

# **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**

**U.S. Nuclear Regulatory Commission  
Office of Nuclear Regulatory Research  
Washington, DC 20555-0001**



## AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

### NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at [www.nrc.gov/NRC/ADAMS/index.html](http://www.nrc.gov/NRC/ADAMS/index.html).

Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, of the Code of *Federal Regulations*, may also be purchased from one of these two sources:

1. The Superintendent of Documents  
U.S. Government Printing Office  
P.O. Box 37082  
Washington, DC 20402-9328  
[www.access.gpo.gov/su\\_docs](http://www.access.gpo.gov/su_docs)  
202-512-1800
2. The National Technical Information Service  
Springfield, VA 22161-0002  
[www.ntis.gov](http://www.ntis.gov)  
1-800-553-6847 or, locally, 703-605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer,  
Reproduction and Distribution  
Services Section  
U.S. Nuclear Regulatory Commission  
Washington, DC 20555-0001

E-mail: [DISTRIBUTION@nrc.gov](mailto:DISTRIBUTION@nrc.gov)

Facsimile: 301-415-2289

Some publications in the NUREG series that are posted at NRC's Web site address [www.nrc.gov/NRC/NUREGS/indexnum.html](http://www.nrc.gov/NRC/NUREGS/indexnum.html) are updated regularly and may differ from the last printed version.

### Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library  
Two White Flint North  
11545 Rockville Pike  
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute  
11 West 42<sup>nd</sup> Street  
New York, NY 10036-8002  
[www.ansi.org](http://www.ansi.org)  
212-642-4900

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG/XXXX) or agency contractors (NUREG/CR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) brochures (NUREG/BR-XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG-0750).

**DISCLAIMER:** This report was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any employee, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed in this publication, or represents that its use by such third party would not infringe privately owned rights.

---

---

# **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**

---

---

Manuscript Completed: August 2000  
Date Published: September 2000

Prepared by  
J. C. Wagner and C. V. Parks

Oak Ridge National Laboratory  
Managed by UT-Battelle, LLC  
P. O. Box 2008  
Oak Ridge, Tennessee 37831-6370

D. D. Ebert, NRC Project Manager

**Prepared for**  
**Division of Systems Analysis and Regulatory Effectiveness**  
**Office of Nuclear Regulatory Research**  
**U.S. Nuclear Regulatory Commission**  
**Washington, DC 20555-0001**  
**NRC Job Code W6479**





## 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 ( $\leq 500$  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.



# CONTENTS

ABSTRACT .....	iii
LIST OF FIGURES.....	vii
LIST OF TABLES .....	ix
ACKNOWLEDGMENT.....	xi
1 INTRODUCTION.....	1
2 SPENT FUEL STORAGE .....	3
3 CALCULATIONAL METHODS.....	5
4 ANALYSES .....	7
4.1 Reference Storage Cell.....	7
4.1.1 Geometric Description .....	7
4.1.2 Determination of the Reactivity Equivalent Fresh Fuel Enrichment (REFFE) ...	7
4.2 Calculations with Soluble Boron Present.....	11
4.2.1 Normal Conditions .....	12
4.2.2 Accident Conditions .....	16
4.3 Calculations for Alternative Storage Configurations .....	17
4.3.1 Checkerboard Configurations .....	17
4.3.2 3-out-of-4 Storage Configurations .....	19
5 CONCLUSIONS.....	23
REFERENCES.....	25



## LIST OF FIGURES

Figure	Page
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. .... 8
2	Calculated $k_{inf}$ as a function of burnup in the reference storage rack configuration (Westinghouse 17 17 OFA assembly with 4.5 wt % $^{235}\text{U}$ initial enrichment). Error bars represent 1 statistical uncertainties..... 9
3	Calculated $k_{inf}$ as a function of enrichment in the reference storage rack configuration (Westinghouse 17 $\times$ 17 OFA assembly). Error bars represent 1 $\sigma$ statistical uncertainties. 10
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 % $^{235}\text{U}$ initial enrichment that has accumulated 33 GWd/MTU burnup. Error bars represent 1 $\sigma$ statistical uncertainties. .... 13
5	Reactivity effect associated with the use of REFFE with soluble boron present. Results correspond to fuel with 4.5 wt % $^{235}\text{U}$ initial enrichment that has accumulated burnups of 25, 33, and 50 GWd/MTU. Error bars represent 1 statistical uncertainties..... 15
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. .... 18
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..... 20



## LIST OF TABLES

Table	Page
1	Comparison of $k_{inf}$ results for the reference storage configuration with various burnups... 11
2	Comparison of $k_{inf}$ results for the reference storage configuration with soluble boron present (Burnup = 33 GWd/MTU)..... 12
3	Comparison of $k_{inf}$ results for the reference storage configuration with soluble boron present for burnups of 25 and 50 GWd/MTU ..... 14
4	Comparison of $k_{inf}$ results for the misplaced fresh fuel assembly accident configuration with soluble boron present (Burnup = 33 GWd/MTU)..... 16
5	Comparison of $k_{inf}$ results for various checkerboard-type configurations ..... 19
6	Comparison of $k_{inf}$ results for various 3-out-of-4-type configurations..... 21



## **ACKNOWLEDGMENT**

This work was performed under contract with the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. The authors acknowledge the initial review and comments provided by Larry Kopp of the Office of Nuclear Reactor Regulation and Dave Ebert of the Office of Nuclear Regulatory Research.

Oak Ridge National Laboratory is managed by UT-Battelle, LLC, under contract number DE-AC05-00OR22725 for the U.S. Department of Energy.



# 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.<sup>1</sup> 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 <sup>135</sup>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.<sup>1</sup>

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 (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<sup>2</sup> 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,<sup>2</sup> along with the recent acceptance of partial credit for soluble boron,<sup>1</sup> 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.<sup>3</sup> 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  $17 \times 17$  OFA assembly with initial enrichment of 4.5 wt %  $^{235}\text{U}$  was used in the depletion calculations.

The criticality calculations were performed with the CSAS25 sequence of SCALE,<sup>3</sup> 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.<sup>4</sup> 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 <sup>2</sup>
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.)		

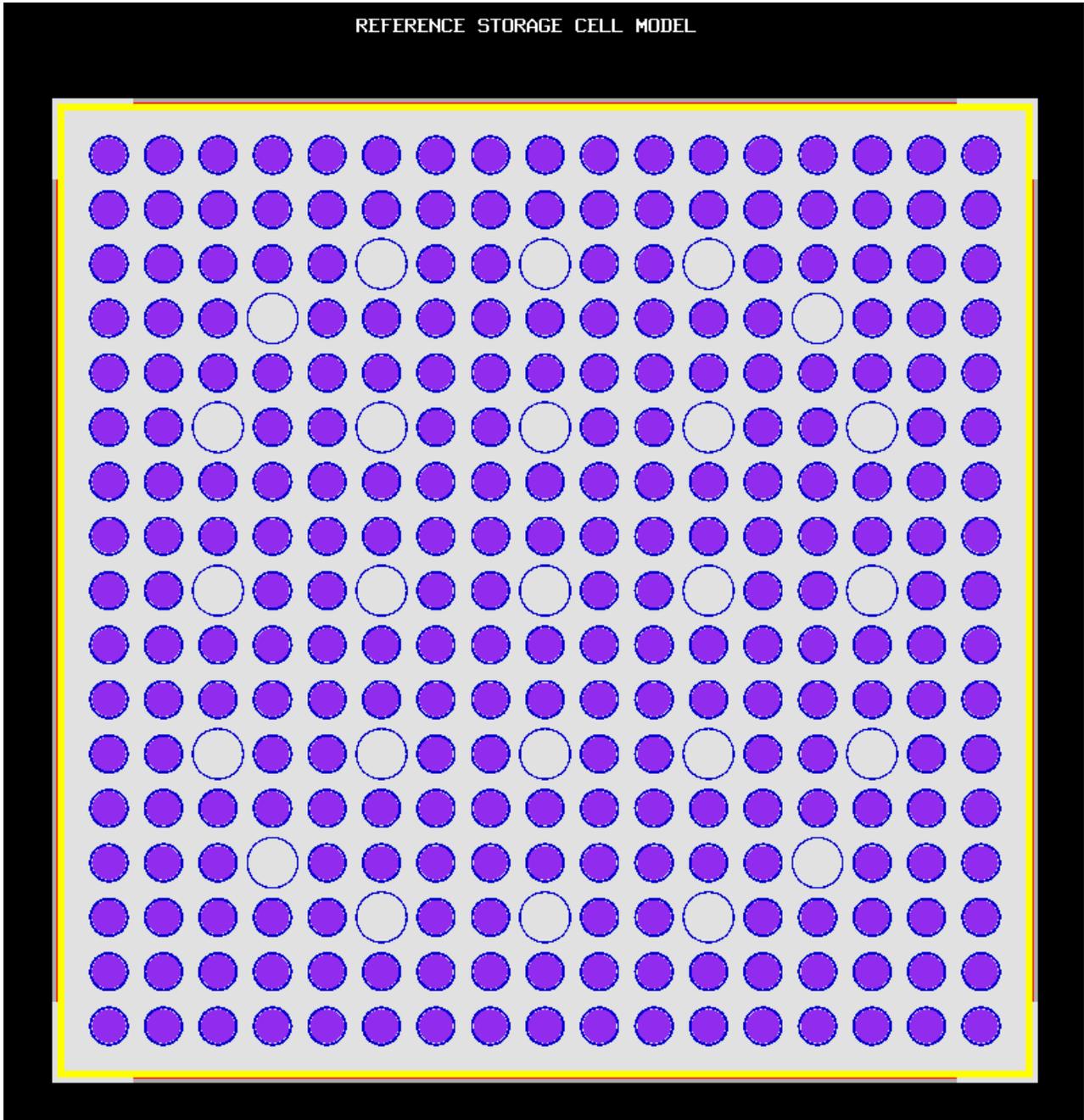
The reference storage configuration consists of an infinite array of storage cells in unborated water, which is modeled as a single storage cell with reflective boundary conditions through the centerline of the composite materials between the cells. The KENO V.a models included axial leakage by modeling 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)

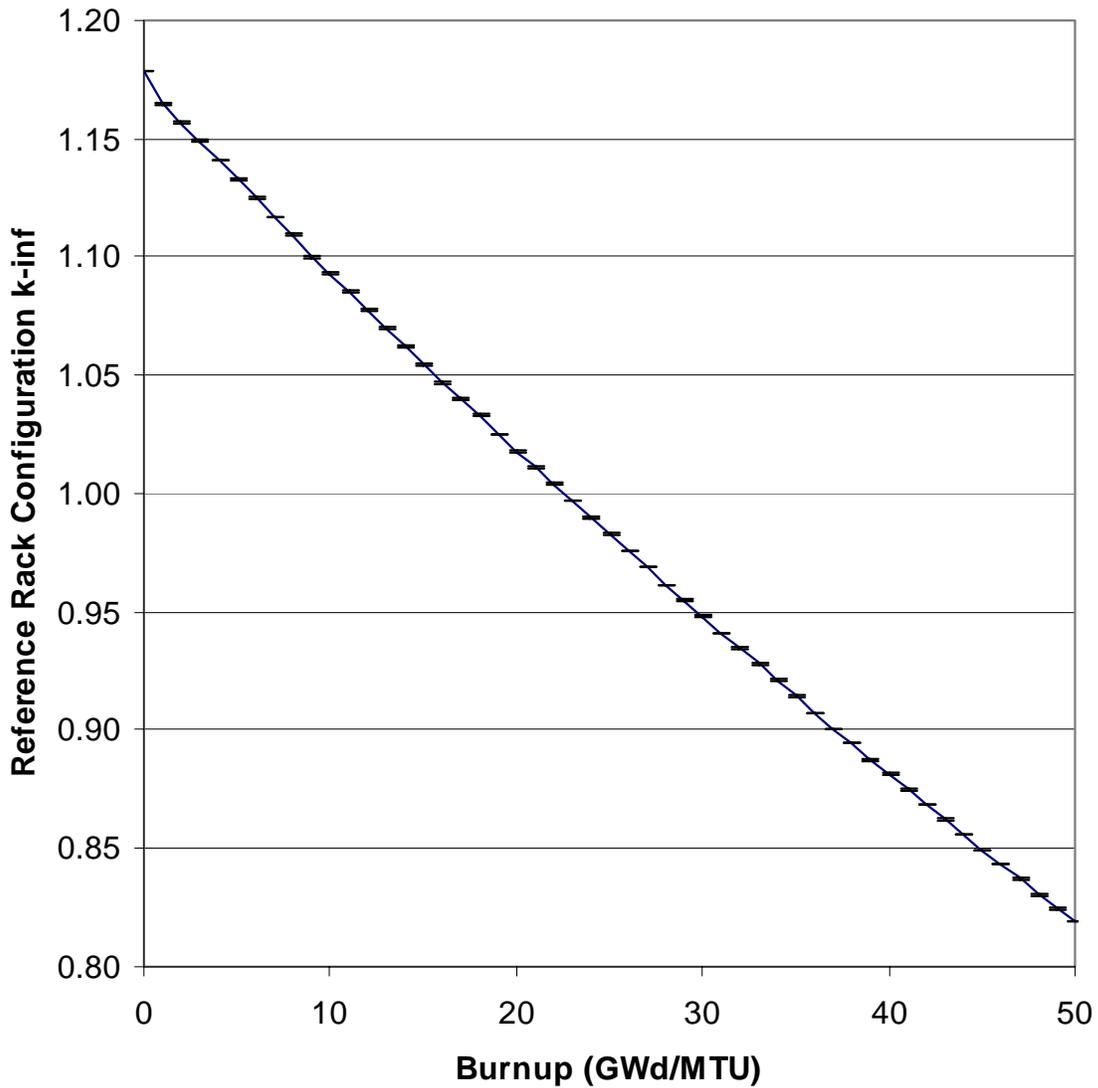
The first step in determining the REFFE is to calculate  $k_{inf}$  as a function of burnup for the reference storage rack configuration with the actual spent fuel isotopics. Consistent with the guidance in Ref. 1, Xe-135 was excluded from the spent fuel isotopics to ensure maximum reactivity. The calculated  $k_{inf}$  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 % <sup>235</sup>U. For use in later analyses of alternative storage configurations, the REFFEs corresponding to burnups of 25 and 50 GWd/MTU were also determined.

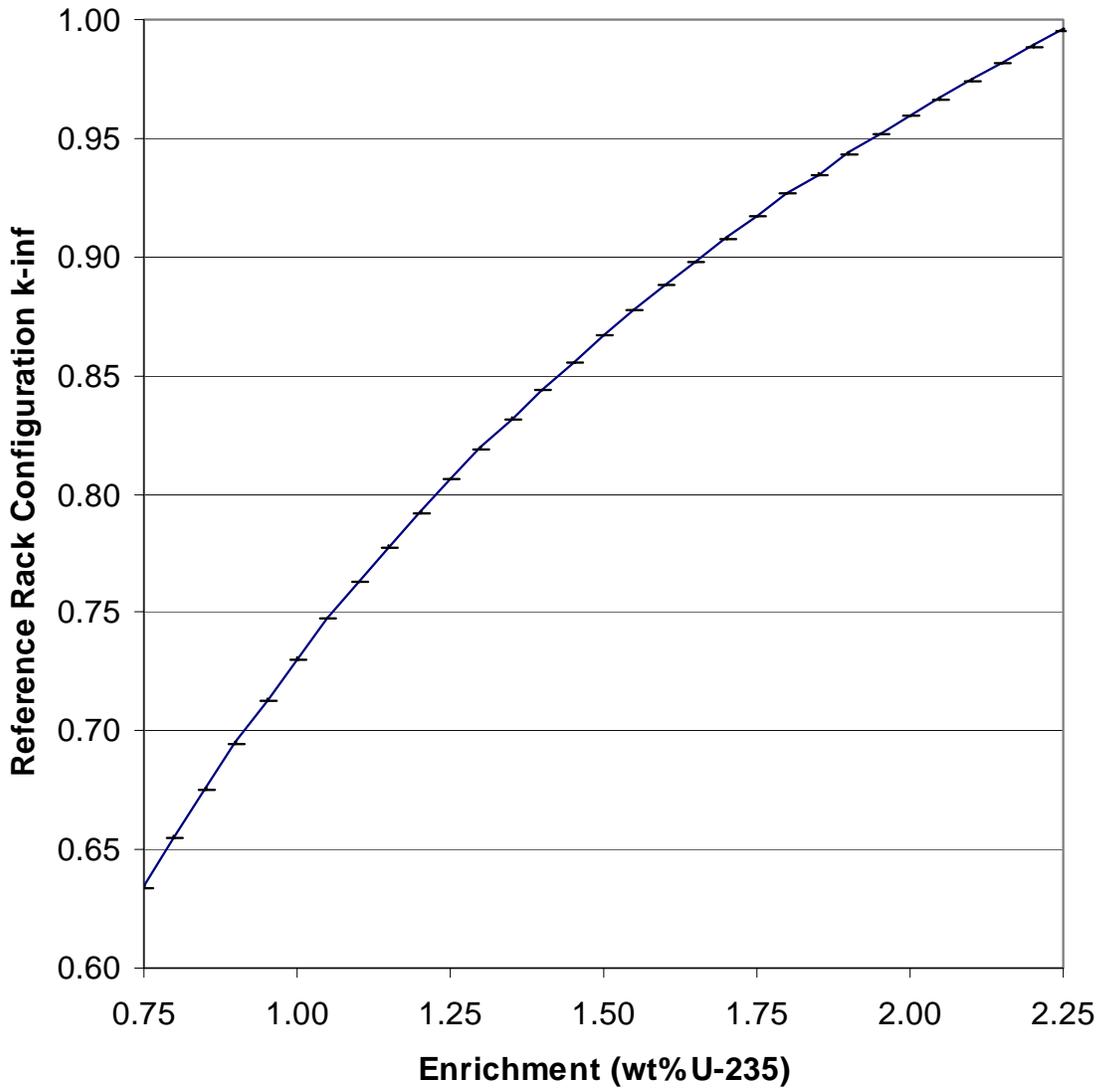
Specific criticality calculations may be performed with the REFFE values and with the actual SNF inventories to verify the reactivity equivalence. Table 1 lists the results of the verification calculations and shows that the calculated  $k_{inf}$  values from the two approaches are statistically equal. The uncertainties listed in Table 1 correspond to 1 $\sigma$ . 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 %  $^{235}\text{U}$  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  $17 \times 17$  OFA assembly). Error bars represent  $1\sigma$  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 % <sup>235</sup> U	0.92770 ± 0.00021	0.92760 ± 0.00023	0.00010 ± 0.00031
Reference, B = 25 GWd/MTU REFFE = 2.1594 wt % <sup>235</sup> U	0.98303 ± 0.00022	0.98345 ± 0.00021	-0.00042 ± 0.00030
Reference, B = 50 GWd/MTU REFFE = 1.2991 wt % <sup>235</sup> 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.<sup>1</sup> 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<sup>1</sup> (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.<sup>4</sup> 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<sup>1</sup> 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.

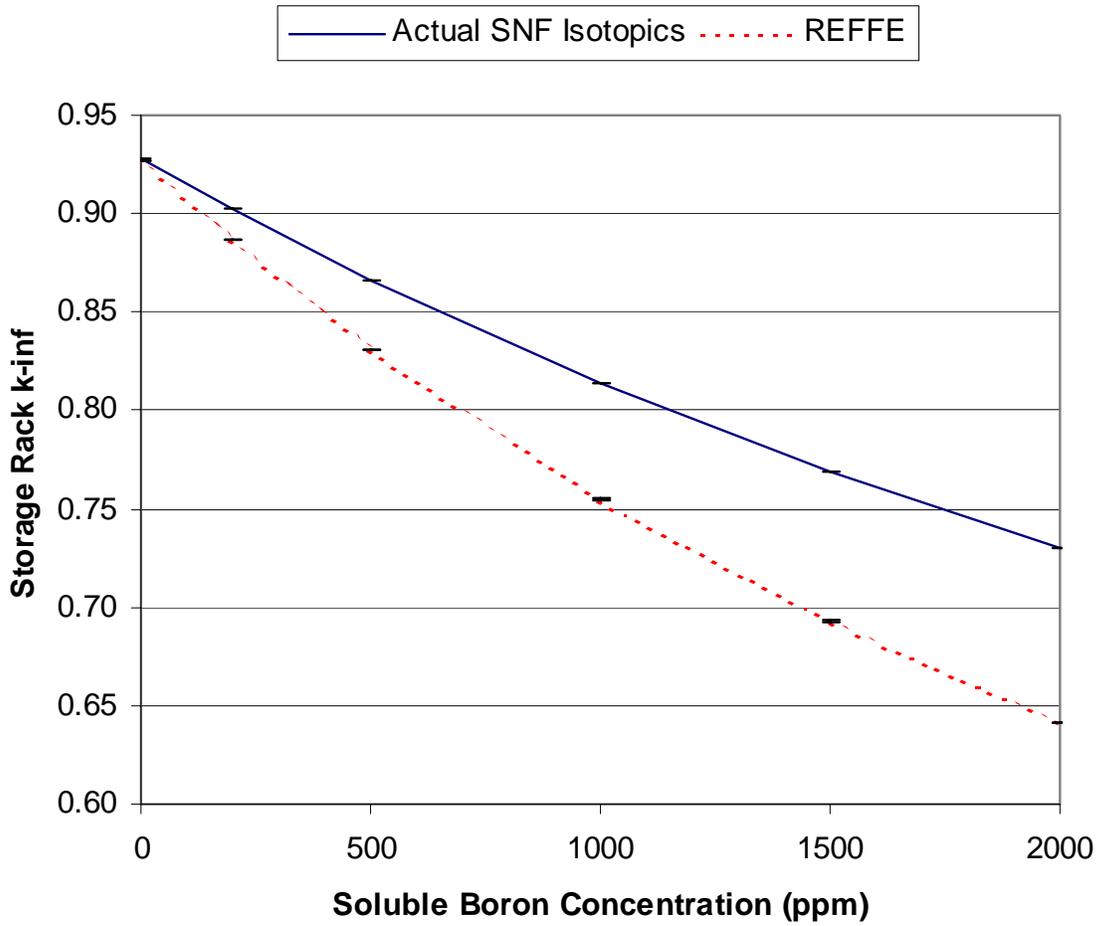
### 4.2.1 Normal Conditions

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  $\Delta k$  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 % $^{235}\text{U}$	
0 (Reference)	$0.92770 \pm 0.00021$	$0.92760 \pm 0.00023$	$0.00010 \pm 0.00031$
200	$0.90232 \pm 0.00020$	$0.88678 \pm 0.00020$	$0.01554 \pm 0.00028$
500	$0.86619 \pm 0.00020$	$0.83126 \pm 0.00019$	$0.03493 \pm 0.00028$
1000	$0.81364 \pm 0.00019$	$0.75482 \pm 0.00018$	$0.05882 \pm 0.00026$
1500	$0.76904 \pm 0.00019$	$0.69285 \pm 0.00016$	$0.07619 \pm 0.00025$
2000	$0.73034 \pm 0.00017$	$0.64171 \pm 0.00015$	$0.08863 \pm 0.00023$

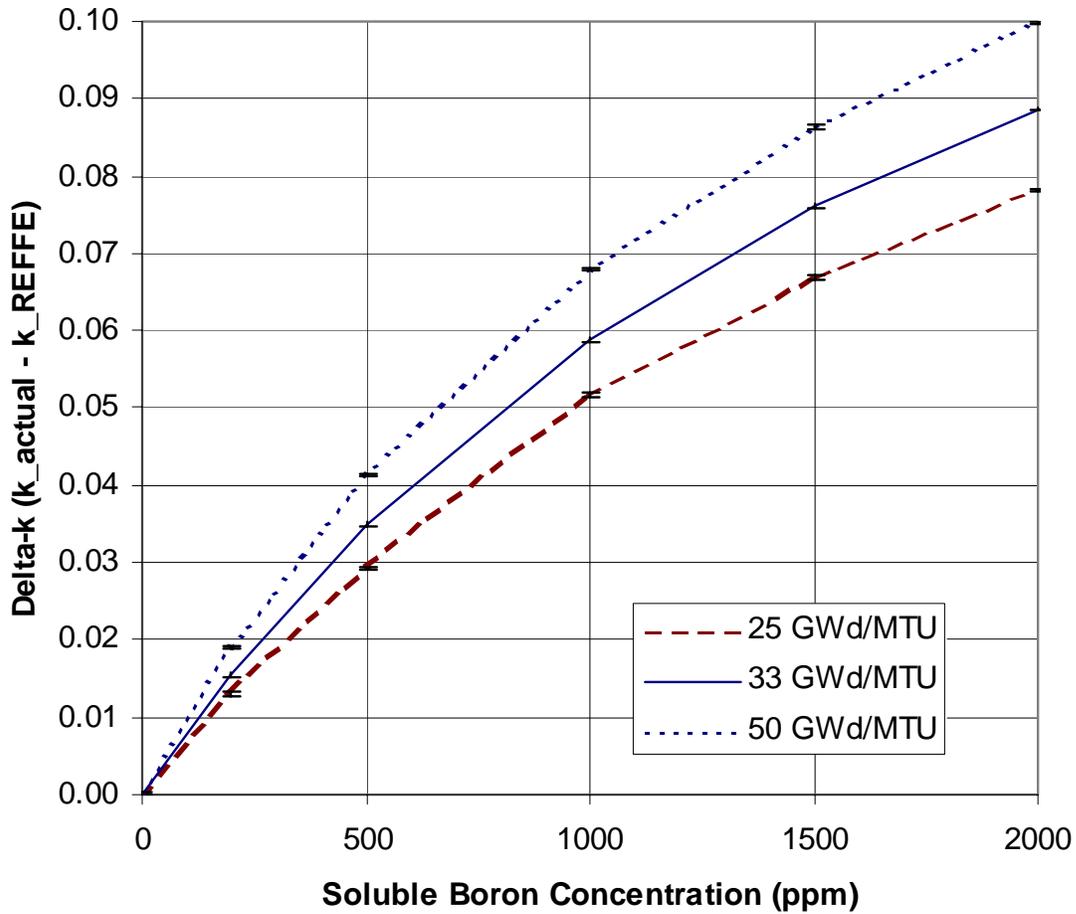
The soluble boron in the water is an effective thermal neutron absorber. Because of its negative reactivity worth, the presence of soluble boron reduces the relative reactivity worth of the fission products and actinide absorbers. In other words, the fission products and actinide absorbers have greater 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<sup>5</sup> 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 REFPE as a function of soluble boron concentration in the reference storage configuration. Results correspond to fuel with 4.5 wt %  $^{235}\text{U}$  initial enrichment that has accumulated 33 GWd/MTU burnup. Error bars represent  $1\sigma$  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 % $^{235}\text{U}$			
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 % $^{235}\text{U}$			
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 % <sup>235</sup>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  $7 \times 7$  array of storage cells with reflective boundary conditions and a fresh 4.5 wt %  $^{235}\text{U}$  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 % $^{235}\text{U}$	
0	$0.95800 \pm 0.00029$	$0.95604 \pm 0.00029$	$0.00196 \pm 0.00041$
200	$0.93173 \pm 0.00026$	$0.92106 \pm 0.00028$	$0.01067 \pm 0.00038$
500	$0.89566 \pm 0.00029$	$0.87447 \pm 0.00028$	$0.02119 \pm 0.00040$

### 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.

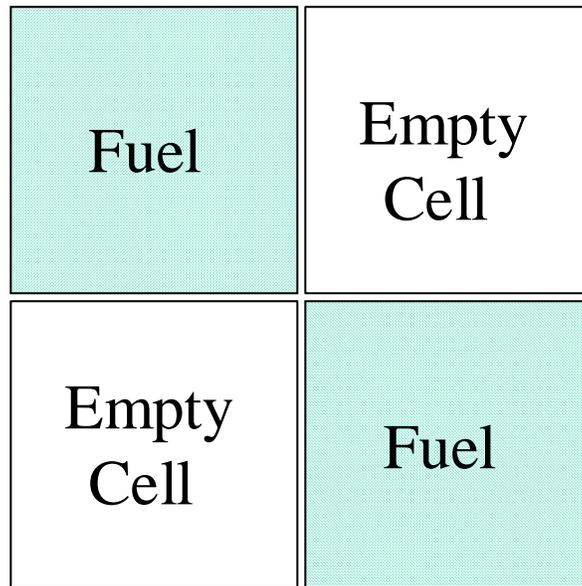
#### 4.3.1 Checkerboard Configurations

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.

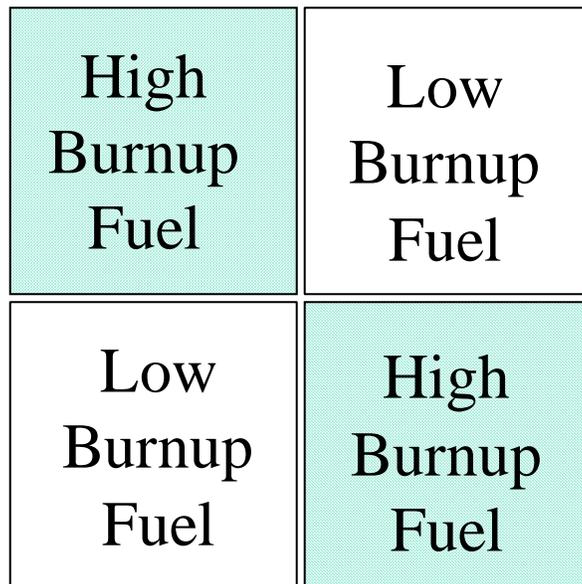
Table 5 compares calculated  $k_{inf}$  values based on actual SNF isotopics and REFFE for several possible checkerboard configurations. Review of the results listed in Table 5 reveals a clear trend for when the use of REFFE produces conservative and nonconservative results. When a REFFE assembly is 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.



(a)



(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.**

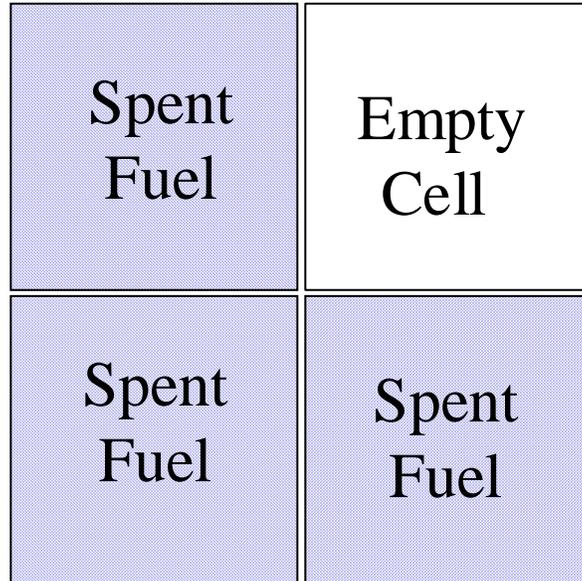
**Table 5 Comparison of  $k_{inf}$  results for various checkerboard-type configurations**

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

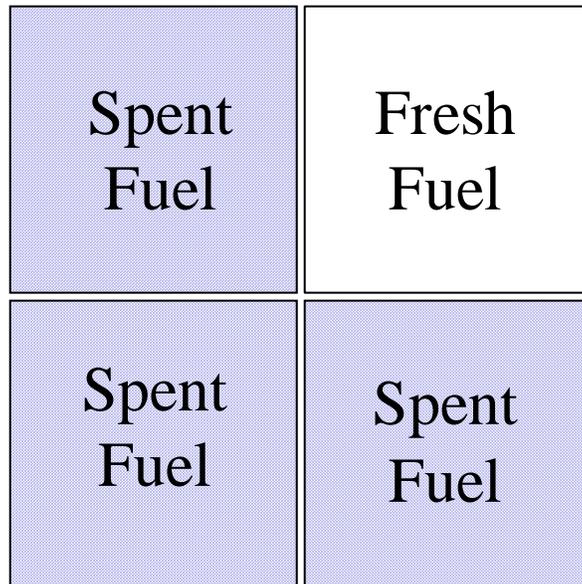
### 4.3.2 3-out-of-4 Storage Configurations

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.



(a)



(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	$0.82314 \pm 0.00022$	$0.82562 \pm 0.00024$	$-0.00248 \pm 0.00033$
3 SNF (33 GWd/MTU) & 1 fresh fuel (1.0 wt % $^{235}\text{U}$ )	$0.88791 \pm 0.00020$	$0.88834 \pm 0.00021$	$-0.00043 \pm 0.00029$
3 SNF (50 GWd/MTU) & 1 fresh fuel (3.5 wt % $^{235}\text{U}$ )	$0.94170 \pm 0.00024$	$0.93992 \pm 0.00025$	$0.00178 \pm 0.00035$



## 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 ( $\leq 500$  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.



## REFERENCES

1. "Guidance on the Regulatory Requirements for Criticality Safety Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC memorandum from L. I. KOPP to T. COLLINS, August 19, 1998, U.S. Nuclear Regulatory Commission (1998).
2. J. C. Neuber, "Criticality Analysis of BWR Spent Fuel Storage Facilities Inside Nuclear Power Plants," Vol. IV, p. 1624 in *Proc. of the 6<sup>th</sup> International Conference on Nuclear Criticality*, September 1999.
3. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Rev. 5 (ORNL/NUREG/CSD-2/R5), Vols. I, II, III, March 1997. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.
4. *Proceedings of the 1991 EEI/UWASTE-EPRI Workshop on At-Reactors Spent Fuel Storage*, Charlotte, North Carolina, October 15-17, 1991, EPRI-TM-100676, Electric Power Research Institute, May 1992.
5. C. V. Parks, M. D. DeHart and J. C. Wagner, *Review and Prioritization of Technical Issues Related to Burnup Credit for LWR Fuel*, NUREG/CR-6665 (ORNL/TM-1999/303), U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, February 2000.



**INTERNAL DISTRIBUTION**

- |        |                 |        |   |
|--------|-----------------|--------|---|
| 1.     | S. M. Bowman    | 22.    | J.-P. Renier  |
| 2.     | B. L. Broadhead | 23.    | R. W. Roussin   |
| 3-7.   | W. C. Carter    | 24.    | J. C. Ryman   |
| 8.     | M. D. DeHart    | 25.    | C. H. Shappert  |
| 9.     | M. B. Emmett    | 26.    | T. E. Valentine   |
| 10.    | I. C. Gauld     | 27-31. | J. C. Wagner  |
| 11.    | C. M. Hopper    | 32.    | R. M. Westfall  |
| 12.    | M. A. Kuliasha  | 33.    | Central Research Library,<br>Document Reference Section |
| 13.    | B. D. Murphy    | 34.    | ORNL Laboratory Records - RC                            |
| 14-18. | C. V. Parks     | 35-50. | ORNL Laboratory Records                                 |
| 19.    | L. M. Petrie    |        |   |
| 20.    | R. T. Primm III |        |   |
| 21.    | C. E. Pugh      |        |   |

**EXTERNAL DISTRIBUTION**

51. S. Anton, Holtec International, 555 Lincoln Drive West, Marlton, NJ 08053
52. A. C. Attard, U.S. Nuclear Regulatory Commission, NRR/DSSA/SRXB, MS O10 B3, Washington, DC 20555
53. M. G. Bailey, Office of Nuclear Material Safety & Safeguards, U.S. Nuclear Regulatory Commission, MS O13 D13, Washington, DC 20555
54. M. C. Brady Raap, Battelle, Pacific Northwest National Laboratory, P.O. Box 999 / MS K8-34, Richland, WA 99352
55. R. J. Cacciapouti, Yankee Atomic Electric Co., 1617 Worcester Rd., Framington, MA 01701
56. D. E. Carlson, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, MS O13 D13, Washington, DC 20555
57. J. M. Conde López, Consejo de Seguridad Nuclear, Jefe de Area de Ingeniería Nuclear, Subdirección General de Tecnología Nuclear, Justo Dorado, 11, 28040 Madrid, Spain
58. P. Cousinou, Institut de Protection et de Sûreté Nucleaire, Département de Recherches en Sécurité, CECI B.P. 6 – 92265 Fontenzy-Aux-Roses, Cedex, France
59. T. W. Doering, 920 Morning Sun Court, Las Vegas, NV 89110
- 60-64. D. D. Ebert, U.S. Nuclear Regulatory Commission, RES/DSARE/SMSAB, MS T10 K8, Washington, DC 20555
65. J. H. Flack, U.S. Nuclear Regulatory Commission, RES/DSARE/SMSAB, MS T10 K8, Washington, DC 20555
66. R. N. B. Gmal, Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH, Leiter der Gruppe Kritikalität, Forschungsgelände, 85748 Garching b. München
67. A. Haghghat, Pennsylvania State University, University Park, PA 16802

68. D. B. Lancaster, Nuclear Consultants.com, 320 South Corl Street, State College, PA 16801
69. R. Y. Lee, U.S. Nuclear Regulatory Commission, RES/DSARE/SMSAB, MS T10 K8, Washington, DC 20555
70. A. J. Machiels, Electric Power Research Institute, Advanced Nuclear Technology, Energy Conservation Division, 3412 Hillview Ave., Palo Alto, CA 94304-1395
71. L. Markova, Ustav jaderného výzkumu Řež, Theoretical Reactor Physics, Nuclear Research Institute, Czech Republic, 25068 REZ
72. J. C. Neuber, SIEMENS AG, KWU NS-B, Berliner Str. 295-303, D-63067 OFFENBACH AM MAIN, Germany
- 73–74. Office of Scientific and Technical Information, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831
75. P. M. O’Leary, Framatome Technologies, 3315 Old Forest Road, P.O. Box 10935, Lynchburg, VA 24506-0935
76. V. A. Perin, U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, MS T10 K08, Washington, DC 20555
77. B. Petrovic, Westinghouse Electric Company, Science and Technology Department, 1344 Beulah Road, Pittsburgh, PA 15235
78. E. L. Redmond II, Holtec International, 555 Lincoln Drive West, Marlton, NJ 08053
79. C. Rombough, CTR Technical Services, Inc., 5619 Misty Crest Dr., Arlington, TX 76017-4147
80. E. Sartori, OECD/NEA Data Bank, Le Seine-Saint Germain, 12 Boulevard des Iles, F-92130 Issy-les-Moulineaux, France
81. A. P. Ulses, U.S. Nuclear Regulatory Commission, NRR/DSSA/SRXB, MS O10 B3, Washington, DC 20555
82. S. E. Turner, HOLTEC International, 230 Normandy Circle East, Palm Harbor, FL 34683
83. B. H. White, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, MS O13 D13, Washington, DC 20555
84. C. J. Withee, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, MS O13 D13, Washington, DC 20555

NRC FORM 335 (2-89) NRCM 1102 3201, 3202	U.S. NUCLEAR REGULATORY COMMISSION  <b>BIBLIOGRAPHIC DATA SHEET</b> <i>( See instructions on the reverse )</i>	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)  NUREG/CR-6683 ORNL/TM-2000/230		
2. TITLE AND SUBTITLE  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	3. DATE REPORT PUBLISHED	<table border="1"> <tr> <td style="text-align: center;">MONTH September</td> <td style="text-align: center;">YEAR 2000</td> </tr> </table>	MONTH September	YEAR 2000
	MONTH September	YEAR 2000		
	4. FIN OR GRANT NUMBER W6479			
5. AUTHOR(S)  J. C. Wagner and C. V. Parks	6. TYPE OF REPORT  Technical			
	7. PERIOD COVERED <i>(Inclusive Dates)</i>			
8. PERFORMING ORGANIZATION — NAME AND ADDRESS <i>(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)</i> Oak Ridge National Laboratory Managed by UT-Battelle, LLC Oak Ridge, TN 37831-6370				
9. SPONSORING ORGANIZATION — NAME AND ADDRESS <i>(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Regulatory Commission, and mailing address.)</i> Division of Systems Analysis and Regulatory Effectiveness Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, DC 20555-0001				
10. SUPPLEMENTARY NOTES D. D. Ebert, NRC Project Manager				
11. ABSTRACT <i>(200 words or less)</i> <p>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 <math>k_{inf}</math> estimates based on reactivity "equivalent" fresh fuel enrichment (REFFE) to <math>k_{inf}</math> 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.</p>				
12. KEY WORDS/DESCRIPTORS <i>(List words or phrases that will assist researchers in locating the report.)</i>  criticality safety, burnup credit, spent fuel storage, spent fuel pool	13. AVAILABILITY STATEMENT unlimited			
	14. SECURITY CLASSIFICATION  <i>(This Page)</i> unclassified  <i>(This Report)</i> unclassified			
	15. NUMBER OF PAGES			
	16. PRICE			

