CAC-97-162

Byron and Braidwood Spent Fuel Rack Criticality Analysis Using Soluble Boron Credit

May 1997

H. Q. Lam
M. M. Baker

Prepared : 5/16/97
H. Q. Lam
Criticality Services Team

Verified: S. Srinilta 5/16/97
S. Srinilta
Criticality Services Team

Approved: B. J. Johansen, 5/16/97
B. J. Johansen, Manager
Core Analysis C

Westinghouse
Commercial Nuclear Fuel Division

Table of Contents

List of Tables

List of Figures

1.0 Introduction

This report presents the results of a criticality analysis of the Commonwealth Edison Byron/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 spent fuel storage rack design considered herein is an existing array of fuel racks, previously qualified(2)(3) (with Boraflex) for storage of various Westinghouse 17x17 OFA fuel assembly types with maximum enrichments up to 5.0 w/o ^{235}U. Multiple storage configurations are currently allowed. These configurations allow fuel assemblies with maximum enrichments up to 5.0 w/o ^{235}U (with burnup or IFBA credits) to be stored.

The Byron/Braidwood spent fuel racks are being reanalyzed to allow storage of Westinghouse 17x17 OFA fuel assemblies with nominal enrichments up to 5.00 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 4.70 w/o ^{235}U or satisfy a minimum number of Integral Fuel Burnable Absorbers (IFBA) for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 500 ppm.

Spent Fuel Rack Region 2 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 1.14 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 1250 ppm.

3-out-of-4 Checkerboard Storage	Storage of Westinghouse 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 1.64 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. 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 1550 ppm.
2-out-of-4 Checkerboard Storage	Storage of Westinghouse 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 4.10 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1650 ppm.

Spent Fuel Rack Failed Assembly Cells 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 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 200 ppm.

The Byron/Braidwood 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} conditions). Soluble boron credit is used to provide safety margin by maintaining 95/95 $K_{eff} \leq 0.95$ including uncertainties, tolerances, and accident conditions in the presence of spent fuel pool soluble boron.

1.1 Design Description

The Byron/Braidwood spent fuel Region 1 storage racks consist of three cell types which differ in the number of sides which contain Boral sheets. The Region 1 storage cells are shown in Figure 1 on page 44 (interior cells with four Boral sheets), Figure 2 on page 45 (side peripheral cells with three Boral sheets), and Figure 3 on page 46 (corner peripheral cells with two Boral sheets). The Region 2 storage cell is shown in Figure 4 on page 47 and the Failed Assembly storage cell is shown in Figure 5 on page 48 with nominal dimensions provided on the figures. The overall layout of the Byron/Braidwood spent fuel pool is shown in Figure 6 on page 49.

The fuel parameters relevant to this analysis are given in Table 1 on page 28. 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 remain bounding.

The fuel rod and guide 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 instrumentation 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 inserting neutron poison between them. However, in this analysis no credit is taken for the presence of Boraflex panels in the racks.

In this report, the reactivity of the spent fuel racks 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 Byron/Braidwood spent fuel pool. This parameter provides significant negative reactivity in the criticality analysis of the spent fuel racks and will be used here 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 Byron/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 0.0077 ΔK with a 95 percent probability at a 95 percent confidence level on the bias of 0.0030 ΔK. These values will be used throughout this report as needed.

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 No Soluble Boron 95/95 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 is analyzed for the Region 1 spent fuel storage racks. The configuration contains fuel assemblies of the same fuel enrichment of 4.70 w/o ^{235}U in all of the cells. The analyses are based on the interior cell configuration shown in Figure 1. Peripheral cell locations are addressed in Section 8.1.

3.2 No Soluble Boron 95/95 K_{eff} Calculations

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 the Byron/Braidwood Region 1 spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 28 for fuel parameters).
2. Fuel assemblies contain uranium dioxide at a nominal enrichment of 4.70 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 equivalent or conservative calculations of reactivity for all fuel assemblies, 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 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.
10. The fuel assembly array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. All available storage cells are loaded with fuel assemblies.
12. Only interior cell locations (which contain Boral sheets on all four sides) are considered.

With the above assumptions, the KENO-Va calculations of K_{eff} under normal conditions resulted in a K_{eff} of 0.98264 for Westinghouse 17x17 OFA fuel assemblies, as shown in Table 2 on page 29.

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 are included:

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

Water Temperature: A reactivity bias 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, perturbation calculations are performed using PHOENIX-P. For the 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, stainless steel wall thickness, and Boral inserts. 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 enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 4.70 w/o ^{235}U 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 28) is considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 200.0% (the nominal reference values are listed in Table 1 on page 28) 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 conservative ±0.007 inch tolerance about the nominal Boral sheet thickness of 0.075 inch is considered. The actual tolerance is ±0.004 inch.

Assembly Position: The KENO-Va reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of 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.

The 95/95 K_{eff} for the Region 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 29 and results in a 95/95 K_{eff} of 0.99944.

Since K_{eff} is less than 1.0, the Byron/Braidwood Region 1 spent fuel racks will remain subcritical when all cells are loaded with 4.70 w/o ^{235}U Westinghouse 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties. In Section 3.4, IFBA equivalencing will be used to allow storage of assemblies with higher initial enrichments up to 5.00 w/o ^{235}U.

3.3 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 Region 1 all cell storage in the Byron/Braidwood spent fuel racks are the same as those in Section 3.2 except for assumption 9 regarding the moderator soluble boron concentration. The moderator used is water with 400 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.92920 as shown in Table 3 on page 30.

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 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 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, stainless steel wall thickness, and Boral inserts. Uncertainties associated with calculation and methodology accuracy are also considered in the statistical summation of uncertainty components.

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

The 95/95 K_{eff} for the Byron/Braidwood spent fuel rack Region 1 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 3 on page 30 and results in a 95/95 K_{eff} of 0.94569 for Westinghouse 17x17 OFA fuel assemblies.

Since K_{eff} is less than 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the Region 1 all cell storage of Westinghouse 17x17 OFA fuel assemblies in the Byron/Braidwood spent fuel racks. Storage of fuel assemblies with nominal enrichments up to 4.70 w/o ^{235}U is acceptable for Westinghouse 17x17 OFA fuel in all cells of the Region 1 spent fuel racks including the presence of 400 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 reference K_{eff} for 4.70 w/o ^{235}U fuel stored in the Byron/Braidwood Region 1 spent fuel racks was determined in Section 3.2. 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 stored in the Byron/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 28 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. This assumption results in equivalent or conservative calculations of reactivity for all fuel assemblies, 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. 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.
11. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
12. All available storage cells are loaded with fuel assemblies.
13. Only interior cell locations (which contain Boral sheets on all four sides) are considered.

The results of the IFBA credit reactivity equivalencing for the Byron/Braidwood Region 1 spent fuel racks are provided in Table 4 on page 31.

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 Table 4 is 0 ppm. The total soluble boron credit required for the Byron/Braidwood Region 1 spent fuel racks is 400 ppm including the effects of tolerances and uncertainties.

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 No Soluble Boron 95/95 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 are analyzed for Region 2 of the spent fuel storage racks. The first configuration contains fuel assemblies of the same enrichment of 1.14 w/o in all of the cells. The second configuration uses a 3-out-of-4 assembly checkerboard with 1 empty cell and 3 assemblies of 1.64 w/o in the other cells. The third configuration uses a 2-out-of-4 assembly checkerboard with 2 diagonally adjacent empty cells and 2 assemblies of 4.10 w/o in the other diagonally adjacent cells. The three configurations are shown in Figure 7 on page 50.

4.2 No Soluble Boron 95/95 K_{eff} Calculations

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 the Byron/Braidwood Region 2 spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 28 for fuel parameters).
2. Fuel assemblies contain uranium dioxide at the nominal 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. This assumption results in equivalent or conservative calculations of reactivity for all fuel assemblies, 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 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.
10. The fuel assembly array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
11. All allowable storage cells are loaded with fuel assemblies.

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 are included:

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

Water Temperature: A reactivity bias 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, perturbation calculations are performed using PHOENIX-P. For the Byron/Braidwood spent fuel rack Region 2 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 enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference 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 28) is considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 200.0% (the nominal reference values are listed in Table 1 on page 28) 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: A conservative +0.021/−0.059 inch tolerance about a nominal 9.011 inch reference cell pitch is considered. The actual cell pitch is 9.03±0.04 inches.

Stainless Steel Thickness: The ±0.005 inch tolerance about the nominal 0.06 inch reference stainless steel thickness for all rack structures is considered.

Assembly Position: The KENO-Va reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of 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.

4.2.1 All Cell No Soluble Boron 95/95 K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the all cell configuration under nominal conditions with no soluble boron in the moderator resulted in a K_{eff} of 0.96885, as shown in Table 5 on page 32.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 5 and results in a 95/95 K_{eff} of 0.99631.

Since K_{eff} is less than 1.0 including uncertainties at a 95/95 probability/confidence level, the Region 2 spent fuel racks will remain subcritical when all cells are loaded with Westinghouse 17x17 OFA fuel assemblies having a nominal enrichment no greater than 1.14 w/o ^{235}U and no soluble boron is present in the spent fuel pool water.

4.2.2 3-out-of-4 Checkerboard No Soluble Boron 95/95 K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the 3-out-of-4 checkerboard configuration under nominal conditions with no soluble boron in the moderator resulted in a K_{eff} of 0.97629, as shown in Table 7 on page 34.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 7 and results in a 95/95 K_{eff} of 0.99662.

Since K_{eff} is less than 1.0 including uncertainties at a 95/95 probability/confidence level, the Region 2 spent fuel racks will remain subcritical for the 3-out-of-4 checkerboard configuration storage of Westinghouse 17x17 OFA 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 1.64w/o ^{235}U and no soluble boron is present in the spent fuel pool water.

4.2.3 2-out-of-4 Checkerboard No Soluble Boron 95/95 K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the 2-out-of-4 checkerboard configuration under nominal conditions with no soluble boron in the moderator resulted in a K_{eff} of 0.97643, as shown in Table 9 on page 36.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 9 and results in a 95/95 K_{eff} of 0.99664.

Since K_{eff} is less than 1.0 including uncertainties at a 95/95 probability/confidence level, the Region 2 spent fuel racks will remain subcritical for the 2-out-of-4 checkerboard configuration storage of Westinghouse 17x17 OFA fuel assemblies in a 2x2 checkerboard arrangement with two diagonally adjacent cells containing fuel assemblies having a nominal enrichment no greater than 4.10 w/o ^{235}U and the remaining 2 cells empty and no soluble boron is present in the spent fuel pool water.

4.3 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 storage in the Region 2 spent fuel racks are similar to those in Section 4.2 except for assumption 9 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 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/Braidwood spent fuel rack Region 2 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 same tolerance and uncertainty components as in the No Soluble Boron case are considered in the total uncertainty statistical summation.

4.3.1 All Cell Soluble Boron Credit K_{eff} Calculation

With the previously stated assumptions, the KENO-Va calculation for the all cell configuration under nominal conditions with 150 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91991, as shown in Table 6 on page 33.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 and results in a 95/95 K_{eff} of 0.94743.

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 Westinghouse 17x17 OFA fuel assemblies in the Region 2 spent fuel racks. Storage of fuel assemblies with nominal enrichments no greater than 1.14 w/o ^{235}U is acceptable in all cells including the presence of 150 ppm soluble boron.

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

With the previously stated assumptions, the KENO-Va calculation for the 3-out-of-4 checkerboard configuration under nominal conditions with 200 ppm soluble boron in the moderator resulted in a K_{eff} of 0.91935, as shown in Table 8 on page 35.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 8 and results in a 95/95 K_{eff} of 0.93999.

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 Westinghouse 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 1.64w/o ^{235}U is acceptable including the presence of 200 ppm soluble boron.

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

With the previously stated assumptions, the KENO-Va calculation for the 2-out-of-4 checkerboard configuration under nominal conditions with 200 ppm soluble boron in the moderator resulted in a K_{eff} of 0.92785, as shown in Table 10 on page 37.

The 95/95 K_{eff} is developed by adding the temperature and methodology biases and the statistical sum of independent uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 10 and results in a 95/95 K_{eff} of 0.94663.

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 Westinghouse 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 4.10 w/o ^{235}U and the remaining 2 cells empty is acceptable including the presence of 200 ppm soluble boron.

4.4 Burnup and Decay Time Credit Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than those described in Section 4.2 in the Byron/Braidwood Region 2 spent fuel racks is achievable by using the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion and the radioactive decay of the spent fuel actinide isotopes within the fuel assemblies. For burnup credit, a series of reactivity calculations is performed to generate a set of enrichment and 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 51, Figure 9 on page 52, and Figure 10 on page 53 show the constant K_{eff} contours generated for the all cell configuration, the 3-out-of-4 configuration, and the 2-out-of-4 configuration, respectively, 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 is 400 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 550 ppm for the all cells configuration, 550 ppm for the 3-out-of-4 checkerboard configuration, and 250 ppm for the 2-out-of-4 checkerboard configuration.

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.

Decay Time Credit is an extension of the Burnup Credit process which includes the time since an assembly was last discharged as a variable which gains additional margin in reactivity and reduces the minimum burnup requirements. Decay time credit is used here only for the all cell and 3-out-of-4 configurations. Spent fuel decay time credit results from the radioactive decay of isotopes in the spent fuel to daughter isotopes, which results in reduced reactivity. One of the major contributors is the decay of ^{241}Pu to ^{241}Am. In this report, credit is taken only for the decay of actinide isotopes. Decay of the fission products has the effect of further reducing the reactivity of the spent fuel.

For decay time credit, a series of reactivity calculations are performed to generate an ordered set of enrichment, fuel assembly discharge burnup, and decay time parameters which all yield the desired equivalent K_{eff} when stored in the spent fuel storage racks.

In the decay time methodology reported here, the fission product isotopes are frozen at the concentrations existing at the time of discharge of the fuel (except ^{135}Xe which is removed). These calculations are performed at different discharge burnups. The actinide isotopes are allowed to decay based on their natural process. The loss in reactivity due to the radioactive decay of the spent fuel results in reducing the minimum burnup needed to meet the reactivity requirements. Thus for different decay times, a family of curves is generated. In the decay time methodology the following assumptions are used in the PHOENIX-P models:

1. Fuel assemblies are modeled using the same criteria as Section 4.1
2. Fuel is depleted using a conservatively high soluble boron letdown curve to enhance the buildup of plutonium making the fuel more reactive in the spent fuel storage racks. Sensitivity studies have shown that spectrum effects are also conservative for the decay time calculation.
3. No credit for fission product isotopic decay is used.
4. Actinide only isotopes decay is used.
5. Nominal spent fuel rack configuration/dimensions are used.

With the above assumptions, the calculation of the decay time burnup credit curves are found to be conservative for use in the spent fuel pool criticality analysis.

It is important to recognize that the curves in Figure 8, Figure 9, and Figure 10 are 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, Figure 9, and Figure 10 are also provided in Table 11 on page 38, Table 12 on page 39, and Table 13 on page 40, respectively. Use of linear interpolation between the tabulated values is acceptable since the change in reactivity is approximately linear as a function of enrichment between the tabulated points.

5.0 Criticality Analysis of Failed Assembly Storage Racks

This section describes the analytical techniques and models employed to perform the criticality analysis for the storage of fuel in the Failed Assembly storage racks with credit for soluble boron.

Section 5.1 describes the allowed storage configurations for fuel assemblies in the Failed Assembly storage racks. Section 5.2 describes the No Soluble Boron 95/95 K_{eff} KENO-Va calculations. Finally, Section 5.3 discusses the results of the spent fuel rack K_{eff} soluble boron credit calculations.

5.1 Configuration Descriptions

Only one configuration is analyzed for the Failed Assembly spent fuel storage racks. The configuration contains fuel assemblies of the same fuel enrichment of 5.00 w/o ^{235}U in all of the cells.

5.2 No Soluble Boron 95/95 K_{eff} Calculations

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 the Byron/Braidwood Failed Assembly spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 28 for fuel parameters).
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 equivalent or conservative calculations of reactivity for all fuel assemblies, 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. The moderator is water with 0 ppm soluble 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 fuel assembly array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
10. All allowable storage cells are loaded with fuel assemblies.

With the above assumptions, the KENO-Va calculations of K_{eff} under normal conditions resulted in a K_{eff} of 0.94753 for Westinghouse 17x17 OFA fuel assemblies, as shown in Table 14 on page 41.

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 are included:

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

Water Temperature: A reactivity bias 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, perturbation calculations are performed using PHOENIX-P. For the Failed Assembly spent fuel rack all cell storage configuration, UO_2 material tolerances are considered along with construction tolerances related to the 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 enrichment tolerance of ±0.05 w/o ^{235}U about the nominal reference enrichment of 5.00 w/o ^{235}U 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 28) is considered.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 200.0% (the nominal reference values are listed in Table 1 on page 28) is considered.

Storage Cell Pitch: The +0.38/–0.50 inch tolerance about the nominal 21.0 inch reference cell pitch is considered.

Stainless Steel Wall Thickness: The ±0.0625 inch tolerance about the nominal 0.125 inch reference stainless steel cell wall thickness is considered.

Assembly Position: The KENO-Va reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells. Conservative calculations show that an increase in reactivity can occur if the corners of 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.

The 95/95 K_{eff} for the Failed Assembly 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 14 on page 41 and results in a 95/95 K_{eff} of 0.96330.

Since K_{eff} is less than 1.0, the Byron/Braidwood Failed Assembly spent fuel racks will remain subcritical when all cells are loaded with 5.00 w/o ^{235}U Westinghouse 17x17 OFA fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

5.3 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 Failed Assembly all cell storage in the Byron/Braidwood spent fuel racks are the same as those in Section 5.2 except for assumption 8 regarding the moderator soluble boron concentration. The moderator used is water with 100 ppm soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a K_{eff} of 0.92064 as shown in Table 15 on page 42.

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 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 Failed Assembly spent fuel rack all cell storage configuration, UO_2 material tolerances are considered along with construction tolerances related to the 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 same tolerance and uncertainty components as in the No Soluble Boron case are considered in the total uncertainty statistical summation.

The 95/95 K_{eff} for the Byron/Braidwood spent fuel rack Failed Assembly 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 15 on page 42 and results in a 95/95 K_{eff} of 0.93543 for Westinghouse 17x17 OFA fuel assemblies.

Since K_{eff} is less than 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the Failed Assembly all cell storage of Westinghouse 17x17 OFA fuel assemblies in the Byron/Braidwood spent fuel racks. Storage of fuel assemblies with nominal enrichments up to 5.00 w/o ^{235}U is acceptable for Westinghouse 17x17 OFA fuel in all cells of the Failed Assembly spent fuel racks including the presence of 100 ppm soluble boron.

6.0 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 Region 1, Region 2, and Failed Assembly storage areas, this accident is bounded by the fuel assembly misload 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.

Calculations were performed for the Byron/Braidwood storage configurations to determine the reactivity change caused by a change in the Byron/Braidwood spent fuel pool water temperature outside the normal range (50°F to 160°F). For the change in spent fuel pool water temperature accident, a temperature range of 32°F to 240°F is considered. 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 assembly misload accident, calculations were performed to show the largest reactivity increase caused by a Westinghouse 17x17 OFA fuel assembly misplaced into a storage cell for which the restrictions on location, enrichment, or burnup are not satisfied. The assembly misload 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 16 on page 43.

7.0 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. Table 16 on page 43 summarizes the storage configurations and corresponding soluble boron credit requirements.

Based on the above discussion, should a spent fuel water temperature change accident or a fuel assembly misload accident occur in the Region 1, Region 2, or Failed Assembly spent fuel racks, K_{eff} will be maintained less than or equal to 0.95 due to the presence of at least 550 ppm (no fuel handling) or 1650 ppm (during fuel handling) of soluble boron in the Byron/Braidwood spent fuel pool water.

8.0 Storage Configuration Interface Requirements

The Byron/Braidwood spent fuel pool is composed of three different types of racks, designated as Region 1, Region 2, and Failed Assembly cells. 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 different checkerboard zones and the boundary between a 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 containing rack cells and ensuring that each of these 2x2 matrices conforms 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). The fuel assemblies in each of these 2x2 matrices of storage cells are required to meet the checkerboard requirements determined for the given region.

8.1 Interface Requirements Within Region 1

Region 1 contains three distinct cell types. The majority of Region 1 cells are denoted as Type 1, interior cells with Boral sheets on all four sides, as shown in Figure 1 on page 44. The small number of remaining cells are located on the periphery of the Region 1 rack modules and are denoted as Type 2 and Type 3. Type 2 cells are side peripheral cells with Boral sheets only on the three interior sides, as shown in Figure 2 on page 45. Type 3 cells are corner peripheral cells with Boral sheets only on the two interior sides, as shown in Figure 3 on page 46.

Most of the peripheral cells face either a concrete wall or at least 9.0 inches of open water (interface requirements between Region 1 and Region 2). Therefore, the analyses presented in Section 3, which are based on interior cells, remain bounding for these cells for storage of Westinghouse 17x17 OFA fuel assemblies with an initial nominal enrichment no greater than 4.70 w/o ^{235}U or equivalent in any cell location.

However, Region 1 peripheral cells that face other Region 1 rack modules are not bounded by the Section 3 analyses for all cell storage. Additional analyses show that the results presented in Section 3 remain bounding if the following Region 1 interface requirements are met.

The boundary between Region 1 rack modules must be configured using a 3-out-of-4 checkerboard arrangement with empty cells. 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. This requirement is necessary since the peripheral cell exterior sides do not contain Boral sheets.

8.2 Interface Requirements Within Region 2

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

All Cell Storage Next to 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 in the checkerboard storage zone uses 1.64 w/o fuel assemblies alternating with empty cells. Figure 11 on page 54 illustrates the carryover configuration.
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 carryover in the 2-out-of-4 storage zone uses 4.10 w/o fuel assemblies alternating with empty cells. Figure 12 on page 55 illustrates the carryover configuration.

8.3 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.

8.4 Interface Requirements Between Region 2 and Failed Assembly Cells

There is no interface requirement between Region 2 and Failed Assembly cells.

8.5 Interface Requirements Between Offset Racks

The Byron/Braidwood spent fuel pool layout, shown in Figure 6 on page 49, allows for the possibility that storage cells in adjacent rack modules may not be precisely aligned. Calculations were performed for each of the allowable storage configurations to determine the reactivity change caused by this offset between adjacent rack modules. No additional interface requirements are needed for the all cell storage configuration between offset rack modules. However, the boundary between 3-out-of-4 storage regions must be configured such that one row is fully loaded and the adjacent row is loaded with fuel assemblies alternating with empty cells. The boundary between 2-out-of-4 storage regions in adjacent racks must be configured such that one row of empty cells is maintained at the boundary (the vacant row can be positioned in either rack). These requirements are necessary since rack offset can potentially increase reactivity in 3-out-of-4 and 2-out-of-4 storage configurations along the interface with non-aligned racks.

9.0 Summary of Criticality Results

For the storage of Westinghouse 17x17 OFA fuel assemblies in the Byron/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 No Soluble Boron 95/95 conditions, and less than or equal to 0.95 including uncertainties, tolerances and accident conditions with the presence of spent fuel pool soluble boron. This report shows that the acceptance criteria for criticality is met for the Byron/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 4.70 w/o ^{235}U or satisfy a minimum number of Integral Fuel Burnable Absorbers (IFBA) for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 500 ppm.

Spent Fuel Rack Region 2 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 1.14 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 1250 ppm.
3-out-of-4 Checkerboard Storage	Storage of Westinghouse 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 1.64 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. 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 1550 ppm.
2-out-of-4 Checkerboard Storage	Storage of Westinghouse 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 4.10 w/o ^{235}U or satisfy a minimum burnup requirement for higher initial enrichments up to 5.00 w/o ^{235}U. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent. The soluble boron credit required for this storage configuration is 1650 ppm.

Spent Fuel Rack Failed Assembly Cells 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 5.00 w/o ^{235}U. The soluble boron credit required for this storage configuration is 200 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".

Table 1. Fuel Parameters Employed in the Criticality Analysis

Parameter	Westinghouse 17x17 OFA
Number of Fuel Rods per Assembly	264
Fuel Rod Zirc-4 Clad O.D. (inch)	0.360
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. Byron/Braidwood Region 1 All Cell Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.98264**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00122
TOTAL Bias	0.00892
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00181
UO_2 Density Tolerance	0.00240
Fuel Pellet Dishing Variation	0.00139
Cell Inner Diameter	0.00149
Cell Pitch	0.00518
Cell Wall Thickness	0.00090
Wrapper Thickness	0.00043
Boral Thickness	0.00101
Asymmetric Assembly Position	0.00222
Calculational Uncertainty (95/95)	0.00249
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00788

$$\sqrt{\sum_{i=1}^{11} ((\text{tolerance}_i \text{ ... or ... } \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.99944**

Table 3. Byron/Braidwood Region 1 All Cell Storage Soluble Boron Credit K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.92920**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00096
TOTAL Bias	0.00866
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00203
UO_2 Density Tolerance	0.00300
Fuel Pellet Dishing Variation	0.00174
Cell Inner Diameter	0.00136
Cell Pitch	0.00493
Cell Wall Thickness	0.00087
Wrapper Thickness	0.00041
Boral Thickness	0.00097
Asymmetric Assembly Position	0.00175
Calculational Uncertainty (95/95)	0.00224
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00783

$$\sqrt{\sum_{i=1}^{11} ((\text{tolerance}_i \text{ ... or ... } \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.94569**

Table 4. Summary of Minimum IFBA Requirements for Byron/Braidwood Region 1

Nominal Enrichment (w/o ^{235}U)	Region 1 IFBA Requirement		
	1.0X*	1.5X*	2.0X*
4.70	0	0	0
>4.70	16	16	16
5.00	16	16	16

* Denotes nominal IFBA loadings of 1.5 mg-^{10}B/in (1.0X), 2.25 mg-^{10}B/in (1.5X), and 3.0 mg-^{10}B/in (2.0X).

The lowest IFBA pattern offered by Westinghouse contains 16 IFBA rods.

Table 5. Byron/Braidwood Region 2 All Cell Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.96885**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00048
TOTAL Bias	0.00818
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01712
UO_2 Density Tolerance	0.00365
Fuel Pellet Dishing Variation	0.00214
Cell Inner Diameter	0.00015
Cell Pitch	0.00593
Cell Wall Thickness	0.00384
Asymmetric Assembly Position	0.00000
Calculational Uncertainty (95/95)	0.00132
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01928

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.99631**

Table 6. Byron/Braidwood Region 2 All Cell Storage Soluble Boron Credit K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.91991**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00037
TOTAL Bias	0.00807
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01718
UO_2 Density Tolerance	0.00412
Fuel Pellet Dishing Variation	0.00242
Cell Inner Diameter	0.00015
Cell Pitch	0.00626
Cell Wall Thickness	0.00325
Asymmetric Assembly Position	0.00000
Calculational Uncertainty (95/95)	0.00130
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01945

$$\sqrt{\sum_{i=1}^{9}\left(\left(\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i\right)^2\right)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.94743**

Table 7. Byron/Braidwood Region 2 3-out-of-4 Checkerboard Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.97629**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00021
TOTAL Bias	0.00791
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00993
UO_2 Density Tolerance	0.00332
Fuel Pellet Dishing Variation	0.00196
Cell Inner Diameter	0.00008
Cell Pitch	0.00416
Cell Wall Thickness	0.00336
Asymmetric Assembly Position	0.00000
Calculational Uncertainty (95/95)	0.00177
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01242

$$\sqrt{\sum_{i=1}^{9}\left(\left(\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i\right)^2\right)}$$

Final K_{eff} Including Uncertainties & Tolerances: 0.99662

Table 8. Byron/Braidwood Region 2 3-out-of-4 Checkerboard Storage Soluble Boron Credit K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.91935**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00020
TOTAL Bias	0.00790
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.01012
UO_2 Density Tolerance	0.00389
Fuel Pellet Dishing Variation	0.00228
Cell Inner Diameter	0.00006
Cell Pitch	0.00448
Cell Wall Thickness	0.00272
Asymmetric Assembly Position	0.00001
Calculational Uncertainty (95/95)	0.00175
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.01274

$$\sqrt{\sum_{i=1}^{9}\left(\left(\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i\right)^2\right)}$$

Final K_{eff} Including Uncertainties & Tolerances:	**0.93999**

Table 9. Byron/Braidwood Region 2 2-out-of-4 Checkerboard Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.97643**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00423
TOTAL Bias	0.01193
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00235
UO_2 Density Tolerance	0.00249
Fuel Pellet Dishing Variation	0.00140
Cell Inner Diameter	0.00008
Cell Pitch	0.00381
Cell Wall Thickness	0.00326
Asymmetric Assembly Position	0.00392
Calculational Uncertainty (95/95)	0.00233
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00828

$$\sqrt{\sum_{i=1}^{9}\left(\left(\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i\right)^2\right)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.99664**

Table 10. Byron/Braidwood Region 2 2-out-of-4 Checkerboard Storage Soluble Boron Credit K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.92785**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00271
TOTAL Bias	0.01041
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00238
UO_2 Density Tolerance	0.00275
Fuel Pellet Dishing Variation	0.00162
Cell Inner Diameter	0.00004
Cell Pitch	0.00325
Cell Wall Thickness	0.00245
Asymmetric Assembly Position	0.00482
Calculational Uncertainty (95/95)	0.00231
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00837

$$\sqrt{\sum_{i=1}^{9}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.94663**

Table 11. Summary of Burnup Requirements for Byron/Braidwood Region 2 All Cell Configuration

Enrich.	Decay Time (years)																
	0	1	2	3	4	5	6	7	8	9	10	12	14	15	16	18	20
1.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.30	7381	7243	7104	6969	6842	6724	6617	6520	6433	6355	6282	6151	6026	5965	5904	5794	5727
1.50	11308	11045	10801	10577	10371	10183	10010	9852	9705	9569	9442	9208	8999	8906	8824	8705	8685
1.80	16583	16182	15824	15502	15211	14945	14699	14471	14258	14056	13866	13518	13219	13091	12982	12835	12811
2.00	19766	19299	18886	18519	18186	17882	17601	17339	17091	16858	16637	16234	15891	15746	15623	15449	15389
2.20	22737	22220	21766	21362	20998	20664	20355	20064	19790	19531	19286	18841	18464	18306	18169	17966	17854
2.40	25535	24981	24496	24064	23674	23316	22983	22670	22375	22095	21832	21353	20950	20780	20632	20397	20225
2.60	28197	27616	27106	26651	26239	25860	25507	25176	24863	24567	24288	23784	23360	23179	23019	22751	22520
2.80	30755	30153	29622	29147	28715	28317	27946	27598	27270	26961	26670	26145	25702	25511	25339	25039	24753
3.00	33233	32616	32067	31572	31121	30704	30316	29953	29612	29290	28989	28446	27985	27784	27600	27268	26938
3.20	35653	35022	34456	33942	33471	33036	32631	32253	31899	31567	31256	30697	30218	30006	29809	29447	29085
3.40	38032	37388	36804	36269	35778	35323	34901	34509	34142	33799	33480	32904	32406	32183	31973	31584	31202
3.60	40379	39723	39119	38563	38051	37576	37136	36728	36349	35996	35667	35075	34556	34321	34099	33685	33296
3.80	42702	42031	[illegible]	40830	40295	[illegible]	39342	38919	38527	38163	37825	37214	36674	36426	36191	35757	35371
4.00	45002	44315	43671	43070	42513	[illegible]	41522	41084	40679	40304	39956	39326	38764	38504	38256	37804	37429
4.20	47274	66569	45904	45283	44705	44171	43678	43225	42808	42422	42064	41413	40829	40557	40298	39831	39470
4.40	49509	68786	48102	47461	46866	46316	45809	45343	44914	44517	44148	43477	42872	42589	42321	41842	41492
4.60	51695	50953	50252	49598	48989	48428	47910	47434	46994	46588	46209	45518	44895	44604	44329	43841	43490
4.80	53812	53051	52340	51678	51065	50499	49976	49493	49046	48631	48243	47535	46898	[illegible]	46325	45829	45458
4.95	55340	54567	53853	53193	52583	52019	51497	51013	50563	50142	49749	49030	48388	48093	47815	47315	46909
5.00	55836	55080	54345	53687	53080	52518	51998	51514	51063	50642	50247	49525	48883	48588	48311	47810	47387

Table 12. Summary of Burnup Requirements for Byron/Braidwood Region 2 3-out-of-4 Checkerboard Configuration

Enrich.	Decay Time (years)																
	0	1	2	3	4	5	6	7	8	9	10	12	14	15	16	18	20
1.64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.00	6253	6186	6124	6068	6017	5971	5931	5896	5865	5840	5819	5786	5762	5750	5738	5707	5658
2.20	8809	8710	8614	8523	8439	8361	8290	8227	8172	8123	8082	8017	7968	7947	7925	7872	7790
2.40	11288	11155	11026	10904	10788	10681	10583	10494	10415	10345	10284	10185	10109	10075	10042	9968	9862
2.60	13693	13526	13366	13214	13070	12937	12814	12701	12600	12509	12428	12294	12188	12141	12096	12000	11878
2.80	16030	15830	15639	15459	15289	15132	14986	14852	14730	14620	14520	14350	14212	14151	14093	13976	13842
3.00	18305	18071	17851	17644	17451	17271	17104	16951	16810	16680	16563	16358	16186	16110	16038	15901	15760
3.20	20521	20255	20006	19775	19559	19359	19173	19001	18843	18690	18560	18320	18115	18023	17937	17730	17637
3.40	22685	22387	22111	21856	21620	21401	21197	21009	20833	20669	20517	20243	20004	19897	19798	19621	19475
3.60	24801	24472	24171	23894	23638	23401	23181	22976	22785	22605	22437	22130	21859	21737	21625	21429	21281
3.80	26874	26517	26191	25892	25618	25364	25128	24908	24702	24508	24324	23987	23685	23549	23424	23211	23059
4.00	28909	28525	28176	27858	27565	27295	27044	26809	26589	26381	26183	25817	25488	25339	25202	24971	24814
4.20	30912	30504	30133	29794	29484	29198	28932	28683	28449	28228	28017	27626	27273	27113	26965	26716	26550
4.40	32888	32457	32065	31708	31381	31078	30797	30534	30287	30053	29831	29417	29045	28875	28718	28453	28271
4.60	34841	34390	33980	33604	33259	32940	32644	32367	32106	31861	31628	31197	30809	30632	30468	30187	29982
4.80	36777	36310	35882	35488	35125	34788	34476	34184	33911	33655	33413	32968	32571	32390	32221	31923	31689
4.95	38220	37743	37303	36895	36518	36168	35843	35540	35258	34993	34746	34294	33895	33712	33541	33232	32968
5.00	38700	38220	37776	37364	36982	36628	36298	35991	35706	35439	35189	34736	34336	34154	33982	33669	33395

Table 13. Summary of Burnup Requirements for Byron/Braidwood Region 2 2-out-of-4 Checkerboard Configuration

Enrich.	Burnup
4.10	0
4.20	368
4.40	1258
4.60	2298
4.80	3426
5.00	4577

Table 14. Byron/Braidwood Failed Assembly All Cell Storage No Soluble Boron 95/95 K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.94753**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00003
TOTAL Bias	0.00773
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00146
UO_2 Density Tolerance	0.00226
Fuel Pellet Dishing Variation	0.00132
Cell Pitch	0.00041
Cell Wall Thickness	0.00452
Asymmetric Assembly Position	0.00453
Calculational Uncertainty (95/95)	0.00236
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00804

$$\sqrt{\sum_{i=1}^{8}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: **0.96330**

Table 15. Byron/Braidwood Failed Assembly All Cell Storage Soluble Boron Credit K_{eff}

Nominal KENO-Va Reference Reactivity:	**0.92064**
Calculational & Methodology Biases:	
Methodology (Benchmark) Bias	0.00770
Pool Temperature Bias (50°F - 160°F)	0.00002
TOTAL Bias	0.00772
Tolerances & Uncertainties:	
UO_2 Enrichment Tolerance	0.00144
UO_2 Density Tolerance	0.00245
Fuel Pellet Dishing Variation	0.00136
Cell Pitch	0.00030
Cell Wall Thickness	0.00311
Asymmetric Assembly Position	0.00389
Calculational Uncertainty (95/95)	0.00248
Methodology Bias Uncertainty (95/95)	0.00300
TOTAL Uncertainty (statistical)	0.00707

$$\sqrt{\sum_{i=1}^{8}((\text{tolerance}_i \ldots \text{or} \ldots \text{uncertainty}_i)^2)}$$

Final K_{eff} Including Uncertainties & Tolerances: 0.93543

Table 16. Summary of the Soluble Boron Credit Requirements

Spent Fuel Rack Region	Storage Configuration	Soluble Boron Required for Tolerances/ Uncertainties (ppm)	Soluble Boron Required for Reactivity Equivalencing (ppm)	Total Soluble Boron Credit Required Without Accidents (ppm)	Soluble Boron Required for Accidents (ppm)	Total Soluble Boron Credit Required With Accidents (ppm)
1	All Cell Storage	400	0	400	100	500
2	All Cell Storage	150	400	550	700	1250
2	3-out-of-4 Checkerboard Storage	200	350	550	1000	1550
2	2-out-of-4 Checkerboard Storage	200	50	250	1400	1650
Failed Assembly	All Cell Storage	100	n/a	100	100	200

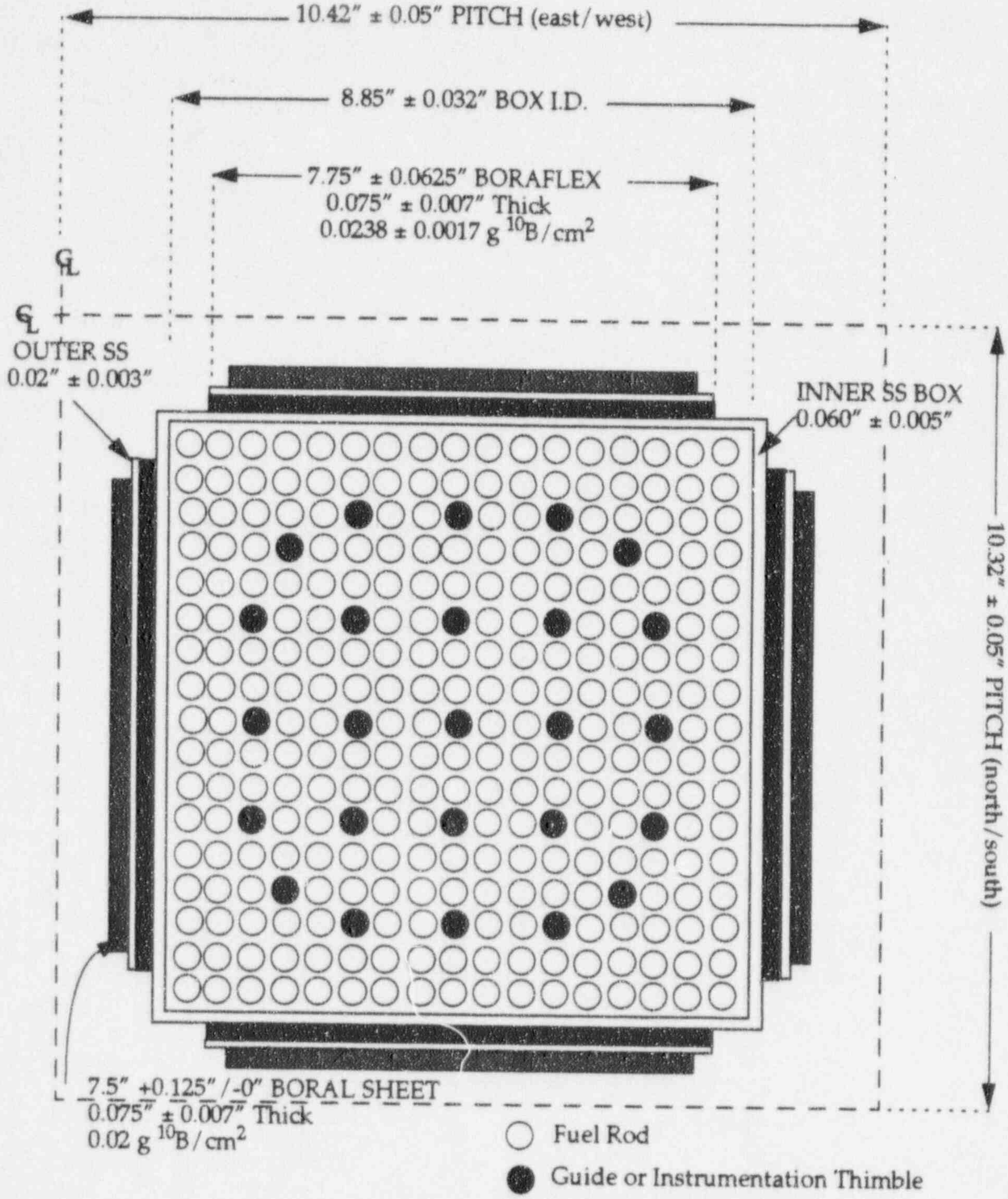


Figure 1. Byron/Braidwood Region 1 Spent Fuel Pool Storage Cell Nominal Dimensions Interior Cells with Boral Sheets on Four Sides

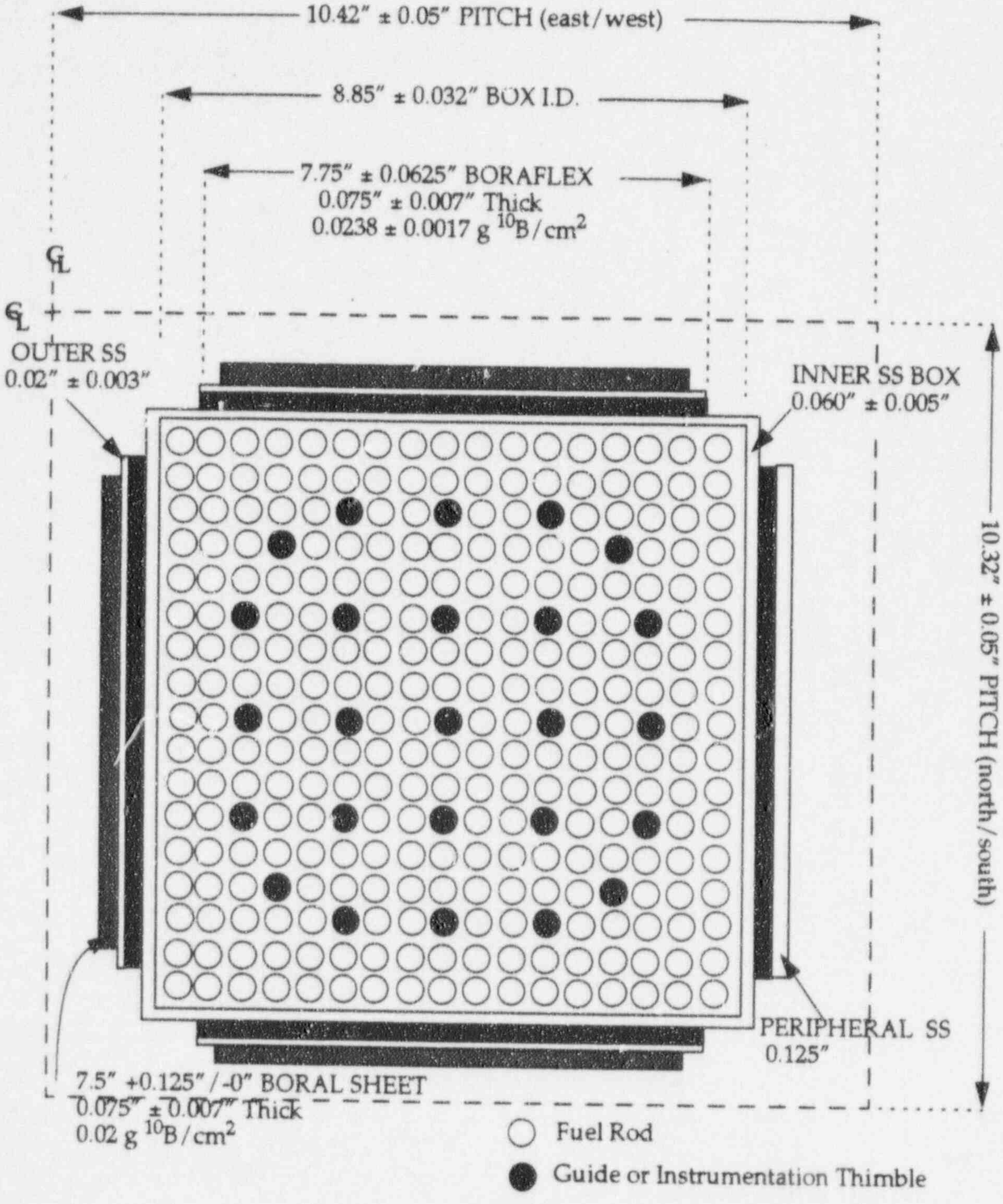


Figure 2. Byron/Braidwood Region 1 Spent Fuel Pool Storage Cell Nominal Dimensions Side Peripheral Cells with Boral Sheets on Three Sides

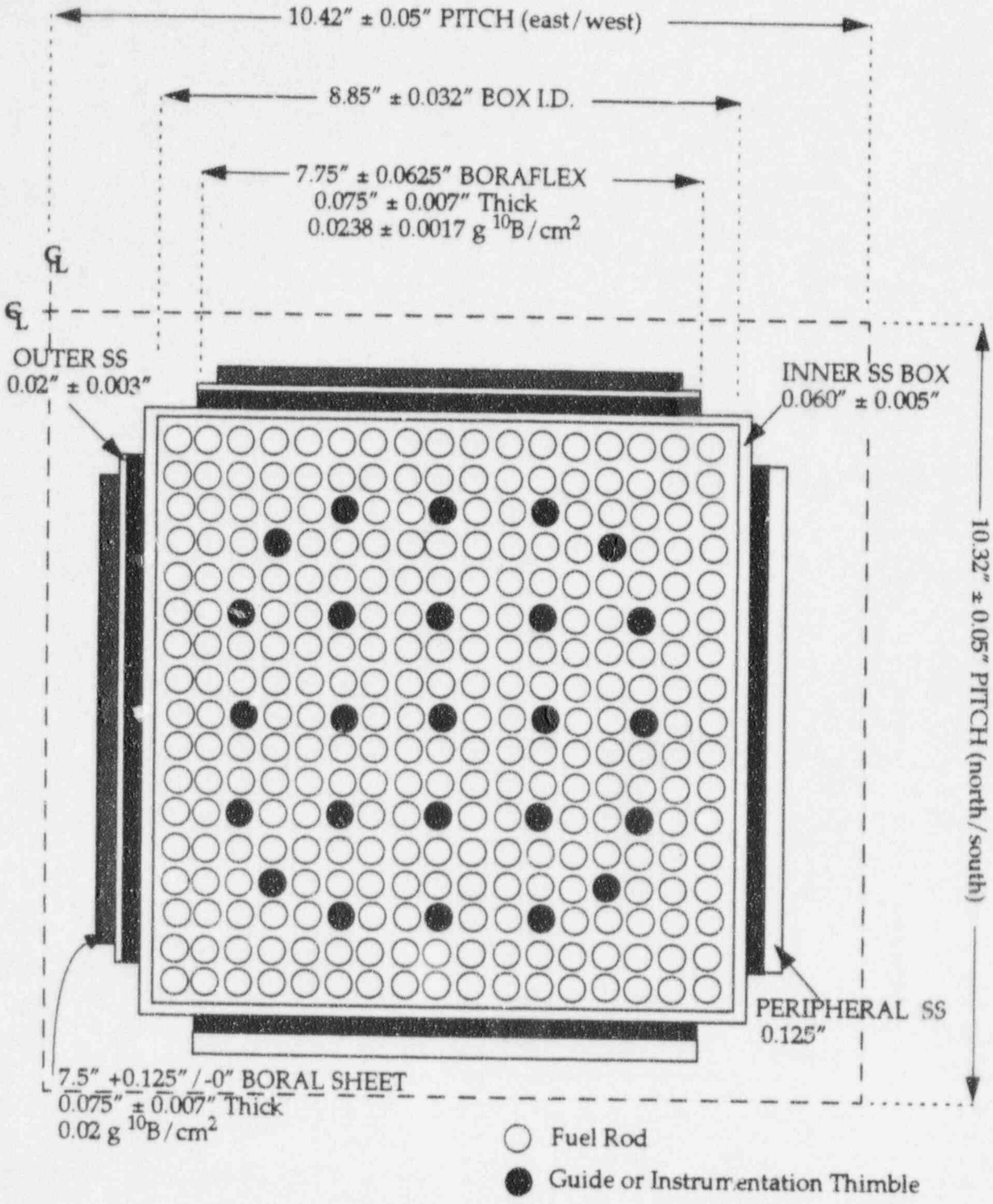


Figure 3. Byron/Braidwood Region 1 Spent Fuel Pool Storage Cell Nominal Dimensions Corner Peripheral Cells with Boral Sheets on Two Sides

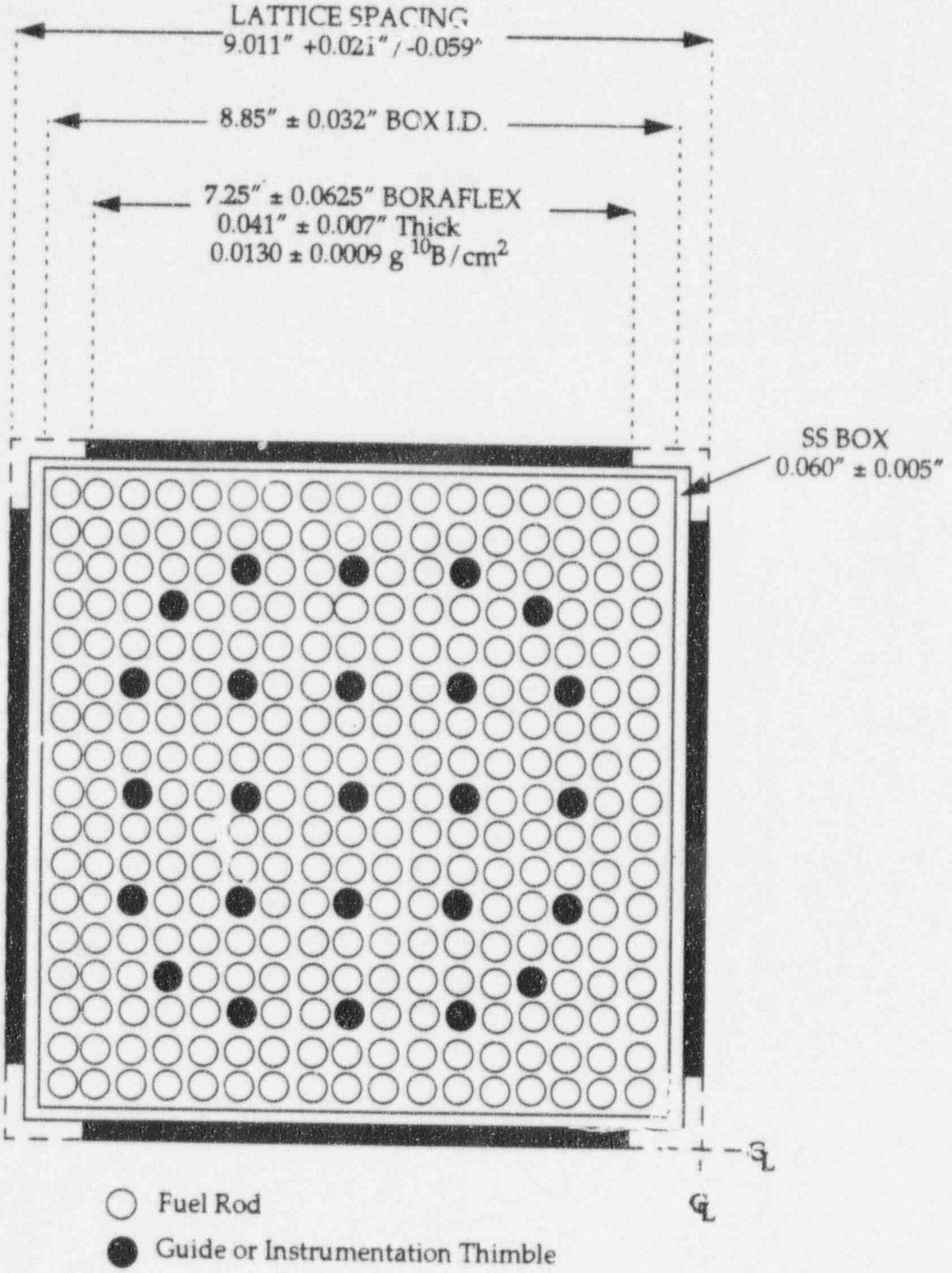


Figure 4. Byron/Braidwood Region 2 Spent Fuel Pool Storage Cell Nominal Dimensions

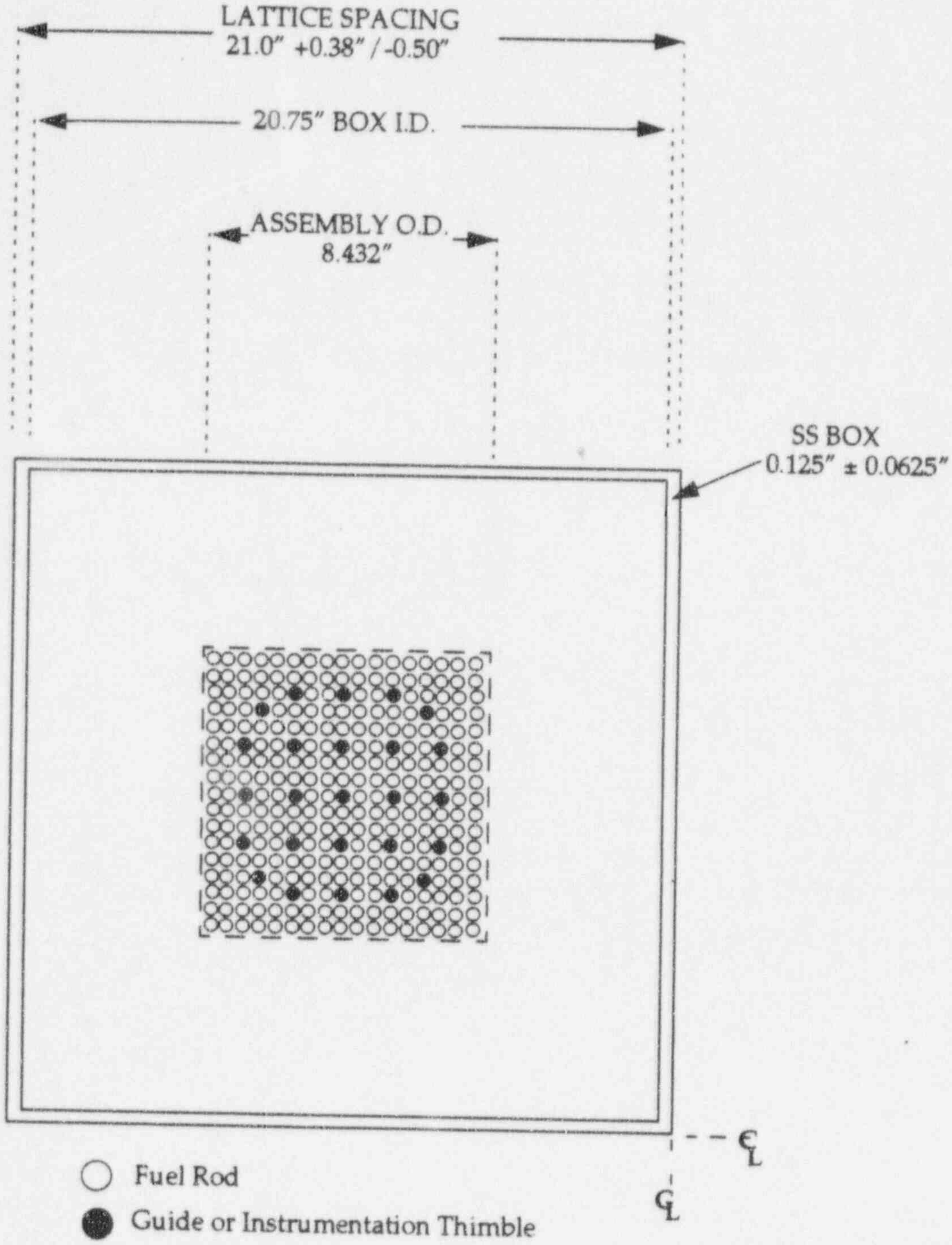
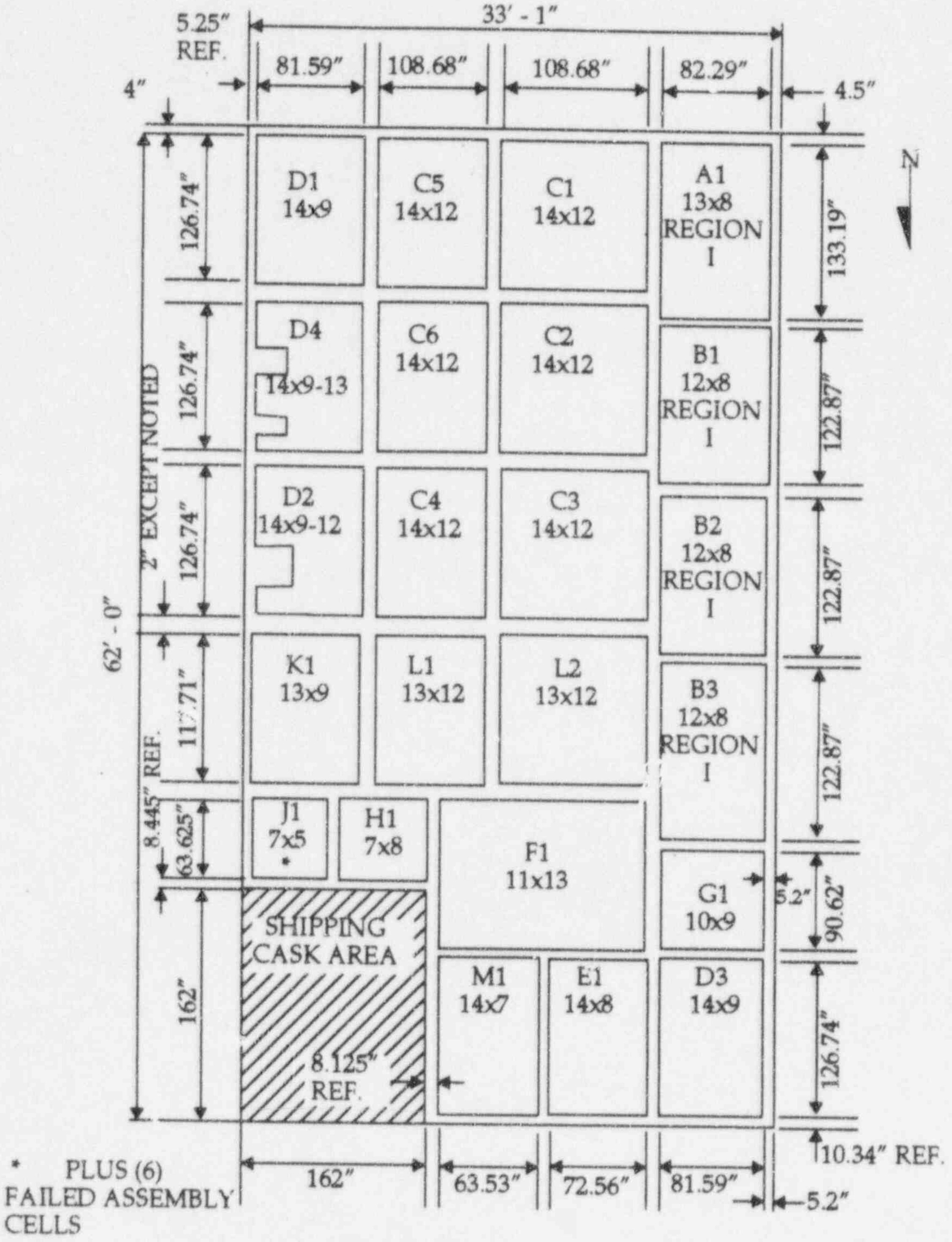


Figure 5. Byron/Braidwood Failed Assembly Spent Fuel Pool Storage Cell Nominal Dimensions



* PLUS (6) FAILED ASSEMBLY CELLS

Figure 6. Byron/Braidwood Spent Fuel Pool Layout

1.14 w/o	1.14 w/o
1.14 w/o	1.14 w/o

Region 2 All Cell Storage

1.64 w/o	1.64 w/o
Empty Cell	1.64 w/o

Region 2 3-out-of-4 Storage

4.10 w/o	Empty Cell
Empty Cell	4.10 w/o

Region 2 2-out-of-4 Storage

Note: All values are initial nominal enrichments.

Figure 7. Byron/Braidwood Region 2 Spent Fuel Storage Configurations

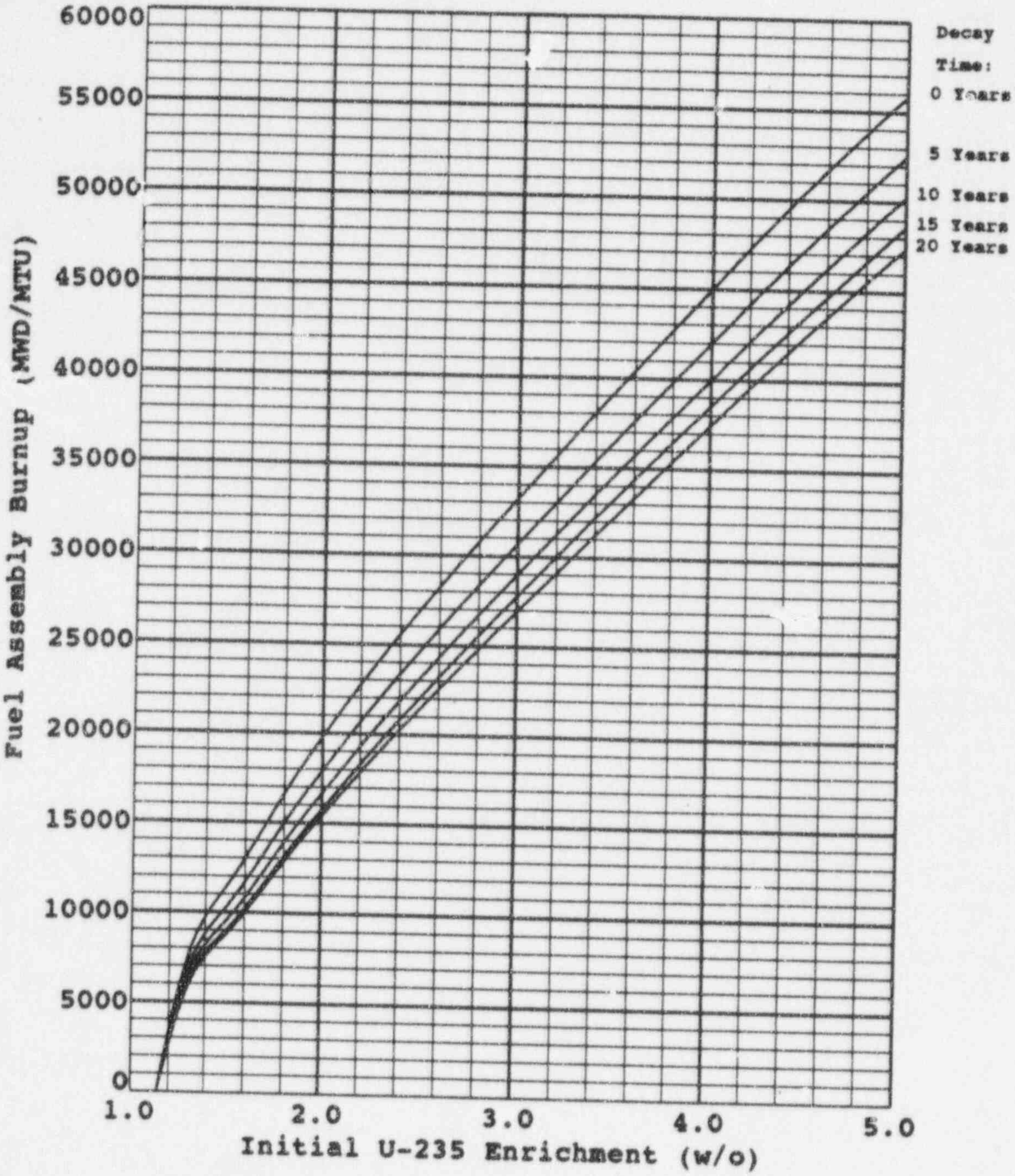


Figure 8. Byron/Braidwood Region 2 All Cell Configuration Burnup Credit Requirements

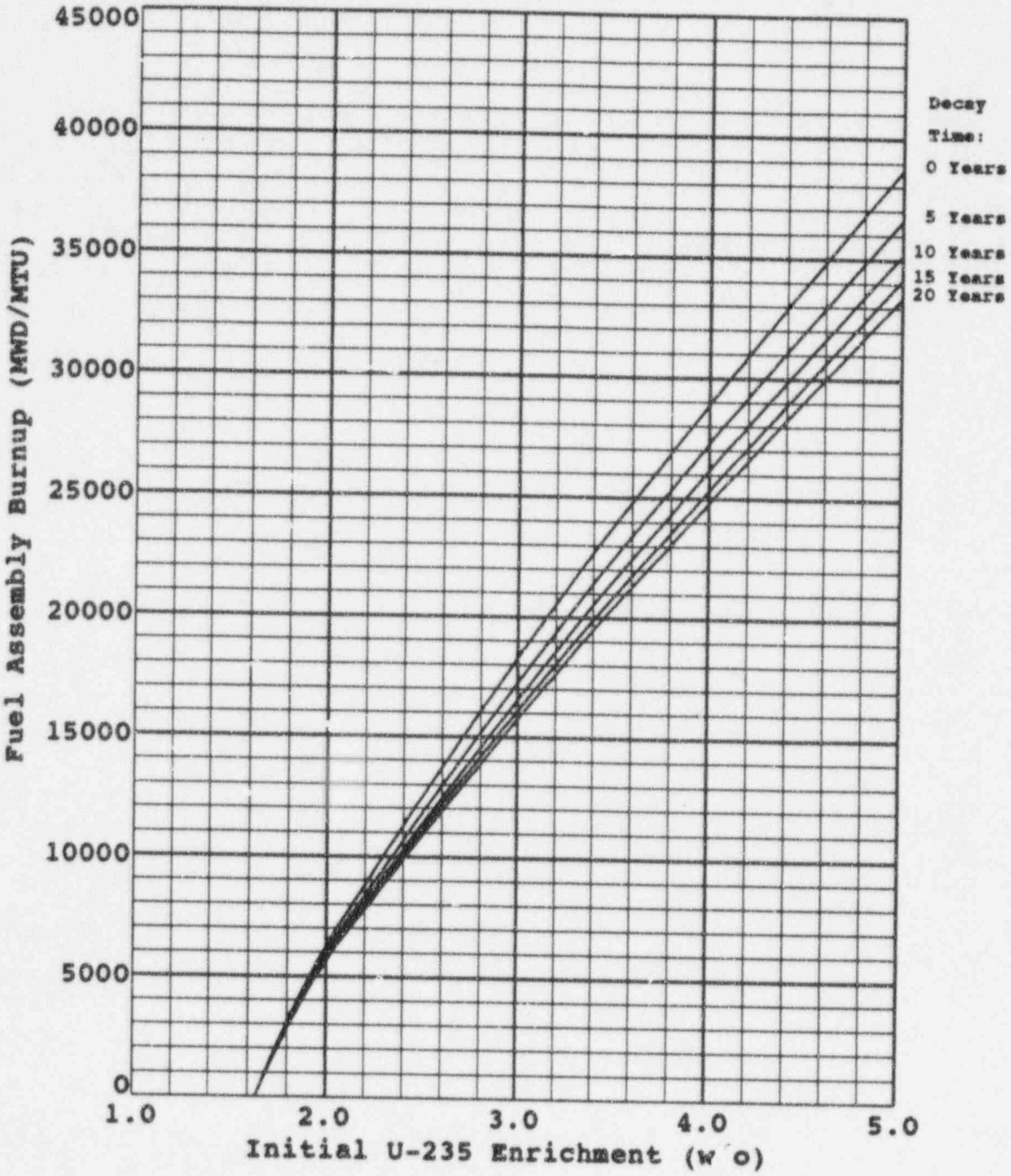


Figure 9. Byron/Braidwood Region 2 3-out-of-4 Checkerboard Configuration Burnup Credit Requirements

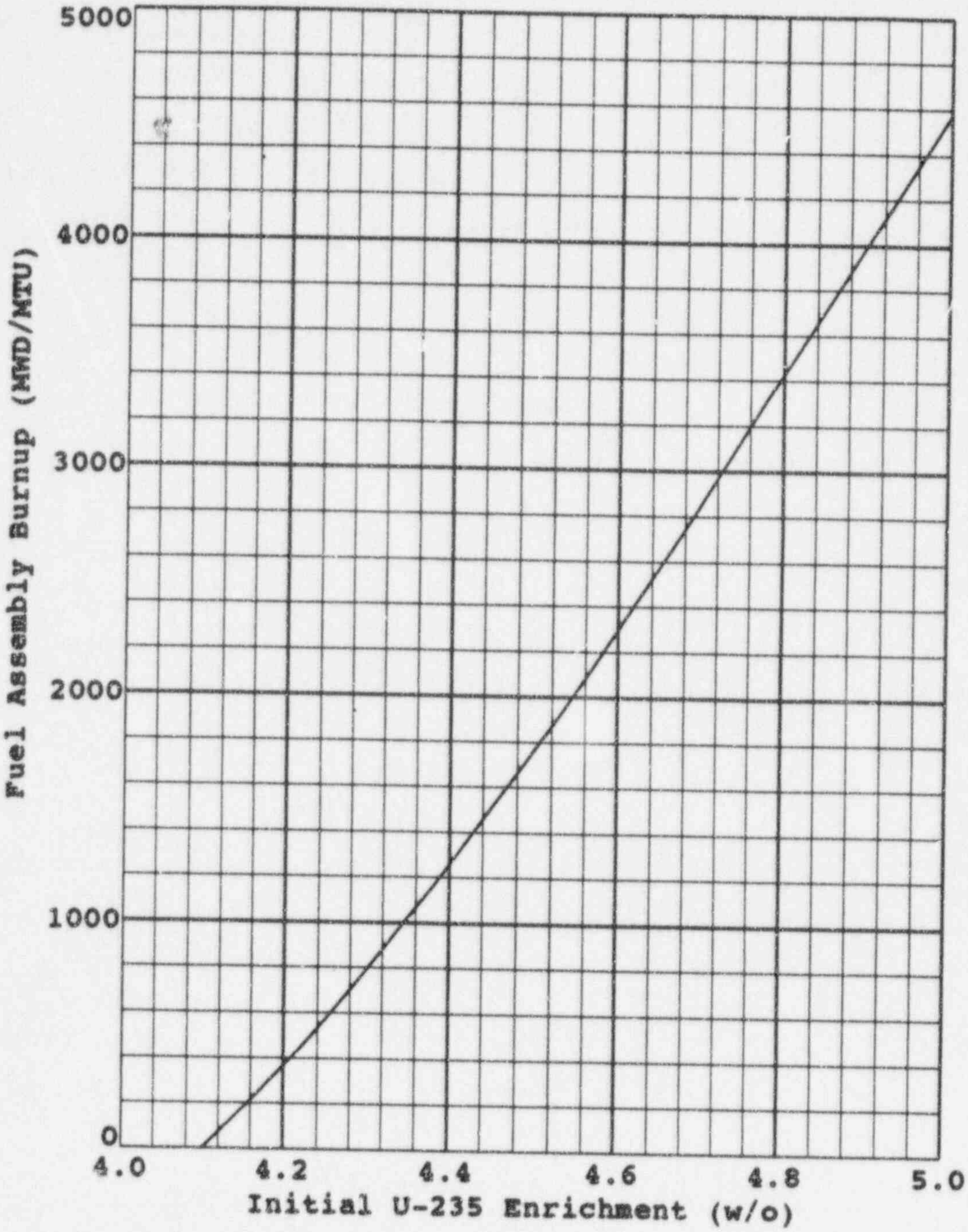
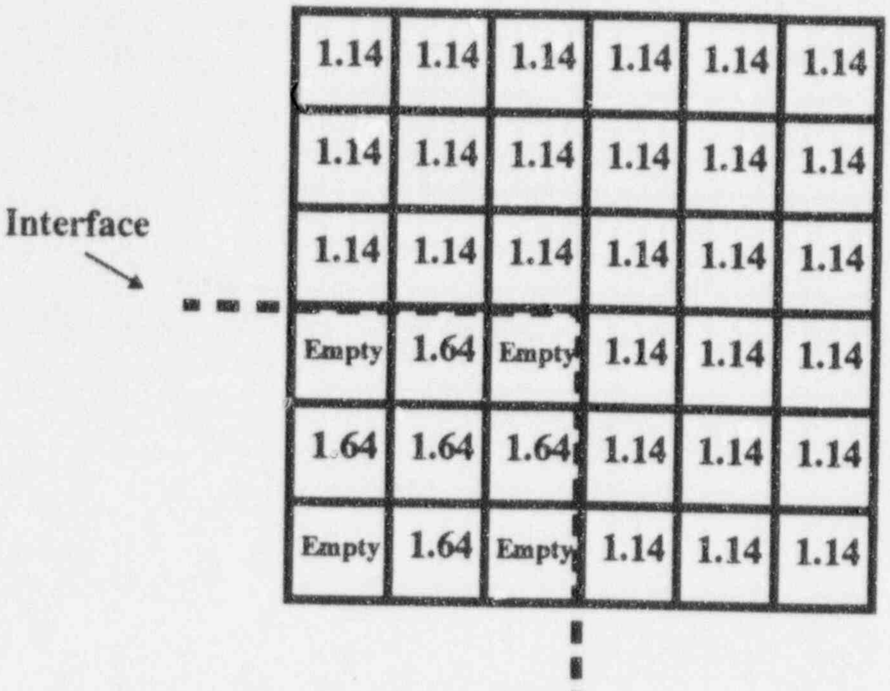
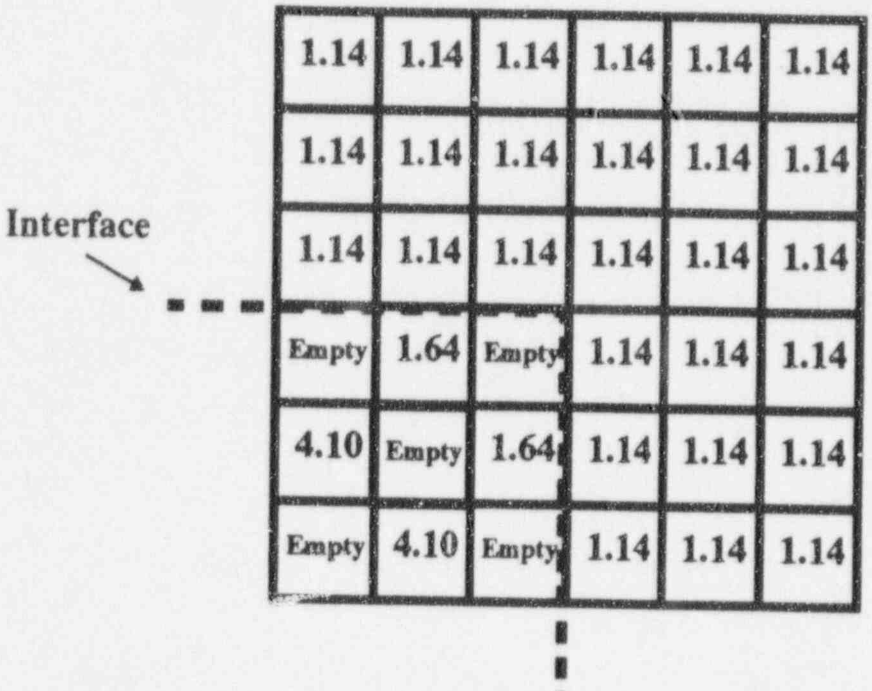


Figure 10. Byron/Braidwood Region 2 2-out-of-4 Checkerboard Configuration Burnup Credit Requirements



1.14	1.14	1.14	1.14	1.14	1.14
1.14	1.14	1.14	1.14	1.14	1.14
1.14	1.14	1.14	1.14	1.14	1.14
Empty	1.64	Empty	1.14	1.14	1.14
1.64	1.64	1.64	1.14	1.14	1.14
Empty	1.64	Empty	1.14	1.14	1.14

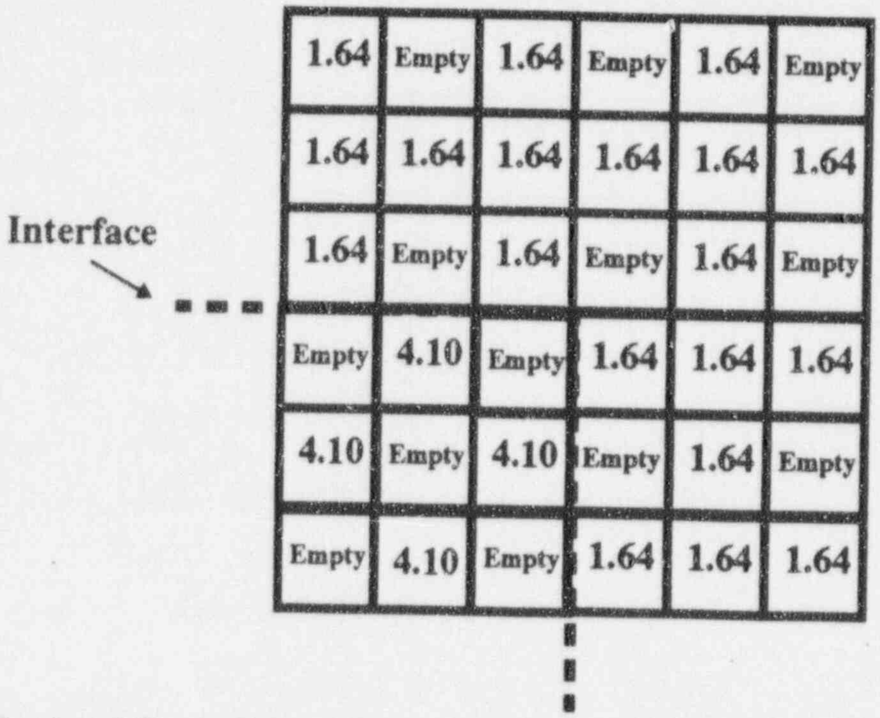
Region 2 Boundary Between All Cell Storage and 3-out-of-4 Storage



1.14	1.14	1.14	1.14	1.14	1.14
1.14	1.14	1.14	1.14	1.14	1.14
1.14	1.14	1.14	1.14	1.14	1.14
Empty	1.64	Empty	1.14	1.14	1.14
4.10	Empty	1.64	1.14	1.14	1.14
Empty	4.10	Empty	1.14	1.14	1.14

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

Figure 11. Region 2 Interface Requirements (All Cell Storage to Checkerboard Storage)



1.64	Empty	1.64	Empty	1.64	Empty
1.64	1.64	1.64	1.64	1.64	1.64
1.64	Empty	1.64	Empty	1.64	Empty
Empty	4.10	Empty	1.64	1.64	1.64
4.10	Empty	4.10	Empty	1.64	Empty
Empty	4.10	Empty	1.64	1.64	1.64

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

Figure 12. Region 2 Interface Requirements (Checkerboard Storage Interface)

Bibliography

1. Newmyer, W.D., *Westinghouse Spent Fuel Rack Criticality Analysis Methodology,* WCAP-14416-NP-A, Revision 1, November 1996.
2. Newmyer, W.D., et al, *Byron and Braidwood Spent Fuel Rack Criticality Analysis Considering Boraflex Gaps and Shrinkage,* June 1994.
3. Newmyer, W.D., et al, *Byron and Braidwood Region 2 Spent Fuel Rack Criticality Analysis With Empty Cell Checkerboarding,* January 1995.
4. Davidson, S. L., et al, *VANTAGE 5 Fuel Assembly Reference Core Report, Addendum 1,* WCAP-10444-PA, March 1986.

ATTACHMENT F

BYRON/BRAIDWOOD
SPENT FUEL POOL DILUTION ANALYSIS

REVISION 3

June 18, 1997

Westinghouse
Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230 0355

June 18, 1997

97CB-G-0095

Ref. 1) 97CB-G-0088,
5/29/97

Mr. John Thomasen
Commonwealth Edison Company
Nuclear Fuel Services
1400 Opus Place - Suite 400
Downers Grove, IL 60515

Dear Mr. Thomasen:

COMMONWEALTH EDISON COMPANY
BYRON/BRAIDWOOD NUCLEAR POWER PLANT
Revision 3 to the Boron Dilution Analysis for Boron Credit CRGR Update

Attached is Revision 3 to the final report for the Boron Dilution Analysis of the Boron Credit CRGR update. The purpose of this revision is to incorporate comments received from ComEd subsequent to the transmittal of Rev. 2 (Ref. 1) based on the attached ComEd NDIT and On-Site Review report.

Please contact me on (412) 374-2112 if you require additional information on these analyses.

Sincerely,

M. J. Weber
Project Engineer
ESBU Commercial Operations

MJW/sh
Attachment

cc: All without attachment unless noted

D. Beddingfield	W PSFS Chicago	
L. Kepley	ComEd Braidwood	
J. Nevling	Fuel Department	
K. S. Petersen	Fuel Department	
D. Redden		
K. Kovar	ComEd Byron	
E. H. Young		
H. Kim		
G. Gosbee	ComEd Braidwood	w/attachments
K. Elam	ComEd Byron	w/attachments

97cbg0088.doc

Nuclear Design Information Transmittal

☒ Safety-Related ☐ Non-Safety-Related ☐ Regulatory Related	Originating Organization: ☒ ComEd ☐ Other (specify) ______	NDIT No. BRW-DIT-97-195

Station: Braidwood Unit(s): 0

Design Change Authority No.: ______

System Designation: FH

Page 1 of ~~2~~ 3
6/16/97

To: Gary J. Corpora, Westinghouse Electric Corporation

Subject:

Boron Dilution Analysis Documentation Supplement

Greg Gosbee Preparer	SED Engineer Position	Preparer's Signature	6/16/97 Date
Dave Graves Reviewer	SED FH Engineer Position	Reviewer's Signature	6/16/97 Date

Status of Information: ☒ Approved for Use ☐ Unverified ☐ Engineering Judgment

Method and Schedule of Verification for Unverified NDITs:

Description of Information:

The attached information documents the volume of the Boron Recycle System Hold-up Tank and the soon to be revised Condensate Storage Tank volume.

Purpose of Issuance: To provide Westinghouse Corporation with necessary plant specific data needed to support the Byron/Braidwood Spent Fuel Pool Boron Dilution Analysis, which in turn is needed to support a Byron/Braidwood Tech Spec amendment which assumes all Boraflex material is gone. This NDIT is a supplement to NDIT #BRW-DIT-97-119.

Source of Information: The sources of the information are listed individually.

Distribution: L. Kepley, G. Gosbee, K. Kovar (Byron), J. Thomasen (Nuclear Fuel Services), G. Corpora (W).

File No.: ______ **CHRON No.:** ______

1. Boron Recycle System HUT Volume

Volume of the Boron Recycle System Hold-up tank.

Braidwood's Answer: 125,000 gallons

Source: Sargeant and Lundy Braidwood Station drawing, M-65, Rev. BA

Prepared by: Date: 6/16/97

Verified by: Date: 6/16/97

Page 2 of 3

2. Volume of the Condensate Storage Tank

Volume of the Condensate Storage tank at Braidwood Station only. The CST volume will be greater than the current 500,000 gallon capacity, after the modification to increase its volume occurs within the next few years.

Braidwood's Answer: 650,000 gallons

Source: Exempt Change number E20-2-96-209-2002

Prepared by: Date: 6/16/97

Verified by: Date: 6/16/97

On-Site Review 97-064

ACCEPTANCE OF WESTINGHOUSE SPENT FUEL POOL (SFP) DILUTION ANALYSIS

PURPOSE:

The purpose of this On-Site Review is to document the review and acceptance by Byron Station of the Westinghouse Report "SPENT FUEL POOL DILUTION ANALYSIS" that describes the possible dilution paths of the SFP and the resulting significance of them. The purpose of the review is to verify:

1. The inputs used by Westinghouse in the analysis are correct, and
2. Westinghouse's methodologies and assumptions are valid when applied to ComEd.

EXECUTIVE SUMMARY:

ComEd is pursuing Boron Credit for the Criticality Analysis for the Byron and Braidwood SFPs. In order to support such a Licensing Amendment Request, a deterministic analysis of the possibility for dilution of the SFP below the boron concentration that ensures k_{eff} remains below 0.95 must be performed and submitted to the NRC.

The methodology of the Westinghouse analysis was to:

1. Identify all possible dilution paths,
2. Calculate a bounding flowrate for each path, and
3. Determine the resulting dilution from each event.

The limiting dilution event was then evaluated for mitigating factors. The conclusion of this evaluation was that the limiting dilution event would be introduction of PW through the FC purification loop since this flowpath is allowed by Station procedures and is, therefore, a viable scenario. The results of this event would be a bounding dilution flowrate of 220 gpm, causing a SFP High Level alarm within 40 minutes, the PWST losing 91,000 gallons of water, and high Aux. Bldg. Sump levels. These conditions would have to be ignored or ineffectively addressed for 7 hours prior to the SFP boron concentration decreasing to 1650 ppm, where k_{eff} could reach 0.95.

It must be noted that more severe scenarios were postulated. The most severe event would be a failure of a 3" WM station in the FHB that would spray 420 gpm of demin water straight into the pool. This would result in reaching the SFP high level alarm within 21 minutes and reaching 1650 ppm within 3 hours 36 minutes. However, proper end caps, caution cards, and procedural controls are believed to be in place to prevent this event. It must also be further noted that should localized or complete dilution of the SFP to 0 ppm occur, criticality in the pool would still be prevented ($k_{eff} < 1.0$) due to the double acceptance criteria of the SFP Criticality Analysis.

BASES FOR FINDINGS AND RECOMMENDATIONS:

Upon review of the attached report, all credible dilution sources have been identified.

An additional dilution source was identified by this review that was not included in the report. The hydraulic system for the Fuel Transfer System uses demin water for its fluid. Should this system develop a leak, the contents of its small reservoir could dilute the SFP. The manual makeup valve from WM to this reservoir is normally closed and thus does not pose a concern. If the makeup valve were inadvertently left open when a leak occurs, the flow through the ¾" line would be bounded by other scenarios.

Also, it was identified that there are 4, not 3, Station Heat fan heaters on the 426' elevation of the Fuel Handling building. The fourth fan heater is tucked on the west side of the Z-15 I-beam pillar such that it could not direct a spray of water into the SFP or berm area. Even if it could spray water into the SFP from its location, the consequences of the event would be negligibly affected since the limiting factor for this event is the 130 gpm makeup to the surge tank once the initial 6000 gallons in the surge tank is emptied.

Upon the review of the Calc Note and methodology, it is believed all results are conservative.

1. Dilution flowrates are assumed high. For example, any missing information from piping isometrics yielded the assumption of no resistance to flow in the missing section. A nominal 30% reduction in piping resistance was applied to a certain computer code output.

2. The volume of the SFP was assumed low. The Cask Pit was left out of the volume even though the sluice gate is normally open. The SFP was assumed to be totally full of fuel assemblies, but the volume calculated was still nearly 20,000 gallons more than a UFSAR assumed volume. The UFSAR volume was conservatively used. This should bound any other items that could possibly be in the SFP. The level is always assumed to be at the low level alarm at the beginning of any dilution event.

3. Dilution source volumes are assumed high.

4. The initial SFP boron concentration is assumed to be at the Tech Spec Limit of 2000 ppm even though admin controls normally maintain the boron concentration above 2300 ppm.

The assumption of complete mixing of the SFP volume is reasonable. Even if FC system flowrate is only 4000 gpm, the entire content of the SFP is still turned over in about 2 hours. Considering the natural convention due to decay heat from the Fuel Assemblies and the fact that the FC suction and discharge piping are physically separated, the turnover of the SFP volume is sufficient to fully mix the SFP during the time for a dilution event to cause the SFP boron concentration to reach 1650 ppm.

Finally, it is believed that there are sufficient administrative controls, alarms, indications, and operating practices to preclude any of these dilution events from occurring.

CONTINGENCY ACTIONS:

There are no contingency actions required by this OSR.

LIST OF ATTACHMENTS:

1. BYRON/BRAIDWOOD SPENT FUEL POOL DILUTION ANALYSIS, May 14, 1997

BYRON/BRAIDWOOD

SPENT FUEL POOL DILUTION ANALYSIS

Prepared By: Gary J. Corpora

Verified By: K N

Rev. 3, 6/17/97

WESTINGHOUSE ELECTRIC CORPORATION

Table of Contents

FIGURES

1.0 INTRODUCTION

A boron dilution analysis has been completed for crediting boron in the Byron and Braidwood spent fuel rack criticality analysis. The boron dilution analysis includes an evaluation of the following plant specific features:

- Dilution Sources
- Boration Sources
- Instrumentation
- Administrative Procedures
- Piping
- Loss of Offsite Power Impact
- Boron Dilution Initiating Events
- Boron Dilution Times and Volumes

The boron dilution analysis was completed to ensure that sufficient time is available to detect and mitigate the dilution before the spent fuel rack criticality analysis 0.95 k_{eff} design basis is exceeded.

2.0 SPENT FUEL POOL AND RELATED SYSTEM FEATURES

This section provides background information on the spent fuel pool and its related systems and features. A one-line diagram of the spent fuel pool related systems is provided as Figure 1. The spent fuel pool is shared between the two Units at Byron and at Braidwood. For the purposes of this evaluation, the spent fuel pool and its related systems are sufficiently similar between Byron and Braidwood that they will be treated as identical. Any significant differences will be identified, so that this report will be bounding for all four Units.

2.1 Spent Fuel Pool

The design purpose of the spent fuel pool is to provide for the safe storage of irradiated fuel assemblies. The pool is filled with borated water. The water removes decay heat, provides shielding for personnel handling the fuel, and reduces the amount of radioactive gases released during a fuel handling accident. Pool water evaporation takes place on a continuous basis, requiring periodic makeup. The makeup source can be unborated water, since the evaporation process does not carry off the boron. Evaporation actually increases the boron concentration in the pool.

The spent fuel pool is a reinforced concrete structure with a minimum 3/16 inch welded steel liner. The water-tight liner has dedicated drain lines with sight glasses to collect and detect liner leakage. The pool structure is designed to meet seismic requirements. The pool is approximately 39 feet deep. The top of the pit is located on the 426' elevation of the fuel handling building. The bottom of the pit is at the 385' elevation.

There are 31 ventilation openings located approximately 7" above the normal water level. Each opening is designed to pull 400 CFM from the pool surface to minimize uncontrolled escape of tritium through evaporation. In the event of excessive makeup flow into the pool, the pool would overflow into the scupper to be collected in the floor drain system, preventing entry into the ventilation system. On the floor elevation there is a 4" curb surrounding the pool and an overflow opening to the refueling canal. The curb, in addition to an open floor drain, minimizes any pool dilution source from the floor elevation level.

As shown in Figure 2, the pool area includes a dry cask loading pit which is connected to the pool through normally open gates. This pit contains pool water, but is normally used to store tools. A transfer canal lies adjacent to the two pools and connects to the reactor refueling water cavity for either Unit during refueling operations. The pool and the transfer canal are connected by fuel transfer slots that can be closed by pneumatically sealed gates. The accidental opening of the gates, if the canal were dry, would lower the water level approximately 6'-10", leaving 19'-2" of water over the top of the active fuel. The elevation of the top of the gates, when installed, is approximately just below the floor level of the spent fuel pool area. The removable gates are designed to support the full height of water remaining on the pool side after the canal side is completely drained.

The gates between the pool and the transfer canal are normally closed. The volume of the pit, including the cask loading pit, is approximately 560,000 gallons to the low level alarm elevation of 424'-2". The majority of the water volume displaced by objects in the pit is by the spent fuel assemblies. The maximum number of assembly locations is 2870. Currently, several of these locations are unusable. However, Byron is considering a re-rack design which would upgrade the unusable sites to usable status. Since it is conservative to assume all sites are usable, the volume of all 2870 assemblies (53,000 gallons) is subtracted from the total pit volume. The racks themselves occupy a relatively small volume(7300 gallons), but they are subtracted as well. Finally, since the cask loading pit has no means to recirculate its water volume with that of the pit(although the gate is normally open), its volume will be neglected. When the above volumes are subtracted from the pit volume, the remaining water volume is conservatively rounded down to 474,000 gallons at the low level alarm setpoint elevation of 424'-2".

2.2 Spent Fuel Storage Racks

The spent fuel racks are designed to support and protect the spent fuel assemblies under normal and credible accident conditions. Their design ensures the ability to withstand combinations of dead loads, live loads (fuel assemblies), and safe shutdown earthquake loads.

2.3 Spent Fuel Pool Cooling System

The spent fuel pool cooling system is designed to remove, from the shared spent fuel pool, the heat generated by stored spent fuel elements. System design does not incorporate redundant active components except for the spent fuel pool pump and heat exchanger. Alternate cooling capability can be made available under anticipated malfunctions or failures. System piping is configured so that failure of any pipeline in the cooling system does not drain the spent fuel pool below the top of the stored spent fuel assemblies.

The system is capable of handling a maximum heat load with 84 normally discharged fuel assemblies plus a freshly off loaded core consisting of 193 fuel assemblies.

The portion of the spent fuel pool cooling system which, if it failed, could result in a significant release of pool water is seismically designed.

Each of the two trains of the cooling system consists of a pump, a heat exchanger, valves, piping and instrumentation. The pump takes suction from the fuel pool at an inlet located below the pool water level, transfers the pool water through a heat exchanger and returns it back into the pool through an outlet located below and a large distance away from the cooling system inlet. The return line is designed to prevent siphoning. The heat exchangers are cooled by component cooling water.

2.4 Spent Fuel Pool Cleanup System

The spent fuel pool cleanup system is designed to maintain water clarity and to control borated water chemistry. The cleanup system is connected to the spent fuel pool cooling system. About 100 gpm of the spent fuel pool cooling pump(s) discharge flow can be diverted to the cleanup loop, which includes the spent fuel pool demineralizers and filters. The filters remove particulates from the spent fuel pool water and the spent fuel pool demineralizer removes ionic impurities.

The refueling water purification loop also uses the spent fuel pool demineralizer and filters to clean up the refueling water storage tank after refueling operations. The flow rate in the loop is limited to 100 gpm to accommodate the design flow of the spent fuel pool demineralizer.

The spent fuel pool has a surface skimmer system designed to provide optical clarity by removing surface debris. The system consists of two surface skimmers, a single strainer, a single pump and one filter. The skimmer pump is a centrifugal pump with a 100 gpm capacity. The pump discharge flow passes through the filter to remove particulates. It returns to the spent fuel pool.

2.5 Dilution Sources

2.5.1 Chemical and Volume Control System (CVCS)

The Chemical and Volume Control System (CVCS) connects with the spent fuel pool cooling system via the boric acid blender. Primary water and concentrated boric acid are supplied to the blender at pre-determined flow rates to generate water at a desired boron concentration. This connection is used to supply water (primary water blended with borated water) at a specific boron concentration to the pools. The connection is downstream of the boric acid blender and is isolated by a normally closed valve and a blind flange. When makeup is required, a connection is made at the flange and a 50 foot length of 1.5" hose is run to the spent fuel pool. The supply from the blender to the spent fuel pool cooling system can have a boron concentration from 0 to 7700 ppm depending on the control setting for the blender. This connection is a source of makeup water if the pools are losing inventory. When delivering blended flow, this connection can deliver a flow rate of 160 gpm to the spent fuel pool. Should the primary water flow control valve fail open during makeup from this source, the flow would increase to approximately 185 gpm.

2.5.2. Boron Recycle System (BRS)

The BRS connects to the spent fuel pool at two locations. The first connection is a 3" line from the outlet of the spent fuel pool heat exchangers to the BRS recycle holdup tanks. This connection is normally isolated and is used to transfer water from the spent fuel pool to the BRS recycle holdup tanks. The isolation is by one manual valve.

There is no check valve between the BRS recycle holdup tanks and this connection to the spent fuel pool cooling system. However, it is not credible that water would back up from the tank to the spent fuel pool cooling system. In the situation where the BRS recycle holdup tank is misaligned to the spent fuel pool through this connection, water from the spent fuel pool cooling system would flow to the tank due to available elevation head. Thus, this path would only result in the loss of water from the pool if the normally closed valve were to fail or be left open. The holdup tanks also have a high level alarm, which annunciates in the control room.

The second connection between the spent fuel pool and the BRS is from the BRS recycle evaporator feed pump discharge header to the transfer canal suction/discharge piping. This is a normally isolated

3" line that is an additional source of makeup water to the pool/transfer canal. The rate of addition is up to approximately 100 gpm. Two normally closed manual valves are used to isolate this connection.

The recycle evaporator feed pumps can take suction off either of the two BRS recycle holdup tanks. However, by procedure, only one pump is aligned to one holdup tank at a time. Manual valve manipulations are required to switch the pump suction to another tank. Each BRS recycle holdup tank has a total volume of approximately 125,000 gallons and can be at a boron concentration from 0 ppm up to 2500 ppm.

2.5.3 Primary Water System

The primary water (reactor makeup) system connects to the spent fuel pool cooling system directly in the cleanup subsystem, and indirectly through the boric acid blender (Section 2.5.1), the spent resin flushing pump, and the local station in the spent fuel pit area. Using the direct connection, the contents of the primary water storage tank can be transferred directly to the spent fuel pool cooling system via the primary water pumps. The direct connection is normally isolated from the primary water system by a closed manual valve. Primary water can enter the system either downstream of the spent fuel pit filter or downstream of the spent fuel pit demineralizer filter. The latter flow path has less resistance and therefore can pass a higher flow rate of primary water. This flow rate is estimated to be 220 pgm. The direct connection is used as the normal water supply to the spent fuel pool and is a source of makeup water in case of a loss of spent fuel pool inventory. This same connection is also used to flush spent resin from the spent fuel pit demineralizers to the disposal facility.

The primary water system consists of two primary water storage tanks and two primary water pumps shared between both Units. During normal operation, one primary water pump is running on recirculation to provide primary water on demand to multiple users. Each primary water storage tank contains approximately 500,000 gallons of non-borated, reactor grade water.

When primary water is used to flush spent resin, the demineralizer is isolated from the cleanup loop by one manual valve. If this valve were left open, primary water could be transferred into the spent fuel pit. This flow alignment would be the same as for normal makeup to the spent fuel pit. The flow from this pathway, as stated above, is estimated to be 220 gpm.

The primary water pump can also be used to boost or to bypass the spent resin flushing pump for resin transfer. Neither alignment is used or covered by procedure at Byron, but the pump bypass is used at Braidwood. Primary water can enter the spent fuel pool cleanup loop during a spent fuel pit demineralizer spent resin transfer operation if the demineralizer process outlet isolation valve is left open. Flow from this pathway is estimated to be 195 gpm.

Finally, the 2" primary water station in the spent fuel pit area is isolated by a normally closed valve and a capped connection. The flow from this pathway is estimated to be 256 gpm.

2.5.4 Demineralized Water System

The demineralized water system takes suction from a condensate storage tank and a demineralized flushing water pump for each Unit. Byron's condensate storage tank is 500,000 gallons, while Braidwood has proposed a modification to increase its tank volume to 650,000 gallons. Each discharge header includes seven demineralized water hose stations in the vicinity of the pool: four 3/4" lines, two 2" lines, and one 3' line. Each of these stations includes a normally closed valve, a capped connection, and a warning tag to contact the Shift Engineer or Fuel Handling Supervisor to evaluate the impact of the water addition. The maximum flow from one of the 2" supply lines is estimated to be 340 gpm. The maximum flow from the 3" supply line is estimated to be 420 gpm. These flows are considered to bound flow from the 3/4" lines.

2.5.5 Component Cooling Water System

Component cooling water is the cooling medium for the spent fuel pool cooling system heat exchangers. There is no direct connection between the component cooling system and the spent fuel pool cooling system. If, however, a leak were to develop in a heat exchanger that is in service, the connection would be made. Since the component cooling system normally operates at a slightly higher pressure than the spent fuel pool cooling system, it is expected that a breach in a spent fuel pool cooling system heat exchanger tube would result in non-borated component cooling water entering the spent fuel pool cooling system.

It would be expected that the flow rate of any leakage of component cooling water into the spent fuel pool cooling system would be very low due to the small difference in operating pressures between the two systems. Even if there was significant leakage from the component cooling water system to the spent fuel pool, the impact on the spent fuel pool boron concentration would be minimal because a loss of water from the component cooling water surge tank would initiate alarms and control room indications to alert the control room operators.

If the alarms which would alert the control room operators of a component cooling water system leak were to fail and leakage from the component cooling water system to the spent fuel pool cooling system were to continue undetected, the component cooling water surge tank would be periodically refilled with water from a makeup system. Since the component cooling surge tank would be refilled from the primary water and/or demineralized water systems, this scenario would be bounded by the dilution events discussed in Section 2.5.2 and 2.5.3.

Because a spent fuel pool heat exchanger leak is bounded by other analyzed events, it is not considered further in this analysis.

2.5.6 Drain Systems

The equipment or floor drain systems connect directly to the spent fuel pool cooling system and skimmer system at the drain connections for the spent fuel pit pumps, heat exchangers (tube side), filters, demineralizers, demineralizer filters, the skimmer pump, and skimmer filter. Each connection has a normally closed valve to isolate it. Back flow through these paths is not considered credible, because the situation would cause water to back up through floor drains in a number of locations before getting into the spent fuel pool cooling system.

2.5.7 Fire Protection System

In the case of a loss of spent fuel pool inventory, three local fire hose stations are potential makeup sources. Each of these stations is capable of providing 191 gpm of non-borated water under normal conditions. Any planned addition of fire system water to the spent fuel pool would be under the control of an approved procedure and the effect of the addition of the non-borated water from the fire system on the spent fuel pool boron concentration would be addressed.

There are fire protection hose supply lines located under the hose stations outside the spent fuel pool area. If any of these lines were to break, a significant amount of water would, if not isolated by operator action, be released into the area outside and beneath the spent fuel pool area. The fire protection system contains instrumentation which would alarm in the control room should this type of flow develop in the fire protection system. Thus, the break of any of the fire protection hose supply lines is not considered further in this analysis.

2.5.8 Reverse Osmosis System

In addition to the permanently installed spent fuel pool cleanup system, there is a portable skid-mounted reverse osmosis system that can be used to remove silica from the spent fuel pool. The system is part of a separate, single loop which takes suction directly from the spent fuel pool, passes the water by the reverse osmosis membrane and then returns it to the spent fuel pool. The system operates at up to 67 gpm. Along with the removal of the silica, the system will remove some amount of boron and thus requires special administrative controls when placed in service.

Based on Byron operating data, the reverse osmosis system removes up to 65% of the boron from the spent fuel pool water that passes through the system. As a result, the reverse osmosis system will be considered a 67 gpm source of non-borated water to the spent fuel pool. However, unlike the dilution sources discussed above, dilution of the spent fuel pool resulting from operation of the reverse osmosis system will not result in an increase in the spent fuel pool level.

2.5.9 Spent Fuel Pit Demineralizers

The two spent fuel pit demineralizers each have a maximum capacity of 39 ft^3 of 1:1 equivalent mixed bed resin. This implies a volume ratio of 60%/40% anion to cation resin. If we assume the beds were loaded with 100% anion, it would bound the capacity to remove boron when it is first aligned to the system. Each demineralizer would be operated at a nominal 100 gpm flow rate. Similar to the reverse osmosis package, dilution of the spent fuel pool resulting from operation of the demineralizer will not result in an increase in the spent fuel pool level.

2.5.10 Station Heating System

This closed system supplies hot water to four fan heaters in the spent fuel pit area. However, only three fans are close to the spent fuel pit. The system includes a 6000 gallon surge tank and a recirculation pump. Since the system is not seismically designed, it is assumed that the fans break off during an earthquake, exposing the 1" feed and return water lines which blow down directly into the spent fuel pit. It is estimated that up to 420 gpm could blow down from each fan, or a total of 1260 gpm from the system. The volume of the system is consists primarily of the surge tank. However, automatic makeup is provided from the demineralized water system through a 1.5" line which is aligned on low surge tank pressure.

2.5.11 Dilution Source and Flow Rate Summary

Based on the evaluation of potential spent fuel pool dilution sources summarized above, the following dilution sources were determined to be capable of providing a significant amount of non-borated water to the spent fuel pool. The potential for these sources to dilute the spent fuel pool boron concentration to the design basis boron concentration (550 ppm) will be evaluated in Section 3.0.

SOURCE	APPROXIMATE FLOW RATE (GPM)
CVCS	
- CVCS Blender	185
BRS	
- Holdup Tank to Transfer Canal	100
Primary Water System	
- SFP demineralizer filter outlet (makeup)	220
- SFP demineralizer filter outlet (resin flush)	220
- via Spent Resin Flushing Pump	195
- 2" PW station near SFP	256
Demineralized Water System	
- 2" station at SFP	340
- 3" station at SFP	420
Fire Protection System	
- Fire hose station at SFP	191
Reverse Osmosis System	67
SFP Demineralizers	200
Station Heating System	
- Heater hot water lines	1260

2.6 Boration Sources

The normal source of borated water to the spent fuel pool is from the refueling water storage tank. An alternate source of borated water to the spent fuel pool is through the blender and a temporary connection in the Chemical and Volume Control System. It is also possible to borate the spent fuel pool by the addition of dry boric acid directly to the spent fuel pool water.

2.6.1 Chemical and Volume Control System

The Chemical and Volume Control System (CVCS) is the alternate borated makeup source for the spent fuel pool. The CVCS blender is connected to the spent fuel pool cooling system by a temporary 1.5" hose connection. This connection is used to supply water at a specific boron concentration to the pools. Concentrated boric acid is supplied to the CVCS blender from boric acid tanks via the boric acid transfer pumps. Primary water is supplied to the CVCS blender from the primary water storage tanks via the primary water pumps. Flow controllers are used to control the boric acid and primary water flow rates to the blender and to establish the desired boron concentration in the water being sent to the spent fuel pool. The rate of addition through this connection is up to 160 gpm when providing blended flow. The supply from the blender to the spent fuel pool cooling system can have a boron concentration of up to approximately 2300 ppm depending on the control setting for the blender.

Alternatively, the makeup system can be set to provide only boric acid flow to the spent fuel pit. In this mode, the flow is limited to 40 gpm, but the concentration can be as high as 7700 ppm. The mass injection rate of boron is higher in this mode than in the blended mode described above.

2.6.2 Refueling Water Storage Tank

Both the Unit 1 and Unit 2 refueling water storage tanks (RWST) connect to the spent fuel pool through separate inlet and outlet lines. These connections are used to purify the RWST water when the purification loop is isolated from the spent fuel pool cooling system. Normally, these connections can each supply borated water to the spent fuel pool via the refueling water purification pumps to the inlet to the spent fuel pit cooling system purification loop. Both refueling water purification pumps are powered from a safeguards bus power supply. They must be re-started manually following a loss of offsite power. The RWSTs are required by Technical Specifications to be kept at a minimum boron concentration of 2300 ppm.

2.6.3 Direct Addition of Boric Acid

If necessary, the boron concentration of the spent fuel pool can be increased by emptying bags of dry boric acid directly into the spent fuel pool. The dry boric acid will dissolve into the spent fuel pool water and will be mixed throughout the pool by the spent fuel pit cooling system flow and by the thermal convection created by the spent fuel decay heat. (see section 3.1 for further discussion on spent fuel pool mixing.)

2.7 Spent Fuel Pool Instrumentation

Instrumentation is available to monitor spent fuel pool water level and temperature. Additional instrumentation is provided to monitor the pressure and flow of the spent fuel pool cleanup system, and pressure and temperature of the spent fuel pool cooling system.

The instrumentation provided to monitor the temperature of the water in the spent fuel pool is indicated locally and annunciated in the control room. The water level instrumentation alarms, high and low level, are annunciated in the control room. The instrumentation which monitors radiation levels in the spent fuel pool area provides high radiation alarms locally in the spent fuel pool enclosure and in the control room.

A change of one foot in spent fuel pool level with the dry cask loading pit and the transfer canal isolated requires approximately 14,000 gallons of water. If the pool level was raised from the low level alarm point to the high level alarm (7.5"), a dilution of approximately 8750 gallons could occur before an alarm would be received in the control room. If the spent fuel pool boron concentration were at 2000 ppm initially, such a dilution would only result in a reduction of the pool boron concentration of approximately 36 ppm.

2.8 Administrative Controls

The following administrative controls are in place to control the spent fuel pool boron concentration and water inventory:

1. Procedures are available to aid in the identification and termination of dilution events.

2. The procedures for loss of inventory (other than evaporation) specify that borated makeup sources be used as makeup sources. The procedures specify that non-borated sources only be used as a last resort.

3. In accordance with procedures, plant personnel perform rounds in the spent fuel pool enclosure once every eight hours. The personnel making rounds to the spent fuel pool are trained to be aware of the change in the status of the spent fuel pool. They are instructed to check the temperature and level in the pool and conditions around the pool during plant rounds.

4. Administrative controls (warning tags on primary water and demineralized water stations in the spent fuel pit area) are placed on some of the potential dilution paths.

5. The current administrative limit on spent fuel pit boron concentration is a minimum of 2300 ppm.

6. The proposed Technical Specifications associated with the use of soluble boron credit will require spent fuel pool boron concentration to be verified on a frequency commensurate with the results of this analysis.

Prior to implementation of the License Amendment allowing credit for soluble boron in the spent fuel pool criticality analysis, current administrative controls on the spent fuel pool boron concentration and water inventory have been evaluated and procedures were upgraded as necessary to ensure that the boron concentration is formally controlled during both normal and accident situations. The procedures ensure that the proper provisions, precautions and instructions will be in place to control the pool boron concentration and water inventory.

2.9 Piping

There are no systems (other than those listed in section 2.5.1 to 2.5.8) identified which have piping in the vicinity of the spent fuel pool which could result in a dilution of the spent fuel pool if they were to fail.

The fire protection, primary water, and demineralized water line stations, if damaged, could provide a source of spent fuel pool dilution. However, as discussed in Section 3.2, the physical arrangement of the area surrounding the spent fuel pool would limit the amount of water which could flow into the spent fuel pool.

2.10 Loss of Offsite Power Impact

Of the dilution sources listed in Section 2.5.9, only the fire protection system is capable of providing non-borated water to the spent fuel pool during a loss of offsite power.

The loss of offsite power would affect the ability to respond to a dilution event. The spent fuel pool level instrumentation is not powered from emergency diesel generator-backed power supplies. However, emergency power can be manually cross-tied when required.

The CVCS blender makeup system is not available as a source of borated water to the spent fuel pool upon a loss of offsite power. Both refueling water purification pumps are powered from a safeguards supply and would be available to deliver borated water from the RWST. They must be manually re-started following a loss of offsite power. In addition, the RWST can be gravity-drained to the spent fuel pool through the refueling water purification pumps, if necessary, to provide a borated water source. Finally, manual addition of dry boric acid to the pool could be used if it became necessary to increase the spent fuel pool boron concentration during a loss of offsite power.

Currently, the spent fuel pool cooling pumps are not automatically restarted following a loss of offsite power and are supplied by power supplies backed by non-safeguards feeds from the diesel generators. However, safeguards power supplies can be manually aligned to provide power to the pumps, if necessary.

3.0 SPENT FUEL POOL DILUTION EVALUATION

3.1 Calculation of Boron Dilution Times and Volumes

For the purposes of evaluating spent fuel pool dilution times and volumes, the total pool volume available for dilution, as described in section 2.1, is conservatively assumed to be 474,000 gallons.

Based on the criticality analysis (Reference 1), the soluble boron concentration required to maintain the spent fuel pool boron concentration at $k_{eff} < 0.95$, including uncertainties and burnup, with a 95% probability at a 95% confidence level (95/95) is 550 ppm.

The spent fuel pool boron concentration is currently maintained between 2300 and 2400 ppm. If the concentration falls below 2300 ppm, Byron enters a Limiting Condition of Operation Action Requirement procedure and Braidwood uses administrative procedures to restore and monitor the concentration. However, for the purposes of evaluating the dilution times and volumes, the initial spent fuel pool boron concentration is assumed to be at the proposed Technical Specification limit of 2000 ppm. The evaluations are based on the spent fuel pool boron concentration being diluted from 2000 ppm to 550 ppm. To dilute the combined pool volume of 474,000 gallons from 2000 ppm to 550 ppm would conservatively require 612,000 gallons of non-borated water, based on a feed-and-bleed operation (constant volume).

This analysis assumes thorough mixing of all the non-borated water added to the spent fuel pool with the contents of the spent fuel pool. Refer to Figure 3. Based on the design flow of 4500 gpm per spent fuel pit pump, the 474,000 gallon system volume is turned over approximately every two hours with one pump running, which is the normal alignment. It is unlikely, with cooling flow and convection from the spent fuel decay heat, that thorough mixing would not occur. However, if mixing was not adequate, it would be conceivable that a localized pocket of non-borated water could form somewhere in the spent fuel pool. This possibility is addressed by the calculation in Reference 1 which shows that the spent fuel rack K_{eff} will be less than 1.0 on a 95/95 basis with the spent fuel pool filled with non-borated water. Thus, even if a pocket of non-borated water formed in the spent fuel pool, K_{eff} would not exceed 1.0 anywhere in the pool.

The time to dilute the spent fuel pool depends on the initial volume of the pool and the postulated rate of dilution. The dilution volumes and times for the dilution scenarios discussed in Sections 3.2 and 3.3 are calculated based on the following equation:

$t_{end} = \ln (C_o / C_{end}) V/Q$ (Equation 1)

Where:

C_o = the boron concentration of the pool volume at the beginning of the event (2000 ppm)

C_{end} = the boron endpoint concentration (550 ppm)

Q = dilution rate (gallons/minute)

V = volume (gallons) of spent fuel pool (474,000)

t_{end} = time to reach C_{end} (minutes)

3.2 Evaluation of Boron Dilution Events

The potential spent fuel pool dilution events that could occur are evaluated below:

3.2.1 Dilution From BRS Recycle Holdup Tanks

The contents of a BRS recycle holdup tank can be transferred via the recycle evaporator feed pumps directly to the spent fuel pool transfer canal suction/discharge piping. The flow path to the transfer canal is through a line that is isolated by one normally closed valve. This connection is a designated source of makeup water in a loss of spent fuel pool inventory event. Because the flow from the recycle evaporator feed pumps discharges only into the transfer canal, the dilution source from the BRS recycle holdup tanks would not affect the spent fuel pool if it were isolated from the transfer canal. Each of the two BRS recycle holdup tanks has a total volume of approximately 125,000 gallons. The water in the tanks can have a boron concentration from 0 ppm to 2500 ppm. Any amount of boron in the BRS recycle holdup tank water would reduce the dilution of the spent fuel pool resulting from the transfer of BRS recycle holdup tank water to the spent fuel pool. If it is assumed that the transfer canal is connected to the spent fuel pool, the pool volume would increase from 474,000 gallons to approximately 617,000 gallons. To dilute this volume from 2000 ppm to 550 ppm would require 796,000 gallons of unborated water. The combined contents of the two BRS recycle holdup tanks (approximately 250,000 gallons) is less than the required dilution volume.

The BRS recycle evaporator feed pumps can take suction from either of the two BRS recycle holdup tanks. Administrative procedures specify that the pumps are aligned to one holdup tank at a time.

Manual valve manipulations are required to switch the pump suction to another tank. Thus, it is assumed for the purposes of this evaluation that only the contents of one BRS recycle holdup tank is available for a spent fuel pool dilution event. The 125,000 gallons of water contained in one BRS recycle holdup tank is less than the 612,000 gallons necessary to dilute the spent fuel pool/transfer canal from 2000 ppm to 550 ppm. It is also very unlikely that more than one BRS recycle holdup tank would be transferred to the canal during an unplanned dilution event. Finally, the holdup tank contents are transferred directly to the transfer canal, which is connected to the spent fuel pit by only the canal gate and therefore is not well mixed with the spent fuel pool. Because of these factors, the BRS recycle holdup tanks are not considered a credible dilution source for the purposes of this analysis.

3.2.2 Dilution From Primary Water Storage Tanks

The contents of the primary water storage tanks can be transferred via the primary water pumps directly or indirectly to the spent fuel pool.

The primary water system consists of two primary water storage tanks and two primary water pumps shared between both Units. Primary water can be supplied to the spent fuel pool cooling system from the tanks and pumps associated with either Unit. The two primary water storage tanks each contain approximately 500,000 gallons of non-borated reactor grade water. Thus, the contents of one tank is not sufficient to dilute the spent fuel pool from 2000 to 550 ppm.

The path from the primary water pumps to the spent fuel pool via the boric acid blender is limited by the makeup system controls to a maximum of approximately 185 gpm. If the temporary hose connection were left unattended, and assuming the makeup control system were set to provide only primary water (not a blended flow) it would take 47 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 55 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron. If the makeup controls are set to provide borated water, the spent fuel pool dilution rate would be reduced. The controls which supply the non-borated water to the blender utilize an integrator to limit the amount of water that can be supplied to the blender. If the blender controls were set to provide only a limited amount of water, the dilution of the spent fuel pool would be reduced.

This connection is normally isolated from the primary water system by a closed manual valve. It can be used as the normal makeup supply to the spent fuel pool and is a source of makeup water in case of a loss of spent fuel pool inventory event.

The path from the primary water pumps to the spent fuel pool via the connection downstream of the spent fuel pit demineralizer filter can provide approximately 220 gpm. If the manual isolation valve were left unattended, it would take 40 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 46 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

The path from the primary water pumps to the spent fuel pool via the spent fuel pit demineralizer resin flushing connection can provide approximately 195 gpm. If the manual isolation valve were left unattended, it would take 45 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 52 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

The path from the primary water pumps to the spent fuel pool via the 2" station in the spent fuel pit area can provide approximately 256 gpm. If the temporary hose connection were left unattended, it would take 34 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 40 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

3.2.3 Dilution From Demineralized Water System

The non-borated contents of the condensate storage tanks can be transferred directly to the spent fuel pool. The demineralized water system includes a condensate storage tank and a demineralized water flushing pump for each Unit.

The path from the demineralized water pump to the spent fuel pool via the 3" hose station can provide approximately 420 gpm. If the temporary hose connection were left unattended, it would take 21 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 24 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

The path from the demineralized water pump to the spent fuel pool via one of the 2" hose stations can provide approximately 340 gpm. If the temporary hose connection were left unattended, it would take

26 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 30 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

Normally, only one condensate storage tank is aligned for service. The volume of one of Byron's tanks (500,000 gallons) is less than the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron. The volume of one of Braidwood's proposed tanks (650,000 gallons) will be greater than 612,000 gallons.

3.2.4 Dilution from Fire Protection System

The fire protection system draws from a basin between the cooling towers (Byron) or a lake (Braidwood) and is an unlimited supply of makeup. The path from the fire water pump to the spent fuel pool via one of the three fire hose stations in the spent fuel pit area can provide approximately 191 gpm. If the hose were left unattended, it would take 46 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 53 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

3.2.5 Dilution from Station Heating System

This is a closed system which provides heated water to three fans located near the spent fuel pool for area heating. A large circulating pump provides hot water at approximately 120 psig. Since the system is not seismically qualified, an earthquake could rupture the supply and return lines from each fan box and the hot water system could blow down into the pool. Based on an estimated blowdown flow of 1260 gpm, it would take about 6 minutes to increase the spent fuel pool level from the low to high alarm setpoints. However, in reality, even though automatic makeup is provided from the demineralized water system, this large flow rate is not indefinite. At 1260 gpm, the 6000 gallon surge tank would be emptied in approximately five minutes. On a low tank pressure signal, the demineralized water makeup connection would be aligned. This connection is a 1.5" diameter pipe, so its flow capacity would be limited to approximately 130 gpm, based on a 20 ft./sec. velocity. Thus, about 6000 gallons would be added to the spent fuel pool quickly, then dilution would continue at about 130 gpm until the operator took action. Thus, a total of 506,000 gallons (at Byron) could be added to the spent fuel pool if the surge tank and condensate storage tank were both emptied, which is less than the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron. For Braidwood, a total of 656,000 gallons could be added, which exceeds the 612,000 gallons. In this case, after the initial 6000 gallons were added to the spent fuel pool, it would take approximately 4 days to provide the remaining 606,000 gallons required to dilute the pool from 2000 to 500 ppm.

3.2.6 Dilution Resulting From Seismic Events or Random Pipe Breaks

A seismic event could cause piping ruptures in the vicinity of the spent fuel pool in piping that is not seismically qualified. The only piping within the immediate vicinity of the spent fuel pool that could result in dilution of the spent fuel pool if it ruptures during a seismic event are the six 1" feed and return lines for the hot water system feeding the area heaters discussed in Section 3.2.7.

For a seismic event with offsite power available, rupture of the primary water and demineralized water stations in the spent fuel pit area are bounded by the analyses in Sections 3.2.2 and 3.2.3. If offsite power is not available, the primary and demineralized water systems would not operate and thus there would be no dilution source.

In the event of a break in one of the fire protection hose station supply lines which are outside the spent fuel pool enclosure but in the general area surrounding the spent fuel pool, water would approach the spent fuel pool, but would be blocked by the 4" curb surrounding the pool. In addition, there is an open stairwell and floor drains through which this water would drain to lower elevations of the fuel handling building. For the purposes of this analysis, it is conservatively assumed that a fire protection hose station line break floods the entire area, including the inside of the spent fuel pool enclosure to a depth of four inches. This is conservative because of the number of openings to the lower floors and because there is a drop area opening leading to bay doors in the building. Even before the water level reached four inches, the drop area would be capable of draining the full flow of any fire protection hose station supply line break.

Once the water depth was equalized at four inches inside the curb (pool side) and outside curb (floor area). the driving head to force additional water into the enclosure would be significantly reduced. At that point, most of the flow from the pipe break would bypass the spent fuel pool enclosure, taking the path of least resistance around the enclosure to the drop area opening.

The total amount of water added to the spent fuel pool enclosure to raise the water level to four inches above the floor would be approximately 30,400 gallons assuming the spent fuel pool was initially at a level equivalent to the low level alarm setpoint. This is much less than the 612,000 gallons required to dilute the spent fuel pool from 2000 ppm to 550 ppm. While a limited amount of flow through the enclosure would continue until the line break were isolated, a fire protection system line break of this magnitude would be readily detected in the control room and break flow would be terminated long before enough water could enter the spent fuel pool enclosure to reduce the pool boron concentration to 550 ppm.

Because of the limited flow into the spent fuel pool enclosure, and because a fire protection hose station supply line break would be terminated long before the spent fuel pool boron concentration would be reduced to 550 ppm, this event is not considered a credible event and is given no further consideration in this analysis.

3.2.7 Dilution From Reverse Osmosis System

No credit is taken for the Boraflex neutron absorber panels in the spent fuel racks. Therefore, it may be desirable to remove the silica from the spent fuel pool water to facilitate compliance with the EPRI primary water chemistry guidance's following a refueling outage. Currently, Byron has an operating procedure for a reverse osmosis system, while Braidwood has no procedure, nor any plans to use such a system. For the purposes of this analysis, it is assumed that the reverse osmosis system described in Section 2.5.8 would be used at Byron or Braidwood to remove the silica from the spent fuel pool water.

Water would be taken from the spent fuel pool cooling system or directly from the spent fuel pool, would be passed by the reverse osmosis membrane where the silica would be removed, and then would be returned to the spent fuel pool cooling loop or the spent fuel pool. Along with the removal of the silica, the system will remove some amount of boron from the water passing through it. As a consequence, the discharge returning to the spent fuel pool would have a lower concentration of boron than the suction coming from the spent fuel pool. The reverse osmosis system operates at approximately 67 gpm.

During the setup of the reverse osmosis system, samples would be taken from the output of the system to determine the rate of silica and boron removal. Using that information, administrative controls would be put in place to ensure boron levels in the spent fuel pool would remain above the required value during reverse osmosis operations. Typically, 35% of the boron contained in the spent fuel pool water passing through the reverse osmosis system will be returned to the spent fuel pool.

For the purposes of this dilution analysis, it will be assumed that the reverse osmosis system removes all of the boron from the spent fuel pool water that passes through the system. As a result, the reverse osmosis system will be considered a 67 gpm source of non-borated water to the spent fuel pool. However, unlike the dilution sources discussed above, dilution of the spent fuel pool resulting from operation of the reverse osmosis system will not result in an increase in the spent fuel pool level. Assuming the reverse osmosis system operates as a 67 gpm dilution source, it would take the system 152 hours to reduce the spent fuel pool boron concentration from 2000 ppm to 550 ppm. During that period, Byron's operating procedure requires periodic sampling during operation of the reverse osmosis system. This sampling frequency would identify any reduction in the spent fuel boron concentration well before the 550 ppm limit would be reached.

Because the reverse osmosis system rejects a small flow to the waste system, makeup must be provided to restore spent fuel pit level. The reverse osmosis operation procedure requires that a hose be connected to the CVCS makeup system. Based on the discussion in Section 2.5.1, if only primary water were aligned instead of a blended flow from the CVCS makeup system, a maximum of 185 gpm would be provided. Thus, it may be assumed that dilution from the CVCS occurs during normal operation of the reverse osmosis system, resulting in a total dilution flow rate of 252 gpm. If the temporary hose connection were left unattended, it would take 35 minutes to increase the spent fuel pool level from the low to high alarm setpoints, and 41 hours to provide the 612,000 gallons required to dilute the pool from 2000 to 550 ppm boron.

However, operator attention is required during reverse osmosis operation, and therefore, a rapid increase in spent fuel pit level would be noticed and corrected quickly. Dilution of the spent fuel pool from 2000 ppm to 550 ppm resulting from the use of the reverse osmosis system is not considered credible due to the length of time that would be required to dilute the spent fuel pool to that concentration, operator attention during operation, the boron sampling required by the special administrative controls that would be in place during the use of the reverse osmosis system. Because the dilution of the spent fuel pool from 2000 ppm to 550 ppm by the reverse osmosis system is not considered a credible event, it is given no further consideration in this analysis.

3.2.8 Dilution From Spent Fuel Pool Demineralizer

When the spent fuel pool demineralizer is first placed in service after being recharged with fresh resin, it can initially remove boron from the water passing through it. In the worst case, assuming 39 ft^3 of anion resin per demineralizer, up to 27 ppm of boron could be removed from the spent fuel pool water before the resin would become saturated. Since each demineralizer normally utilizes a mixed bed of anion and cation resin, less boron would actually be removed before saturation. Because of the small amount of boron removed by the demineralizers, it is not considered a credible dilution source for the purposes of this evaluation.

3.3 Summary of Dilution Events

The limiting scenario is based on using the primary water connection to the spent fuel pool cleanup subsystem for either makeup (when the process isolation valve is normally opened), or for transferring spent resin (when the process isolation valve is inadvertently left open). This connection is the only flowpath for unborated water authorized for use under normal plant conditions by procedure. Other connections to the primary or demineralized water systems are available, but would only be a dilution source during a seismic event when it may be assumed that the piping stations in the spent fuel pit area break upstream of the isolation valves. This would result in flooding of the spent fuel pit area which is shown not to be a concern as explained in section 3.2.6.

For the limiting scenario to successfully result in the dilution of the spent fuel pool from 2000 ppm to 550 ppm, the addition of 612,000 gallons of water to the spent fuel pool over a period of 46 hours would have to go unnoticed. The first indication of such an event would be high level alarms in the control room from the pool level instrumentation. If the high level alarms fail, it is reasonable to expect that the significant increase in pool level and eventual pool overflow that would result from a pool dilution event will be readily detected by plant operators in time to take mitigative actions. A pool overflow condition would result in flooding of the fuel handling building sumps, and significant input flow rates (i.e., > 200 gpm) would result in high sump level alarms. Although area radiation monitors are available, relatively clean spent fuel pool contents might not set off an alarm. In addition, it can be assumed that the operator rounds through the spent fuel pool area that occur once per eight hours will detect the increase in the pool level even if the alarms fail and the flooding is not detected.

Furthermore, for any dilution scenario to successfully add 612,000 gallons of water to the spent fuel pool, plant operators would have to fail to question or investigate the continuous makeup of water to the primary or demineralized water storage tanks for the required time period, and fail to recognize that the need for 612,000 gallons of makeup was unusual.

4.0 CONCLUSIONS

A boron dilution analysis has been completed for the spent fuel pool. As a result of this spent fuel pool boron dilution analysis, it is concluded that an unplanned or inadvertent event which would result in the dilution of the spent fuel pool boron concentration from 2000 ppm to 550 ppm is not a credible event. This conclusion is based on the following:

In order to dilute the spent fuel pool to the design k_{eff} of 0.95, a substantial amount of water (612,000 gallons) is needed. To provide this volume, an operator would have to initiate the dilution flow, then abandon monitoring of pit level, and ignore tagged valves, administrative procedures, and a high level alarm.

Since such a large water volume turnover is required, a spent fuel pool dilution event would be readily detected by plant personnel via alarms, flooding in the fuel handling building or by normal operator rounds through the spent fuel pool area.

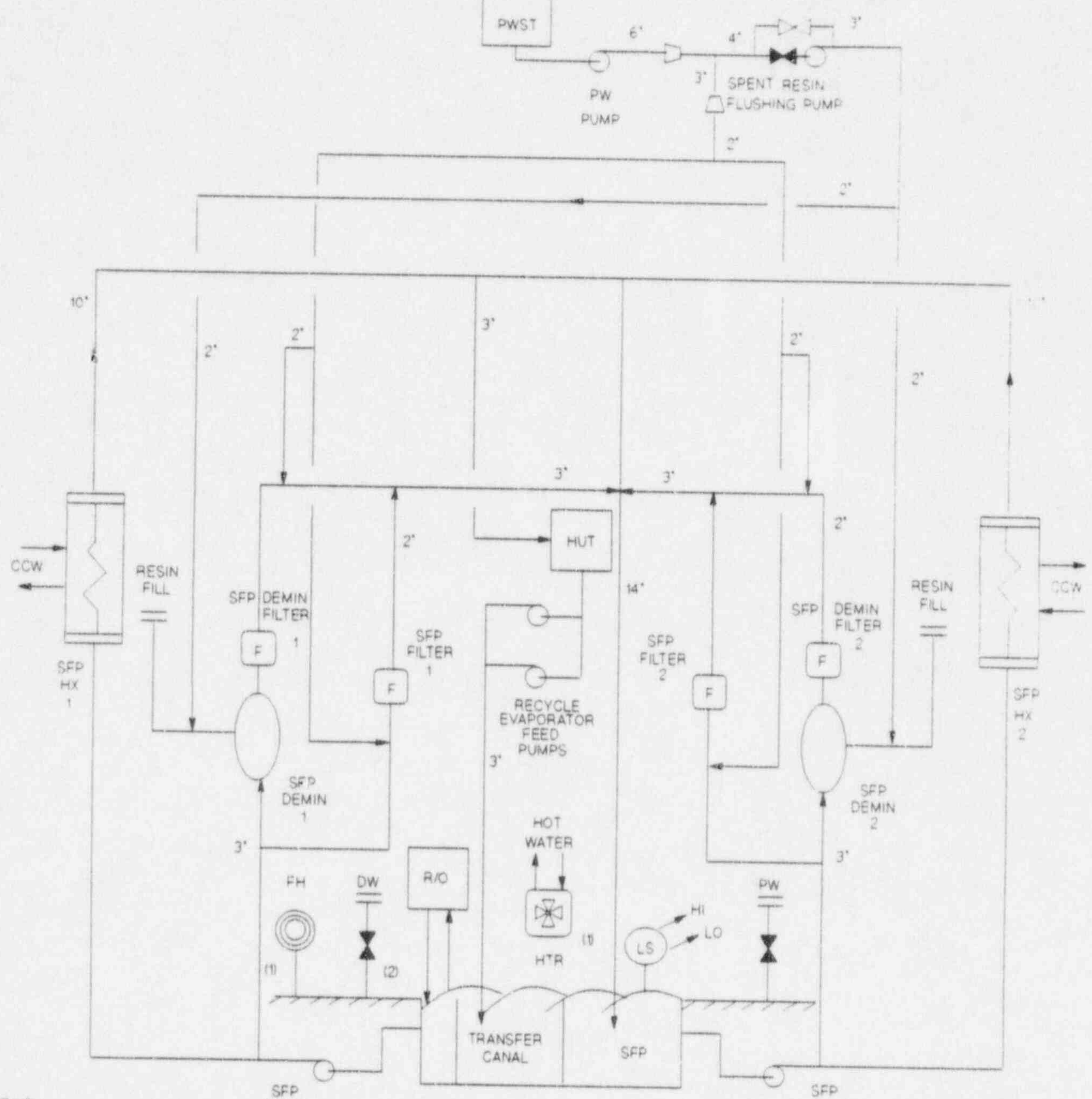
It should be noted that this boron dilution evaluation was conducted by evaluating the time and water volumes required to dilute the spent fuel pool from 2000 ppm to 550 ppm. The 550 ppm end point was utilized to ensure that K_{eff} for the spent fuel racks would remain less than or equal to 0.95. As part of the criticality analysis for the spent fuel racks (Reference 1), a calculation has been performed on a 95/95 basis to show that the spent fuel rack K_{eff} remains less than 1.0 with non-borated water in the pool. Thus, even if the spent fuel pool were diluted to zero ppm, which would take significantly more water than evaluated above, the spent fuel would be expected to remain subcritical and the health and safety of the public would be assured.

5.0 REFERENCES

1. Commonwealth Edison Company, Byron and Braidwood Units 1 and 2 Spent Fuel Rack Criticality Analysis Using Soluble Boron Credit, May, 1997

Figure 1

SPENT FUEL POOL AND RELATED SYSTEMS



LEGEND:

CCW Component Cooling Water
DW Demineralized Water
FH Fire Hose
HI High Alarm
HTR Heater
HUT Holdup Tank
LO Low Alarm
LS Level Switch
PW Primary Water
PWST Primary Water Storage Tank
R/O Reverse Osmosis

NOTES:

(1) Typical of 3
(2) Typical of 5

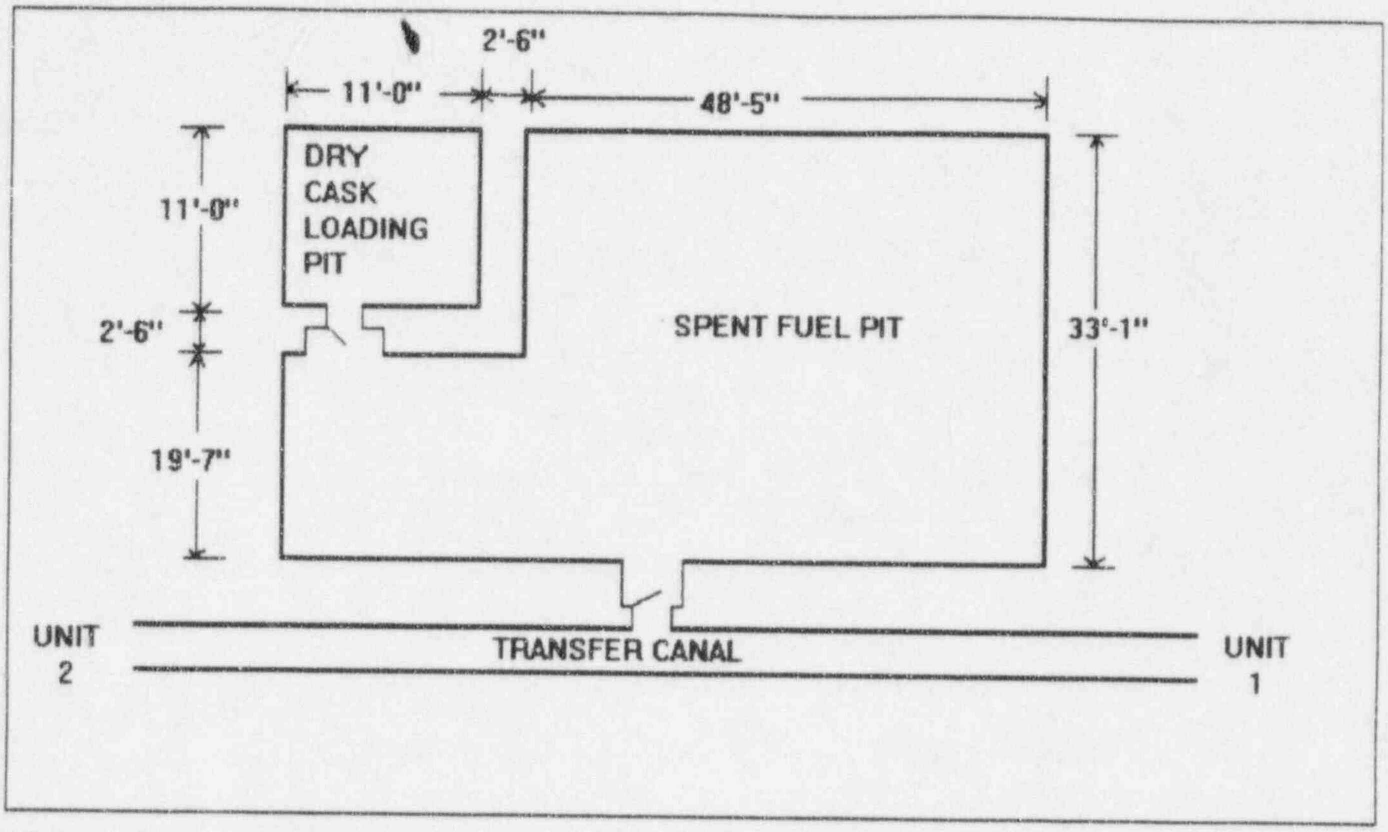


Figure 2 - Spent Fuel Pit Plan View 1

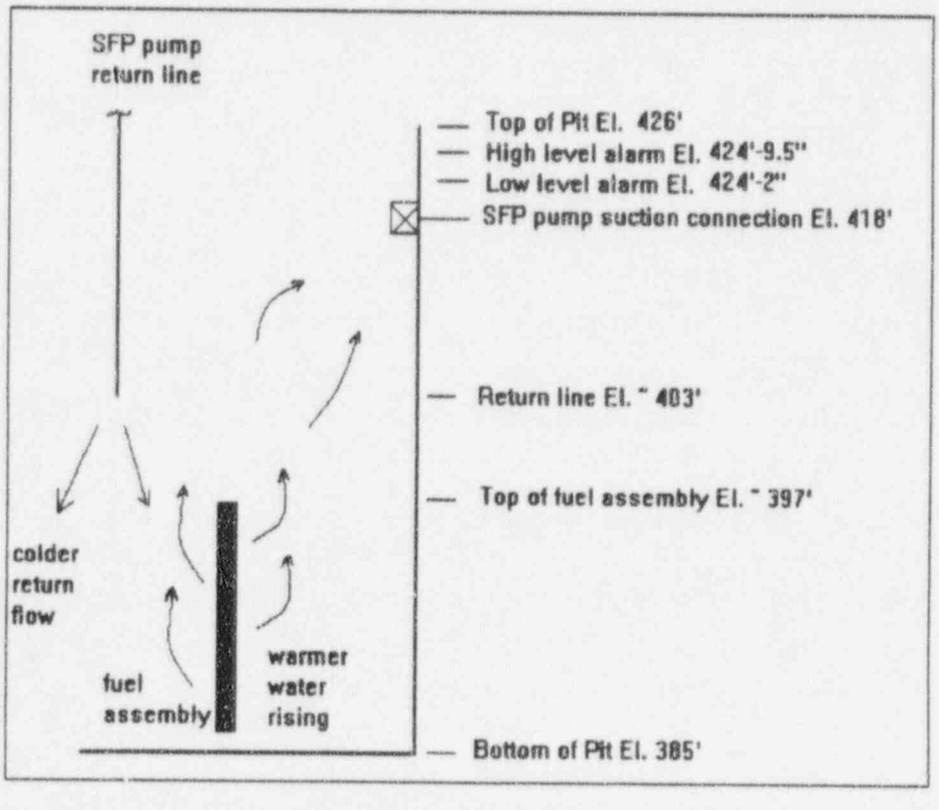


Figure 3 - Spent Fuel Pool Fluid Mixing 1