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

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M. M. Baker
S. K. Kapil
J. R. Lesko
R. N. Milanova
K. R. Robinson
J. R. Secker
T. R. Wathey

Prepared: *K. R. Robinson*
K. R. Robinson
Criticality Services Team

Verified: *S. Srinilta*
S. Srinilta
Criticality Services Team

Approved: *M. W. Fecteau*
M. W. Fecteau, Manager
Core Analysis A



Westinghouse
Commerical Nuclear Fuel Division

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The original version of the criticality report used the original WOG methodology which was not approved for use due to comments by the NRC CRGR. Revision 1 of this report reflected the current NRC approved methodology in WCAP-14416-NP-A Revision 1. Revision 2 of this report is being revised to update Figure 8 on page 71 to be consistent with the data in Table 7 for the all cell configuration.

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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 (design) enrichments up to 5.00 w/o ²³⁵U in the storage cell locations using credit for checkerboard configurations, burnup credit, and Integral Fuel Burnable Absorber (IFBA) ⁽²⁾ credit. The nominal fuel enrichment for the region is the enrichment of the fuel ordered from the manufacturer. This analysis does not take any credit for the presence of the spent fuel rack Boraflex poison panels. 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 all cell locations. Fuel assemblies must have an initial nominal enrichment no greater than 1.79 w/o ²³⁵ U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 450 ppm. Including accidents, the soluble boron credit required for this storage configuration is 950 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 2.45 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 100 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1150 ppm. |

Unit 2 Enrichment Limits

- All Cell Storage** Storage of 17x17 fuel assemblies in all cell locations. Fuel assemblies must have an initial nominal enrichment no greater than 1.77 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, 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 2.40 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1050 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 50 ppm. Including accidents, 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 3.20 w/o ^{235}U (up to 5.00 w/o ^{235}U 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. Alternatively, the center (high enrichment) cell of the 3x3 checkerboard may be loaded with any assembly which meets a maximum infinite multiplication factor (K_{∞}) value of 1.410 at cold reactor core conditions. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 500 ppm. Including accidents, soluble boron credit required for this storage configuration is 1050 ppm.

The Vogtle Units 1 and 2 spent fuel rack analysis is based on maintaining $K_{eff} < 1.0$ including uncertainties and tolerances on a 95/95 basis without the presence of any soluble boron in the storage pool (No Soluble Boron 95/95 K_{eff} condition). 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 64 and the Vogtle Unit 2 spent fuel storage cell is shown in Figure 2 on page 65 with nominal dimensions provided in each figure.

The fuel parameters relevant to this analysis are given in Table 1 on page 51. The fuel rod, guide tube and instrumentation tube claddings 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, guide tubes, and the instrumentation tube. Results are presented for whichever fuel type, 17x17 STANDARD (STD) or 17x17 Optimized Fuel Assembly (OFA), is bounding for a particular storage configuration. With the conservative assumptions of the analyses (e.g. grids are not modeled), 17x17 VANTAGE-5H (V5H) fuel assemblies provide equivalent reactivity to 17x17 STD fuel assemblies and 17x17 VANTAGE-5 (V5) fuel assemblies provide equivalent reactivity to 17x17 OFA fuel assemblies.

The Vogtle Unit 2 spent fuel storage contains 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⁽³⁾ 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 66. The criticality analysis for the Vogtle Unit 2 all cell, 3-out-of-4 checkerboard and 2-out-of-4 checkerboard configurations was based on an equivalent cell pitch which yields a reactivity equivalent to or slightly conservative relative to the reactivity of the as-built 3x3 array in rack module A-5 with the worst combination of water gap spacings. For the 3x3 configuration, the cell pitch is based on the average minimum water gap spacing for the limiting 3x3 array of rack cells in rack module A-5 which yields a slightly conservative rack reactivity. The cell models used as the basis for the calculations of reactivity in the Vogtle Unit 2 spent fuel racks can be seen in Figure 3 on page 66.

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 rack is analyzed such that K_{eff} remains less than 1.0 under No Soluble Boron 95/95 K_{eff} conditions 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 the Vogtle Unit 1 and 2 spent fuel pool. This parameter provides significant negative reactivity in the criticality analysis of the spent fuel rack and will be used here in conjunction with administrative controls to offset the reactivity increase when ignoring the presence of the spent fuel rack Boraflex poison panels. Soluble boron credit provides sufficient relaxation in the enrichment limits of the spent fuel racks.

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 rack array will be less than or equal to 0.95.

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⁽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 uncertainty on the bias of 0.00300 ΔK . These values will be used in this report.

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.

Section 3.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations. Section 3.2 discusses the results of the spent fuel rack 95/95 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 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD fuel assembly design is more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 1.79 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.
11. All available storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.94250, as shown in Table 2 on page 52.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P calculations were performed. For the Vogtle Unit 1 spent fuel rack all cell storage configuration, UO₂ 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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

²³⁵U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ²³⁵U about the nominal reference enrichment of 1.79 w/o ²³⁵U was considered.

UO₂ Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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.

Asymmetric Assembly Position: 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.

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 95/95 K_{eff} for the Vogtle Unit 1 spent fuel rack all cell storage configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 2 on page 52 and results in a 95/95 K_{eff} of 0.99784.

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical when all cells are loaded with 1.79 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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 3.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is 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 0.88054.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 2 on page 52 and results in a 95/95 K_{eff} of 0.93457.

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 1.79 w/o ^{235}U is acceptable in all cells including the presence of 200 ppm soluble boron.

3.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 1.79 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 67 shows the constant K_{eff} contours generated for all cell storage in the Vogtle Unit 1 spent fuel racks. The curve of Figure 4 represents combinations of fuel enrichment and discharge burnup which yield a conservative rack multiplication factor (K_{eff}) as compared to the rack loaded with 1.79 w/o ^{235}U Westinghouse 17x17 STD fuel assemblies at zero burnup in all cell locations. The 17x17 STD fuel assembly design provides a conservative reactivity relative to the 17x17 OFA design at all enrichment and burnup combinations shown in Figure 4 for the curve.

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 200 ppm required in Section 3.2. This results in a total soluble boron requirement of 450 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 53. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 4 is approximately linear between the tabulated points.

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 effect of axial burnup distribution on assembly reactivity has thus been addressed in the development of the Vogtle Unit 1 all cell storage burnup credit limit.

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.

Section 4.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations. Section 4.2 discusses the results of the spent fuel rack 95/95 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 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD fuel assembly design is more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 2.45 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.
11. Fuel storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies in a 3-out-of-4 checkerboard arrangement. 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. Figure 6 on page 69 shows the 3-out-of-4 checkerboard configurations.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.95418, as shown in Table 4 on page 54.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P calculations were performed. For the Vogtle Unit 1 spent fuel rack 3-out-of-4 checkerboard configuration, UO₂ 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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

²³⁵U Enrichment: The standard DOL enrichment tolerance of ±0.05 w/o ²³⁵U about the nominal reference enrichment of 2.45 w/o ²³⁵U was considered.

UO₂ Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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.

Asymmetric Assembly Position: Conservative calculations show that an increase in reactivity can occur if the corners of the three fuel assemblies were positioned together. This reactivity increase was considered.

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 95/95 K_{eff} for the Vogtle Unit 1 spent fuel rack 3-out-of-4 checkerboard configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 4 and results in a 95/95 K_{eff} of 0.99578.

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical when 3-out-of-4 cells are loaded with 2.45 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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 4.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is 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 0.89720.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 4 on page 54 and results in a 95/95 K_{eff} of 0.93777.

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 2.45 w/o ^{235}U is acceptable in 3-out-of-4 cells including the presence of 200 ppm soluble boron.

4.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 2.45 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 5 on page 68 shows the constant K_{eff} contours generated for 3-out-of-4 cell storage in the Vogtle Unit 1 spent fuel racks. The curve of Figure 5 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as compared to the rack loaded with 2.45 w/o ^{235}U Westinghouse 17x17 STD fuel assemblies at zero burnup in 3-out-of-4 cell locations. The 17x17 STD fuel assembly design provides a conservative reactivity relative to the 17x17 OFA design at all enrichment and burnup combinations shown in Figure 5 for the curve.

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 5 was 150 ppm. This is additional boron above the 200 ppm required in Section 4.2. This results in a total soluble boron requirement of 350 ppm.

It is important to recognize that the curve in Figure 5 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 5 are also provided in Table 3 on page 53. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 3 is approximately linear between the tabulated points.

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 effect of axial burnup distribution on assembly reactivity has thus been addressed in the development of the Vogtle Unit 1 3-out-of-4 cell storage burnup credit limit.

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.

Section 5.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations and Section 5.2 discusses the results of the spent fuel rack 95/95 K_{eff} soluble boron credit calculations.

5.1 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 OFA fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 OFA fuel assembly design is more reactive than the Westinghouse 17x17 STD fuel assembly design.
2. 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 are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.

11. Fuel storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies in a 2-out-of-4 checkerboard arrangement as shown in Figure 6 on page 69. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.93670, as shown in Table 5 on page 55.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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 5.0 w/o ^{235}U was considered.

UO_2 Density: A $\pm 2.0\%$ variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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.

Asymmetric Assembly Position: Conservative calculations show that an increase in reactivity can occur if the corners of the two fuel assemblies were positioned together. This reactivity increase was considered.

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 95/95 K_{eff} for the Vogtle Unit 1 spent fuel rack 2-out-of-4 checkerboard configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 on page 55 and results in a 95/95 K_{eff} of 0.95741.

Since K_{eff} is less than 1.0, the Vogtle Unit 1 spent fuel racks will remain subcritical when 2-out-of-4 cells are loaded with 5.00 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.

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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 5.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is replaced with water containing 100 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.92077.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 on page 55 and results in a 95/95 K_{eff} of 0.93835.

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.

Section 6.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations. Section 6.2 discusses the results of the spent fuel rack 95/95 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 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD fuel assembly design is more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 1.77 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.
11. All available storage cells are loaded with fuel assemblies which are symmetrically positioned (centered within the storage cell).

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.96819, as shown in Table 6 on page 56.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P calculations were performed. For the Vogtle Unit 2 spent fuel rack all cell storage configuration, UO₂ 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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

²³⁵U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ²³⁵U about the nominal reference enrichment of 1.77 w/o ²³⁵U was considered.

UO₂ Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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 equivalent cell pitch of 10.34 inches was assumed (see Section 1.1 for discussion of equivalent cell).

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

Asymmetric Assembly Position: 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.

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 95/95 K_{eff} for the Vogtle Unit 2 spent fuel rack all cell storage configuration, is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 and results in a 95/95 K_{eff} of 0.99851.

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical when all cells are loaded with 1.77 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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 6.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is replaced with water containing 150 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case with 150 ppm soluble boron in the moderator resulted in a K_{eff} of 0.92003.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 on page 56 and results in a 95/95 K_{eff} of 0.94998.

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 1.77 w/o ^{235}U is acceptable in all cells including the presence of 150 ppm soluble boron.

6.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 1.77 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 8 on page 71 shows the constant K_{eff} contours generated for all cell storage in the Vogtle Unit 2 spent fuel racks. The curve of Figure 8 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as compared to the rack loaded with 1.77 w/o ^{235}U Westinghouse 17x17 STD fuel assemblies at zero burnup in all cell locations. The 17x17 STD fuel assembly design provides a conservative reactivity relative to the 17x17 OFA design at all enrichment and burnup combinations shown in Figure 8 for the curve.

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 8 was 200 ppm. This is additional boron above the 150 ppm required in Section 6.2. This results in a total soluble boron requirement of 350 ppm.

It is important to recognize that the curve in Figure 8 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 8 are also provided in Table 7 on page 57. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 8 is approximately linear between the tabulated points.

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 effect of axial burnup distribution on assembly reactivity has thus been addressed in the development of the Vogtle Unit 2 all cell storage burnup credit limit.

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.

Section 7.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations. Section 7.2 discusses the results of the spent fuel rack 95/95 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 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 STD fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 STD fuel assembly design is more reactive than the Westinghouse 17x17 OFA fuel assembly design.
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 2.40 w/o ^{235}U over the entire length of each rod.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.
11. Fuel storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies in a 3-out-of-4 checkerboard arrangement. 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. Figure 6 on page 69 shows the 3-out-of-4 checkerboard configurations.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.97240, as shown in Table 8 on page 58.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P calculations were performed. For the Vogtle Unit 2 spent fuel rack 3-out-of-4 checkerboard configuration, UO₂ 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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

²³⁵U Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o ²³⁵U about the nominal reference enrichment of 2.40 w/o ²³⁵U was considered.

UO₂ Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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 equivalent cell pitch of 10.34 inches was assumed (see Section 1.1 for discussion of equivalent cell).

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

Asymmetric 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 three fuel assemblies were positioned together. This reactivity increase was considered.

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 95/95 K_{eff} for the Vogtle Unit 2 spent fuel rack 3-out-of-4 checkerboard configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 8 and results in a 95/95 K_{eff} of 0.99464.

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical when 3-out-of-4 cells are loaded with 2.40 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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 7.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is 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 0.91440.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 8 on page 58 and results in a 95/95 K_{eff} of 0.93716.

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 2.40 w/o ^{235}U is acceptable in 3-out-of-4 cells including the presence of 200 ppm soluble boron.

7.3 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with initial enrichments higher than 2.40 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 9 on page 72 shows the constant K_{eff} contours generated for 3-out-of-4 storage in the Vogtle Unit 2 spent fuel racks. The curve of Figure 9 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as compared to the rack loaded with 2.40 w/o ^{235}U Westinghouse 17x17 STD fuel assemblies at zero burnup in 3-out-of-4 cell locations. The 17x17 STD fuel assembly design provides a conservative reactivity relative to the 17x17 OFA design at all enrichment and burnup combinations shown in Figure 9 for the curve.

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 calculator 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 9 was 150 ppm. This is additional boron above the 200 ppm required in Section 7.2. This results in a total soluble boron requirement of 350 ppm.

It is important to recognize that the curve in Figure 9 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 9 are also provided in Table 7 on page 57. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 8 is approximately linear between the tabulated points.

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 effect of axial burnup distribution on assembly reactivity has thus been addressed in the development of the Vogtle Unit 2 3-out-of-4 cell storage burnup credit limit.

8.6 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.

Section 8.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations and Section 8.2 discusses the results of the spent fuel rack 95/95 K_{eff} soluble boron credit calculations.

8.1 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 OFA fuel design (see Table 1 on page 51 for fuel parameters). Calculations show that for the enrichment and storage configuration considered here, the Westinghouse 17x17 OFA fuel assembly design is more reactive than the Westinghouse 17x17 STD fuel assembly design.
2. 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 are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
10. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.

1. Fuel storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies in a 2-out-of-4 checkerboard arrangement as shown in Figure 6 on page 69. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.94622, as shown in Table 9 on page 59.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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 5.0 w/o ^{235}U was considered.

UO_2 Density: A $\pm 2.3\%$ variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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 equivalent cell pitch of 10.34 inches was assumed. (see Section 1.1 for discussion of equivalent cell).

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

Asymmetric Assembly Position: Conservative calculations show that an increase in reactivity can occur if the corners of the two fuel assemblies were positioned together. This reactivity increase was considered.

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 95/95 K_{eff} for the Vogtle Unit 2 spent fuel rack 2-out-of-4 checkerboard configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 9 on page 59 and results in a 95/95 K_{eff} of 0.96067.

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical when 2-out-of-4 cells are loaded with 5.0 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.

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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 8.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator is replaced with water containing 50 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.93390.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 9 on page 59 and results in a 95/95 K_{eff} of 0.94737.

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 5.0 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.

Section 9.1 describes the no soluble boron 95/95 K_{eff} KENO-Va calculations. Section 9.2 discusses the results of the spent fuel rack 95/95 K_{eff} soluble boron credit calculations. Section 9.3 presents the results of calculations performed to show the minimum burnup requirements for the eight peripheral assemblies with initial enrichments above those determined in Section 9.1. Section 9.4 presents the results of calculations performed to show the minimum IFBA requirements for enrichments greater than 3.20 w/o ^{235}U in the center assembly of the 3x3 checkerboard. Finally Section 9.4.1 discusses the infinite multiplication factor.

9.1 No Soluble Boron 95/95 K_{eff} Calculation

To determine the enrichment required to maintain $K_{eff} < 1.0$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 equation for determining the final 95/95 K_{eff} is defined in Reference 1.

The following assumptions are used to develop the No Soluble Boron 95/95 K_{eff} 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 are based on the Westinghouse 17x17 STD and OFA fuel designs (see Table 1 on page 51 for fuel parameters).
2. Westinghouse 17x17 fuel assemblies stored in the middle of the 3x3 checkerboard contain uranium dioxide at a fixed nominal enrichment of 3.20 w/o ^{235}U over the entire length of each rod. Calculations show that at this enrichment, OFA fuel is more reactive with no soluble boron present.
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. Calculations show that at this enrichment, STANDARD fuel is more reactive with no soluble boron present. This arrangement of OFA surrounded by STD fuel in the 3x3 checkerboard configuration provides a conservative reactivity when compared to other fuel type configurations, including all OFA or all STD fuel.
4. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
5. No credit is taken for any natural or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.

6. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
7. No credit is taken for any spacer grids or spacer sleeves.
8. No credit is taken for any burnable absorber in the fuel rods.
9. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
10. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm³ is used.
11. The array is infinite in the lateral (x and y) extent and finite in the axial (vertical) extent.
12. Fuel storage cells are loaded with symmetrically positioned (centered within the storage cell) fuel assemblies in a 3x3 checkerboard arrangement as shown in Figure 7 on page 70.

With the above assumptions, the KENO-Va calculations of K_{eff} under nominal conditions resulted in a K_{eff} of 0.96865, as shown in Table 10 on page 60.

Temperature and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 1.0 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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

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 3.20 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 $\pm 2.0\%$ variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 51) 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 51) 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 cell pitch of 10.306 inches was assumed (see Section 1.1 for discussion of the cell pitch assumed).

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

Asymmetric Assembly Position: Conservative calculations show that an increase in reactivity can occur if the corners of four adjacent fuel assemblies are positioned together. This reactivity increase was considered.

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 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 10 on page 60 and results in a 95/95 K_{eff} of 0.99911.

Since K_{eff} is less than 1.0, the Vogtle Unit 2 spent fuel racks will remain subcritical when cells are loaded in a 3x3 checkerboard with a 3.20 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 is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the temperature bias of a normal pool temperature range and the effects of material and construction tolerance variations. A final 95/95 K_{eff} is 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 are similar to those in Section 9.1 except for assumptions 2 and 10. Assumption 2 is different since the limiting fuel type for the center assembly of the 3x3 configuration with 200 ppm soluble boron is STANDARD fuel. Assumption 10 is different since the moderator is replaced with water containing 200 ppm soluble boron. The all STD fuel case in the 3x3 checkerboard configuration provides a conservative reactivity when compared to other fuel type configurations with 200 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.90946, as shown in Table 10 on page 60.

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, additional PHOENIX-P 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. To evaluate the reactivity effect of asymmetric assembly positioning within the storage cells, KENO-Va calculations were performed.

The same tolerance and uncertainty components as in the No Soluble Boron case were considered in the total uncertainty statistical summation:

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 10 on page 60 and results in a 95/95 K_{eff} of 0.94047.

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 3.20 w/o ^{235}U 17x17 fuel assembly surrounded by 1.48 w/o ^{235}U 17x17 fuel assemblies including the presence of 200 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 peripheral 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 10 on page 73 shows the constant K_{eff} contours generated for peripheral cells of the 3x3 checkerboard in the Vogtle Unit 2 spent fuel racks. The curve of Figure 10 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as compared to the rack loaded with 1.48 w/o ^{235}U fuel assemblies at zero burnup in

peripheral cell locations of a 3x3 checkerboard. The 17x17 STD fuel assembly design provides a conservative reactivity relative to the 17x17 OFA design at all enrichment and burnup combinations shown in Figure 10 for the curve.

Uncertainties associated with burnup credit include a reactivity uncertainty of $0.01 \Delta K$ 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 10 was 300 ppm. This is additional boron above the 200 ppm required in Section 9.2. This results in a total soluble boron requirement of 500 ppm.

It is important to recognize that the curve in Figure 10 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 10 are also provided in Table 7 on page 57. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 8 is approximately linear between the tabulated points.

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 effect of axial burnup distribution on assembly reactivity has thus been addressed in the development of the Vogtle Unit 2 3x3 checkerboard burnup credit limit.

9.4 IFBA Credit Reactivity Equivalencing

Storage of fresh fuel assemblies with nominal enrichments greater than 3.20 w/o ^{235}U 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. Reactivity equivalencing with IFBA is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers. IFBAs consist of neutron absorbing material applied as a thin zirconium diboride (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 are 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 are used for the IFBA rod assemblies in the PHOENIX-P models:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 51 for fuel parameters). IFBA credit calculations using the OFA design will bound the requirements for the STD design.
2. The fuel assembly is modeled at its most reactive point in life.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.

4. No credit is taken for any natural enrichment or reduced enrichment axial blankets. This assumption results in either equivalent or conservative calculations of reactivity for all fuel assemblies used at Vogtle, including those with annular pellets at the fuel rod ends.
5. No credit is taken for any ^{234}U or ^{236}U in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. Nominal IFBA rod ^{10}B loadings of 1.50 milligrams ^{10}B per inch (1.0X), 1.875 milligrams ^{10}B per inch (1.25X) and 2.25 milligrams ^{10}B per inch (1.5X) are 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/cm³.
10. The array is infinite in the lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.
11. Standard Westinghouse IFBA patterns (including previous standard patterns) for 17x17 fuel assemblies were considered.

Figure 11 on page 74 shows the IFBA requirements for center assembly enrichments greater than 3.20 w/o ^{235}U that result in equivalent rack reactivity for the Vogtle Unit 2 3x3 checkerboard spent fuel rack configuration. The data in Figure 11 is also provided on Table 11 on page 61 for 1.0X, 1.25X and 1.5X IFBA loadings.

It is important to recognize that the curves in Figure 11 are 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 are 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 11 is bounded by the 300 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 500 ppm.

9.4.1 Infinite Multiplication Factor

The infinite multiplication factor, K_{∞} , is used as a reference criticality reactivity point, and offers an alternative method for determining the acceptability of fuel assembly storage in the middle cell of the Vogtle Unit 2 3x3 checkerboard spent fuel racks. The fuel assembly K_{∞} calculations are performed using PHOENIX-P. The following assumptions are used to develop the infinite multiplication factor model:

1. The fuel assembly is modeled at its most reactive point in life and no credit is taken for any burnable absorbers in the assembly.
2. The fuel rods are Westinghouse 17x17 OFA at an enrichment of 3.20 w/o ^{235}U over the infinite length of each rod (this is the maximum nominal enrichment that can be placed in the middle cell of the spent fuel racks for the 3x3 checkerboard configuration without IFBA rods).
3. The fuel array model is based on a unit assembly configuration (infinite in the lateral and axial extents) in Vogtle Unit 2 reactor geometry (no rack).
4. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm³.

Calculation of the infinite multiplication factor results in a reference K_{∞} of 1.410. This includes a 1% ΔK reactivity bias to conservatively account for calculational uncertainties. This bias is consistent with the standard conservatism included in the Vogtle Unit 2 core design refueling shutdown margin calculations. All fuel assemblies placed in the spent fuel racks must comply with the enrichment versus number of IFBA rods curves in Figure 11 or have a reactivity less than or equal to the above value. Meeting either of these conditions assures that the maximum spent fuel rack reactivity will then be less than or equal to 0.95.

10.0 Fuel Rod Storage Canister Criticality

A criticality analysis⁽⁴⁾ was performed for the Fuel Rod Storage Canister (FRSC) which was provided to Vogtle. This report compared the FRSC, loaded with 5.0 w/o ²³⁵U fuel rods, to an intact assembly with 5.0 w/o ²³⁵U fuel rods. The conclusion was that the FRSC is less reactive than an assembly with 5.0 w/o ²³⁵U fuel rods. However, this analysis was done independent of any rack geometry. Therefore, for storage of the FRSC in the racks, the FRSC must be treated as if it were an assembly with enrichment and burnup of the rod in the canister with the most limiting combination of enrichment and burnup.

11.0 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 misplacement of a fuel assembly inside the spent fuel racks. |

However, three 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 outside the normal operating range. The second accident would be dropping an assembly into an already loaded cell and the third 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 62.

For the accident of dropping of a fuel assembly into an already loaded cell, the upward axial leakage of that cell will be reduced, however the overall effect on the rack reactivity will be insignificant. This is because the total axial leakage in both the upward and downward directions for the entire spent fuel array is worth about 0.003 ΔK . Thus, minimizing the upward-only leakage of just a single cell will not cause any significant increase in rack reactivity. Furthermore, the neutronic coupling between the dropped assembly and the already loaded assembly will be low due to several inches of assembly nozzle structure which would separate the active fuel regions. Therefore, this accident would be bounded by the misload accident.

For the assembly misload accident, calculations were performed to show the largest reactivity increase caused by a 5.00 w/o Westinghouse 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 amount of soluble boron required to offset each of the postulated accidents was determined with PHOENIX-P calculations, where the impact of the reactivity equivalencing methodologies on the soluble boron is appropriately taken into account. The additional amount of soluble boron for accident conditions needed beyond the required boron for uncertainties and burnup is shown in Table 12.

12.0 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 63 summarizes the storage configurations and corresponding soluble boron credit requirements.

Based on the above discussion, K_{eff} will be maintained less than or equal to 0.95 for all considered configurations due to the presence of at least 1150 ppm soluble boron in the Vogtle Unit 1 spent fuel pool water and 1250 ppm in the Vogtle Unit 2 spent fuel pool water.

13.0 Storage Configuration Interface Requirements

The Vogtle Units 1 and 2 spent fuel pools have been analyzed for all cell storage, where all cells share the same storage requirements and limits, and several checkerboard storage configurations, where neighboring cells have different requirements and limits.

The boundary between different empty cell checkerboard zones and the boundary between an empty cell checkerboard zone and an all cell storage zone must be controlled to prevent an undesirable increase in reactivity. This is accomplished by examining all possible 2x2 matrices of rack cells near the boundary (within the first few rows of the boundary) and ensuring that each of these 2x2 matrices conforms to checkerboard restrictions for the given region (or for 1 of the 2 regions if the 2x2 matrix of rack cells crosses over the interface boundary).

For example, consider a fuel assembly location E in the following matrix of storage cells.

A	B	C
D	E	F
G	H	I

Four 2x2 matrices of storage cells which include storage cell E are created in the above figure. They include (A,B,D,E), (B,C,E,F), (E,F,H,I), and (D,E,G,H). Each of these 2x2 matrices of storage cells is required to meet the checkerboard requirements determined for the given region.

The boundary between the 3x3 checkerboard zone and the empty cell checkerboard zones must be controlled to prevent an undesirable increase in reactivity. This is accomplished by examining all possible 3x3 matrices of rack cells which include a highly enriched assembly or equivalent from the 3x3 checkerboard configuration and ensuring that each of these 3x3 matrices conforms to restrictions for the 3x3 checkerboard [e.g. only 1 out of 9 assemblies may be at the high enrichment (3.20 w/o ^{235}U - Unit 2 only) or equivalent for the 3x3 checkerboard configuration]. However, on the empty cell checkerboard side of the boundary only, 2x2 matrices of rack cells near the boundary (within the first few rows of the boundary) should be reviewed to ensure that the empty cell checkerboard restrictions are met.

The boundary between the 3x3 checkerboard zone and the all cell storage zone must be controlled to prevent an undesirable increase in reactivity. This is accomplished by examining all possible 3x3 matrices of rack cells which include a highly enriched assembly or equivalent from the 3x3 checkerboard configuration and ensuring that each of these 3x3 matrices conforms to restrictions for the 3x3 checkerboard [e.g. only 1 out of 9 assemblies may be at the high enrichment (3.20 w/o ^{235}U - Unit 2 only) or equivalent for the 3x3 checkerboard configuration]. The low enrichment of the 3x3 checkerboard configuration meets the requirements for storage in the all cell region, and thus, placement of the low enrichment assemblies or equivalent from the 3x3 checkerboard configuration on the all cell side of the boundary will meet the criticality limits of these analyses.

13.1 Interface Requirements within Vogtle Racks

The following discussion of interface requirements illustrates example configurations that demonstrate the interface requirements discussed in Section 13.0 which are applicable to the Vogtle Units 1 and 2 Spent Fuel Racks:

All Cell Storage Next to 3-out-of-4 Storage

The boundary between all cell storage and 3-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the 3-out-of-4 storage region uses alternating empty cells and cells containing assemblies at the 3-out-of-4 configuration enrichment (2.45 w/o ^{235}U for Unit 1, 2.40 w/o ^{235}U for Unit 2) or equivalent. Figure 12 on page 75 illustrates the configuration at the boundary.

All Cell Storage Next to 2-out-of-4 Storage

The boundary between all cell storage and 2-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the 2-out-of-4 storage region uses alternating empty cells and cells containing assemblies at the 3-out-of-4 configuration enrichment (2.45 w/o ^{235}U for Unit 1, 2.40 w/o ^{235}U for Unit 2) or equivalent. Figure 12 on page 75 illustrates the configuration at the boundary.

2-out-of-4 Storage Next to 3-out-of-4 Storage

The boundary between 2-out-of-4 storage and 3-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the 3-out-of-4 storage region contain alternating empty cells and cells containing fuel assemblies at the 3-out-of-4 enrichment (2.45 w/o ^{235}U for Unit 1, 2.40 w/o ^{235}U for Unit 2) or equivalent. Figure 13 on page 76 illustrates the configuration at the boundary.

All Cell Storage Next to 3x3 Checkerboard Storage (Unit 2 only)

The boundary between all cell storage and 3x3 checkerboard storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the all cell storage region uses the enrichment of the low enrichment assemblies (1.48 w/o ^{235}U) of the 3x3 checkerboard configuration or equivalent. Figure 14 on page 77 illustrates the configuration at the boundary.

**3-out-of-4 Storage Next to
3x3 Checkerboard Storage
(Unit 2 only)**

The boundary between 3-out-of-4 storage and 3x3 checkerboard storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the 3-out-of-4 storage region contain the enrichment of the low enrichment assemblies (1.48 w/o ^{235}U) of the 3x3 checkerboard configuration or equivalent. The second row of cells after the boundary in the 3-out-of-4 storage region should contain alternating empty cells and cells containing fuel assemblies at the 3-out-of-4 enrichment (2.40 w/o ^{235}U) or equivalent. Figure 15 on page 78 illustrates the configuration at the boundary.

**2-out-of-4 Storage Next to
3x3 Checkerboard Storage
(Unit 2 Only)**

The boundary between 2-out-of-4 storage and 3x3 checkerboard storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of cells after the boundary in the 2-out-of-4 storage region contain the enrichment of the low enrichment assemblies (1.48 w/o ^{235}U) of the 3x3 checkerboard configuration or equivalent. The second row of cells after the boundary in the 2-out-of-4 storage region contain alternating empty cells and cells containing fuel assemblies at the 3-out-of-4 enrichment (2.40 w/o ^{235}U) or equivalent. Figure 15 on page 78 illustrates the configuration at the boundary.

Open Water Cells

For all configurations at Vogtle Units 1 and 2, an open water cell is permitted in any location of the spent fuel pool to replace an assembly since the water cell will not cause any increase in reactivity in the spent fuel pool.

**Non-Assembly
Components**

For all configurations at Vogtle Units 1 and 2, non-assembly components may be stored in open cells of the spent fuel pool provided at least one row of empty cells separates the components from the stored fuel.

**Neutron Source and
RCCA in a Cell**

The placement of a neutron source or Rod Cluster Control Assemblies (RCCA) will not cause any increase in reactivity in the spent fuel pool because the neutron source and RCCA are absorbers which reduce reactivity. Therefore, neutron sources and RCCA may be stored in an empty cell or in an assembly.

**Non-Fuel Bearing
Assembly Components**

Non-Fuel Bearing Assembly components (i.e. thimble plugs, Wet Annular Burnable Absorbers, etc.) may be stored in assemblies without affecting the storage requirements of that assembly.

14.0 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 No Soluble Boron 95/95 conditions, 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 all cell locations. Fuel assemblies must have an initial nominal enrichment no greater than 1.79 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 450 ppm. Including accidents, the soluble boron credit required for this storage configuration is 950 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 2.45 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 100 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1150 ppm.

Unit 2 Enrichment Limits

- All Cell Storage** Storage of 17x17 fuel assemblies in all cell locations. Fuel assemblies must have an initial nominal enrichment no greater than 1.77 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, 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 2.40 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 350 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1050 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 concentration that results in a K_{eff} of less than 0.95 was calculated as 50 ppm. Including accidents, 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 3.20 w/o ^{235}U (up to 5.00 w/o ^{235}U 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. Alternatively, the center (high enrichment) cell of the 3x3 checkerboard may be loaded with any assembly which meets a maximum infinite multiplication factor (K_{∞}) value of 1.410 at cold reactor core conditions. The soluble boron concentration that results in a K_{eff} of less than 0.95 was calculated as 500 ppm. Including accidents, the soluble boron credit required for this storage configuration is 1050 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 Computational Methods for Nuclear Criticality Safety"; and the NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage".

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
Fuel Rod 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	1.2110
Rod Pitch (inch)	0.496	0.496
Number of 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 95/95 K_{eff} for Vogtle Unit 1

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.94250	0.88054
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00986	0.00915
TOTAL Bias	0.01756	0.01685
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00860	0.00859
UO ₂ Density Tolerance	0.00331	0.00377
Fuel Pellet Dishing Variation	0.00170	0.00198
Cell Inner Dimension	0.00000	0.00003
Cell Pitch	0.03421	0.03464
Cell Wall Thickness	0.00972	0.00695
Asymmetric Assembly Position	0.00789	0.00551
Calculational Uncertainty (95/95)	0.00178	0.00177
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.03778	0.03718
	$\sqrt{\sum_{i=1}^9 ((tolerance_i \dots or \dots uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	0.99784	0.93457

Table 3. Minimum Burnup Requirements for Vogtle Unit 1

Nominal Enrichment (w/o ²³⁵U)	All Cell Burnup (MWD/MTU)	3-out-of-4 Checkerboard Burnup (MWD/MTU)	2-out-of-4 Checkerboard Burnup (MWD/MTU)
1.79	0	0	0
2.00	3879	0	0
2.20	7001	0	0
2.40	9712	0	0
2.45	10342	0	0
2.60	12140	1488	0
2.80	14391	3415	0
3.00	16550	5282	0
3.20	18684	7097	0
3.40	20838	8866	0
3.60	23039	10597	0
3.80	25292	12296	0
4.00	27584	13972	0
4.20	29880	15630	0
4.40	32127	17279	0
4.60	34250	18924	0
4.80	36155	20574	0
5.00	37728	22235	0

Table 4. 3-out-of-4 Checkerboard 95/95 K_{eff} for Vogtle Unit 1

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.95418	0.89720
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00578	0.00513
TOTAL Bias	0.01348	0.01283
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00505	0.00513
UO ₂ Density Tolerance	0.00281	0.00325
Fuel Pellet Dishing Variation	0.00165	0.00190
Cell Inner Dimension	0.00002	0.00000
Cell Pitch	0.02486	0.02553
Cell Wall Thickness	0.00846	0.00591
Asymmetric Assembly Position	0.00720	0.00542
Calculational Uncertainty (95/95)	0.00200	0.00200
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.02812	0.02774
	$\sqrt{\sum_{i=1}^9 ((tolerance_i \dots or \dots uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	0.99578	0.93777

Table 5. 2-out-of-4 Checkerboard 95/95 K_{eff} for Vogtle Unit 1

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.93670	0.92077
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00026	0.00013
TOTAL Bias	0.00796	0.00783
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00152	0.00158
UO ₂ Density Tolerance	0.00229	0.00248
Fuel Pellet Dishing Variation	0.00138	0.00139
Cell Inner Dimension	0.00001	0.00005
Cell Pitch	0.00597	0.00599
Cell Wall Thickness	0.00509	0.00406
Asymmetric Assembly Position	0.00873	0.00420
Calculational Uncertainty (95/95)	0.00253	0.00233
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.01275	0.00975
$\sqrt{\sum_{i=1}^9 ((tolerance_i \dots or \dots uncertainty_i)^2)}$		
Final K_{eff} Including Uncertainties & Tolerances:	0.95741	0.93835

Table 6. All Cell Storage 95/95 K_{eff} for Vogtle Unit 2

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.96819	0.92003
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00915	0.00913
TOTAL Bias	0.01685	0.01683
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00898	0.00899
UO ₂ Density Tolerance	0.00334	0.00362
Fuel Pellet Dishing Variation	0.00175	0.00188
Cell Inner Dimension	0.00019	0.00007
Cell Pitch	0.00437	0.00436
Cell Wall Thickness	0.00331	0.00263
Asymmetric Assembly Position	0.00664	0.00608
Calculational Uncertainty (95/95)	0.00180	0.00168
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.01347	0.01312
	$\sqrt{\sum_{i=1}^9 ((tolerance_i \dots or \dots uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	0.99851	0.94998

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)	2-out-of-4 Checkerboard Burnup (MWD/MTU)	3x3 Checkerboard Burnup (*) (MWD/MTU)
1.48	0	0	0	0
1.60	0	0	0	3223
1.77	0	0	0	7206
1.80	591	0	0	7846
2.00	4182	0	0	11708
2.20	7268	0	0	14987
2.40	9980	0	0	17841
2.60	12431	2034	0	20406
2.80	14714	4000	0	22795
3.00	16908	5906	0	25101
3.20	19071	7758	0	27393
3.40	21246	9564	0	29720
3.60	23456	11329	0	32108
3.80	25706	13063	0	34561
4.00	27986	14770	0	37062
4.20	30265	16459	0	39571
4.40	32497	18136	0	42027
4.60	34617	19808	0	44347
4.80	36540	21483	0	46426
5.00	38168	23167	0	48136

(*) Burnup required on peripheral fuel assemblies.

Table 8. 3-out-of-4 Checkerboard 95/95 K_{eff} for Vogtle Unit 2

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.97240	0.91440
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00503	0.00493
TOTAL Bias	0.01273	0.01263
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00532	0.00544
UO ₂ Density Tolerance	0.00284	0.00328
Fuel Pellet Dishing Variation	0.00166	0.00190
Cell Inner Dimension	0.00013	0.00000
Cell Pitch	0.00315	0.00328
Cell Wall Thickness	0.00275	0.00199
Asymmetric Assembly Position	0.00453	0.00557
Calculational Uncertainty (95/95)	0.00206	0.00196
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.00951	0.01013
$\sqrt{\sum_{i=1}^9 ((tolerance_i \dots or \dots uncertainty_i)^2)}$		
Final K_{eff} Including Uncertainties & Tolerances:	0.99464	0.93716

Table 9. 2-out-of-4 Checkerboard 95/95 K_{eff} for Vogtle Unit 2

	No Soluble Boron	Soluble Boron Credit
Nominal KENO-Va Reference Reactivity:	0.94622	0.93390
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	0.00770	0.00770
Pool Temperature Bias (50°F - 185°F)	0.00031	0.00032
TOTAL Bias	0.00801	0.00802
Tolerances & Uncertainties:		
UO ₂ Enrichment Tolerance	0.00150	0.00158
UO ₂ Density Tolerance	0.00227	0.00233
Fuel Pellet Dishing Variation	0.00140	0.00142
Cell Inner Dimension	0.00007	0.00006
Cell Pitch	0.00075	0.00078
Cell Wall Thickness	0.00162	0.00152
Asymmetric Assembly Position	0.00369	0.00026
Calculational Uncertainty (95/95)	0.00250	0.00092
Methodology Bias Uncertainty (95/95)	0.00300	0.00300
TOTAL Uncertainty (statistical)	0.00644	0.00545
	$\sqrt{\sum_{i=1}^n ((tolerance_i \dots or \dots uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	0.96067	0.94737