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Vogtle Units 1 and 2 Spent Fuel Rack Criticality Analysis With Credit for Soluble Boron

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1.0 Introduction

This report presents the results of a criticality analysis of the Vogtle Units 1 and 2 spent fuel storage racks with credit for spent fuel pool soluble boron. The methodology employed here is contained in the topical report, "Westinghouse Spent Fuel Rack Criticality Analysis Methodology"[1].

The Vogtle Units 1 and 2 spent fuel racks have been reanalyzed to allow storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 5.00 w/o ^{235}U in the allowable storage cell locations using soluble boron credit. This analysis will also ignore the presence of the spent fuel rack Boraflex poison panels. The analysis uses the maximum feasible $K_{eff} < 1.0$ condition to determine the acceptable storage of 17x17 fuel assemblies with no credit for soluble boron and soluble boron credit to provide safety margin by maintaining $K_{eff} \leq 0.95$ including uncertainties, tolerances and accident conditions in the presence of spent fuel pool soluble boron.

The following storage configurations and enrichment limits were considered in this analysis:

Unit 1 Enrichment Limits

All Cell Storage	Storage of 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 2.00 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 850 ppm.
3-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 2.70 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 950 ppm.
2-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1100 ppm.

Unit 2 Enrichment Limits

All Cell Storage	Storage of 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 1.82 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 750 ppm.
3-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 2.54 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 950 ppm.
2-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1250 ppm.
3x3 Checkerboard Storage	Storage of Westinghouse 17x17 fuel assemblies with nominal enrichments no greater than 4.00 w/o ^{235}U (equivalent enrichment with IFBA credit) in the center of a 3x3 checkerboard. The surrounding fuel assemblies must have an initial nominal enrichment no greater than 1.48 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 800 ppm.

The Vogtle Units 1 and 2 spent fuel rack analysis is based on maintaining $K_{eff} < 1.0$ under maximum feasible conditions with no soluble boron for storage of 17x17 fuel assemblies. Soluble boron credit is used to provide safety margin by maintaining $K_{eff} \leq 0.95$ including uncertainties, tolerances and accident conditions in the presence of spent fuel pool soluble boron.

1.1 Design Description

The Vogtle Unit 1 spent fuel storage cell is shown in Figure 1 on page 53 and the Vogtle Unit 2 spent fuel storage cell is shown in Figure 2 on page 54 with nominal dimensions provided on each figure.

The fuel parameters relevant to this analysis are given in Table 1 on page 40. The fuel rod and guide tube cladding are modeled with zircaloy in this analysis. This is conservative with respect to the Westinghouse ZIRLO product which is a zirconium alloy containing additional elements

including niobium. Niobium has a small absorption cross section which causes more neutron capture in the cladding regions resulting in a lower reactivity. Therefore, this analysis is conservative with respect to fuel assemblies containing ZIRLO cladding in fuel rods and guide tubes.

The Vogtle Unit 2 spent fuel storage racks contain as-built storage racks which are not consistent with the nominal dimensions provided in Figure 2. Specifically, the as-built spacing between storage cells is not consistent with the nominal spacing between storage cells. A criticality analysis[2] was previously performed to address the inconsistencies between the nominal storage rack cell water gap spacing and as-built storage rack cell water gap spacings. Based on data from the previous analysis, the as-built water gap spacings of rack module A-5 were determined to bound all the rack modules in the Vogtle Unit 2 spent fuel pool. The limiting water gap spacings for the worst case 3x3 array of cells in rack module A-5 is shown in Figure 3 on page 55. The criticality analysis performed in this report was based on an equivalent cell shown in Figure 3 which yields a reactivity which is equivalent to the reactivity of the as-built 3x3 array in rack module A-5 with the worst combination of water gap spacings. This equivalent cell was used as a basis for the calculations of reactivity in the Vogtle Unit 2 spent fuel racks.

1.2 Design Criteria

Criticality of fuel assemblies in a fuel storage rack is prevented by the design of the rack which limits fuel assembly interaction. This is done by fixing the minimum separation between fuel assemblies and controlling the placement of assemblies into selected storage cells.

In this report, the reactivity of the spent fuel racks was analyzed such that K_{eff} remains less than 1.0 under maximum feasible conditions with no soluble boron as defined in Reference 1. To provide safety margin in the criticality analysis of the spent fuel racks, credit is taken for the soluble boron present in all PWR spent fuel pools.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array will be less than or equal to 0.95. This requirement as currently stated in ANSI 57.2-1983[3], and the NRC paper, OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications,[4] does not allow for reactivity credit due to the presence of soluble boron. This criticality analysis report takes exception to this and shows that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array is less than 1.0 under maximum feasible conditions and less than or equal to 0.95 when credit is taken for the presence of a portion of the spent fuel pool soluble boron as defined in the topical report, "Westinghouse Spent Fuel Rack Criticality Analysis Methodology"[1].

2.0 Analytical Methods

The criticality calculation method and cross-section values are verified by comparison with critical experiment data for fuel assemblies similar to those for which the racks are designed. This benchmarking data is sufficiently diverse to establish that the method bias and uncertainty will apply to rack conditions which include strong neutron absorbers, large water gaps, low moderator densities and spent fuel pool soluble boron.

The design method which insures the criticality safety of fuel assemblies in the fuel storage rack is described in detail in the Westinghouse Spent Fuel Rack Criticality Analysis Methodology topical report, WCAP-14416[1]. This report describes the computer codes, benchmarking, and methodology which are used to calculate the criticality safety limits presented in this report for Vogtle Units 1 and 2.

As determined in the benchmarking in the topical report, the method bias using the described methodology of NITAWL-II, XSDRNPM-S and KENO-Va is 0.00770 ΔK with a 95 percent probability at a 95 percent confidence level on the bias of 0.00300 ΔK. These values will be used throughout this report as needed.

3.0 Criticality Analysis of Unit 1 All Cell Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in all cells of the Vogtle Unit 1 spent fuel storage racks with credit for soluble boron.

Section 3.1 describes the maximum feasible K_{eff} KENO-Va calculations. Section 3.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 3.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 3.1.

3.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in all cells of the Vogtle Unit 1 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 40 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD design was more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 2.00 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. All available storage cells were loaded with fuel assemblies.

With the above assumptions, the KENO-Va calculation resulted in a K_{eff} of 0.98111 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.01067 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for all cell storage in the Vogtle Unit 1 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above, the result was:

$$K_{eff} = 0.98111 + 0.01067 + 0.00770 = 0.99948$$

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical under maximum feasible conditions when all cells are loaded with 2.00 w/o ^{235}U 17x17 fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

3.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for all cell storage in the Vogtle Unit 1 spent fuel racks were similar to those in Section 3.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 300 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case with 300 ppm soluble boron in the moderator resulted in a K_{eff} of 0.88950.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 1 spent fuel rack all cell storage configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 2.00 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The +0.050/-0.025 inch tolerance about the nominal 8.80 inch reference cell I.D. was considered.

Storage Cell Pitch: The +0.00/–0.320 inch tolerance about the nominal 10.60 inch reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.015 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 2 on page 41 and results in a maximum K_{eff} of 0.94494.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for all cell storage of 17x17 fuel assemblies in the Vogtle Unit 1 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 2.00 w/o ^{235}U is acceptable in all cells including the presence of 300 ppm soluble boron.

3.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 2.00 w/o ^{235}U in all cells of the Vogtle Unit 1 spent fuel racks is achievable by means of burnup credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 4 on page 56 shows the constant K_{eff} contours generated for all cell storage in the Vogtle Unit 1 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with 2.00 w/o ^{235}U fuel assemblies at zero burnup in all cell locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 4 was 250 ppm. This is additional boron above the 300 ppm required in Section 3.2. This results in a total soluble boron credit of 550 ppm.

It is important to recognize that the curve in Figure 4 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. For convenience, the data from Figure 4 are also provided in Table 3 on page 42. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 4 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Vogtle Unit 1 all cell storage burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Vogtle Unit 1 all cell storage burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Vogtle Unit 1 all cell storage burnup credit limit is not necessary.

4.0 Criticality Analysis of Unit 1 3-out-of-4 Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in 3-out-of-4 cells of the Vogtle Unit 1 spent fuel storage racks with credit for soluble boron.

Section 4.1 describes the maximum feasible K_{eff} KENO-Va calculations. Section 4.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 4.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 4.1.

4.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in 3-out-of-4 cells of the Vogtle Unit 1 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 40 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD design was more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 2.70 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. Fuel storage cells were loaded with fuel assemblies in a 3-out-of-4 checkerboard arrangement as shown in Figure 5 on page 57. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells.

With the above assumptions, the KENO-Va calculation resulted in a K_{eff} of 0.97740 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00615 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for the storage of fuel in 3-out-of-4 cells in the Vogtle Unit 1 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above, the result was:

$$K_{eff} = 0.97740 + 0.00615 + 0.00770 = 0.99125$$

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical under maximum feasible conditions when 3-out-of-4 cells are loaded with 2.70 w/o ^{235}U 17x17 fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

4.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 3-out-of-4 cell storage in the Vogtle Unit 1 spent fuel racks were similar to those in Section 4.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 300 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case with 300 ppm soluble boron in the moderator resulted in a K_{eff} of 0.90121.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 1 spent fuel rack 3-out-of-4 checkerboard configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 2.70 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The +0.050/-0.025 inch tolerance about the nominal 8.80 inch reference cell I.D. was considered.

Storage Cell Pitch: The +0.00/–0.320 inch tolerance about the nominal 10.60 inch reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.015 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 4 on page 43 and results in a maximum K_{eff} of 0.94233.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for 3-out-of-4 storage of 17x17 fuel assemblies in the Vogtle Unit 1 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 2.70 w/o ^{235}U is acceptable in 3-out-of-4 cells including the presence of 300 ppm soluble boron.

4.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 2.70 w/o ^{235}U in 3-out-of-4 cells of the Vogtle Unit 1 spent fuel racks is achievable by means of burnup credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 4 on page 56 shows the constant K_{eff} contours generated for 3-out-of-4 cell storage in the Vogtle Unit 1 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with 2.70 w/o ^{235}U fuel assemblies at zero burnup in all cell locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 4 was 200 ppm. This is additional boron above the 300 ppm required in Section 4.2. This results in a total soluble boron credit of 500 ppm.

It is important to recognize that the curve in Figure 4 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. For convenience, the data from Figure 4 are also provided in Table 3 on page 42. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 4 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Vogtle Unit 1 3-out-of-4 cell storage burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Vogtle Unit 1 3-out-of-4 cell storage burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Vogtle Unit 1 3-out-of-4 cell storage burnup credit limit is not necessary.

5.0 Criticality Analysis of Unit 1 2-out-of-4 Storage

This section describes the analytical techniques and models employed to perform the criticality analysis for the storage of fuel in 2-out-of-4 cells of the Vogtle Unit 1 spent fuel storage racks with credit for soluble boron.

Section 5.1 describes the maximum feasible K_{eff} KENO-Va calculations and section 5.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations.

5.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in 2-out-of-4 cells of the Vogtle Unit 1 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD and 17x17 OFA fuel designs (see Table 1 on page 40 for fuel parameters).
2. Westinghouse 17x17 STD and 17x17 OFA fuel assemblies contain uranium dioxide at a nominal enrichment of 5.00 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. Fuel storage cells were loaded with fuel assemblies in a 2-out-of-4 checkerboard arrangement as shown in Figure 5 on page 57. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent.

With the above assumptions, the KENO-Va calculations of K_{eff} under normal conditions resulted in a K_{eff} of 0.93263 and 0.93670 for Westinghouse STD and OFA fuel assemblies, respectively. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00028 ΔK and 0.00024 ΔK for Westinghouse STD and OFA fuel assemblies, respectively. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for the storage of fuel in 2-out-of-4 cells in the Vogtle Unit 1 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal}	=	normal conditions KENO-Va K_{eff}
B_{temp}	=	temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)
B_{method}	=	method bias determined from benchmark critical comparisons

Substituting the calculated values in the order listed above for Westinghouse STD fuel, the result was:

$$K_{eff} = 0.93263 + 0.00028 + 0.00770 = 0.94061$$

Substituting the calculated values in the order listed above for Westinghouse OFA fuel, the result was:

$$K_{eff} = 0.93670 + 0.00024 + 0.00770 = 0.94464$$

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical under maximum feasible conditions when 2-out-of-4 cells are loaded with 5.00 w/o ^{235}U 17x17 STD or 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

5.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 2-out-of-4 cell storage in the Vogtle Unit 1 spent fuel racks were similar to those in Section 5.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 100 ppm soluble boron for both the Westinghouse 17x17 STD and 17x17 OFA fuel assembly types.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.91126 and 0.92077 for Westinghouse STD and OFA fuel assembly types, respectively.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 1 spent fuel rack 2-out-of-4 checkerboard configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 5.00 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The +0.050/-0.025 inch tolerance about the nominal 8.80 inch reference cell I.D. was considered.

Storage Cell Pitch: The +0.00/–0.320 inch tolerance about the nominal 10.60 inch reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.015 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 on page 44 and results in a maximum K_{eff} of 0.92947 and 0.93754 for Westinghouse STD and OFA fuel assembly types, respectively.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for 2-out-of-4 cell storage of 17x17 fuel assemblies in the Vogtle Unit 1 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 5.00 w/o ^{235}U is acceptable in 2-out-of-4 cells including the presence of 100 ppm soluble boron.

6.0 Criticality Analysis of Unit 2 All Cell Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in all cells of the Vogtle Unit 2 spent fuel storage racks with credit for soluble boron.

Section 6.1 describes the maximum feasible K_{eff} KENO-Va calculations. Section 6.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 6.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 6.1.

6.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in all cells of the Vogtle Unit 2 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 40 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD design was more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 1.82 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. All available storage cells were loaded with fuel assemblies.

With the above assumptions, the KENO-Va calculation resulted in a K_{eff} of 0.97863 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00931 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for all cell storage in the Vogtle Unit 2 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above, the result was:

$$K_{eff} = 0.97863 + 0.00931 + 0.00770 = 0.99564$$

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical under maximum feasible conditions when all cells are loaded with 1.82 w/o ^{235}U 17x17 fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

6.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for all cell storage in the Vogtle Unit 2 spent fuel racks were similar to those in Section 6.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 200 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case with 200 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91531.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 2 spent fuel rack all cell storage configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 1.82 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The ±0.030 inch tolerance about the nominal 8.75 inch reference cell I.D. was considered.

Storage Cell Pitch: The ±0.040 inch tolerance about the nominal 10.40 inch (E-W) and 10.58 inch (N-S) reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 on page 45 and results in a maximum K_{eff} of 0.94409.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for all cell storage of 17x17 fuel assemblies in the Vogtle Unit 2 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 1.82 w/o ^{235}U is acceptable in all cells including the presence of 200 ppm soluble boron.

6.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 1.82 w/o ^{235}U in all cells of the Vogtle Unit 2 spent fuel racks is achievable by means of burnup credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 6 on page 58 shows the constant K_{eff} contours generated for all cell storage in the Vogtle Unit 2 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with 1.82 w/o ^{235}U fuel assemblies at zero burnup in all cell locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 6 was 250 ppm. This is additional boron above the 200 ppm required in Section 6.2. This results in a total soluble boron credit of 450 ppm.

It is important to recognize that the curve in Figure 6 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. For convenience, the data from Figure 6 are also provided in Table 7 on page 46. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 6 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Vogtle Unit 2 all cell storage burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Vogtle Unit 2 all cell storage burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Vogtle Unit 2 all cell storage burnup credit limit is not necessary.

7.0 Criticality Analysis of Unit 2 3-out-of-4 Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in 3-out-of-4 cells of the Vogtle Unit 2 spent fuel storage racks with credit for soluble boron.

Section 7.1 describes the maximum feasible K_{eff} KENO-Va calculations. Section 7.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 7.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 7.1.

7.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in 3-out-of-4 cells of the Vogtle Unit 2 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 40 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD design was more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 2.54 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. Fuel storage cells were loaded with fuel assemblies in a 3-out-of-4 checkerboard arrangement as shown in Figure 5 on page 57. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells.

With the above assumptions, the KENO-Va calculation resulted in a K_{eff} of 0.98443 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00522 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for the storage of fuel in 3-out-of-4 cells in the Vogtle Unit 2 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above, the result was:

$$K_{eff} = 0.98443 + 0.00522 + 0.00770 = 0.99735$$

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical under maximum feasible conditions when 3-out-of-4 cells are loaded with 2.54 w/o ^{235}U 17x17 fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

7.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 3-out-of-4 storage in the Vogtle Unit 2 spent fuel racks were similar to those in Section 7.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 250 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case with 250 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91778.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 2 spent fuel rack 3-out-of-4 checkerboard configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 2.54 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The ±0.030 inch tolerance about the nominal 8.75 inch reference cell I.D. was considered.

Storage Cell Pitch: The ±0.040 inch tolerance about the nominal 10.40 inch (E-W) and 10.58 inch (N-S) reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 8 on page 47 and results in a maximum K_{eff} of 0.93983.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for 3-out-of-4 storage of 17x17 fuel assemblies in the Vogtle Unit 2 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 2.54 w/o ^{235}U is acceptable in 3-out-of-4 cells including the presence of 250 ppm soluble boron.

7.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 2.54 w/o ^{235}U in 3-out-of-4 cells of the Vogtle Unit 2 spent fuel racks is achievable by means of burnup credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 6 on page 58 shows the constant K_{eff} contours generated for 3-out-of-4 storage in the Vogtle Unit 2 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with 2.54 w/o ^{235}U fuel assemblies at zero burnup in 3-out-of-4 cell locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 6 was 200 ppm. This is additional boron above the 250 ppm required in Section 7.2. This results in a total soluble boron credit of 450 ppm.

It is important to recognize that the curve in Figure 6 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. For convenience, the data from Figure 6 are also provided in Table 7 on page 46. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 6 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Vogtle Unit 2 3-out-of 4 cell storage burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Vogtle Unit 2 3-out-of-4 cell storage burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Vogtle Unit 2 3-out-of-4 cell storage burnup credit limit is not necessary.

8.0 Criticality Analysis of Unit 2 2-out-of-4 Storage

This section describes the analytical techniques and models employed to perform the criticality analysis for the storage of fuel in 2-out-of-4 cells of the Vogtle Unit 2 spent fuel storage racks with credit for soluble boron.

Section 8.1 describes the maximum feasible K_{eff} KENO-Va calculations and section 8.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations.

8.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in 2-out-of-4 cells of the Vogtle Unit 2 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD and 17x17 OFA fuel designs (see Table 1 on page 40 for fuel parameters).
2. Westinghouse 17x17 STD and 17x17 OFA fuel assemblies contain uranium dioxide at a nominal enrichment of 5.00 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. No credit was taken for any burnable absorber in the fuel rods.
8. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
9. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
10. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. Fuel storage cells were loaded with fuel assemblies in a 2-out-of-4 checkerboard arrangement as shown in Figure 5 on page 57. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent.

With the above assumptions, the KENO-Va calculations of K_{eff} under normal conditions resulted in a K_{eff} of 0.93575 and 0.94622 for both Westinghouse STD and OFA fuel assemblies, respectively. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00059 ΔK and 0.00027 ΔK for Westinghouse STD and OFA fuel assemblies, respectively. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for the storage of fuel in 2-out-of-4 cells in the Vogtle Unit 2 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above for Westinghouse STD fuel, the result was:

$$K_{eff} = 0.93575 + 0.00059 + 0.00770 = 0.94404$$

Substituting the calculated values in the order listed above for Westinghouse OFA fuel, the result was:

$$K_{eff} = 0.94622 + 0.00027 + 0.00770 = 0.95419$$

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical under maximum feasible conditions when 2-out-of-4 cells are loaded with 5.00 w/o ^{235}U 17x17 STD or 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

8.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 2-out-of-4 storage in the Vogtle Unit 2 spent fuel racks were similar to those in Section 8.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 50 ppm soluble boron for both the Westinghouse 17x17 STD and 17x17 OFA fuel assembly types.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.92588 and 0.93412 for Westinghouse STD and OFA fuel assembly types, respectively.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 2 spent fuel rack 2-out-of-4 checkerboard configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U **Enrichment:** The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 5.00 w/o ^{235}U was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The ±0.030 inch tolerance about the nominal 8.75 inch reference cell I.D. was considered.

Storage Cell Pitch: The ±0.040 inch tolerance about the nominal 10.40 inch (E-W) and 10.58 inch (N-S) reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 9 on page 48 and results in a maximum K_{eff} of 0.93934 and 0.94794 for Westinghouse 17x17 STD and 17x17 OFA fuel assembly types, respectiveiy.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for 2-out-of-4 cell storage of 17x17 fuel assemblies in the Vogtle Unit 2 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 5.00 w/o ^{235}U is acceptable in 2-out-of-4 cells including the presence of 50 ppm soluble boron.

9.0 Criticality Analysis of Unit 2 3x3 Checkerboard

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the storage of fuel in a 3x3 checkerboard in the Vogtle Unit 2 spent fuel storage racks with credit for soluble boron.

Section 9.1 describes the maximum feasible K_{eff} KENO-Va calculations. Section 9.2 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 9.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 9.1.

9.1 Maximum Feasible K_{eff} Calculation

The following assumptions were used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in a 3x3 checkerboard in the Vogtle Unit 2 spent fuel storage rack:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 40 for fuel parameters). Calculations show that the Westinghouse 17x17 STD design was the most reactive fuel assembly type.
2. Westinghouse 17x17 STD fuel assemblies stored in the middle of the 3x3 checkerboard contain uranium dioxide at a nominal enrichment of 4.00 w/o ^{235}U over the entire length of each rod.
3. Westinghouse 17x17 STD fuel assemblies surrounding the center of the 3x3 checkerboard contain uranium dioxide at a nominal enrichment of 1.48 w/o ^{235}U over the entire length of each rod.
4. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
5. No credit was taken for any natural or reduced enrichment axial blankets.
6. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
7. No credit was taken for any spacer grids or spacer sleeves.
8. No credit was taken for any burnable absorber in the fuel rods.
9. No credit was taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume was replaced with water.
10. The moderator was water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm^3 was used.
11. The array was infinite in lateral (x and y) extent and finite in axial (vertical) extent.
12. Fuel storage cells were loaded with fuel assemblies in a 3x3 checkerboard arrangement as shown in Figure 5 on page 57.

With the above assumptions, the KENO-Va calculations of K_{eff} under normal conditions resulted in a K_{eff} of 0.98373. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 185°F) was 0.00772 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology was 0.00770 ΔK.

Based on the results above, the following equation was used to develop the maximum feasible K_{eff} for the storage of fuel in a 3x3 checkerboard in the Vogtle Unit 2 spent fuel storage racks:

$$K_{eff} = K_{normal} + B_{temp} + B_{method}$$

where:

K_{normal} = normal conditions KENO-Va K_{eff}

B_{temp} = temperature bias for normal temperature range of spent fuel pool water (50°F to 185°F)

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

Substituting the calculated values in the order listed above, the result was:

$$K_{eff} = 0.98373 + 0.00772 + 0.00770 = 0.99915$$

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical under maximum feasible conditions when cells are loaded in a 3x3 checkerboard with a 4.00 w/o ^{235}U 17x17 fuel assembly surrounded by 1.48 w/o ^{235}U 17x17 fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

9.2 Soluble Boron Credit K_{eff} Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va was used to establish a nominal reference reactivity and PHOENIX-P was used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} was developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the temperature and method biases and the nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 3x3 checkerboard storage in the Vogtle Unit 2 spent fuel racks were similar to those in Section 9.1 except for assumption 10 regarding the moderator soluble boron concentration. The moderator was replaced with water containing 250 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.91902.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases were included:

Methodology: The benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

Water Temperature: A reactivity bias determined in PHOENIX-P was applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 185°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations were performed. For the Vogtle Unit 2 spent fuel rack 3x3 checkerboard configuration, UO_2 material tolerances were considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall thickness. Uncertainties associated with calculation and methodology accuracy were also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components were considered in the total uncertainty statistical summation:

^{235}U **Enrichment:** The standard DOE enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 4.00 w/o ^{235}U for the center assembly and 1.48 w/o ^{235}U for the surrounding assemblies was considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 40) was considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 40) was considered.

Storage Cell I.D.: The ±0.030 inch tolerance about the nominal 8.75 inch reference cell I.D. was considered.

Storage Cell Pitch: The ±0.040 inch tolerance about the nominal 10.40 inch (E-W) and 10.58 inch (N-S) reference cell pitch was considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.075 inch reference stainless steel wall thickness was considered.

Assembly Position: The KENO-Va reference reactivity calculation assumed fuel assemblies were symmetrically positioned (centered) within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of the four fuel assemblies were positioned together. This reactivity increase was considered in the statistical summation of spent fuel rack tolerances.

Calculation Uncertainty: The 95 percent probability/95 percent confidence level uncertainty on the KENO-Va nominal reference K_{eff} was considered.

Methodology Uncertainty: The 95 percent probability/95 percent confidence uncertainty in the benchmarking bias as determined for the Westinghouse KENO-Va methodology was considered.

The maximum K_{eff} was developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 10 on page 49 and results in a maximum K_{eff} of 0.94931.

Since K_{eff} is less than or equal to 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the 3x3 checkerboard storage configuration of 17x17 fuel assemblies in the Vogtle Unit 2 spent fuel racks when cells are loaded in a 3x3 checkerboard with a 4.00 w/o 17x17 fuel assembly surrounded by 1.48 w/o ^{235}U 17x17 fuel assemblies including the presence of 250 ppm soluble boron.

9.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 1.48 w/o ^{235}U in the surrounding cells of the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks is achievable by means of burnup credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 6 on page 58 shows the constant K_{eff} contours generated for surrounding cells of the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with 1.48 w/o ^{235}U fuel assemblies at zero burnup in surrounding cell locations of a 3x3 checkerboard.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 6 was 200 ppm. This is additional boron above the 250 ppm required in Section 9.2. This results in a total soluble boron credit of 450 ppm.

It is important to recognize that the curve in Figure 6 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. For convenience, the data from Figure 6 are also provided in Table 7 on page 46. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 6 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Vogtle Unit 2 3x3 checkerboard burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative

burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Vogtle Unit 2 3x3 checkerboard burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Vogtle Unit 2 3x3 checkerboard burnup credit limit is not necessary.

9.4 IFBA Credit Reactivity Equivalencing

Storage of fuel assemblies with nominal enrichments greater than 4.00 w/o U^{235} in the middle cell of the 3x3 checkerboard in the Vogtle Unit 2 spent fuel storage racks is achievable by means of IFBA credit using reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers (IFBA)[5]. IFBAs consist of neutron absorbing material applied as a thin ZrB_2 coating on the outside of the UO_2 fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

A series of reactivity calculations were performed to generate a set of IFBA rod number versus enrichment ordered pairs which all yield the equivalent K_{eff} when the fuel is stored in the middle of the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks. The following assumptions were used for the IFBA rod assemblies in the PHOENIX-P models:

1. The fuel assembly parameters relevant to the criticality analysis were based on the Westinghouse 17x17 STD design (see Table 1 on page 40 for fuel parameters).
2. The fuel assembly was modeled at its most reactive point in life.
3. The fuel pellets were modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit was taken for any natural enrichment or reduced enrichment axial blankets.
5. No credit was taken for any ^{234}U or ^{236}U in the fuel, nor was any credit taken for the buildup of fission product poison material.
6. No credit was taken for any spacer grids or spacer sleeves.
7. The IFBA absorber material was a zirconium diboride (ZrB_2) coating on the fuel pellet. Nominal IFBA rod ^{10}B loadings of 1.50 milligrams ^{10}B per inch (1.0X) and 2.25 milligrams ^{10}B per inch (1.5X) were used in determining the IFBA requirement.
8. The IFBA ^{10}B loading was reduced by 16.67% to conservatively model a minimum poison length of 120 inches.
9. The moderator was pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm^3.
10. The array was infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.
11. Standard Westinghouse IFBA patterns for 17x17 fuel assemblies were considered.

Figure 7 on page 59 shows the constant K_{eff} contour generated for the Vogtle Unit 2 spent fuel racks. The data in Figure 7 is also provided on Table 11 on page 50 for both 1.0X and 1.5X IFBA rods.

It is important to recognize that the curve in Figure 7 is based on reactivity equivalence calculations for the specific enrichment and IFBA combinations in actual rack geometry (and not just on simple comparisons of individual fuel assembly infinite multiplication factors). In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered.

Uncertainties associated with IFBA credit include a 5% manufacturing tolerance and a 10% calculational uncertainty on the ^{10}B loading of the IFBA rods. The amount of additional soluble boron needed to account for these uncertainties in the IFBA credit requirement of Figure 7 was 50 ppm. This is additional boron above the 250 ppm required in Section 9.2. The 50 ppm needed for IFBA credit is bounded by the 200 ppm required for burnup credit in the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks. Therefore, the total soluble boron credit required for the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks remains at 450 ppm.

10.0 Discussion of Postulated Accidents

Most accident conditions will not result in an increase in K_{eff} of the rack. Examples are:

Fuel assembly drop on top of rack	The rack structure pertinent for criticality is not excessively deformed and the dropped assembly which comes to rest horizontally on top of the rack has sufficient water separating it from the active fuel height of stored assemblies to preclude neutronic interaction.
Fuel assembly drop between rack modules or between rack modules and spent fuel pool wall	Typically, the design of the spent fuel racks and fuel handling equipment is such that it precludes the insertion of a fuel assembly in other than prescribed locations. However, in cases where this is not true, the reactivity increase caused by this accident is bounded by the mis-placement of a fuel assembly inside the spent fuel racks.

However, two accidents can be postulated for each storage configuration which can increase reactivity beyond the analyzed condition. The first postulated accident would be a change in the spent fuel pool water temperature and the second would be a misload of an assembly into a cell for which the restrictions on location, enrichment, or burnup are not satisfied. All accident conditions are analyzed without the presence of Boraflex neutron absorbing panels.

For the change in spent fuel pool water temperature accident, a temperature range of 32°F to 240°F is considered. Calculations were performed for all Vogtle Unit 1 and 2 storage configurations to determine the reactivity change caused by a change in the Vogtle Units 1 and 2 spent fuel pool water temperature outside the normal range (50°F to 185°F). The results of these calculations are tabulated in Table 12 on page 51.

For the misloaded assembly accident, calculations were performed to show the largest reactivity increase caused by a 5.00 w/o 17x17 STD or OFA unirradiated fuel assembly misplaced into a storage cell for which the restrictions on location, enrichment, or burnup are not satisfied. The results of these calculations are also tabulated in Table 12.

For an occurrence of the above postulated accident conditions, the double contingency principle of ANSI/ANS 8.1-1983 can be applied. This states that one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Thus, for these postulated accident conditions, the presence of additional soluble boron in the storage pool water (above the concentration required for normal conditions and reactivity equivalencing) can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

The reactivity change due to the presence of soluble boron in the Vogtle Units 1 and 2 spent fuel pool has been calculated with PHOENIX-P and is shown in Figure 8 on page 60 for Vogtle Unit 1 and Figure 9 on page 61 for Vogtle Unit 2.

The amount of soluble boron required to offset each of the postulated accidents was determined from Figure 8 for Vogtle Unit 1 and from Figure 9 for Vogtle Unit 2. The additional amount of soluble boron for accident conditions needed beyond the required boron for uncertainties and burnup is shown in Table 12.

Based on the above discussion, should a loss of spent fuel pool cooling accident or a fuel assembly misload occur in the Vogtle Units 1 and 2 spent fuel racks, K_{eff} will be maintained less than or equal to 0.95 due to the presence of at least 1100 ppm of soluble boron in the Vogtle Unit 1 spent fuel pool water and 1250 ppm in the Vogtle Unit 2 spent fuel pool.

11.0 Soluble Boron Credit Summary

Spent fuel pool soluble boron has been used in this criticality analysis to offset storage rack and fuel assembly tolerances, calculational uncertainties, uncertainty associated with reactivity equivalencing (burnup credit and IFBA credit) and the reactivity increase caused by postulated accident conditions. The total soluble boron concentration required to be maintained in the spent fuel pool is a summation of each of these components. Table 13 on page 52 summarizes the storage configurations and corresponding soluble boron credit requirements.

12.0 Summary of Criticality Results

For the storage of Westinghouse 17x17 fuel assemblies in the Vogtle Units 1 and 2 spent fuel storage racks, the acceptance criteria for criticality requires the effective neutron multiplication factor, K_{eff}, to be less than 1.0 under maximum feasible conditions with no soluble boron, and less than or equal to 0.95 including uncertainties, tolerances and accident conditions in the presence of spent fuel pool soluble boron. This report shows that the acceptance criteria for criticality is met for the Vogtle Units 1 and 2 spent fuel racks for the storage of Westinghouse 17x17 fuel assemblies under both normal and accident conditions with soluble boron credit and the following storage configurations and enrichment limits:

Unit 1 Enrichment Limits

All Cell Storage	Storage of 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 2.00 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 850 ppm.
3-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 2.70 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 950 ppm.
2-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1100 ppm.

Unit 2 Enrichment Limits

All Cell Storage	Storage of 17x17 fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 1.82 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 750 ppm.
3-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 2.54 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 950 pm.
2-out-of-4 Checkerboard Storage	Storage of 17x17 fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1250 ppm.
3x3 Checkerboard Storage	Storage of Westinghouse 17x17 fuel assemblies with nominal enrichments no greater than 4.00 w/o ^{235}U (equivalent enrichment with IFBA credit) in the center of a 3x3 checkerboard. The surrounding fuel assemblies must have an initial nominal enrichment no greater than 1.48 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron credit required for this storage configuration is 800 ppm.

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7 Fuel Handling System; ANSI 57.2-1983, "Design Objectives for LWR Spent Fuel Storage Facilities at Nuclear Power Stations," Section 6.4.2; ANSI N16.9-1975, "Validation of Calculational Methods for Nuclear Criticality Safety"; and the NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage". This criticality analysis report also takes exception to the requirement that no reactivity credit may be taken for the presence of soluble boron in the spent fuel pool as stated in ANSI 57.2-1983[3] and the NRC position paper[4] and shows that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array is less than 1.0 under maximum feasible conditions (no soluble boron) and less than or equal to 0.95 when credit is taken for the presence of spent fuel pool soluble boron.

Table 1. Nominal Fuel Parameters Employed in the Criticality Analysis

Parameter	Westinghouse 17x17 STD	Westinghouse 17x17 OFA
Number of Fuel Rods per Assembly	264	264
Rod Zirc Clad O.D. (inch)	0.3740	0.3600
Clad Thickness (inch)	0.0225	0.0225
Fuel Pellet O.D. (inch)	0.3225	0.3088
Fuel Pellet Density (% of Theoretical)	95	95
Fuel Pellet Dishing Factor (%)	1.2074	1.211
Rod Pitch (inch)	0.496	0.496
Number of Zirc Guide Tubes	24	24
Guide Tube O.D. (inch)	0.482	0.474
Guide Tube Thickness (inch)	0.016	0.016
Number of Instrument Tubes	1	1
Instrument Tube O.D. (inch)	0.482	0.474
Instrument Tube Thickness (inch)	0.016	0.016

Table 2. All Cell Storage Soluble Boron Credit K_{eff} for Vogtle Unit 1

Nominal KENO-Va Reference Reactivity:	**0.88950**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00978
TOTAL Bias	0.01748
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00754
UO_2 Density Toierance	0.00375
Fuel Pellet Dishing Variation	0.00195
Cell Inner Diameter	0.00007
Cell Pitch	0.03607
Cell Wall Thickness	0.00613
Asymmetric Assembly Position	0.00393
Calculational Uncertainty (95/95)	0.00182
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.03796
Final K_{eff} Including Uncertainties & Tolerances:	**0.94494**

Table 3. Minimum Burnup Requirements for Vogtle Unit 1

Nominal Enrichment (w/o ^{235}U)	All Cell Burnup (MWD/MTU)	3-out-of-4 Checkerboard Burnup (MWD/MTU)
2.00	0	0
2.20	2647	0
2.40	5185	0
2.60	7622	0
2.70	8806	0
2.80	9967	846
3.00	12229	2524
3.20	14416	4183
3.40	16537	5824
3.60	18600	7445
3.80	20614	9048
4.00	22589	10632
4.20	24532	12197
4.40	26453	13744
4.60	28359	15271
4.80	30260	16780
5.00	32165	18270

Table 4. 3-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for the Vogtle Unit 1

Nominal KENO-Va Reference Reactivity:	**0.90121**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00531
TOTAL Bias	0.01301
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00458
UO_2 Density Tolerance	0.00329
Fuel Pellet Dishing Variation	0.00192
Cell Inner Diameter	0.00006
Cell Pitch	0.02634
Cell Wall Thickness	0.00518
Asymmetric Assembly Position	0.00453
Calculational Uncertainty (95/95)	0.00200
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.02811
Final K_{eff} Including Uncertainties & Tolerances:	**0.94233**

Table 5. 2-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for the Vogtle Unit 1

	17x17 STD	17x17 OFA
Nominal KENO-Va Reference Reactivity:	**0.91126**	**0.92077**
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00017	0.00008
TOTAL Bias	0.00787	0.00778
Tolerances & Uncertainties:		
UO_2 Enrichment Tolerance	0.00149	0.00156
UO_2 Density Tolerance	0.00221	0.00257
Fuel Pellet Dishing Variation	0.00124	0.00148
Cell Inner Diameter	0.00001	0.00005
Cell Pitch	0.00610	0.00611
Cell Wall Thickness	0.00429	0.00413
Asymmetric Assembly Position	0.00526	0.00084
Calculational Uncertainty (95/95)	0.00246	0.00233
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.01034	0.00899
Final K_{eff} Including Uncertainties & Tolerances:	**0.92947**	**0.93754**

Table 6. All Cell Storage Soluble Boron Credit K_{eff} for Vogtle Unit 2

Nominal KENO-Va Reference Reactivity:	**0.91531**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00920
TOTAL Bias	0.01690
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00870
UO_2 Density Tolerance	0.00371
Fuel Pellet Dishing Variation	0.00194
Cell Inner Diameter	0.00100
Cell Pitch	0.00454
Cell Wall Thickness	0.00236
Asymmetric Assembly Position	0.00295
Calculational Uncertainty (95/95)	0.00175
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01188
Final K_{eff} Including Uncertainties & Tolerances:	**0.94409**

Table 7. Minimum Burnup Requirements for Vogtle Unit 2

Nominal Enrichment (w/o ^{235}U)	All Cell Burnup (MWD/MTU)	3-out-of-4 Checkerboard Burnup (MWD/MTU)	3x3 Checkerboard Burnup (*) (MWD/MTU)
1.48	0	0	0
1.82	0	0	6912
2.00	2713	0	10201
2.20	5580	0	13603
2.40	8309	0	16774
2.54	10144	0	18877
2.60	10913	619	19752
2.70	12162	1598	21159
2.80	13410	2576	22566
3.00	15811	4401	25246
3.20	18130	6135	27815
3.40	20378	7812	30296
3.60	22[illegible]	[illegible]	32706
3.80	247[illegible]	[illegible]	35061
4.00	26795	12723	37371
4.20	28852	14361	39645
4.40	30878	16003	41886
4.60	32880	17640	44098
4.80	34859	19256	46276
5.00	36820	20828	48417

(*) Burnup required on surrounding fuel assemblies.

Table 8. 3-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for Vogtle Unit 2

Nominal KENO-Va Reference Reactivity:	**0.91778**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00514
TOTAL Bias	0.01284
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00508
UO_2 Density Tolerance	0.00330
Fuel Pellet Dishing Variation	0.00192
Cell Inner Diameter	0.00100
Cell Pitch	0.00338
Cell Wall Thickness	0.00187
Asymmetric Assembly Position	0.00395
Calculational Uncertainty (95/95)	0.00200
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00921
Final K_{eff} Including Uncertainties & Tolerances:	**0.93983**

Table 9. 2-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for Vogtle Unit 2

	17x17 STD	17x17 OFA
Nominal KENO-Va Reference Reactivity:	**0.92588**	**0.93412**
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00046	0.00019
TOTAL Bias	0.00816	0.00789
Tolerances & Uncertainties:		
UO_2 Enrichment Tolerance	0.00148	0.00146
UO_2 Density Tolerance	0.00232	0.00242
Fuel Pellet Dishing Variation	0.00134	0.00135
Cell Inner Diameter	0.00004	0.00100
Cell Pitch	0.00077	0.00078
Cell Wall Thickness	0.00154	0.00150
Asymmetric Assembly Position	0.00091	0.00261
Calculational Uncertainty (95/95)	0.00244	0.00238
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.00530	0.00593
Final K_{eff} Including Uncertainties & Tolerances:	**0.93934**	**0.94794**

Table 10. 3x3 Checkerboard Soluble Boron Credit K_{eff} for Vogtle Unit 2

Nominal KENO-Va Reference Reactivity:	**0.91902**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00781
TOTAL Bias	0.01551
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01113
UO_2 Density Tolerance	0.00406
Fuel Pellet Dishing Variation	0.00213
Cell Inner Diameter	0.00100
Cell Pitch	0.00420
Cell Wall Thickness	0.00207
Asymmetric Assembly Position	0.00618
Calculational Uncertainty (95/95)	0.00183
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01478
Final K_{eff} Including Uncertainties & Tolerances:	**0.94931**

Table 11. 3x3 Checkerboard Minimum IFBA Requirement for Vogtle Unit 2

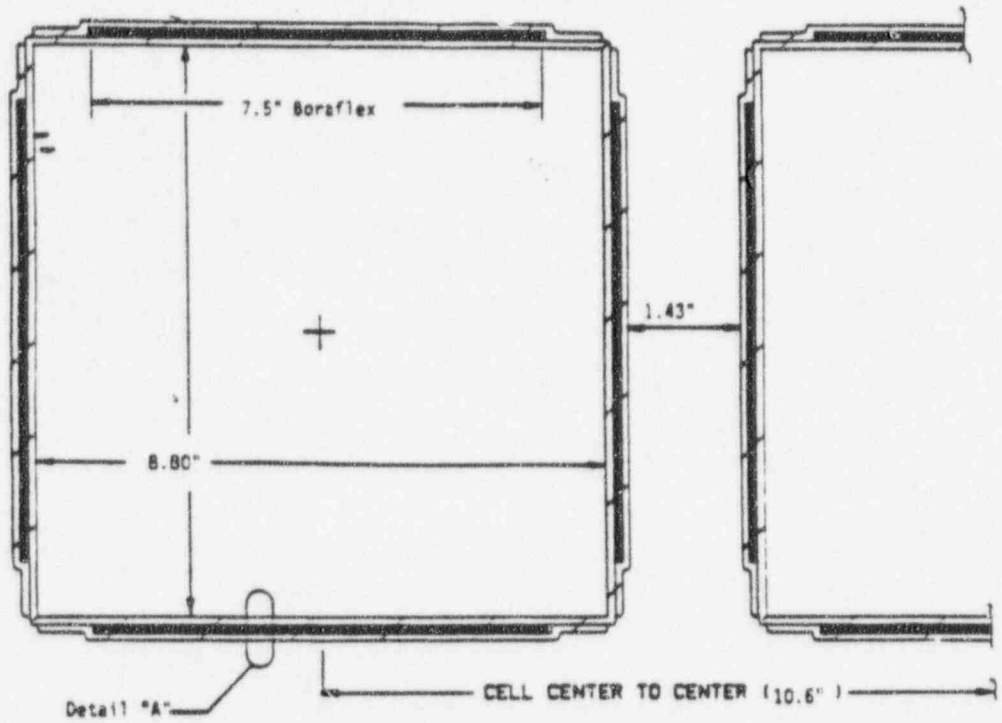
Nominal Enrichment (w/o ^{235}U)	IFBA Requirement 1.0X	IFBA Requirement 1.5X
4.00	0	0
4.20	10	7
4.40	19	13
4.60	27	18
4.80	36	24
5.00	44	30

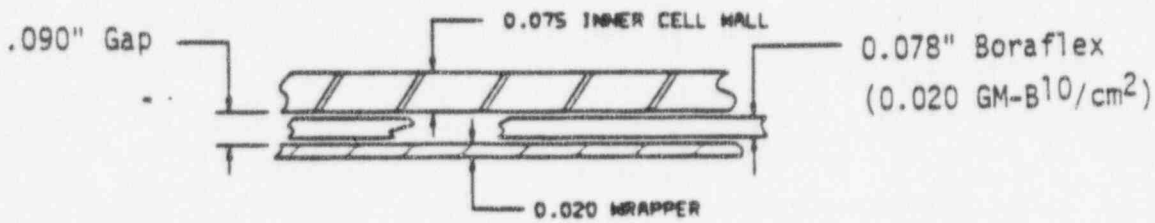
Table 12. Postulated Accident Summary for Vogtle Units 1 and 2

Storage Configuration	Applicable Fuel Assembly Type	Reactivity Increase Caused by Loss of Cooling Accident (ΔK)	Reactivity Increase Caused by Mis-loaded Fuel Assembly Accident (ΔK)	Soluble Boron Required for Accidents (ppm)
Unit 1				
All Cells	17x17 STD or OFA	0.00520	0.05566	300
3-out-of-4 Checkerboard	17x17 STD or OFA	0.00249	0.07096	450
2-out-of-4 Checkerboard	17x17 STD 17x17 OFA	0.0 0.0	0.12519 0.11487	1000 850
Unit 2				
All Cells	17x17 STD or OFA	0.00490	0.05552	300
3-out-of-4 Checkerboard	17x17 STD or OFA	0.00119	0.08260	500
2-out-of-4 Checkerboard	17x17 STD 17x17 OFA	0.0 0.0	0.14380 0.13726	1200 1050
3x3 Checkerboard	17x17 STD or OFA	0.00445	0.05861	350

Table 13. Summary of Soluble Boron Credit Requirements for Vogtle Units 1 and 2

Storage Configuration	Applicable Fuel Assembly Type	Soluble Boron Required for Tolerances/ Uncertainties (ppm)	Soluble Boron Required for Reactivity Equivalencing (ppm)	Soluble Boron Required for Accidents (ppm)	Total Soluble Boron Credit Required (ppm)
Unit 1					
All Cells	17x17 STD or OFA	300	250	300	850
3-out-of-4 Checkerboard	17x17 STD or OFA	300	200	450	950
2-out-of-4 Checkerboard	17x17 STD 17x17 OFA	100 100	n/a n/a	1000 850	1100 950
Unit 2					
All Cells	17x17 STD or OFA	200	250	300	750
3-out-of-4 Checkerboard	17x17 STD or OFA	250	200	500	950
2-out-of-4 Checkerboard	17x17 STD 17x17 OFA	50 50	n/a n/a	1200 1050	1250 1100
3x3 Checkerboard	17x17 STD or OFA	250	200	350	800





DETAIL "A"

Figure 1. Vogtle Unit 1 Spent Fuel Storage Cell Nominal Dimensions

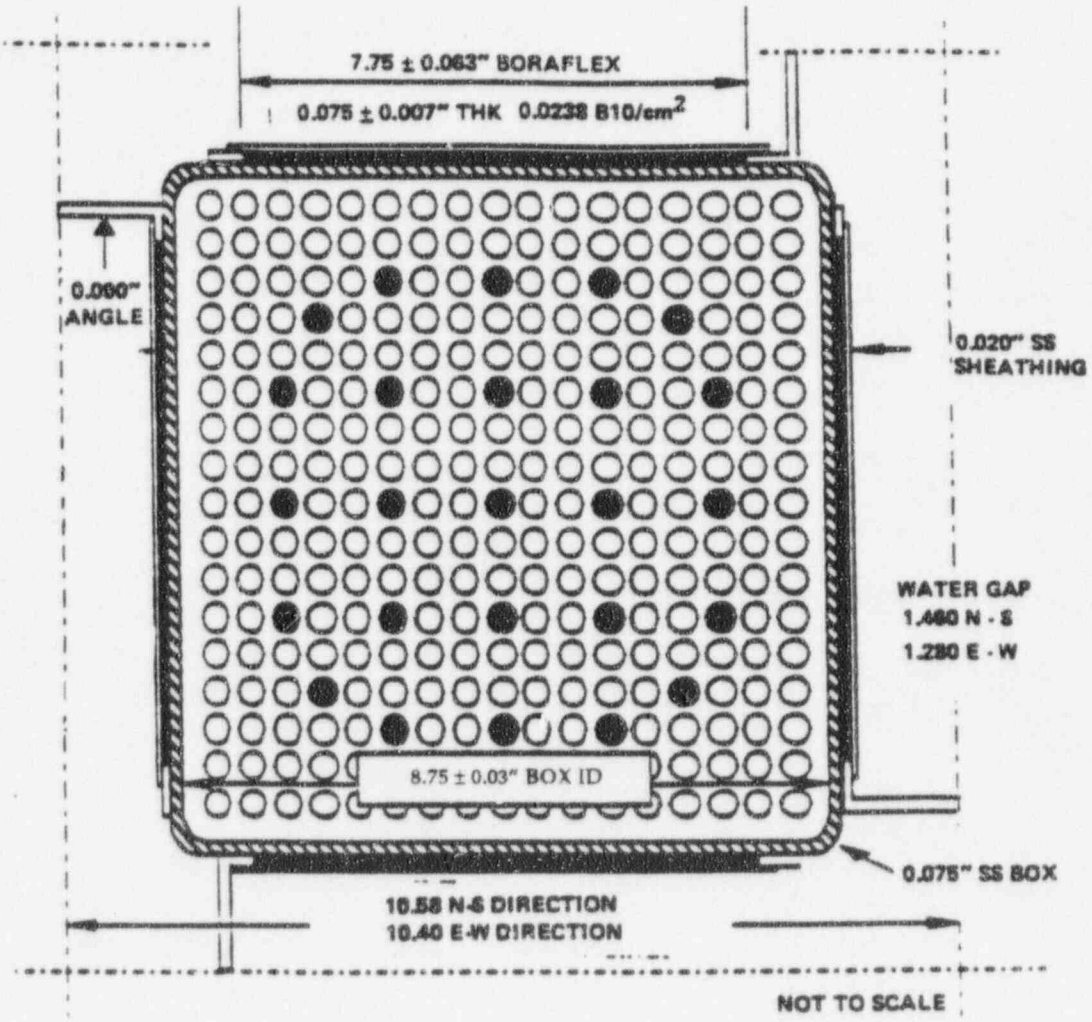
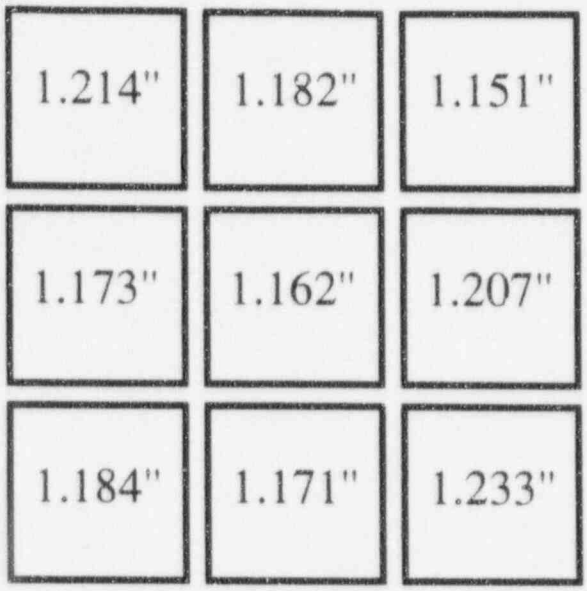
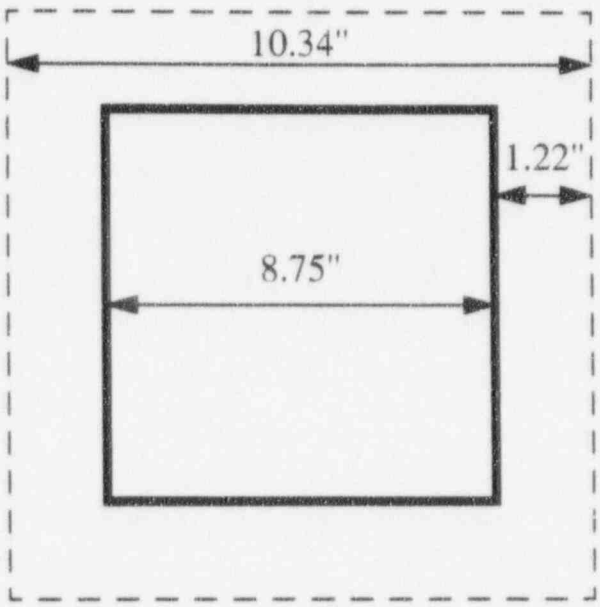


Figure 2. Vogtle Unit 2 Spent Fuel Storage Cell Nominal Dimensions



Rack Module A-5 3x3 Array with Worst Case Average Water Gaps



Reactivity Equivalent Worst Case Cell for Vogtle Unit 2

Figure 3. Vogtle Unit 2 Rack Module A-5 Limiting Water Gaps and Equivalent Cell

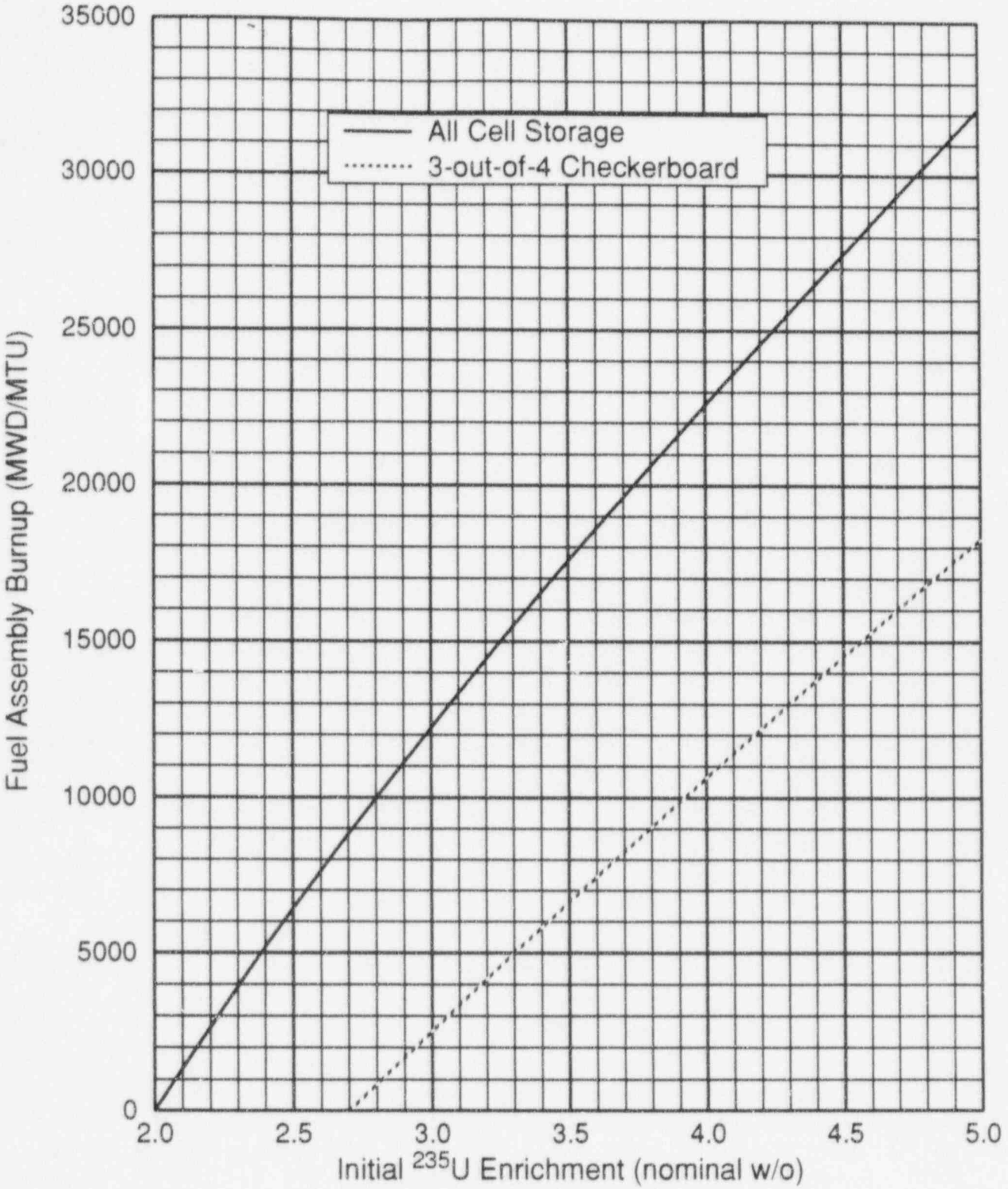
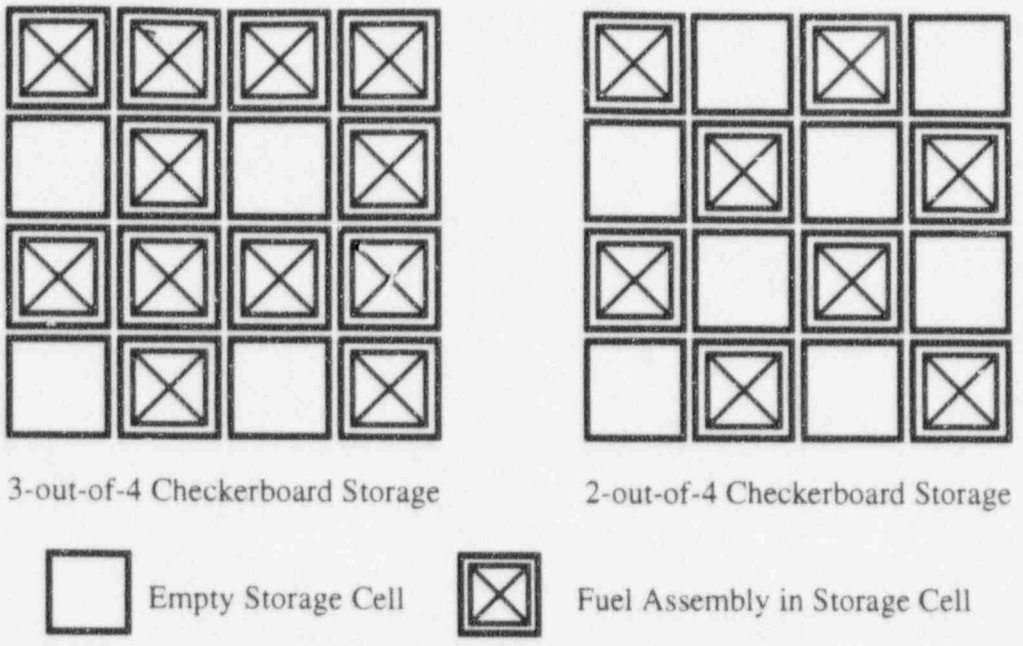


Figure 4. Vogtle Unit 1 Burnup Credit Requirements



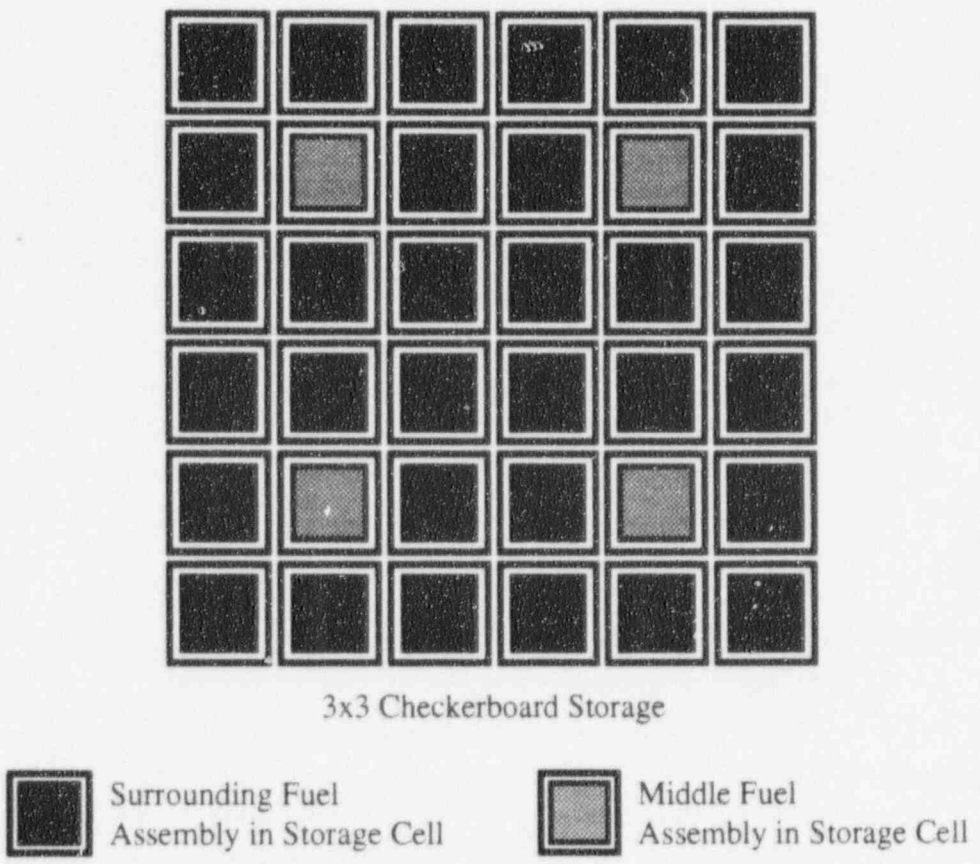


Figure 5. Vogtle Units 1 and 2 Checkerboard Storage Configurations

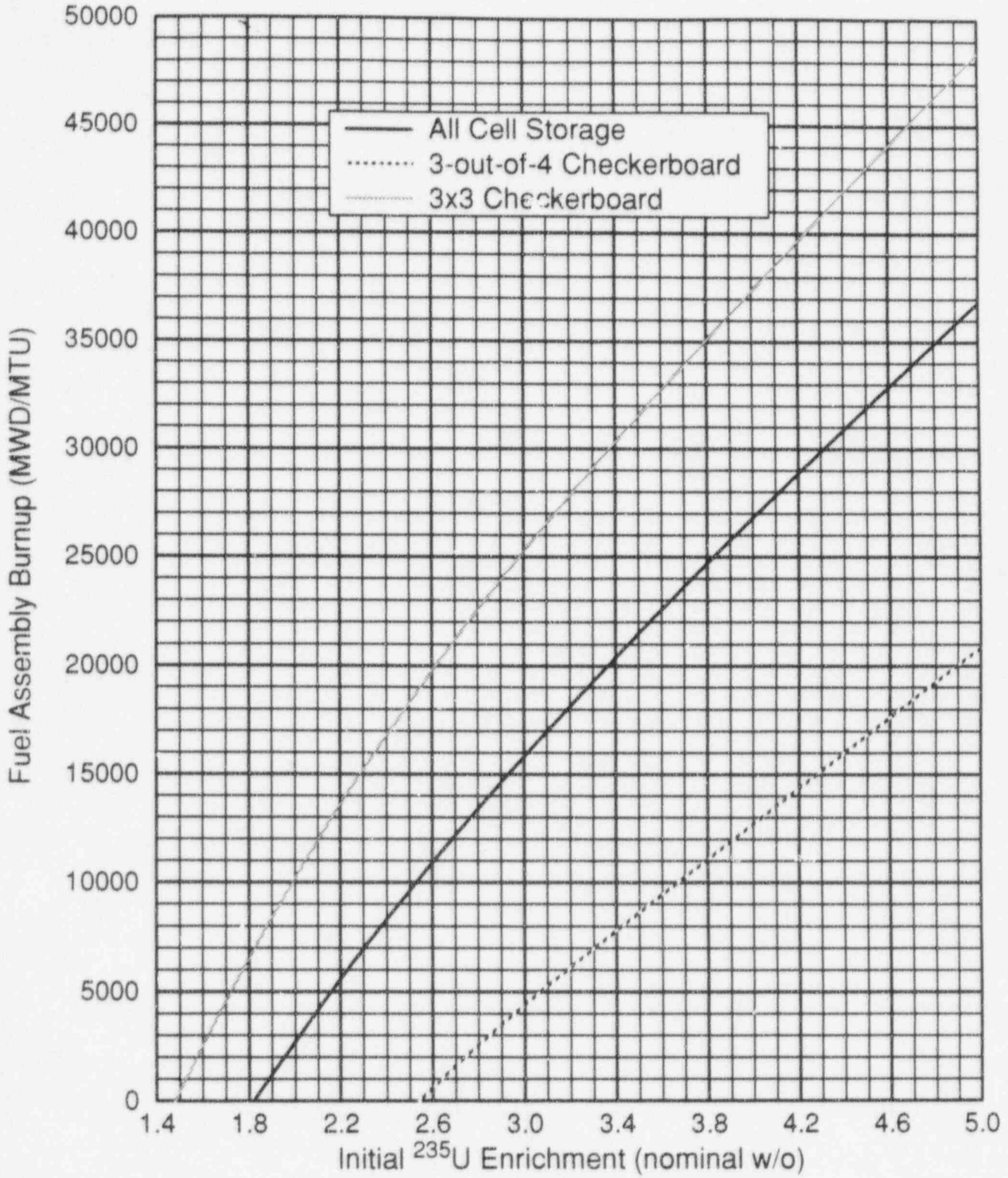


Figure 6. Vogtle Unit 2 Burnup Credit Requirement

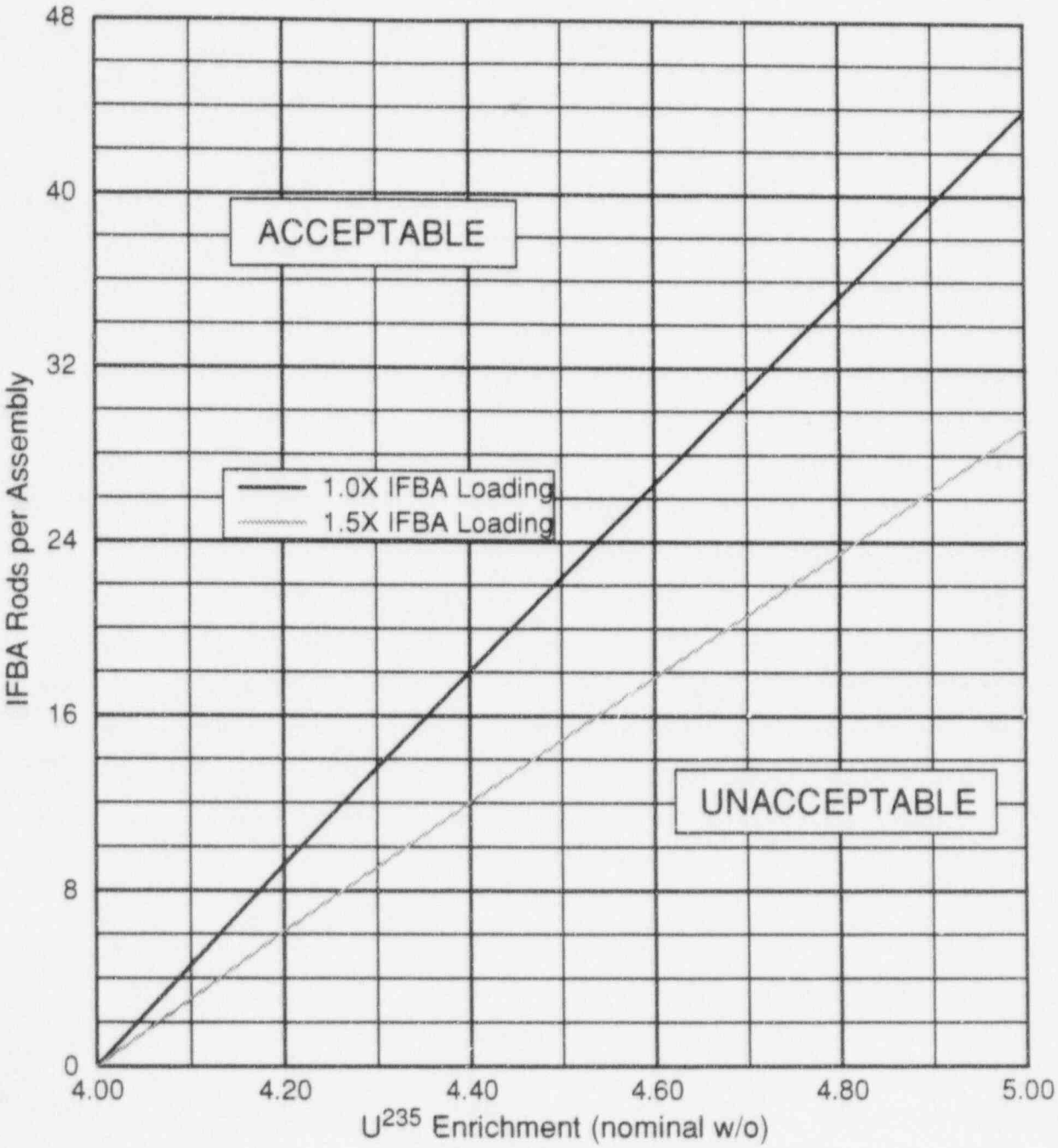


Figure 7. Vogtle Unit 2 3x3 Checkerboard IFBA Requirement

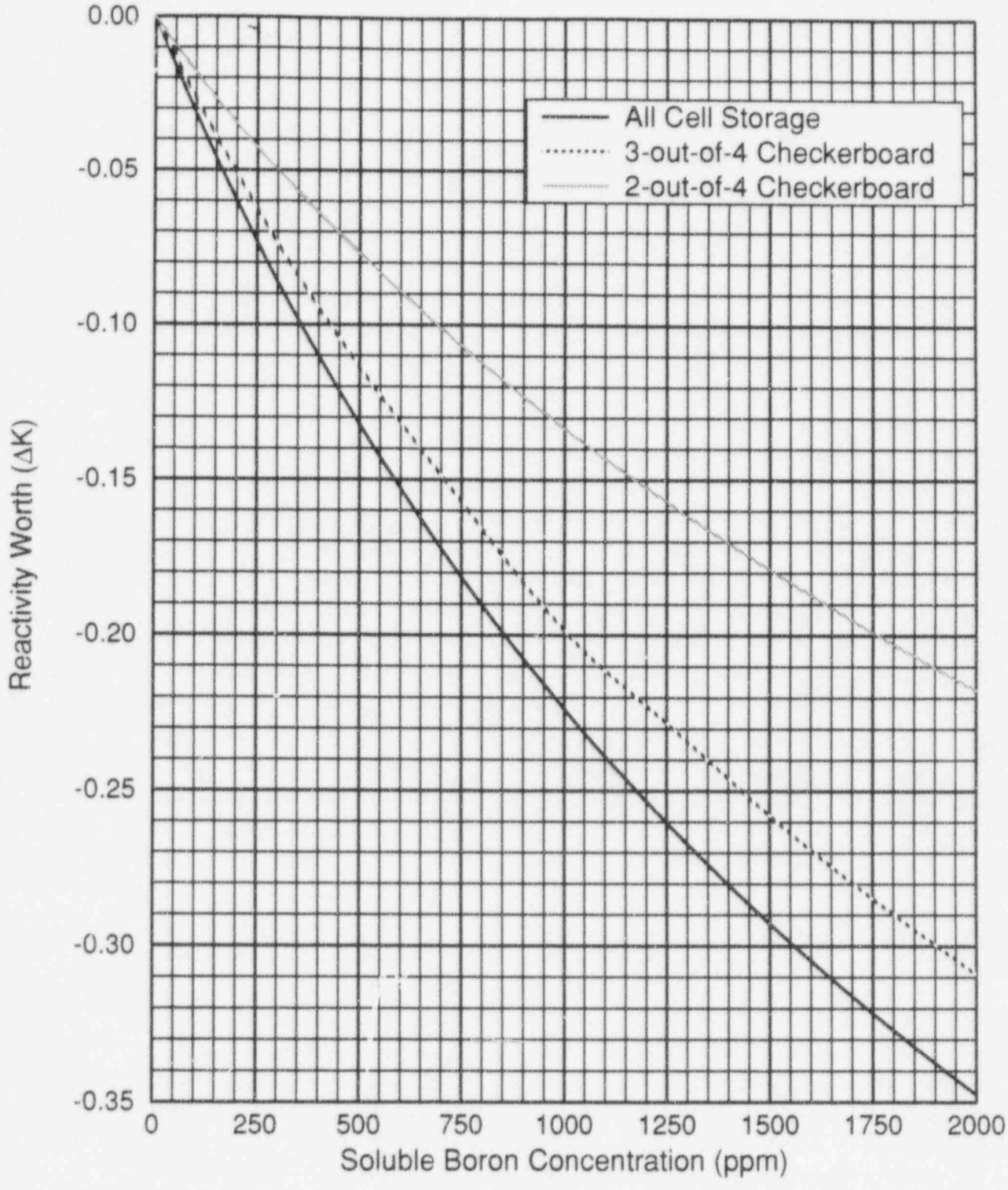


Figure 8. Vogtle Unit 1 Soluble Boron Worth

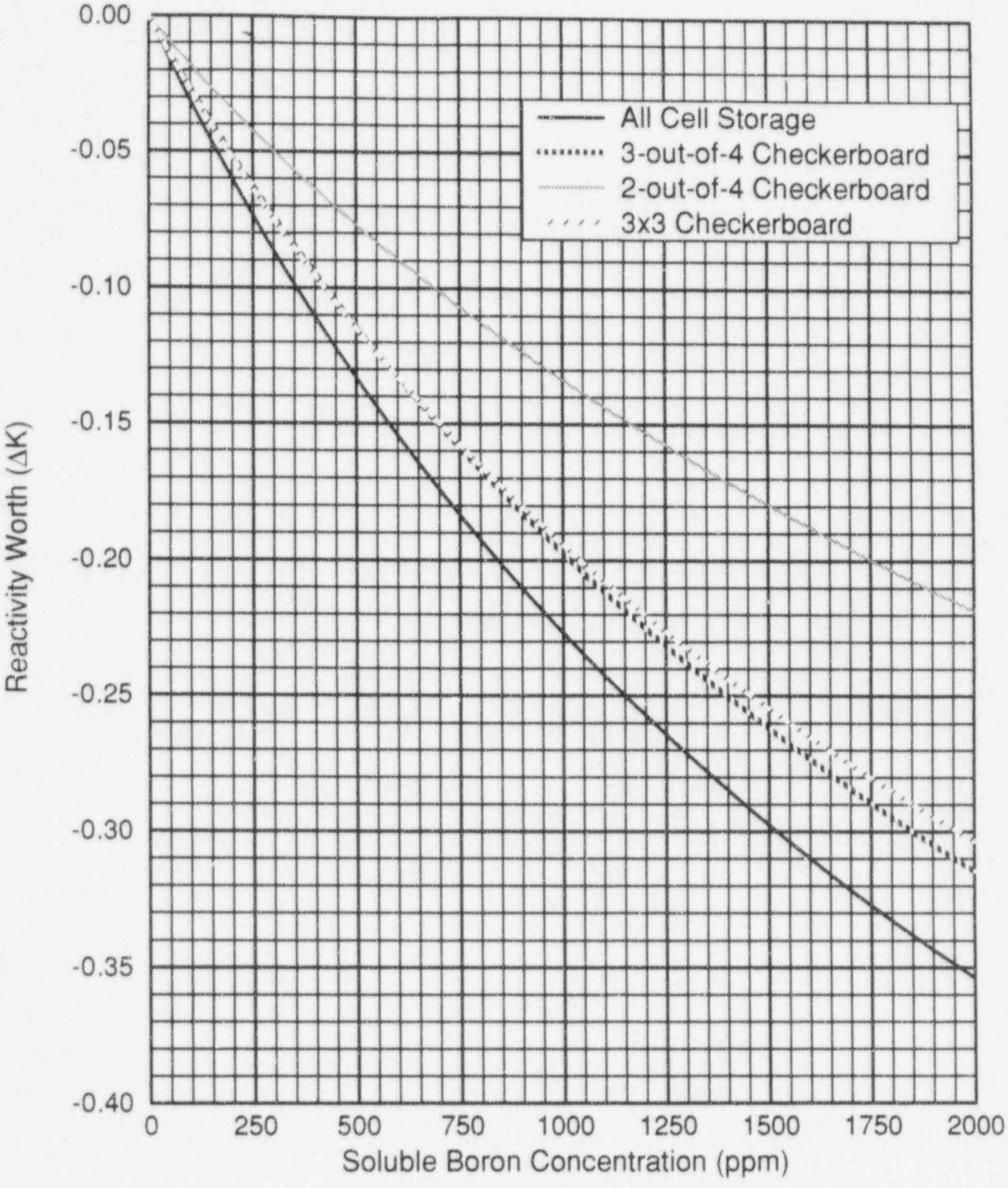


Figure 9. Vogtle Unit 2 Soluble Boron Worth

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