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Byron and Braidwood Spent Fuel Rack Criticality Analysis With Credit for Soluble Boron

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1.0 Introduction

This report presents the results of a criticality analysis of the Commonwealth Edison Byron and Braidwood 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 Byron and Braidwood spent fuel racks are being reanalyzed to allow storage of Westinghouse 17x17 OFA fuel assemblies with nominal enrichments up to 4.95 w/o ^{235}U in the allowable storage cell locations using soluble boron credit (e.g. the concentration of soluble boron required to maintain $K_{eff} \leq 0.95$ including uncertainties, tolerances, and accident conditions). This analysis will also ignore the presence of the spent fuel rack Boraflex poison panels. The following storage configurations and enrichment limits are considered in this analysis:

Spent Fuel Rack Region 1 Enrichment Limits

All Cell Storage — Storage of Westinghouse 17x17 OFA fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 4.80 w/o ^{235}U. Fuel assemblies with enrichments greater than this value must satisfy a minimum number of Integral Fuel Burnable Absorbers (IFBA). The soluble boron credit required for this storage configuration is 500 ppm.

Spent Fuel Rack Region 2 Enrichment Limits

All Cell Storage — Storage of 17x17 OFA fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 1.20 w/o ^{235}U. Fuel assemblies with enrichment greater than this value must satisfy a minimum burnup requirement. The soluble boron credit required for this storage configuration is 1600 ppm.

3-out-of-4 Checkerboard Storage — Storage of 17x17 OFA fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 1.70 w/o ^{235}U or satisfy a minimum burnup requirement. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 1750 ppm.

2-out-of-4 Checkerboard Storage

Storage of 17x17 OFA fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 4.20 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1800 ppm.

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

1.1 Design Description

The Byron and Braidwood spent fuel Region 1 storage cell is shown in Figure 1 on page 32 and the Region 2 storage cell is shown on Figure 2 on page 33 with nominal dimensions provided on the figures. The overall layout of the Byron and Braidwood spent fuel pool is shown in Figure 3 on page 34.

The fuel parameters relevant to this analysis are given in Table 1 on page 23. With the simplifying assumptions employed in this analysis (no grids, sleeves, axial blankets, etc.), the various types of Westinghouse 17x17 OFA fuel (V5,V+ and P+) are beneficial in terms of extending burnup capability and improving fuel reliability, but do not contribute to any meaningful increase in the basic assembly reactivity. This includes small changes in guide tube and instrumentation tube dimensions. Therefore, future fuel assembly upgrades do not require a criticality analysis if the fuel parameters specified in Table 1 continue to remain bounding.

The fuel rod and guide tube cladding are modeled with zircaloy in this analysis. This is conservative with respect to the Westinghouse ZIRLO product which is a zirconium alloy containing additional elements including niobium. Niobium has a small absorption cross section which causes more neutron capture in the cladding regions resulting in a lower reactivity. Therefore, this analysis is conservative with respect to fuel assemblies containing ZIRLO cladding in fuel rods and guide tubes.

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 specific fuel assembly loading patterns in the spent fuel rack is analyzed such that K_{eff} remains less than 1.0 under maximum feasible conditions with no soluble boron as defined in Reference 1. To provide safety margin in the criticality analysis of the spent fuel racks, credit is taken for the soluble boron present in the spent fuel pool.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array will be less than or equal to 0.95. This requirement as currently stated in ANSI 57.2-1983(2), and NRC position paper(3) does not allow for reactivity credit due to the presence of soluble boron. This criticality analysis report will take exception to this and show that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array is less than 1.0 under maximum feasible conditions and less than or equal to 0.95 when credit is taken for the presence of spent fuel pool soluble boron.

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 Byron and Braidwood.

As determined in the benchmarking in the topical report, the method bias using the described methodology of NITAWL-II, XSDRNPM-S and KENO-Va is 0.00770 ΔK with a 95 percent probability at a 95 percent confidence level on the bias of 0.00300 ΔK. These values will be used throughout this report as needed. Specific biases and uncertainties as applied to each of the specific configurations are listed in Table 2 and Tables 4 through 6.

3.0 Criticality Analysis of Region 1 Storage Racks

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

Section 3.1 describes the allowed storage configurations for fuel assemblies in Region 1. Section 3.2 describes the maximum feasible K_{eff} KENO-Va calculations. Section 3.3 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Finally, Section 3.4 presents the results of the calculations performed to determine the minimum number of IFBA required for assemblies with initial enrichments above those determined in Section 3.2.

3.1 Configuration Descriptions

Only one configuration was analyzed for the Region 1 spent fuel storage racks. The configuration contains fuel assemblies of the same fuel enrichment of 4.80 w/o in all of the cells.

3.2 Maximum Feasible K_{eff} Calculation Assumptions

The following assumptions are used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in the three configurations of the Byron and Braidwood Region 1 spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA fuel design (see Table 1 on page 23 for fuel parameters).
2. Fuel assemblies contain uranium dioxide at their nominal ^{235}U enrichments 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.
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. The moderator is pure water (no boron) at a temperature of 68°F. A limiting value of 1.0 gm/cm^3 is used for the density of water to conservatively bound the range of normal (50°F to 160°F) spent fuel pool water temperatures.
9. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
10. All available storage cells are loaded with fuel assemblies.
11. Boraflex poison plates are removed from the spent fuel storage rack. The Boraflex volume is replaced with water.

12. Boral inserts are modeled at the nominal dimensions for width, thickness and length.

The following equation is used to develop the maximum feasible K_{eff} for Region 1 of the spent fuel storage racks:

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

where:

K_{normal}	=	normal conditions KENO-Va K_{eff}
B_{temp}	=	temperature bias for normal temperature range of spent fuel pool water (50°F to 160°F)
B_{method}	=	method bias determined from benchmark critical comparisons

3.2.1 All Cell Maximum Feasible K_{eff} Calculations

With the previously stated assumptions in the all cells configuration, the KENO-Va calculation resulted in a K_{eff} of 0.98564 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 160°F) is 0.00123 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology is 0.00770 ΔK.

Substituting the calculated values in the order listed above for the Region 1 all cell storage, the result is:

$$K_{eff} = 0.98564 + 0.00123 + 0.00770 = 0.99457$$

Since K_{eff} is less than 1.0, the Region 1 spent fuel racks will remain subcritical under maximum feasible conditions when all cells are loaded with 4.80 w/o ^{235}U 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water.

3.3 Soluble Boron Credit K_{eff} Calculation Assumptions

In this 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.

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 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 Region 1 spent fuel racks are similar to those in Section 3.2 except for assumption 8 regarding the moderator soluble boron concentration. The moderator boron concentration is increased by the amount required to maintain $K_{eff} \leq 0.95$.

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 are included:

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

Water Temperature: A reactivity bias determined in PHOENIX-P is applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 160°F).

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

The following tolerance and uncertainty components are 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 ^{235}U enrichments is considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 23) is 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 23) is considered.

Storage Cell I.D.: The ±0.032 inch tolerance about the nominal 8.85 inch reference cell I.D. is considered.

Storage Cell Pitch: The ±0.050 inch tolerance about the nominal 10.32 inch (north/south) and 10.42 inch (east/west) reference cell pitch is considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.060 inch reference stainless steel cell wall thickness is considered.

Stainless Steel Wrapper Thickness: The ±0.003 inch tolerance about the nominal 0.020 inch wrapper thickness is considered.

Boral Thickness: A maximum Boral sheet thickness of 0.148 inches was assumed.

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

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

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

3.3.1 Region 1 Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions and the all cells configuration, the KENO-Va calculation for the nominal case with 450 ppm soluble boron in the moderator resulted in a K_{eff} of 0.92660.

The maximum K_{eff} is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 2 on page 24 and results in a maximum K_{eff} of 0.94856.

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 OFA fuel assemblies in the Region 1 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 4.80 w/o ^{235}U is acceptable in all cells including the presence of 450 ppm soluble boron.

3.4 IFBA Credit Reactivity Equivalencing

Storage of fuel assemblies with nominal enrichments greater than those determined in Section 3.2 is achievable by means of IFBA credit using the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers (IFBA)[4]. IFBAs consist of neutron absorbing material applied as a thin ZrB_2 coating on the outside of the UO_2 fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

A couple of reactivity calculations were performed to determine the number of IFBA rods which yield an equivalent or lower K_{eff} for 5.0 w/o fuel when the fuel is stored in the Byron and Braidwood Region 1 spent fuel racks. The following assumptions were used for the IFBA rod assemblies in the PHOENIX-P models:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 23 for fuel parameters).
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.
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. The IFBA absorber material is a zirconium diboride (ZrB_2) coating on the fuel pellet. Each IFBA rod has a nominal poison material loading of 1.50 milligrams ^{10}B per inch, which is the minimum standard loading offered by Westinghouse for 17x17 OFA fuel assemblies.
8. For reduced length IFBA, the IFBA ^{10}B loading is reduced by 25% to conservatively model a minimum poison length of 108 inches.
9. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm^3.
10. The array is infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.

The results of the IFBA credit reactivity equivalencing for the Byron and Braidwood Region 1 spent fuel racks are provided in Table 3 on page 25, and Figure 4 on page 35.

It is important to recognize that the curve in Figure 4 is based on reactivity equivalence calculations (i.e. holding rack K_{eff} constant) for the specific enrichment and IFBA combinations in actual rack geometry (and not just on simple comparisons of individual fuel assembly infinite multiplication factors). In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered.

The total soluble boron credit required for the Byron and Braidwood Region 1 spent fuel racks remains at 450 ppm including the effects of tolerances and uncertainties. Uncertainties associated with IFBA credit include a 5% manufacturing tolerance and a 10% calculational uncertainty on the ^{10}B loading of the IFBA rods.

4.0 Criticality Analysis of Region 2 Storage Racks

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

Section 4.1 describes the allowed storage configurations for fuel assemblies in Region 2. Section 4.2 describes the maximum feasible K_{eff} KENO-Va calculations. Section 4.3 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations. Section 4.4 presents the results of calculations performed to show the minimum burnup requirements for assemblies with initial enrichments above those determined in Section 4.2 .

4.1 Configuration Descriptions

Three different configurations were analyzed for Region 2 of the spent fuel storage racks. The first configuration contains fuel assemblies of the same fuel enrichment of 1.20 w/o in all of the cells. The second configuration uses a 3-of-4 assembly checkerboard with 1 empty cell and 3 assemblies of 1.70 w/o in the other cells. The third configuration uses a 2-of-4 assembly checkerboard with 2 diagonally adjacent empty cells and 2 assemblies of 4.20 w/o in the other diagonally adjacent cells. The checkerboard configurations are shown in Figure 5 on page 36.

4.2 Maximum Feasible K_{eff} Calculation Assumptions

The following assumptions are used to develop the maximum feasible KENO-Va model for storage of fuel assemblies in the five configurations of the Byron and Braidwood Region 2 spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA fuel design (see Table 1 on page 23 for fuel parameters).
2. Fuel assemblies contain uranium dioxide at their nominal ^{235}U enrichments 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.
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. The moderator is pure water (no boron) at a temperature of 68°F. A limiting value of 1.0 gm/cm^3 is used for the density of water to conservatively bound the range of normal (50°F to 160°F) spent fuel pool water temperatures.
9. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.

10. All available storage cells are loaded with fuel assemblies.

11. Boraflex poison plates are removed from the Region 2 spent fuel storage rack. The Boraflex volume is replaced with water.

The following equation is used to develop the maximum feasible K_{eff} for Region 2 of the spent fuel storage racks:

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

where:

K_{normal}	=	normal conditions KENO-Va K_{eff}
B_{temp}	=	temperature bias for normal temperature range of spent fuel pool water (50°F to 160°F)
B_{method}	=	method bias determined from benchmark critical comparisons

4.2.1 All Cells Maximum Feasible K_{eff} Calculation

With the previously stated assumptions in the all cells configuration, the KENO-Va calculation resulted in a K_{eff} of 0.98689 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 160°F) is 0.00046 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology is 0.00770 ΔK.

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

$$K_{eff} = 0.98689 + 0.00046 + 0.00770 = 0.99505$$

Since K_{eff} is less than 1.0, the Region 2 spent fu[illegible] racks will remain subcritical under maximum feasible conditions when all cells are loaded with 1.20 w/o ^{235}U 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water.

4.2.2 3-out-of-4 Checkerboard Maximum Feasible K_{eff} Calculation

With the previously stated assumptions in the 3-out-of-4 checkerboard configuration, the KENO-Va calculation resulted in a K_{eff} of 0.98906 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 160°F) is 0.00020 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology is 0.00770 ΔK.

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

$$K_{eff} = 0.98906 + 0.00020 + 0.00770 = 0.99696$$

Since K_{eff} is less than 1.0, the Region 2 spent fuel racks will remain subcritical under maximum feasible conditions when the cells are loaded in the 3-out-of-4 checkerboard configuration with 1.70 w/o ^{235}U 17x17 OFA fuel assemblies in 3 of the 4 cells of a 2X2 cell array and no soluble boron is present in the spent fuel pool water.

4.2.3 2-out-of-4 Checkerboard Maximum Feasible K_{eff} Calculation

With the previously stated assumptions in the 2-out-of-4 checkerboard configuration, the KENO-Va calculation resulted in a K_{eff} of 0.98263 under normal conditions. The reactivity bias calculated in PHOENIX-P for the normal temperature range of the spent fuel pool water (50°F to 160°F) is 0.00200 ΔK. Finally, the methodology bias associated with the benchmarking of the Westinghouse criticality methodology is 0.00770 ΔK.

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

$$K_{eff} = 0.98263 + 0.00200 + 0.00770 = 0.99233$$

Since K_{eff} is less than 1.0, the Region 2 spent fuel racks will remain subcritical under maximum feasible conditions when the cells are loaded in the 2-out-of-4 checkerboard configuration with 4.20 w/o ^{235}U 17x17 OFA fuel assemblies in 2 diagonally adjacent cells of a 2X2 cell array and no soluble boron is present in the spent fuel pool water.

4.3 Soluble Boron Credit K_{eff} Calculations

In this 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.

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 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, 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 storage in the Region 2 spent fuel racks are similar to those in Section 4.2 except for assumption 8 regarding the moderator soluble boron concentration. The moderator boron concentration is increased by the amount required to maintain $K_{eff} \leq 0.95$.

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 are included:

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

Water Temperature: A reactivity bias determined in PHOENIX-P is applied to account for the effect of the normal range of spent fuel pool water temperatures (50°F to 160°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations are performed. For the Byron and Braidwood Region 2 spent fuel rack storage configurations, UO_2 material tolerances are 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 are also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components are 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 ^{235}U enrichment is considered.

UO_2 Density: A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 23) is 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 23) is considered.

Storage Cell I.D.: The ±0.032 inch tolerance about the nominal 8.85 inch reference cell I.D. is considered.

Storage Cell Pitch: The +0.021/–0.059 inch tolerance about the nominal 9.011 inch reference cell pitch is considered.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.06 inch reference stainless steel cell wall thickness is considered.

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

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

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

4.3.1 All Cells Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions and the all cells configuration, the KENO-Va calculation for the nominal case with 250 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91125.

The maximum K_{eff} is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 4 on page 26 and results in a maximum K_{eff} of 0.93834.

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 OFA fuel assemblies in the Region 2 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 1.20 w/o ^{235}U is acceptable in all cells including the presence of 250 ppm soluble boron.

4.3.2 3-out-of-4 Checkerboard Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions and the 3-out-of-4 checkerboard configuration, the KENO-Va calculation for the nominal case with 250 ppm soluble boron in the moderator resulted in a K_{eff} of 0.92013.

The maximum K_{eff} is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 on page 27 and results in a maximum 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 3-out-of-4 checkerboard configuration storage of 17x17 OFA fuel assemblies in the Region 2 spent fuel racks. Storage of fuel assemblies in a 2X2 checkerboard arrangement with 1 empty cell and the remaining 3 cells containing fuel assemblies having a nominal enrichment no greater than 1.70 w/o ^{235}U is acceptable including the presence of 250 ppm soluble boron.

4.3.3 2-out-of-4 Checkerboard Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions and the 2-out-of-4 checkerboard configuration, the KENO-Va calculation for the nominal case with 250 ppm soluble boron in the moderator resulted in a K_{eff} of 0.92111.

The maximum K_{eff} is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 on page 28 and results in a maximum K_{eff} of 0.94008.

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 2-out-of-4 checkerboard configuration storage of 17x17 OFA fuel assemblies in the Region 2 spent fuel racks. Storage of fuel assemblies in a 2X2 checkerboard arrangement with two diagonally adjacent cells containing fuel assemblies having a nominal enrichment no greater than 4.20 w/o ^{235}U with the remaining 2 cells empty is acceptable including the presence of 250 ppm soluble boron.

4.4 Burnup Credit Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than those described in Section 4.2 in the Byron and Braidwood Region 2 spent fuel racks is achievable by means of burnup credit using the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 6 on page 37 shows the constant K_{eff} contours generated for the all cell configuration, the 3-out-of-4 configuration, and the 2-out-of-4 configuration for fuel storage in the Region 2 spent fuel racks. These curves represent combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with zero burnup fuel assemblies with maximum allowed enrichments described in Section 4.2 for the three configurations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 ΔK at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculation and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Figure 6 is 500 ppm for the all cells configuration, 350 ppm for the 3-out-of-4 checkerboard configuration, and 50 ppm for the 2-out-of-4 checkerboard configuration. This is additional boron above the soluble boron required in Section 4.3. This results in a total soluble boron credit of 750 ppm for the all cells configuration, 600 ppm for the 3-out-of-4 checkerboard configuration, and 300 ppm for the 2-out-of-4 checkerboard configuration.

It is important to recognize that the curve in Figure 6 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered. For convenience, the data from Figure 6 are also provided in Table 7 on page 29. Use of linear interpolation between the tabulated values is acceptable since the loss of reactivity is linear as a function of enrichment in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Region 2 burnup credit limits. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Reference 1 results in calculations of conservative burnup credit limits. The evaluations show that axial burnup effects only become important at burnup-enrichment combinations which are above those calculated for the Region 2 burnup credit limits (e.g. 5.0 w/o ^{235}U @ 60,000 MWD/MTU). Therefore, additional accounting of axial burnup distribution effects in the Region 2 burnup credit limit is not necessary.

5.0 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	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.
Fuel assembly drop between rack modules and spent fuel pool wall	For Regions 1 and 2, this accident is bounded by the misloaded fuel assembly accident discussed below since placing a fuel assembly inside the racks next to other fuel assemblies will result in a higher K_{eff}.

However, two accidents can be postulated for each storage configuration which can increase reactivity beyond the analyzed condition. The first postulated accident would be a change in the spent fuel pool water temperature and the second would be a misload of an assembly into a cell for which the restrictions on location, enrichment, or burnup are not satisfied.

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 the Byron and Braidwood storage configurations to determine the reactivity change caused by a change in the Byron and Braidwood spent fuel pool water temperature outside the normal range (50°F to 160°F). The results of these calculations are tabulated in Table 8 on page 30. In all cases, additional reactivity margin is available to the 0.95 K_{eff} limit to allow for temperature accidents. The temperature change accident can occur at any time during operation of the spent fuel pool.

For the misloaded assembly accident, calculations were performed to show the largest reactivity increase caused by a 4.80 w/o 17x17 OFA 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 tabulated in Table 8. The misloaded assembly accident can only occur during fuel handling operations in the spent fuel pool.

For an occurrence of the above postulated accident condition, 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 additional amount of soluble boron for accident conditions needed beyond the required boron for uncertainties and burnup is shown in Table 8 on page 30.

Based on the above discussion, should a spent fuel water temperature change accident or a fuel assembly misload accident occur in the Region 1 or Region 2 spent fuel racks, K_{eff} will be maintained less than or equal to 0.95 due to the presence of at least 750 ppm (no fuel handling) or 1800 ppm (during fuel handling) of soluble boron in the Byron and Braidwood spent fuel pool water.

6.0 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 burnup 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. The total soluble boron is divided into two categories of operation in the spent fuel pool, no fuel handling and fuel handling. During no fuel handling, the only possible accident condition is a temperature change accident. During fuel handling, a misloaded assembly accident is also possible and the amount of soluble boron required bounds the temperature change accident. Table 9 on page 31 summarizes the storage configurations and corresponding soluble boron credit requirements for both fuel handling and non-fuel handling operations.

7.0 Storage Configuration Interface Requirements

The Byron and Braidwood spent fuel pool is composed of two different types of racks, designated as Region 1 and Region 2. Each of these spent fuel pool areas has been analyzed for all cell storage, where all cells share the same storage requirements and limits, and checkerboard storage, where neighboring cells have different requirements and limits.

The boundary between checkerboard zones and the boundary between checkerboarded zones and all cell stored fuel must be controlled to prevent an undesirable increase in reactivity. This is accomplished by examining each 2x2 matrix surrounding a fuel assembly and ensuring that each set of 2x2 neighboring cells conform to checkerboard restrictions for the given region.

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 are required to meet the checkerboard requirements determined for the given region.

7.1 Interface Requirements within Region 1

There is no interface requirement within Region 1.

7.2 Interface Requirements within Region 2

Using the requirement that all 2x2 matrices within the storage racks must conform to every all cell and 2x2 checkerboard requirement, the following interface requirements are applicable to Region 2 storage cells:

Region 2 All Cell Storage Next to Region 2 2-out-of-4 Storage or 3-out-of-4 Storage

The boundary between all cell storage and 2-out-of-4 or 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 carryover uses 1.7 w/o fuel assemblies and empty cells. Figure 7 on page 38 illustrates the carryover configuration.

Region 2 2-out-of-4 Storage Next to Region 2 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 carryover uses 4.20 w/o fuel assemblies and empty cells. Figure 8 on page 39 illustrates the carryover configuration.

7.3 Interface Requirements between Region 1 and Region 2

The boundary between Region 1 and Region 2 must be configured such that one row of vacant cells is maintained between the regions (the vacant row can be positioned in either region). This requirement is necessary since the removal of the Boraflex neutron absorber panels from the criticality analysis increases the amount of neutron interaction between Region 1 and Region 2.

8.0 Summary of Criticality Results

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

Spent Fuel Rack Region 1 Enrichment Limits

All Cell Storage Storage of Westinghouse 17x17 OFA fuel assemblies in any cell location. Fuel assemblies must have an initial nominal enrichment no greater than 4.80 w/o ^{235}U. Fuel assemblies with enrichments greater than this value must contain a minimum number of Integral Fuel Burnable Absorbers (IFBA). The soluble boron credit required for this storage configuration is 500 ppm.

Spent Fuel Rack Region 2 Enrichment Limits

All Cell Storage Storage of 17x17 OFA fuel assemblies with initial nominal enrichments no greater than 1.20 w/o ^{235}U in each interior cell location. Fuel assemblies with initial nominal enrichment greater than 1.20 w/o ^{235}U must satisfy a minimum burnup requirement. The soluble boron credit required for this storage configuration is 1600 ppm.

3-out-of-4 Checkerboard Storage Storage of 17x17 OFA fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 1.70 w/o ^{235}U or satisfy a minimum burnup requirement. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. The soluble boron credit required for this storage configuration is 1750 ppm.

2-out-of-4 Checkerboard Storage Storage of 17x17 OFA fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 4.20 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1800 ppm.

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

Table 1. Nominal Fuel Parameters Employed in the Criticality Analysis

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

Table 2. All Cell Storage Soluble Boron Credit K_{eff} for Byron and Braidwood Region 1

Nominal KENO-Va Reference Reactivity:	**0.92660**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00092
TOTAL Bias	0.00862
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00211
UO_2 Density Tolerance	0.00320
Fuel Pellet Dishing Variation	0.00176
Cell Inner Diameter	0.00151
Cell Pitch (north/south)	0.00248
Cell Pitch (east/west)	0.00227
Cell Wall Thickness	0.00086
Wrapper Thickness	0.00047
Boral Thickness Tolerance	0.01078
Asymmetric Assembly Position	0.00387
Calculational Uncertainty (95/95)	0.00234
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01334

$$\sqrt{\sum_{i=1}^{12}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.94856**

Table 3. Minimum IFBA Requirements for Byron and Braidwood Region 1

Nominal Enrichment (w/o ^{235}U)	IFBA Requirement			
	1.0X*		1.5X*	
	Full Length	Part Length	Full Length	Part Length
4.80	0	0	0	0
5.00	16	16	16	16

* Denotes nominal IFBA loadings of 1.50 mg-^{10}B/in (1.0X) and 2.25 mg-^{10}B/in (1.5X)

Table 4. All Cell Storage Soluble Boron Credit K_{eff} for Byron and Braidwood Region 2

Nominal KENO-Va Reference Reactivity:	**0.91125**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.0077
Pool Temperature Bias (50°F - 160°F)	0.0006
TOTAL Bias	0.0083
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01632
UO_2 Density Tolerance	0.00434
Fuel Pellet Dishing Variation	0.00257
Cell Inner Diameter	0.00012
Cell Pitch	0.00646
Cell Wall Thickness	0.00295
Asymmetric Assembly Position	0.00000
Calculational Uncertainty (95/95)	0.00130
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01879
$\sqrt{\sum_{i=1}^{9}((tolerance_i...or...uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	**0.93834**

Table 5. 3-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for Byron and Braidwood Region 2

Nominal KENO-Va Reference Reactivity:	**0.92013**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00018
TOTAL Bias	0.00788
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00974
UO_2 Density Tolerance	0.00396
Fuel Pellet Dishing Variation	0.00232
Cell Inner Diameter	0.00011
Cell Pitch	0.00457
Cell Wall Thickness	0.00258
Asymmetric Assembly Position	0.00000
Calculational Uncertainty (95/95)	0.00168
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01246

$$\sqrt{\sum_{i=1}^{9}((tolerance_i...or...uncertainty_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.94047**

Table 6. 2-out-of-4 Checkerboard Soluble Boron Credit K_{eff} for Byron and Braidwood Region 2

Nominal KENO-Va Reference Reactivity:	**0.92111**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00229
TOTAL Bias	0.00999
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00231
UO_2 Density Tolerance	0.00283
Fuel Pellet Dishing Variation	0.00163
Cell Inner Diameter	0.00002
Cell Pitch	0.00331
Cell Wall Thickness	0.00211
Asymmetric Assembly Position	0.00591
Calculational Uncertainty (95/95)	0.00229
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00898
$\sqrt{\sum_{i=1}^{9}((tolerance_i...or...uncertainty_i)^2)}$	
Final K_{eff} Including Uncertainties & Tolerances:	**0.94008**

Table 7. Minimum Burnup Requirements for Byron and Braidwood Region 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)
1.20	0	0	0
1.40	6585	0	0
1.70	12659	0	0
2.00	17361	4859	0
2.20	20261	7443	0
2.40	23035	9878	0
2.60	25692	12245	0
2.80	28247	14550	0
3.00	30723	16786	0
3.20	33137	18958	0
3.40	35499	21079	0
3.60	37812	23166	0
3.80	40077	25227	0
4.00	42300	27257	0
4.20	44497	29246	0
4.40	46674	31192	552
4.60	48824	33113	1398
4.80	50927	35030	2440
5.00	53015	36911	3580

Table 8. Postulated Accident Summary for Byron and Braidwood Regions 1 and 2

Storage Configuration	Reactivity Increase Caused by a Temperature Change (ΔK)	Reactivity Increase Caused by Mis-loaded Fuel Assembly Accident (ΔK)	Soluble Boron Required for Postulated Accidents (ppm)
Region 1			
All Cells	0.0010	0.0	50
Region 2			
All Cells	0.0010	0.1054	850
3-out-of-4 Checkerboard	0.0002	0.1500	1150
2-out-of-4 Checkerboard	0.0020	0.1970	1500

Table 9. Summary of Soluble Boron Credit Requirements for Byron and Braidwood Regions 1 and 2

Storage Configuration	Soluble Boron Required for Tolerances/ Uncertainties (ppm)	Soluble Boron Required for Reactivity Equivalencing (ppm)	Soluble Boron Required for Postulated Accidents (ppm)	Total Soluble Boron Credit Required (ppm)
Region 1				
All Cells	450	0	50	500
Region 2				
All Cells	250	500	850	1600
3-out-of-4 Checkerboard	250	350	1150	1750
2-out-of-4 Checkerboard	250	50	1500	1800

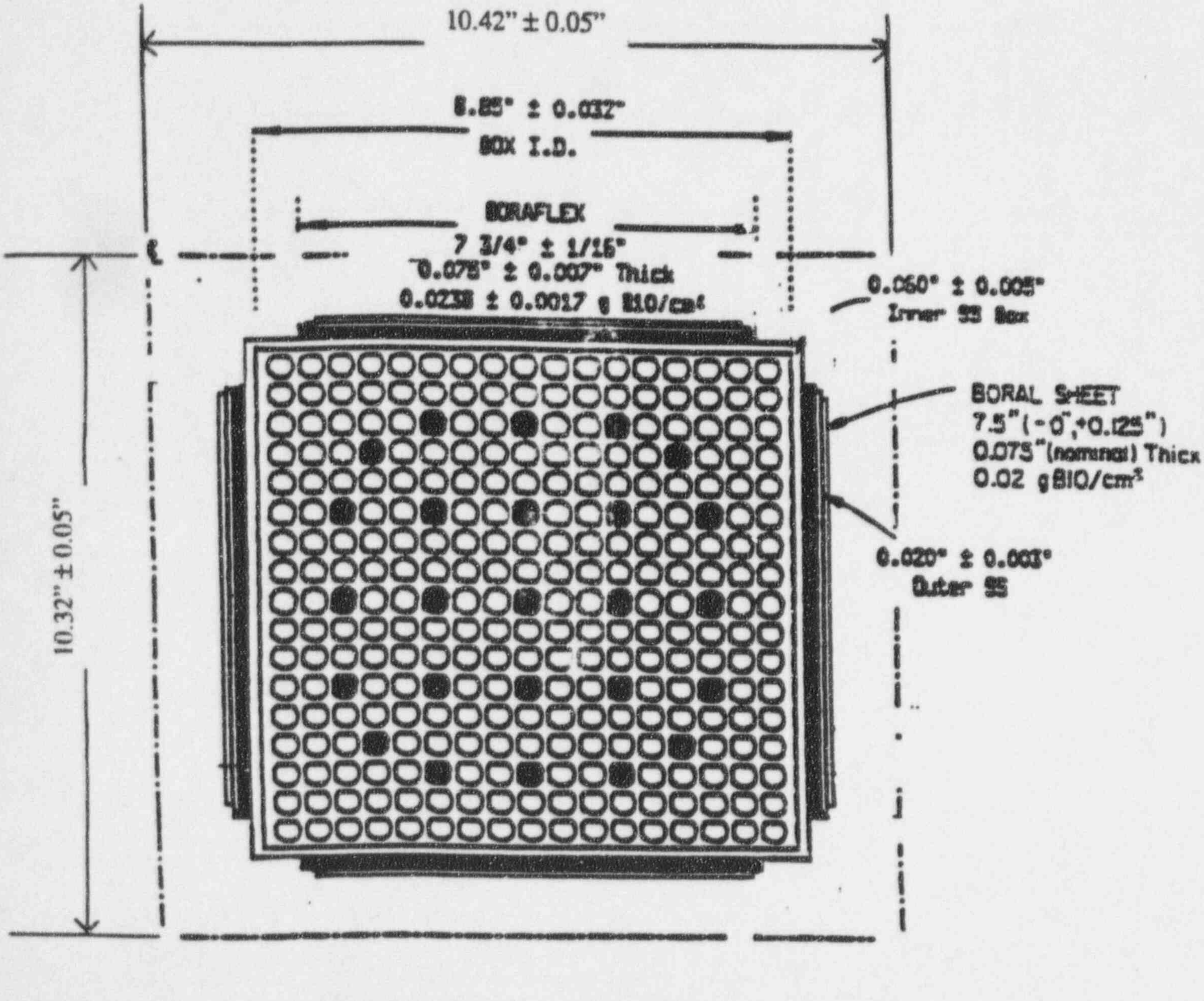


Figure 1. Byron and Braidwood Region 1 Spent Fuel Storage Cell Nominal Dimensions

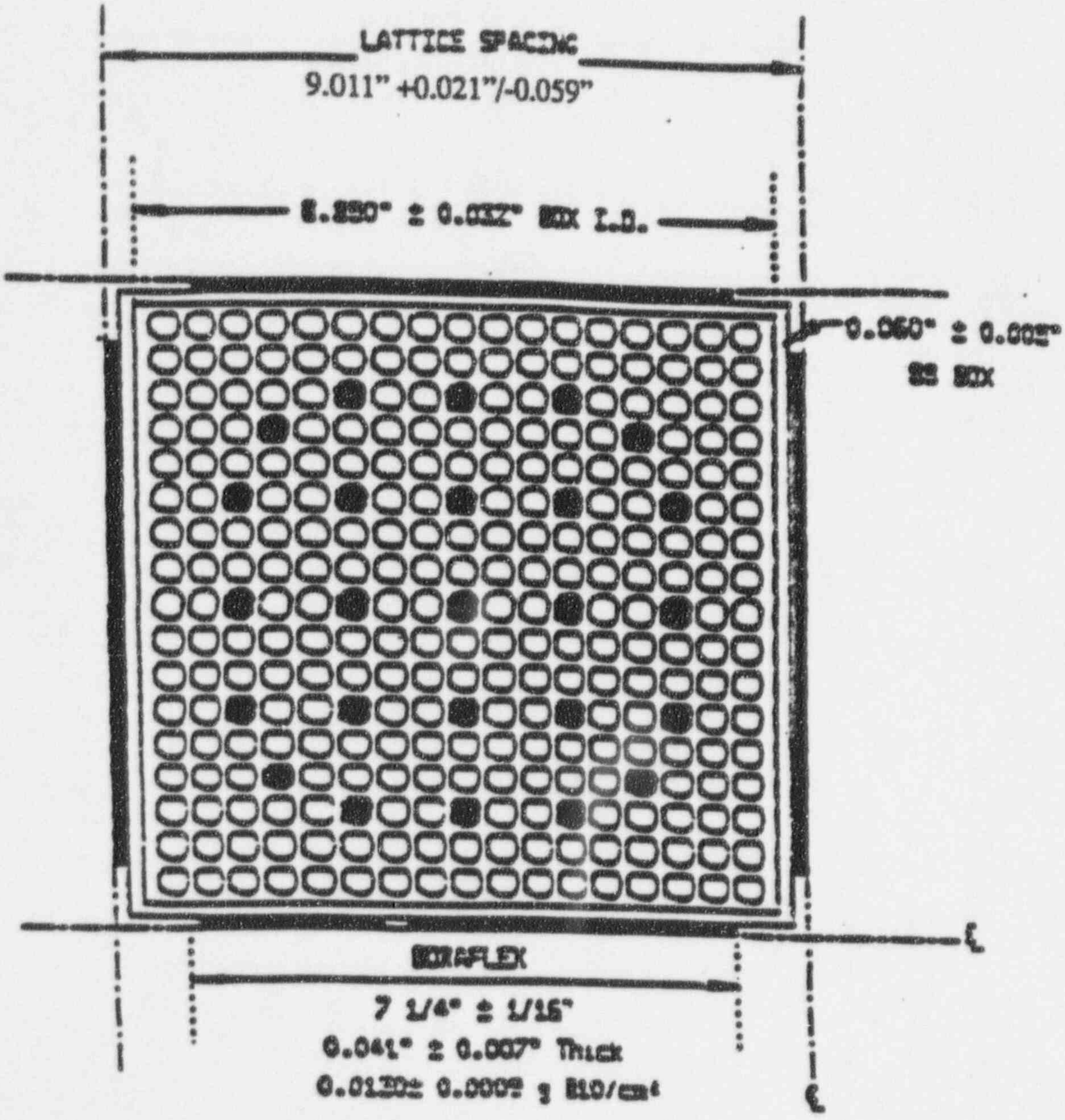


Figure 2. Byron and Braidwood Region 2 Spent Fuel Storage Cell Nominal Dimensions

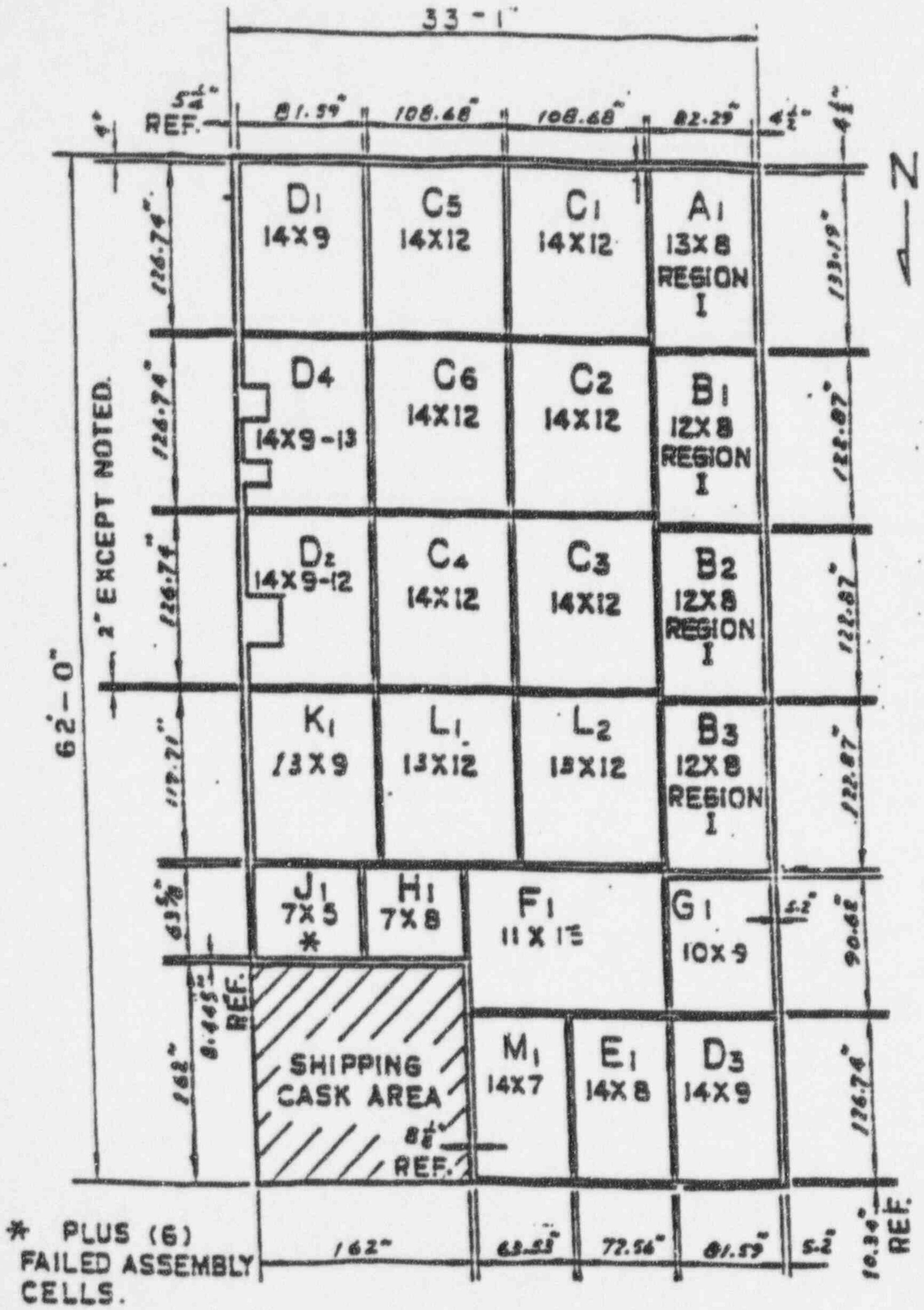


Figure 3. Byron and Braidwood Spent Fuel Pool Layout

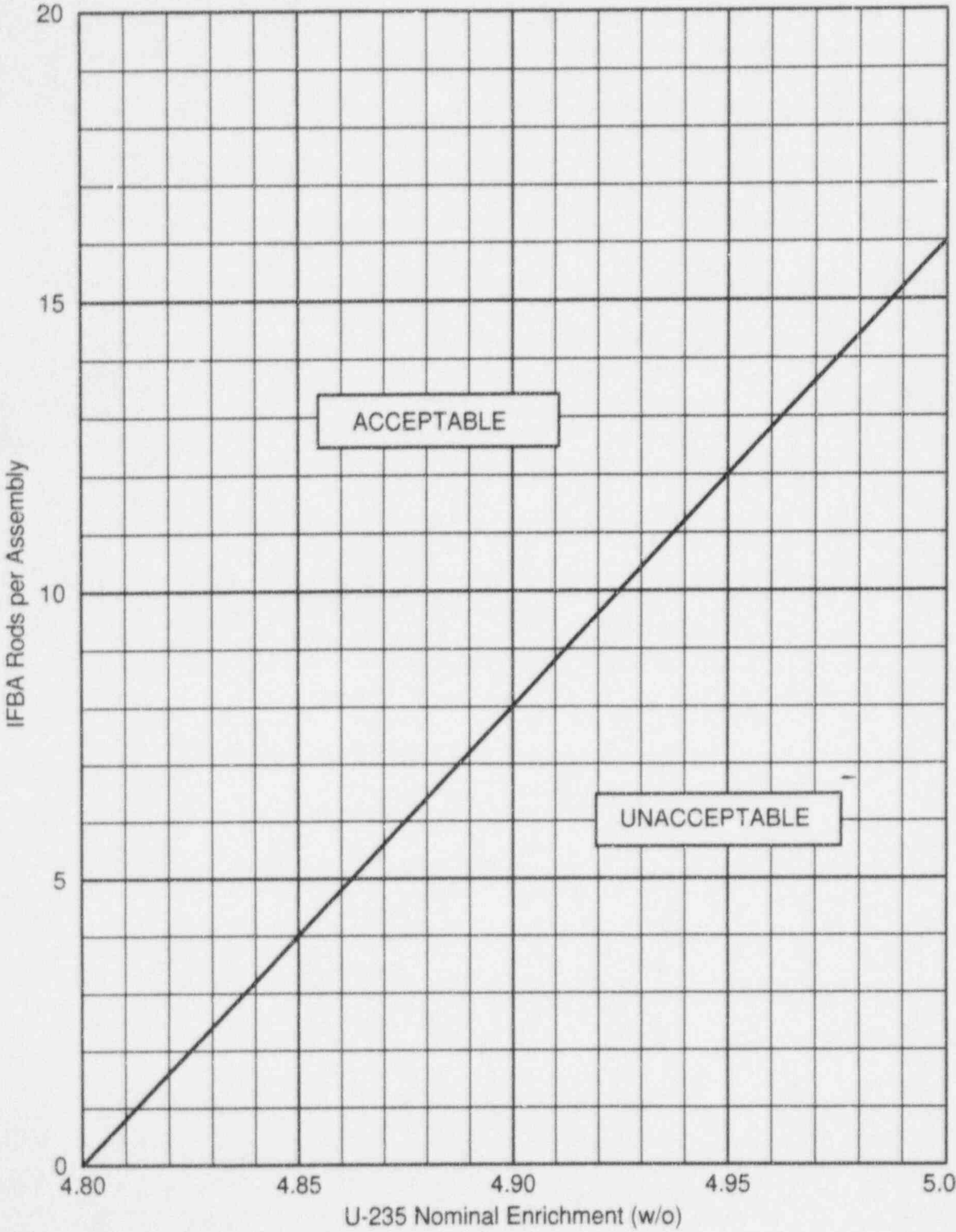


Figure 4. Byron and Braidwood Region 1 IFBA Requirements (4.8 w/o Equivalent)

1.70 w/o	1.70 w/o
1.70 w/o	Empty Cell

Region 2 3-of 4 Storage

4.20 w/o	Empty Cell
Empty Cell	4.20 w/o

Region 2 2-of-4 Storage

Note: All values are nominal enrichments.

Figure 5. Byron and Braidwood Region 2 Checkerboard Storage Configurations

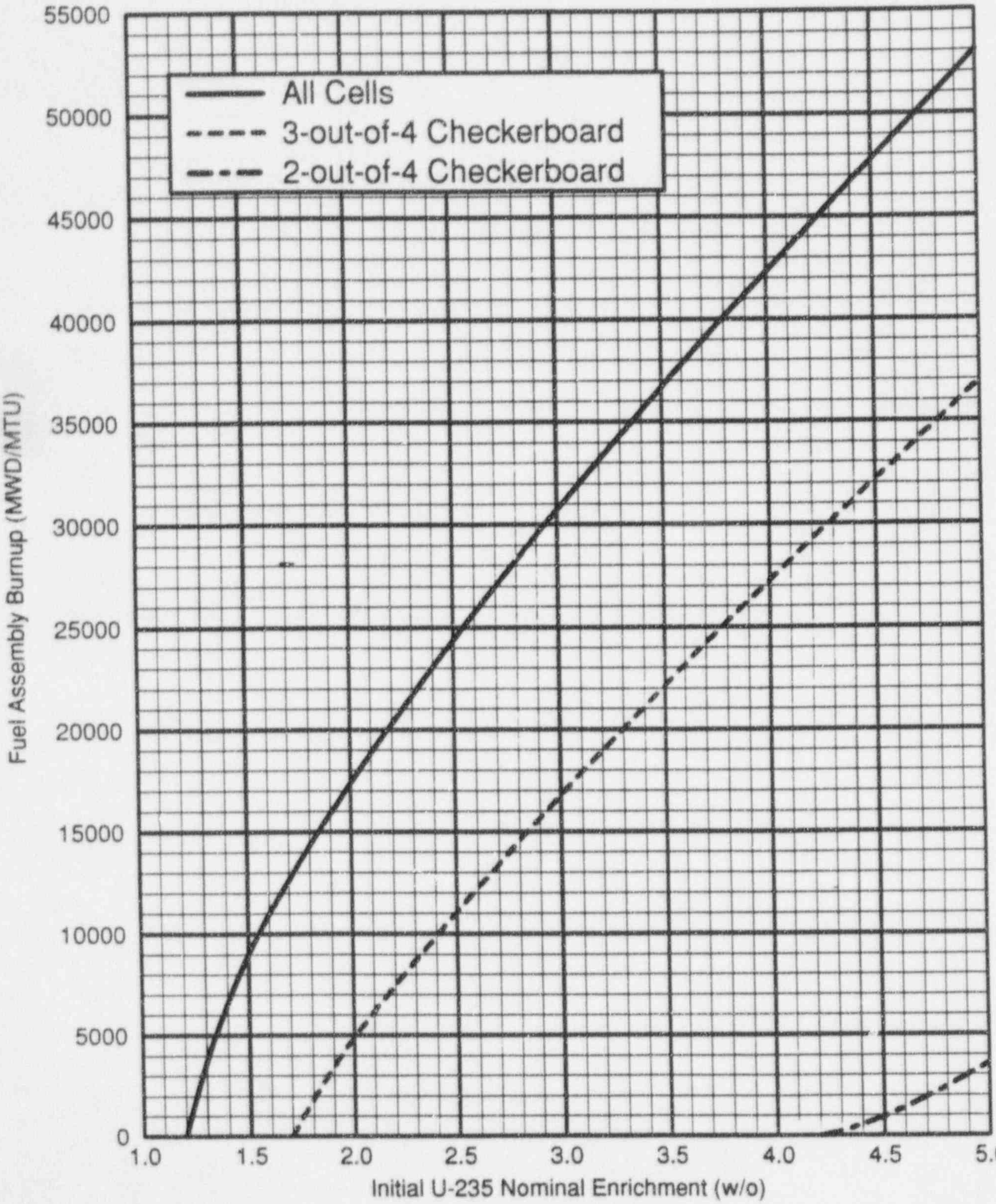
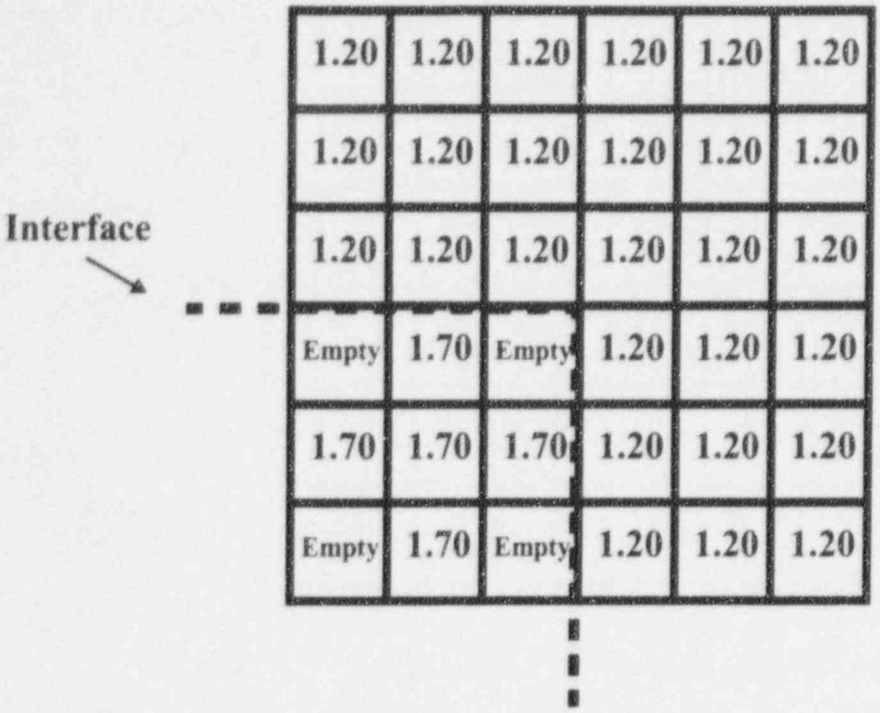
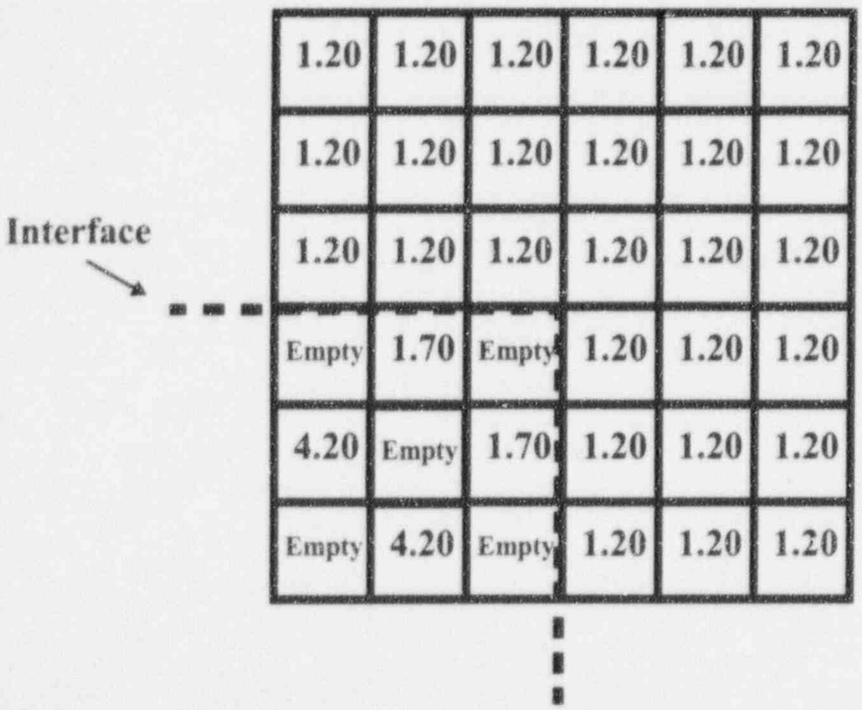


Figure 6. Byron and Braidwood Region 2 Burnup Credit Requirement



Region 2 Boundary Between All Cell Storage and 3-out-of-4 Storage



Region 2 Boundary Between All Cell Storage and 2-out-of-4 Storage

Figure 7. Region 2 Interface Requirements (All Cell Storage to Checkerboard Storage)

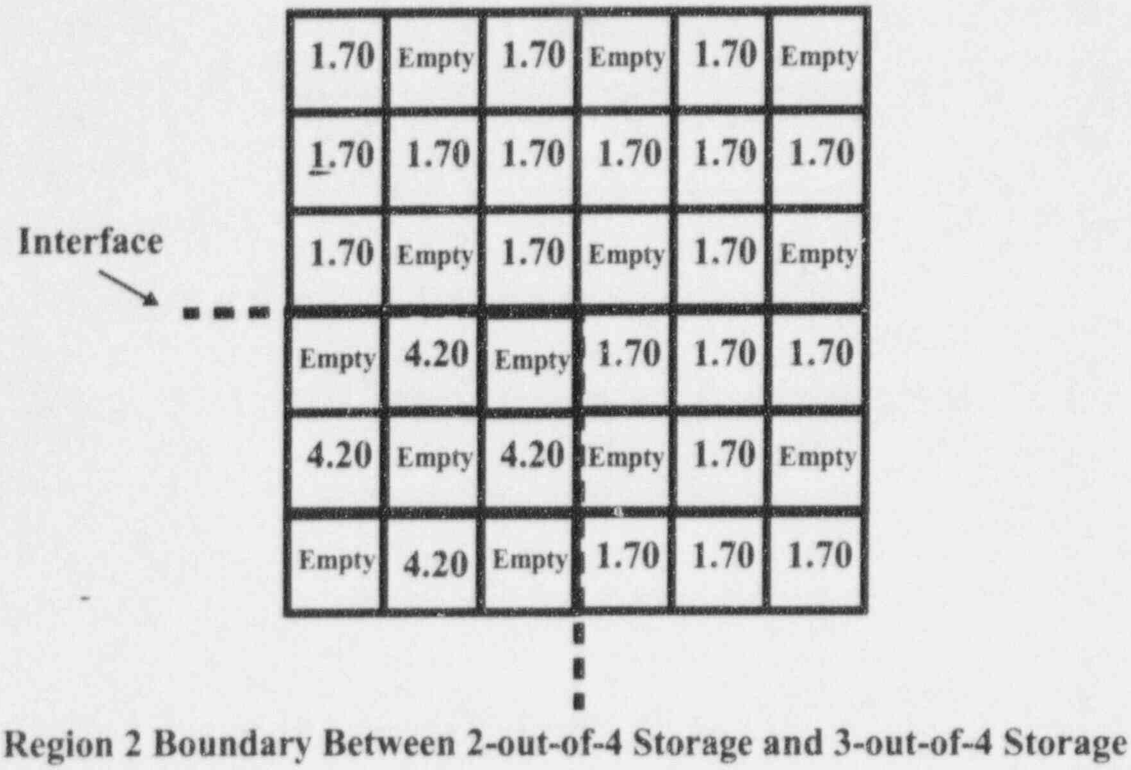


Figure 8. Region 2 Interface Requirements (Checkerboard Storage Interface)

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