1.0 Introduction

The purpose of this report is to document the Westinghouse Spent Fuel Rack Criticality Methodology that ensures the spent fuel rack multiplication factor, K_{eff}, is less than 0.95 as recommended by ANSI 57.2-1983[1] and NRC guidance[2]. The individual sections of this report demonstrate the codes, methods and techniques used to satisfy this criterion on K_{eff}.

Section 2.0, Computer Code Methods and Benchmarking, explains the computer codes used in the evaluation of the spent fuel rack K_{eff} calculations. The methodology of the NITAWL-II, XSDRNPM-S, and KENO-Va codes is discussed and benchmark results are presented to establish a methodology bias and bias uncertainty. The PHOENIX-P computer code is also discussed in this section. PHOENIX-P is a nuclear design code used primarily for core reactor physics calculations but maintains the capability to simulate spent fuel storage rack geometries. The benchmarking of PHOENIX-P is discussed here.

In Section 3.0, Spent Fuel Rack Criticality Calculations, the maximum fresh fuel assembly enrichments that can be stored in the spent fuel racks are determined. The details on the assumptions made to model the spent fuel storage racks and the use of the results are also presented. Specific details are presented on KENO-Va calculations, PHOENIX-P tolerance calculations and the final 95/95 K_{eff} determination.

To allow higher enrichments than those determined in the previous section, Section 4.0, Reactivity Equivalencing Methodology, discusses the techniques used to allow higher fuel assembly enrichments to be stored in the spent fuel storage racks by taking credit for fuel assembly burnup and Integral Fuel Burnable Absorbers (IFBA). This section defines the concept of reactivity equivalencing and discusses the assumptions and uncertainties associated with each reactivity equivalencing technique. The use of PHOENIX-P in each reactivity equivalencing methodology is discussed.

To completely cover possible off-normal conditions in the spent fuel storage racks, Section 5.0, Postulated Accident Methodology, defines the postulated spent fuel rack accidents which are considered in the spent fuel rack criticality analysis. The methodology used to determine the reactivity impact of these accidents is discussed. Finally, the application of the double contingency principle to these spent fuel rack postulated accidents is presented which allows credit for spent fuel pool soluble boron to offset the potential reactivity increase caused by these off-normal conditions.

Finally, Section 6.0, Soluble Boron Credit Methodology, defines how the three previous sections are applied when credit for spent fuel pool soluble boron is used under normal storage configuration conditions. The ~~normal~~ storage configuration is defined using the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} calculation to ensure that the spent fuel rack K_{eff} will be less than 1.0 with a reactivity allowance for uncertainties and tolerances and with no soluble boron under ~~normal~~ specified storage conditions. Soluble boron credit is then used to ~~offset the uncertainties and tolerances and~~ maintain K_{eff} less than or equal to 0.95 as explained. The use of soluble boron credit for reactivity equivalencing uncertainties is discussed. The calculation of postulated accidents crediting soluble boron is discussed. Finally, a summary of all the soluble boron credit requirements is presented.

3.0 Spent Fuel Rack Criticality Calculations

This section describes the analytical techniques and models employed to perform the criticality analysis calculations for spent fuel storage racks.

Section 3.1 describes the fresh fuel assembly reactivity calculations performed for the spent fuel storage racks using defined nominal enrichments, storage configuration and rack conditions. Section 3.2 describes the tolerance calculations used to determine the reactivity uncertainty associated with fuel assembly and storage rack tolerances. Finally, Section 3.3 discusses the final 95 percent probability with a 95 percent confidence interval (95/95) K_{eff} calculation performed to ensure K_{eff} is less than or equal to 0.95.

3.1 Reactivity Calculations using KENO-Va

To show that storage of fuel assemblies in the spent fuel storage racks satisfies the 0.95 K_{eff} criticality acceptance criteria, KENO-Va is used to establish a nominal reference reactivity using fresh fuel assemblies.

The following are the basic assumptions which are used to develop the nominal case KENO-Va model for the spent fuel storage rack calculation:

Spent Fuel Rack Storage Cell: The nominal spent fuel rack storage cell dimensions are used.

Fuel Assembly Types: The fuel assembly parameters relevant to the criticality analysis are listed in Table 5 on page 22. All fuel assembly types considered for storage in the spent fuel storage racks must be evaluated.

Fuel Rod Enrichment: The nominal fresh fuel enrichment ~~modeled for~~ loaded into each fuel pin is modeled. The pin locations within a fuel assembly with multiple enrichments will be considered, if applicable. The maximum fuel rod enrichment loaded into the fuel rods is limited to 5.0 w/o ^{235}U.

Fuel Pellet Density and Dishing Fraction: The nominal values for theoretical density and dishing fraction of the fuel pellets are modeled.

Axial Blankets: If axial blankets are modeled, the length and enrichment of the blanket fuel pellets are considered.

^{234}U and ^{236}U: No amount of ^{234}U or ^{236}U is modeled in the fuel pellet.

Spacer Grids or Sleeves: No amount of material from spacer grids or spacer sleeves is modeled in the fuel assembly.

Burnable Absorbers: No amount of burnable absorber poison material is modeled in the fuel assembly.

Fission Product Poisons: No amount of fission product poison material is modeled in the fuel assembly.

Moderator Temperature and Density: The moderator is pure water (no boron) at a temperature of 68°F and a density of 1.0 gm/cm^3.

Based on the most reactive time after shutdown study and the uncertainty in the PHOENIX-P calculations, the burned fuel assembly is restarted in PHOENIX-P at various burnup steps with no fission product decay at cold (68˚F) spent fuel storage rack conditions with all ^{135}Xe removed. The K_∞ results from these calculations are compared to the nominal rack condition K_∞ at cold spent fuel storage rack conditions with the zero burnup enrichment. An equivalent burnup at each higher enrichment is determined by finding the burnup which yields a K_∞ (including uncertainty) equal to the zero burnup enrichment nominal rack condition K_∞. Multiple sets of burnup-enrichment pairs are used to establish a burnup credit curve which covers the enrichment range of the zero burnup enrichment to the highest enrichment stored in the spent fuel racks.

It is important to recognize that the curve is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered.

To better illustrate this methodology, a sample burnup credit curve is provided in Figure 2 on page 27. Note in Figure 2, the endpoints are (0 MWD/MTU, 2.0 w/o 235U) and (~~33~~35,000 MWD/MTU, 5.0 w/o ^{235}U). The interpretation of the endpoint data is as follows: the reactivity of the spent fuel rack containing 5.0 w/o ^{235}U fuel at ~~33~~35,000 MWD/MTU is equivalent to the reactivity of the rack containing 2.0 w/o ^{235}U fresh fuel. The endpoint data at 5.0 w/o includes a reactivity uncertainty of ~~0.011~~0.012 ΔK consistent with the minimum burnup requirement of ~~33~~35,000 MWD/MTU. Reactivity uncertainty is also applied linearly to all points on Figure 2 consistent with Figure 1.

As part of the burnup credit calculation, no specific uncertainty is added for measured burnup predictions. Uncertainty associated with measured burnups is dependent on the code or method used to predict the measured burnup. Additional burnup necessary to offset any measured burnup uncertainty must be added to the burnup credit requirement determined by the criticality analysis to determine the final acceptance curve for burnup credit.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the burnup credit methodology. Westinghouse evaluations[21] have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described above results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects can cause assembly reactivity to increase only at burnup-enrichment combinations (ex. 4.0 w/o ^{235}U @ 40,000 MWD/MTU) which are well beyond those typically calculated for burnup credit limits. Additional accounting for axial burnup distribution effects is not necessary provided the burnup credit required does not exceed the previously determined limits. These limits are presented in Table 6 on page 23.

4.2 Integral Fuel Burnable Absorber (IFBA) Credit

Storage of fresh fuel assemblies with nominal enrichments greater than those allowed by the methodology in Section 3.0 is achievable using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers (IFBA). IFBAs consist of neutron absorbing material applied

6.0 Soluble Boron Credit Methodology

This section describes the analytical techniques and models employed to perform the criticality analysis calculations for spent fuel storage racks with credit for spent fuel pool soluble boron.

Section 6.1 describes the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} calculation performed for the spent fuel storage racks to show that K_{eff} is less than 1.0 with a reactivity allowance for the uncertainty presented by fuel assembly and storage rack tolerances and no soluble boron credit. Section 6.2 describes ~~the tolerance calculations used to determine the uncertainty presented by fuel assembly and storage rack tolerances and~~ the use of spent fuel pool soluble boron to ~~offset these reactivity uncertainties and~~ maintain K_{eff} less than or equal to 0.95. Section 6.3 discusses the reactivity equivalencing calculations as performed with soluble boron credit. Section 6.4 discusses the calculation of postulated accident conditions with soluble boron credit. Finally, Section 6.5 summarizes the total soluble boron credit required by the spent fuel rack criticality analysis.

~~6.1 Maximum Feasible K_{eff}~~

~~The maximum feasible K_{eff} calculation defines the normal storage configuration for fuel assemblies in the spent fuel storage racks such that the maximum K_{eff} is less than 1.0. Normal storage rack configuration conditions are defined as nominal fuel assembly parameters and spent fuel rack dimensions. This calculation uses the same assumptions listed in Section 3.1. The calculation is performed at cold conditions with no soluble boron in the spent fuel pool water. A temperature bias is calculated to account for the normal operational temperature range of the spent fuel pool water, the method bias is determined from the benchmarking calculations performed in Section 2.1 and the ^{10}B self shielding bias is included, if applicable.~~

~~The final equation for determining the maximum feasible K_{eff} is shown below:~~

$$K_{max.\ feasible} = K_{normal} + B_{temp} + B_{method} + B_{self} \quad (6.1)$$

~~where:~~

~~K_{normal} = normal condition KENO-Va k_{eff}~~

~~B_{temp} = temperature bias for normal operating range~~

~~B_{method} = method bias determined from benchmark critical comparisons~~

~~B_{self} = ^{10}B self shielding bias~~

6.1 No Soluble Boron 95/95 K_{eff}

The no soluble boron 95/95a K_{eff} calculation defines the storage configuration for fuel assemblies in the spent fuel storage racks such that the 95 percent probability at a 95 percent confidence level K_{eff} is less than 1.0. The no soluble boron 95/95 K_{eff} uses the same assumptions listed in Section 3.1, the same tolerances considered in Section 3.2 and the same biases and uncertainties considered in Section 3.3. The calculation is performed at cold conditions with no soluble boron in the spent fuel pool water.

The final equation for determining the no soluble boron 95/95 K_{eff} is shown below:

$$K_{eff} = K_{nominal} + B_{method} + B_{temp} + B_{self} + B_{uncert} \qquad (6.1)$$

$K_{nominal}$ = nominal conditions KENO-Va K_{eff}.

B_{method} = method bias determined from benchmark critical comparisons.

B_{temp} = temperature bias.

B_{self} = ^{10}B self shielding bias, if applicable.

B_{uncert} = statistical summation of uncertainty components =

$$\sqrt{\sum_{i=1}^{n} ((tolerance_i \ldots or \ldots uncertainty_i)^2)}$$ for n tolerances/uncertainties.

The storage configuration used to calculate the ~~maximum feasible~~ no soluble boron K_{eff} using the above equation must be less than 1.0 with no soluble boron. This storage configuration is the basis for fuel assembly storage in the spent fuel pool with credit for soluble boron.

6.2 Soluble Boron Credit K_{eff}

To maintain adequate safety margin for criticality in the spent fuel storage racks, the K_{eff} of the spent fuel storage racks will be shown to be less than or equal to 0.95 with allowances for tolerances and uncertainties in the presence of spent fuel pool soluble boron. The same assumptions of Section ~~3.2~~6.1 are applied here. The only difference between these assumptions and the calculations performed here is the presence of spent fuel pool soluble boron. A spent fuel pool soluble boron concentration is chosen which will provide a K_{eff} that is less than or equal to 0.95 when biases, tolerances and uncertainties are included. The tolerance calculations are performed assuming the presence of this spent fuel pool soluble boron concentration. The final 95/95 K_{eff} calculation is determined using equation 6.1 on page 14. The final 95/95 K_{eff} will be shown to be less than or equal to 0.95 with allowances for biases, tolerances, and uncertainties including the presence of the determined concentration of spent fuel pool soluble boron.

6.3 Reactivity Equivalencing with Soluble Boron Credit

The reactivity equivalencing methodology with soluble boron credit is similar to the methodology discussed in Section 4.0. The major differences are that the reactivity equivalencing calculations are performed based on the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} storage conditions and the uncertainty associated with the reactivity equivalencing methods are covered using credit for soluble boron. A detailed discussion on the specific calculations required for each type of reactivity equivalencing method follows.

6.3.1 Fuel Assembly Burnup Credit with Soluble Boron Credit

The reactivity equivalencing methodology for burnup credit with soluble boron credit is similar to the methodology discussed in Section 4.1. The first major difference is the basis for the PHOENIX-P reactivity calculations. The spent fuel rack restarts with burned fuel assemblies use spent fuel rack conditions which are established using the assumptions of the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} defined in Section 6.1. Using this set of conditions ~~guarantees~~ ensures the spent fuel racks will ~~not return~~ remain subcritical under conditions of no soluble boron for the storage of burned fuel assemblies. As shown later in this section, the amount of soluble boron required to ensure K_{eff} remains less than or equal to 0.95 will also be determined.

The second major difference is the reactivity uncertainty associated with the burnup credit calculations and the uncertainty associated with measured burnup. A reactivity bias is typically applied to the reactivity calculations to account for uncertainties associated with the depletion of the fuel assembly and reactivities computed with PHOENIX-P. Also, if necessary, additional uncertainty is added to the burnup credit requirement to account for uncertainty in the measured burnup. Since the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} condition contains no soluble boron, calculations will be performed at the highest burnup requirement to determine the amount of soluble boron needed to maintain K_{eff} less than 0.95 including the appropriate uncertainty for depletion effects and PHOENIX-P calculations (see Figure 1 on page 25) and appropriate amount of uncertainty on measured burnup. The increase in boron required to offset these uncertainties will be included in the final soluble boron credit requirement.

6.3.2 IFBA Credit with Soluble Boron Credit

The reactivity equivalencing methodology for IFBA credit with soluble boron credit is similar to the methodology discussed ~~in~~ Section 4.2. The number of IFBA rods required and the infinite multiplication factor calculations will be determined using the configuration assumed in the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} defined in Section 6.1. Using this configuration ~~guarantees~~ ensures the spent fuel racks will ~~not return~~ remain subcritical under conditions of no soluble boron. As shown later in this section, the amount of soluble boron required to ensure K_{eff} remains less than or equal to 0.95 will also be determined.

The uncertainty associated with the determination of the IFBA rod requirement will be offset with credit for soluble boron. The uncertainties include the 5% decrease in IFBA ^{10}B loading for manufacturing uncertainty and 10% decrease in the number of IFBA rods for calculational uncertainty. To ensure that K_{eff} is maintained less than 0.95, calculations will be performed which

include enough soluble boron to offset the reactivity increase cause by a 5% decrease in IFBA ^{10}B loading and 10% decrease in the number of IFBA rods for calculational uncertainty. The increase in boron required to offset these uncertainty values will be included in the final soluble boron credit requirement.

The calculation of the infinite multiplication factor for IFBA credit remains the same as Section 4.2.2. The fuel assembly enrichment is defined by the no soluble boron 95/95 storage configuration of Section 6.1. The uncertainty of 0.01 ΔK associated with the infinite multiplication factor calculation is still applied.

6.4 Postulated Accidents with Soluble Boron Credit

The postulated accidents will be considered in the same manner as discussed in Section 5.0. The major differences are in the presence of soluble boron and the interpretation of the double contingency principle.

For the postulated accidents which cause a reactivity increase, the amount of reactivity increase will be calculated as before except the amount of soluble boron as determined in the calculations of Section 6.2 will be present. Based on the double contingency principle, one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Therefore, the presence of soluble boron in the storage pool water at normal concentrations (typically 2000 ppm) can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

To determine the reactivity decrease associated with spent fuel pool soluble boron, the reactivity change due to the presence of spent fuel pool soluble boron is calculated using PHOENIX-P.

Using the results of the PHOENIX-P soluble boron worth calculations, the amount of soluble boron required to offset each reactivity increase caused by accident conditions is determined. The sum of the boron concentrations of Sections 6.2 and 6.3 is the starting point to determine the amount of additional soluble boron needed to offset the reactivity increase caused by the postulated accidents.

6.5 Soluble Boron Credit Summary

To summarize the soluble boron credit calculations, there are four calculations performed using the soluble boron credit methodology which determine three soluble boron credit concentrations. The four calculations are listed below.

1. Determine the storage configuration of the spent fuel racks using ~~maximum feasible~~ no soluble boron 95/95 K_{eff} conditions such that K_{eff} is less than 1.0.
2. Using the resulting configuration from the previous step, calculate the spent fuel rack K_{eff} with soluble boron. Next determine the reactivity uncertainty associated with fuel assembly and storage rack tolerances and combine with the biases and other uncertainties to determine the final 95/95 K_{eff} at the concentration of spent fuel pool soluble boron which maintains K_{eff} less than or equal to 0.95.

3. Use reactivity equivalencing methodologies to determine burnup or IFBA credit for enrichments higher than allowed in step 1. Use soluble boron credit to offset uncertainties associated with each methodology, as appropriate.
4. Determine the increase in reactivity caused by postulated accidents and the corresponding additional amount of soluble boron needed to offset these reactivity increases.

The final soluble boron credit requirement is the summation of the boron credit requirements determined in steps 2, 3 and 4 above. The following equation relates these requirements.

$$SBC_{TOTAL} = SBC_{95/95} + SBC_{RE} + SBC_{PA} \quad (6.2)$$

where:

SBC_{TOTAL} = total soluble boron credit requirement (ppm).

$SBC_{95/95}$ = soluble boron credit required for 95/95 K_{eff} less than or equal to 0.95 (ppm).

SBC_{RE} = soluble boron credit required for reactivity equivalencing methodologies (ppm).

SBC_{PA} = soluble boron credit required for K_{eff} less than or equal to 0.95 under accident conditions (ppm).

The total soluble boron credit requirement along with the storage configuration specified in the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} calculations shows that the spent fuel rack K_{eff} will always be less than or equal to 0.95. Further the ~~maximum feasible~~ no soluble boron 95/95 K_{eff} storage configuration will ensure the K_{eff} remains less than 1.0 with no soluble boron in the spent fuel pool.

Table 6. Axial Burnup Reactivity Bias for PHOENIX-P

Fuel Assembly Burnup (MWD/MTU)	3.0 w/o Enrichment Bias (pcm)*	4.0 w/o Enrichment Bias (pcm)*	5.0 w/o Enrichment Bias (pcm)*
0	-252	-252	-254
20,000	-492	-576	-610
30,000	-248	-372	-463
40,000	39	-87	-243
50,000	211	187	17
60,000	302	426	312

*pcm is defined as $\ln (k_1/k_2)$*1E5