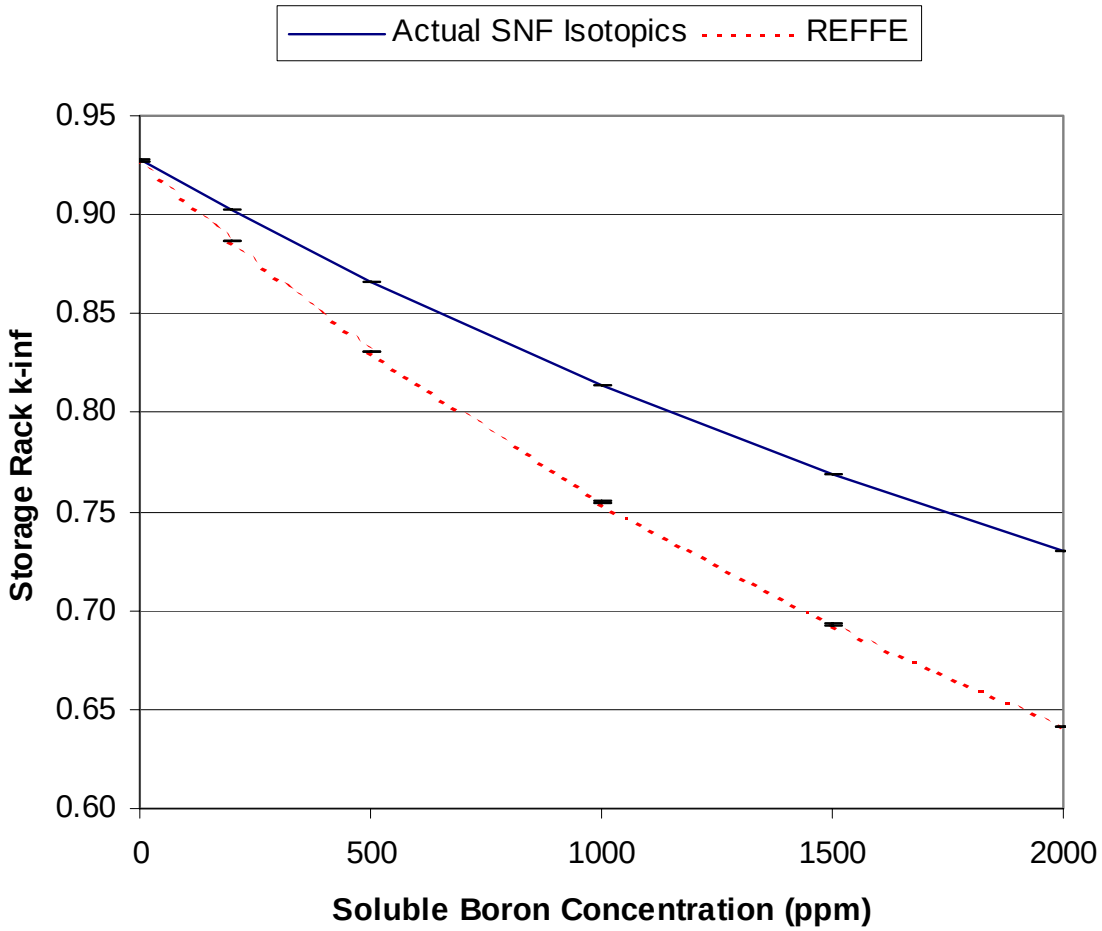


Figure 4 Comparison of k_{inf} values calculated with the actual SNF isotopics and the REFFE as a function of soluble boron concentration in the reference storage configuration. Results correspond to fuel with 4.5 wt % ^{235}U initial enrichment that has accumulated 33 GWd/MTU burnup. Error bars represent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

Table 3 Comparison of k_{inf} results for the reference storage configuration with soluble boron present for burnups of 25 and 50 GWd/MTU

Soluble boron concentration (ppm)	Calculational approach		Difference (k_actual – k_REFFE)
	Actual SNF inventory	REFFE	
Burnup = 25 GWd/MTU, 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/MTU, 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

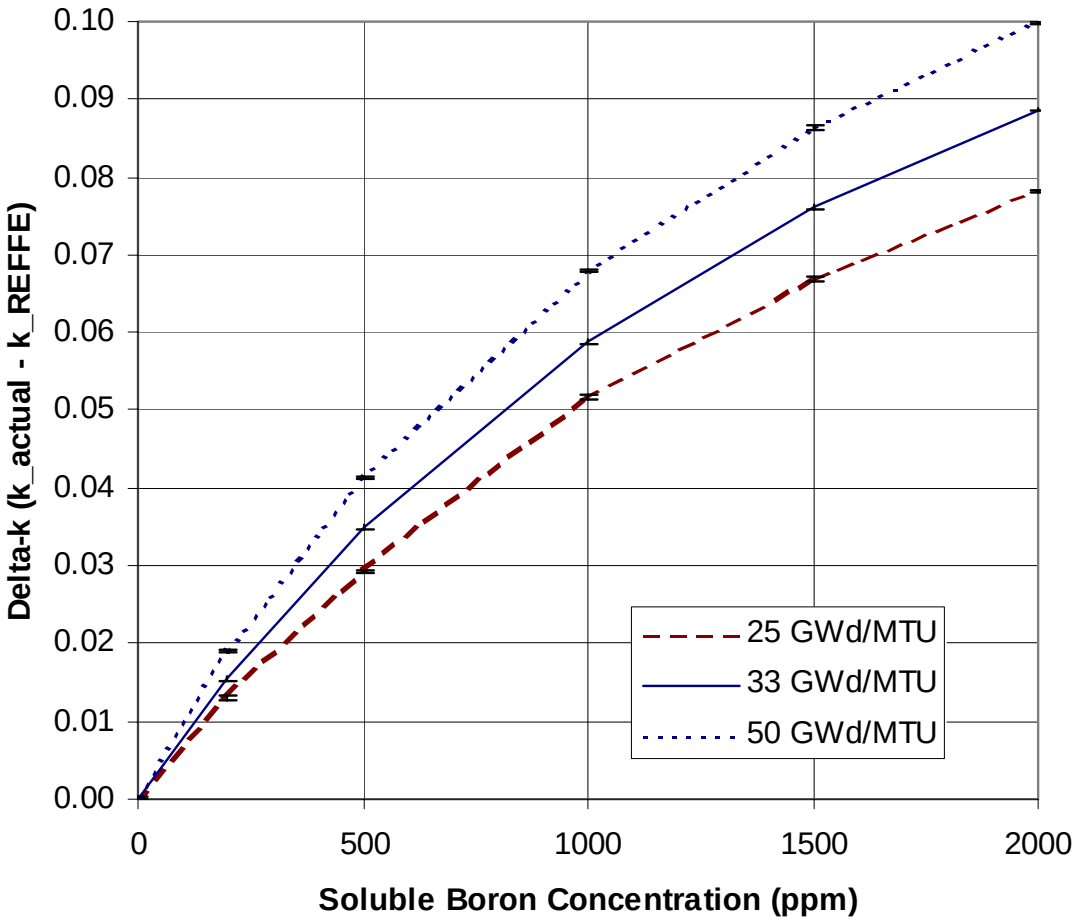


Figure 5 Reactivity effect associated with the use of REFFE with soluble boron present. Results correspond to fuel with 4.5 wt % ^{235}U initial enrichment that has accumulated burnups of 25, 33, and 50 GWd/MTU. Error bars represent 1 statistical uncertainties.

4.2.2 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 actual SNF inventory (for a burnup of 33 GWd/MTU), 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_{inf} values are listed in Table 4. For the condition with no soluble boron present, a small under-estimation (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_{inf} 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 4 Comparison of k_{inf} results for the misplaced fresh fuel assembly accident configuration with soluble boron present (Burnup = 33 GWd/MTU)

Soluble boron concentration (ppm)	Calculational approach		Difference (k_actual – k_REFFE)
	Actual 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

4.3 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.

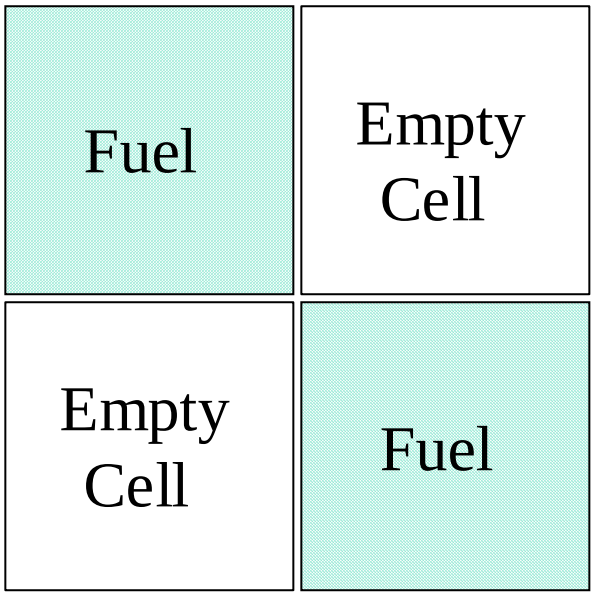
4.3.1 Checkerboard Configurations

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 (1) temporary storage of fresh fuel in racks designed for burned fuel and (2) 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 Figure 6.

Table 5 compares calculated k_{inf} values based on actual SNF isotopics and REFFE for several possible checkerboard configurations. Review of the results listed in Table 5 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 results. In contrast, when a 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 fission products, as well as thermal fission in the REFFE. Therefore, in either case the fission products and actinide absorbers have greater relative negative reactivity worth in these configurations (as compared to the reference configuration). Consequently, the fission products 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.



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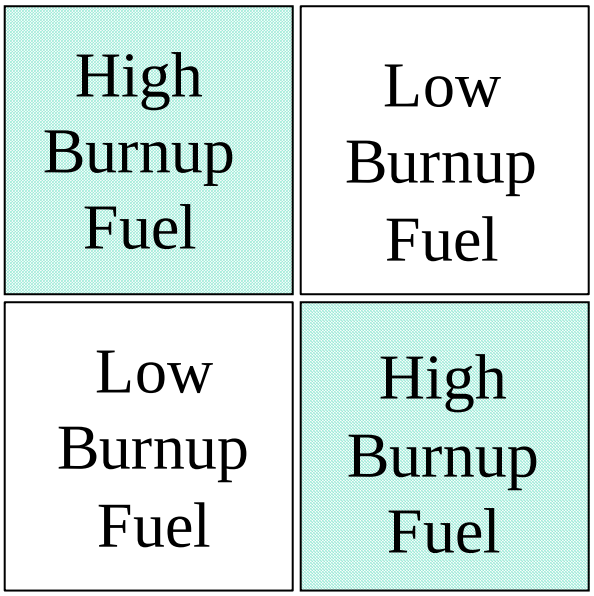


(b)

Figure 6 Examples of checkerboard storage configurations: (a) checkerboard configuration with empty cells; (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.

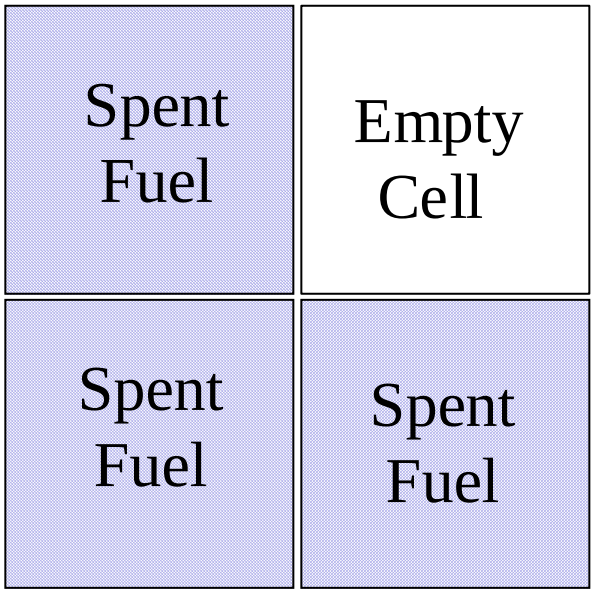
Table 5 Comparison of k_{inf} results for various checkerboard-type configurations

Assemblies in checkerboard configuration	Calculational approach		Difference (k_actual – k_REFFE)
	Actual SNF inventory	REFFE	
SNF (33 GWd/MTU) & empty cells	0.64982 ± 0.00022	0.65599 ± 0.00023	–0.00617 ± 0.00032
SNF (33 GWd/MTU) & fresh fuel (1.0 wt % ^{235}U)	0.83726 ± 0.00020	0.83819 ± 0.00020	–0.00093 ± 0.00028
SNF (33 GWd/MTU) & fresh fuel (2.5 wt % ^{235}U)	0.97979 ± 0.00021	0.97860 ± 0.00021	0.00119 ± 0.00030
SNF (50 GWd/MTU) & fresh fuel (3.5 wt % ^{235}U)	0.98774 ± 0.00024	0.98658 ± 0.00023	0.00116 ± 0.00033
SNF(50 GWd/MTU) & SNF (25 GWd/MTU)	0.90686 ± 0.00020	0.90664 ± 0.00020	0.00022 ± 0.00028

4.3.2 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 Figure 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 6 compares calculated k_{inf} values based on actual SNF isotopics and REFFE for two possible 3-out-of-4 configurations. Review of the results listed in Table 6 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 the previous subsection for checkerboard configurations. Similar to the results for checkerboard configurations, the differences appear to be on the order of a few tenths of a percent.



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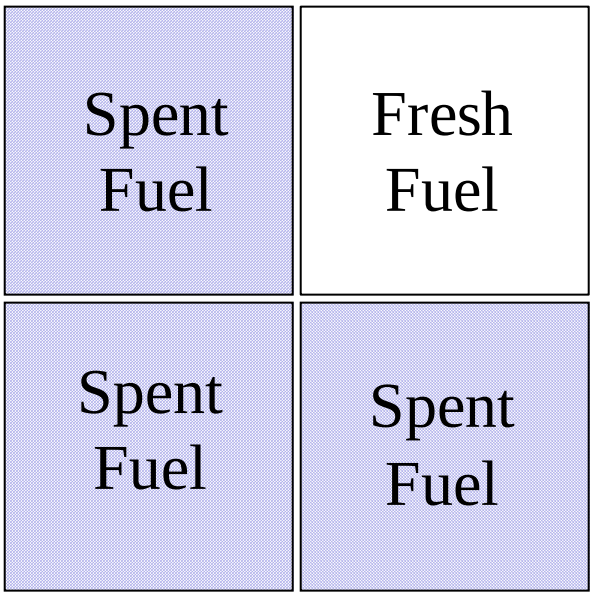

(b)

Figure 7 Examples of 3-out-of-4 storage configurations: (a) 3-out-of-4 configuration with an empty cell; (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.

Table 6 Comparison of k_{inf} results for various 3-out-of-4-type configurations

Assemblies in 3-out-of-4 configuration	Calculational approach		Difference (k_actual – k_REFFE)
	Actual SNF inventory	REFFE	
3 SNF (33 GWd/MTU) & 1 empty cell	0.82314 ± 0.00022	0.82562 ± 0.00024	-0.00248 ± 0.00033
3 SNF (33 GWd/MTU) & 1 fresh fuel (1.0 wt % ^{235}U)	0.88791 ± 0.00020	0.88834 ± 0.00021	-0.00043 ± 0.00029
3 SNF (50 GWd/MTU) & 1 fresh fuel (3.5 wt % ^{235}U)	0.94170 ± 0.00024	0.93992 ± 0.00025	0.00178 ± 0.00035

5 CONCLUSIONS

The practice of equating the reactivity of spent fuel to the reactivity of fresh fuel, sometimes 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 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_{inf} estimates based on reactivity equivalencing to k_{inf} estimates using the actual 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) and 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 non-conservative results associated with the use of the REFFE. An under-estimation of k_{inf} of more than 3% is shown for a soluble boron concentration of 500 ppm, and the under-estimation is shown to increase with increasing soluble boron concentration. This observation is considered to be important, especially considering the recent allowance of credit for soluble boron up to 5% in reactivity. 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 infinite spent fuel storage configuration. However, an under-estimation of k_{inf} of more than 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 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. 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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11. ABSTRACT ***(200 words or less)***

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 PWR spent fuel pool (SFP) storage conditions. The investigation consists of comparing k_{inf} estimates based on reactivity "equivalent" fresh fuel enrichment (REFFE) to k_{inf} estimates using the actual 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.

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