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# Farley Units 1 and 2 Spent Fuel Rack Criticality Analysis Using Soluble Boron Credit

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# 1.0 Introduction

This report presents the results of a criticality analysis of the Farley Nuclear Plant Units 1 and 2 spent fuel storage racks using credit for soluble boron in the spent fuel pool. 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] (with Boraflex) for storage of various 17x17 fuel assembly types with maximum enrichments up to 5.0 w/o $^{235}U$. In this report, no credit is taken for the presence of Boraflex in the racks. A single storage configuration is currently allowed. This configuration allows fuel assemblies to be stored in an all cell pattern of fuel assemblies with nominal enrichments up to 3.9 w/o $^{235}U$ (with no burnup or IFBA[3]), or up to 5.0 w/o $^{235}U$ (with IFBA credit).

The Farley spent fuel racks are reanalyzed to allow storage of all 17x17 fuel assemblies used at Farley with nominal enrichments up to 5.0 w/o $^{235}U$ in all storage cell locations using credit for checkerboard configurations, burnup credit, and Integral Fuel Burnable Absorber (IFBA) credit. The analysis does not take any credit for the presence of the spent fuel rack Boraflex poison panels. The following storage configurations and enrichment limits are considered in this analysis:

| | |
|---|---|
| **All Cell Storage Enrichment Limits** | Storage of Westinghouse 17x17 fuel assemblies in any cell location with nominal enrichments no greater than 2.15 w/o $^{235}U$. Fuel assemblies with initial nominal enrichments greater than this must satisfy a minimum burnup requirement. |
| **3-out-of-4 Checkerboard Storage Enrichment Limits** | Storage of Westinghouse 17x17 fuel assemblies in a 3-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 3.0 w/o $^{235}U$ or satisfy a minimum burnup requirement for higher initial enrichments. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells. |
| **2-out-of-4 Checkerboard Storage Enrichment Limits** | Storage of Westinghouse 17x17 fuel assemblies in a 2-out-of-4 checkerboard arrangement with empty cells. Fuel assemblies must have an initial nominal enrichment no greater than 5.0 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. |

| | |
|---|---|
| **Burned/Fresh Checkerboard Storage Enrichment Limits** | Storage of Westinghouse 17x17 fuel assemblies in a burned/fresh checkerboard arrangement. Any 2x2 matrix of storage cells consists of 3 cells with fuel assemblies which must have an initial nominal enrichment no greater than 1.6 w/o $^{235}U$ or satisfy a minimum burnup requirement for higher initial enrichments. The remaining fuel assembly must have an initial nominal enrichment no greater than 3.9 w/o $^{235}U$ or satisfy a minimum IFBA requirement for higher initial enrichments. |

The soluble boron concentrations required for these storage configurations are 400 ppm for normal conditions and 850 ppm for accidents.

The Farley 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 Farley spent fuel storage cell rack is depicted in Figure 1 on page 48. Nominal dimensions are provided on the figure.

Fuel types being considered in the analyses include the Westinghouse 17x17 OFA and the Westinghouse 17x17 STD fuel assembly types previously used in the reactors and currently in storage in the Farley spent fuel pool. The Westinghouse 17x17 OFA design is equivalent to the Westinghouse 17x17 VANTAGE 5 fuel type currently in use and is covered by this analysis. The fuel rod cladding, guide tube and instrumentation tube 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 these regions resulting in a lower reactivity. Therefore, this analysis is conservative with respect to fuel assemblies containing ZIRLO™. Thus, the fuel types considered account for all fuel types currently in use or used in the past at Farley. Results are presented for whichever fuel type, OFA or STD, is bounding for the particular configuration.

The fuel parameters relevant to this analysis are given in Table 1 on page 36.

## 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 rack is analyzed such that $K_{eff}$ remains less than 1.0 under No Soluble Boron 95/95 $K_{eff}$ conditions as defined in Reference 1. To provide safety margin in the criticality analysis of the spent fuel racks, credit is taken for the soluble boron present in the Farley spent fuel pool. This parameter provides significant negative reactivity in the criticality analysis of the spent fuel rack and will be used here in conjunction with administrative controls to offset the reactivity increase when ignoring the presence of the spent fuel rack Boraflex poison panels. Soluble boron credit provides sufficient relaxation in the enrichment limits of the spent fuel racks to allow the racks to be used under checkerboarded conditions with no credit for the Boraflex poison panels. If some amount of Boraflex material is considered remaining, the reactivity of the spent fuel rack and the amount of soluble boron required to maintain 95/95 $K_{eff} \leq 0.95$ will be reduced.

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 Farley.

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 $\Delta K$ with a 95 percent probability at a 95 percent confidence level standard deviation on the bias of 0.0030 $\Delta K$. These values will be used throughout this report as needed.

# 3.0 Criticality Analysis of All Cell Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the Farley spent fuel storage racks all cell enrichment limits using credit for soluble boron.

Section 3.1 describes the No Soluble Boron 95/95 $K_{eff}$ KENO-Va calculations performed for the all cell storage configuration. Section 3.2 discusses the results of the spent fuel rack $K_{eff}$ soluble boron credit calculations. Finally, Section 3.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with higher initial enrichments above those determined in Section 3.1. The all cell storage configuration is shown in Figure 2 on page 49.

## 3.1 No Soluble Boron 95/95 $K_{eff}$

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 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 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 Farley spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA and 17x17 STD designs (see Table 1 on page 36 for fuel parameters). The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results. The Westinghouse 17x17 STD design bounds the reactivity of all fuel assembly types for this configuration.
2. Westinghouse 17x17 OFA and STD fuel assemblies contain uranium dioxide at a nominal enrichment of 2.15 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 used at Farley including those with annular pellets at the fuel rod ends, if used in the future.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.

8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm$^3$ is used.

10. The fuel assembly array is conservatively modeled as infinite in lateral (x and y) extent and finite in axial (vertical) extent with a 3 inch water region on the top of the fuel in the axial direction or conservatively modeled as infinite.

11. All available 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 0.96231 for Westinghouse STD fuel assemblies, as shown in Table 2 on page 37.

Calculational 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 was 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 180°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 Farley spent fuel rack all cell storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 2.15 w/o $^{235}$U was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley 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 and results in a 95/95 $K_{eff}$ of 0.99201 for Westinghouse STD fuel assemblies.

Since $K_{eff}$ is less than 1.0 for the limiting fuel type, the Farley spent fuel racks will remain subcritical when all cells are loaded with 2.15 w/o $^{235}U$ Westinghouse 17x17 OFA, VANTAGE 5, or STD fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

## 3.2 Soluble Boron Credit $K_{eff}$ Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the 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 nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for all cell storage in the Farley spent fuel racks are the same as those in Section 3.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator used is water with 200 ppm of soluble boron for the Westinghouse STD fuel assembly type.

With the above assumptions, the KENO-Va calculation for the nominal case results in a $K_{eff}$ of 0.90920 for Westinghouse STD fuel as shown in Table 3 on page 38.

Calculational 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 was 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 180°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations are performed. For the Farley spent fuel rack all cell storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 2.15 w/o $^{235}U$ was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley 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 3 and results in a 95/95 $K_{eff}$ of 0.93741 for Westinghouse STD 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 criterion for criticality is met for the all cell storage of 17x17 fuel assemblies in the Farley spent fuel racks. Storage of fuel assemblies with nominal enrichments up to 2.15 w/o $^{235}U$ is acceptable for Westinghouse OFA, VANTAGE 5, or STD fuel assembly types in all cells of the Farley spent fuel racks including the presence of 200 ppm of soluble boron.

## 3.3 Burnup Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than 2.15 w/o $^{235}U$ for the Westinghouse OFA, VANTAGE 5, and STD fuel types in the Farley spent fuel rack all cell configuration is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion.

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

Figure 3 on page 50 shows the constant $K_{eff}$ contour as a function of assembly average burnup, generated for the Farley spent fuel rack all cell configuration. Curve 1 of Figure 3 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor ($K_{eff}$) as the rack loaded with 2.15 w/o $^{235}U$ fuel (at zero burnup) for Westinghouse STD fuel assemblies in all cell locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 $\Delta K$ at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculational and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Curve 1 on Figure 3 is 200 ppm for the Westinghouse STD fuel assembly type. This is additional boron above the 200 ppm required for Westinghouse STD fuel, as calculated in Section 3.2. This results in a total soluble boron requirement of 400 ppm for the Westinghouse STD fuel assembly type.

It is important to recognize that Curve 1 in Figure 3 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity are implicitly considered. For convenience, the data from Figure 3 is also provided in Table 9 on page 44. Use of linear interpolation between the tabulated values is acceptable since Curve 1 shown in Figure 3 is approximately linear between the tabulated points.

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

# 4.0 Criticality Analysis of 3-out-of-4 Checkerboard Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the Farley spent fuel storage racks 3-out-of-4 cells enrichment limits using credit for soluble boron.

Section 4.1 describes the No Soluble Boron 95/95 $K_{eff}$ KENO-Va calculations performed for the 3-out-of-4 cells storage configuration. Section 4.2 discusses the results of the spent fuel rack $K_{eff}$ soluble boron credit calculations. Finally, Section 4.3 presents the results of calculations performed to show the minimum burnup requirements for assemblies with higher initial enrichments above those determined in Section 4.1. The 3-out-of-4 storage configuration is shown in Figure 2 on page 49.

## 4.1 No Soluble Boron 95/95 $K_{eff}$

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 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 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 Farley spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA and 17x17 STD designs (see Table 1 on page 36 for fuel parameters). The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results. The Westinghouse 17x17 OFA design bounds the reactivity of all fuel assembly types for this configuration.
2. Westinghouse 17x17 OFA and STD fuel assemblies contain uranium dioxide at a nominal enrichment of 3.0 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 used at Farley including those with annular pellets at the fuel rod ends, if used in the future.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.

8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm$^3$ is used.

10. The fuel assembly array is conservatively modeled as infinite in lateral (x and y) extent and finite in axial (vertical) extent with a 3 inch water region on the top of the fuel in the axial direction or conservatively modeled as infinite.

11. Fuel storage cells are loaded with fuel assemblies in a 3-out-of-4 checkerboard arrangement. A 3-out-of-4 checkerboard with empty cells means that no more than 3 fuel assemblies can occupy any 2x2 matrix of storage cells.

With the above assumptions, the KENO-Va calculations of $K_{eff}$ under normal conditions resulted in a $K_{eff}$ of 0.97212 for Westinghouse OFA fuel assemblies, as shown in Table 4 on page 39.

Calculational 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 was 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 180°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 Farley spent fuel rack 3-out-of-4 cells storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 3.0 w/o $^{235}$U was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack 3-out-of-4 cells 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 4 and results in a 95/95 $K_{eff}$ of 0.99558 for Westinghouse OFA fuel assemblies.

Since $K_{eff}$ is less than 1.0 for the limiting fuel type, the Farley spent fuel racks will remain subcritical when 3-out-of-4 cells are loaded with 3.0 w/o $^{235}U$ Westinghouse 17x17 OFA, VANTAGE 5, or STD fuel assemblies and no soluble boron is present in the spent fuel pool water. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

## 4.2 Soluble Boron Credit $K_{eff}$ Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the 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 nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for 3-out-of-4 cells storage in the Farley spent fuel racks are the same as those in Section 4.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator used is water with 200 ppm of soluble boron for the Westinghouse OFA fuel assembly type.

With the above assumptions, the KENO-Va calculation for the nominal case results in a $K_{eff}$ of 0.92351 for Westinghouse OFA fuel as shown in Table 5 on page 40.

Calculational 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 was 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 180°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations are performed. For the Farley spent fuel rack 3-out-of-4 cells storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 of 3.0 w/o $^{235}U$ was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack 3-out-of-4 cells 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 5 and results in a 95/95 $K_{eff}$ of 0.94741 for Westinghouse 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 criterion for criticality is met for the 3-out-of-4 cells storage of 17x17 fuel assemblies in the Farley spent fuel racks. Storage of fuel assemblies with

nominal enrichments up to 3.0 w/o $^{235}U$ is acceptable for Westinghouse OFA, VANTAGE 5, or STD fuel assembly types in 3-out-of-4 cells of the Farley spent fuel racks including the presence of 200 ppm of soluble boron.

## 4.3 Burnup Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than 3.0 w/o $^{235}U$ for the Westinghouse OFA, VANTAGE 5, and STD fuel types in the Farley spent fuel rack 3-out-of-4 cells configuration is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion.

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

Figure 3 on page 50 shows the constant $K_{eff}$ contour as a function of assembly average burnup, generated for the Farley spent fuel rack 3-out-of-4 cells configuration. Curve 3 of Figure 3 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor ($K_{eff}$) as the rack loaded with 3.0 w/o $^{235}U$ fuel (at zero burnup) for Westinghouse OFA fuel assemblies in 3-out-of-4 cells locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 $\Delta K$ at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculational and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Curve 3 on Figure 3 is 100 ppm for the Westinghouse OFA fuel assembly type. This is additional boron above the 200 ppm required for Westinghouse OFA fuel, as calculated in Section 4.2. This results in a total soluble boron requirement of 300 ppm for the Westinghouse OFA fuel assembly type.

It is important to recognize that Curve 3 in Figure 3 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity are implicitly considered. For convenience, the data from Figure 3 is also provided in Table 9 on page 44. Use of linear interpolation between the tabulated values is acceptable since Curve 3 shown in Figure 3 is approximately linear between the tabulated points.

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

# 5.0 Criticality Analysis of 2-out-of-4 Checkerboard Storage

This section describes the analytical techniques and models employed to perform the criticality analysis for the Farley spent fuel storage racks 2-out-of-4 cells enrichment limits.

Section 5.1 describes the No Soluble Boron 95/95 $K_{eff}$ KENO-Va calculations performed for the 2-out-of-4 cells storage configuration. Soluble boron is not required in the spent fuel pool to maintain $K_{eff} \leq 0.95$. There is no burnup requirement for fuel with 5.0 w/o $^{235}U$ or less. The 2-out-of-4 storage configuration is shown in Figure 2 on page 49.

## 5.1 No Soluble Boron 95/95 $K_{eff}$

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 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 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 Farley spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA and 17x17 STD designs (see Table 1 on page 36 for fuel parameters). The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results. The Westinghouse 17x17 OFA design bounds the reactivity of all fuel assembly types for this configuration.
2. Westinghouse 17x17 OFA and STD fuel assemblies contain uranium dioxide at a nominal enrichment of 5.0 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 used at Farley including those with annular pellets at the fuel rod ends, if used in the future.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.

9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm$^3$ is used.

10. The fuel assembly array is conservatively modeled as infinite in lateral (x and y) extent and finite in axial (vertical) extent with a 3 inch water region on the top of the fuel in the axial direction or conservatively modeled as infinite.

11. Fuel storage cells are loaded with fuel assemblies in a 2-out-of-4 checkerboard arrangement. A 2-out-of-4 checkerboard with empty cells means that no 2 fuel assemblies may be stored face adjacent. Fuel assemblies may be stored corner adjacent.

With the above assumptions, the KENO-Va calculations of $K_{eff}$ under normal conditions resulted in a $K_{eff}$ of 0.92764 for Westinghouse OFA fuel assemblies, as shown in Table 6 on page 41.

Calculational 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 was 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 180°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 Farley spent fuel rack 2-out-of-4 cells storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 5.0 w/o $^{235}$U was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack 2-out-of-4 cells storage configuration is developed by adding the temperature and methodology biases and the statistical sum of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 6 and results in a 95/95 $K_{eff}$ of 0.94285 for Westinghouse OFA fuel assemblies.

Since $K_{eff}$ is less than 1.0 for the limiting fuel type, the Farley spent fuel racks will remain subcritical when 2-out-of-4 cells are loaded with 5.0 w/o $^{235}U$ Westinghouse 17x17 OFA, VANTAGE 5 or STD fuel assemblies and no soluble boron is present in the spent fuel pool water.

Soluble boron credit is not needed to provide safety margin because $K_{eff} \leq 0.95$, including tolerances and uncertainties, with no soluble boron.

# 6.0 Criticality Analysis of Burned/Fresh Checkerboard Storage

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the Farley spent fuel storage racks burned/fresh checkerboard enrichment limits using credit for soluble boron.

Section 6.1 describes the No Soluble Boron 95/95 $K_{eff}$ KENO-Va calculations performed for the burned/fresh checkerboard storage configuration. Section 6.2 discusses the results of the spent fuel rack $K_{eff}$ soluble boron credit calculations. Section 6.3 describes reactivity equivalencing. Specifically, Section 6.3.1 presents the results of calculations performed to show the minimum burnup requirements for assemblies with higher initial enrichments than those determined in Section 6.1. Section 6.3.2 presents the results of calculations performed to determine the minimum number of IFBA required for fresh assemblies with higher initial enrichments than those determined in Section 6.1. Finally, Section 6.3.3 discusses the infinite multiplication factor. The burned/fresh storage configuration is shown in Figure 2 on page 49.

## 6.1 No Soluble Boron 95/95 $K_{eff}$

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 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 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 Farley spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA and 17x17 STD designs (see Table 1 on page 36 for fuel parameters). The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results.
2. Westinghouse 17x17 OFA and STD fuel assemblies contain uranium dioxide at nominal enrichments of 3.9 and 1.6 w/o $^{235}U$, respectively, over the entire length of each rod. This arrangement of OFA and STD fuel is bounding for all other fuel types and combinations.
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 used at Farley including those with annular pellets at the fuel rod ends, if used in the future.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 $gm/cm^3$ is used.
10. The fuel assembly array is conservatively modeled as infinite in lateral (x and y) extent and finite in axial (vertical) extent with a 3 inch water region on the top of the fuel in the axial direction or conservatively modeled as infinite.
11. Fuel storage cells are loaded with fuel assemblies in a checkerboard arrangement. The burned/fresh checkerboard consists of three burned fuel assemblies (1.6 w/o) and one fresh assembly (3.9 w/o) in any 2x2 matrix of storage cells.

With the above assumptions, the KENO-Va calculations of $K_{eff}$ under normal conditions resulted in a $K_{eff}$ of 0.96905, as shown in Table 7 on page 42.

Calculational 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 was 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 180°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 Farley spent fuel rack burned/fresh checkerboard storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 of 3.9 (OFA) and 1.6 (STD) w/o $^{235}U$ was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack burned/fresh checkerboard 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 7 and results in a 95/95 $K_{eff}$ of 0.99415.

Since $K_{eff}$ is less than 1.0 for the limiting fuel type, the Farley spent fuel racks will remain subcritical when burned/fresh checkerboard cells are loaded with 3.9 w/o $^{235}U$ Westinghouse 17x17 OFA and 1.6 w/o $^{235}U$ STD fuel assemblies and no soluble boron is present in the spent fuel pool water. Use of other fuel types is bounded as discussed in Assumption 2. In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

## 6.2 Soluble Boron Credit $K_{eff}$ Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, KENO-Va is used to establish a nominal reference reactivity and PHOENIX-P is used to assess the 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 nominal KENO-Va reference reactivity.

The assumptions used to develop the nominal case KENO-Va model for soluble boron credit for burned/fresh checkerboard storage in the Farley spent fuel racks are the same as those in Section 6.1 except for assumption 9 regarding the moderator soluble boron concentration. The moderator used is water with 200 ppm of soluble boron.

With the above assumptions, the KENO-Va calculation for the nominal case results in a $K_{eff}$ of 0.91704 as shown in Table 8 on page 43.

Calculational 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 was 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 180°F).

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX-P perturbation calculations are performed. For the Farley spent fuel rack burned/fresh checkerboard storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 of 3.9 (OFA) and 1.6 (STD) w/o $^{235}U$ was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack burned/fresh checkerboard 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 8 and results in a 95/95 $K_{eff}$ of 0.94025.

Since $K_{eff}$ is less than 0.95 including soluble boron credit and uncertainties at a 95/95 probability/confidence level, the acceptance criterion for criticality is met for the burned/fresh checkerboard storage of 17x17 fuel assemblies in the Farley spent fuel racks. Storage of fuel assemblies with nominal enrichments up to 3.9 and 1.6 w/o $^{235}U$ is acceptable for Westinghouse OFA, VANTAGE 5, and STD fuel assembly types in burned/fresh checkerboard cells of the Farley spent fuel racks including the presence of 200 ppm of soluble boron.

## 6.3 Reactivity Equivalencing

Increased flexibility for storage of higher enrichment fuel assemblies is achievable using reactivity equivalencing. Reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion and the addition of Integral Fuel Burnable Asborbers (IFBA).

### 6.3.1 Burnup Reactivity Equivalencing

Storage of fuel assemblies with enrichments higher than 1.6 w/o $^{235}U$ for the Westinghouse OFA, VANTAGE 5, and STD fuel types in the Farley spent fuel rack burned/fresh checkerboard configuration is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion.

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

Figure 3 on page 50 shows the constant $K_{eff}$ contour as a function of assembly average burnup, generated for the Farley spent fuel rack burned/fresh checkerboard configuration. Curve 2 of Figure 3 represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor ($K_{eff}$) as the rack loaded with 1.6 (STD) w/o $^{235}U$ fuel (at zero burnup) for Westinghouse fuel assemblies in burned/fresh checkerboard locations.

Uncertainties associated with burnup credit include a reactivity uncertainty of 0.01 $\Delta K$ at 30,000 MWD/MTU applied linearly to the burnup credit requirement to account for calculational and depletion uncertainties and 5% on the calculated burnup to account for burnup measurement uncertainty. The amount of additional soluble boron needed to account for these uncertainties in the burnup requirement of Curve 2 on Figure 3 is 150 ppm. This is additional boron above the 200 ppm required for Westinghouse fuel, as calculated in Section 6.2. This results in a total soluble boron requirement of 350 ppm for this configuration.

It is important to recognize that Curve 2 in Figure 3 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity are implicitly considered. For convenience, the data from Figure 3 is also provided in Table 9 on page 44. Use of linear interpolation between the tabulated values is acceptable since Curve 2 shown in Figure 3 is approximately linear between the tabulated points.

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

## 6.3.2 IFBA Credit Reactivity Equivalencing

Storage of fuel assemblies with nominal enrichments greater than 3.90 w/o $^{235}U$ in the burned/fresh checkerboard 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). IFBAs consist of neutron absorbing material applied as a thin $ZrB_2$ coating on the outside of the $UO_2$ fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

A series of reactivity calculations are performed to generate a set of IFBA rod number versus enrichment ordered pairs which all yield the equivalent $K_{eff}$ when the fuel is stored in the burned/fresh checkerboard configuration analyzed for the Farley 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 36 for fuel parameters). The OFA design is equivalent to the VANTAGE 5 design and conservative for STD fuel for the IFBA credit calculation.
2. The fuel assembly is modeled at its most reactive point in life.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural enrichment or reduced enrichment axial blankets.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. The IFBA absorber material is a zirconium diboride ($ZrB_2$) coating on the fuel pellet. Nominal IFBA rod $^{10}B$ loadings of 1.5 milligrams $^{10}B$ per inch (1.0X), 1.88 milligrams $^{10}B$ per inch (1.25X), 2.25 milligrams $^{10}B$ per inch (1.5X), and 3.0 milligrams $^{10}B$ per inch (2.0X) are used in determining the IFBA requirement.
8. For reduced length IFBA, the IFBA $^{10}B$ loading is reduced to 75.0% of nominal 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 conservatively modeled as infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.

11. Standard Westinghouse IFBA patterns for 17x17 fuel assemblies were considered.

The results of the IFBA credit reactivity equivalencing for the Farley burned/fresh checkerboard spent fuel racks are provided in Table 10 on page 45. The results are also illustrated in Figure 4 on page 51, which shows the constant $K_{eff}$ contour generated for this configuration.

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

Uncertainties associated with IFBA credit include a 5% manufacturing tolerance and a 10% calculational uncertainty on the $^{10}B$ loading of the IFBA rods. The amount of additional soluble boron needed to account for these uncertainties in the IFBA credit requirement of Table 10 is 50 ppm. This is additional boron above the 200 ppm required in Section 6.2. The soluble boron needed for IFBA credit is bounded by the 150 ppm required for burnup credit in the Farley burned/fresh checkerboard spent fuel racks as determined in Section 6.3.1. Therefore, the total soluble boron credit required for the Farley spent fuel racks remains at 350 ppm.

## 6.3.3 Infinite Multiplication Factor

The infinite multiplication factor, $K_\infty$, is used as a reference criticality reactivity point, and offers an alternative method for determining the acceptability of fuel assembly storage in the Farley Units 1 and 2 spent fuel racks. The fuel assembly $K_\infty$ calculations are performed using PHOENIX-P. The following assumptions were used to develop the infinite multiplication factor model:

1. The fuel assembly is modeled at its most reactive point in life and no credit is taken for any burnable absorbers in the assembly.
2. The fuel rods are Westinghouse 17x17 OFA at a nominal enrichment of 3.9 w/o $^{235}U$ over the infinite length of each rod (this is the maximum nominal enrichment that can be placed in the spent fuel racks without IFBA rods).
3. The fuel array model is based on a unit assembly configuration (infinite in the lateral and axial extent) in Farley Unit 1 and 2 reactor geometry (no rack).
4. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 g/cm$^3$.

Calculation of the infinite multiplication factor results in a reference $K_\infty$ of 1.455. This includes a 1% $\Delta K$ reactivity bias to conservatively account for calculational uncertainties. This bias is consistent with the standard conservatism included in the Farley Units 1 and 2 core design refueling shutdown margin calculations. All fuel assemblies placed in the spent fuel racks must comply with the enrichment versus number of IFBA rods curve in Figure 4 or have a reactivity less than or equal to the above value. Meeting either of these conditions assures that the maximum spent fuel rack reactivity will then be less than 0.95.

# 7.0 Special Configurations

This section describes the criticality analysis for the storage of eleven damaged fuel assemblies and the Loose Pellet Transport Container in the Farley spent fuel storage racks.

## 7.1 Damaged Assembly Configuration

Contained in the Unit 1 spent fuel pool are eleven damaged assemblies. These assemblies occupy a space of twelve contiguous storage cells as shown in Figure 5 on page 52. These assemblies are nominal 3.0 w/o $^{235}U$ Westinghouse STD fuel. The burnup for each assembly is shown in Figure 5.

Soluble boron credit criticality analysis utilized an "equivalent" enrichment assembly to represent the damaged assembly with highest reactivity. The "equivalent" enrichment assembly is a fresh assembly which has the same reactivity as the burned assembly being represented. PHOENIX-P was used to determine the equivalent enrichment.

Section 7.1.1 describes the No Soluble Boron 95/95 $K_{eff}$ KENO-Va calculations performed for the storage configuration shown in Figure 5. Section 7.1.2 discusses the results of the spent fuel rack $K_{eff}$ soluble boron credit calculations for this configuration.

### 7.1.1 No Soluble Boron 95/95 $K_{eff}$

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 effects of material and construction tolerances. A final 95/95 $K_{eff}$ is developed by statistically combining the individual tolerance impacts on reactivity with the calculational and methodology uncertainties and adding them to 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 the 11 damaged fuel assemblies in the Farley spent fuel storage racks:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 STD design (see Table 1 on page 36 for fuel parameters). All the damaged assemblies are of the Westinghouse 17x17 STD design.
2. The equivalent enrichment Westinghouse 17x17 STD fuel assemblies contain uranium dioxide at a nominal enrichment of 2.35 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. None of the damaged assemblies have axial blankets.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
9. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 gm/cm$^3$ is used.
10. The fuel assembly array is conservatively modeled as infinite in lateral (x and y) extent and finite in axial (vertical) extent with a 3 inch water region on the top of the fuel in the axial direction or conservatively modeled as infinite.
11. The assemblies are modeled in a **4x3 array surrounded by one assembly row with only water present**, as shown in Figure 5. Outside of this row of water are the all cell enrichment assemblies discussed in Section 3 of this report.

With the above assumptions, the KENO-Va calculations of $K_{eff}$ under normal conditions resulted in a $K_{eff}$ of 0.95152 for Westinghouse STD fuel assemblies, as shown in Table 11 on page 46.

Calculational 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 was 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 180°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 Farley spent fuel rack damaged assembly storage configuration, $UO_2$ material tolerances are considered along with construction tolerances related to the cell I.D., storage cell pitch, and stainless steel wall 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 3.0 w/o $^{235}$U was considered.

**$UO_2$ Density:** A ±2.0% variation about the nominal reference theoretical density (the nominal reference values are listed in Table 1 on page 36) was considered.

**Fuel Pellet Dishing:** A variation in fuel pellet dishing fraction from 0.0% to twice the nominal dishing (the nominal reference values are listed in Table 1 on page 36) was considered.

**Storage Cell I.D.:** The ±0.045 inch tolerance about the nominal 8.90 inch reference cell I.D. was considered.

**Storage Cell Pitch:** The ±0.06 inch tolerance about the nominal 10.75 inch reference cell pitch was considered.

**Stainless Steel Thickness:** The ±0.012 inch tolerance about the nominal 0.12 inch reference stainless steel thickness for all rack structures was 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 was considered in the statistical summation of spent fuel rack tolerances.

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

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

The 95/95 $K_{eff}$ for the Farley spent fuel rack damaged assembly storage configuration is developed by adding the temperature and methodology biases and the statistical convolution of independent tolerances and uncertainties to the nominal KENO-Va reference reactivity. The summation is shown in Table 11 and results in a 95/95 $K_{eff}$ of 0.98093 for the Westinghouse STD fuel assemblies.

Since $K_{eff}$ is less than 1.0, the Farley spent fuel racks will remain subcritical for this configuration loaded with 3.0 w/o $^{235}U$ Westinghouse 17x17 STD fuel assemblies and no soluble boron present in the spent fuel pool water. Based on the results of the all cell (No Soluble Boron 95/95 $K_{eff}$ of 0.99201, Section 3.1) and the damaged assembly configuration, the all cell configuration is more reactive and bounds the damaged assembly condition.

In the next section, soluble boron credit will be used to provide safety margin by determining the amount of soluble boron required to maintain $K_{eff} \leq 0.95$ including tolerances and uncertainties.

## 7.1.2 Soluble Boron Credit $K_{eff}$ Calculations

To determine the amount of soluble boron required to maintain $K_{eff} \leq 0.95$, an evaluation was made comparing the all cell results and the damaged assembly configuration. Based on the evaluation, 400 ppm will assure that $K_{eff} \leq 0.95$. In addition to the reactivity equivalencing evaluation, the misload and temperature accidents were considered. From these analyses, it is shown that the damaged fuel storage accident reactivity was much less than that for the all cell condition. Therefore, the accidents would be bounded by the 750 ppm determined for the all cell configuration (Section 8.0). Thus, the criticality evaluation has shown the damaged assembly configuration will meet the spent fuel pool safety limits.

## 7.2 Loose Pellet Transport Container

A criticality analysis was done to evaluate the Loose Pellet Transport Container stored in the Farley spent fuel racks. The transport container is comprised of five pellet canisters. Each canister has the dimension of 7 inches by 5 inches and is 20 inches long. The canister can hold up to a maximum of 1000 pellets. Farley may have up to a total of five canisters capable of storing up to 5000 loose pellets. These five canisters may be stored in the spent fuel rack cell, one on top of the other, occupying only one rack cell in the spent fuel pool. The Farley Loose Pellet Transport Container and spent fuel rack dimensions are shown in Figure 6 on page 53.

In a previous loose pellet evaluation, it has been demonstrated that a random arrangement of pellets is less reactive than a uniform array of stacked pellets at optimal spacing. For the KENO-Va model of this configuration, a series of arrays of stacks of unclad uranium pellets with different pitches within the loose pellet container was generated. The loose pellet container was modeled within the Farley spent fuel racks.

The following assumptions are used to develop the KENO-Va model for storage of the Loose Pellet Transport Container in the Farley spent fuel storage racks:

1. The fuel pellet parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA and STD designs (see Table 1 on page 36 for fuel parameters). The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results.
2. Westinghouse 17x17 OFA and STD fuel pellets contain uranium dioxide at a nominal enrichment of 5.0 w/o $^{235}U$ over the entire length of each stack.
3. The fuel pellets are modeled assuming a conservative theoretical density of 96.0% and a zero dishing fraction.
4. No credit is taken for any natural or reduced enrichment axial blankets.
5. No credit is taken for any $^{234}U$ or $^{236}U$ in the fuel, nor is any credit taken for the buildup of fission product poison material.
6. No credit is taken for any burnable absorber on the fuel pellets
7. No credit is taken for the presence of spent fuel rack Boraflex poison panels. The Boraflex volume is replaced with water.
8. The moderator is water with 0 ppm soluble boron at a temperature of 68°F. A water density of 1.0 $gm/cm^3$ is used.
9. The fuel stack array is conservatively modeled as infinite in lateral (x and y) extent and infinite in axial (vertical) extent.

Based on the results of this study, the 14x10 array size is the most reactive configuration of the loose pellet container. The 14x10 array provides over 0.03 $\Delta K$ margin to the rack limit, including biases, tolerances, and uncertainties. Over the 20 inch height of the canister, each pellet stack would have at least 51 pellets based on the lengths of the OFA and STD fuel pellets (0.370 inches and 0.387 inches, respectively). The 14x10 array would contain 140 stacks. Therefore a total of over 7000 pellets is modeled in the KENO-Va problem within the canister. This is much more conservative than the 1000 pellet limit for each canister. The analysis does not consider annular pellets which are more reactive than solid pellets in this geometry. However, based on the conservative number of pellets in the problem and the low reactivity of the array, the analysis is still conservative. From the study, the reactivity of the loose pellet container problem is considerably less than the nominal KENO-Va reference reactivities of all the other storage configurations in the Farley spent fuel rack. Because the loose pellet container is smaller than the rack cell, the asymmetric placement of the container was also considered. From the analysis performed, it was demonstrated that the reactivity of an asymmetric configuration with the loose pellet container is lower than the reactivity of the all cell asymmetric configuration. Therefore, it is concluded that the five loose pellet canisters, with up to 1000 pellets in each, can be safely stored in one spent fuel pool rack cell, in place of an assembly in any of the Farley approved configurations.

## 7.3 Fuel Rod Storage Canister

A criticality analysis[4] was performed for the Fuel Rod Storage Canister (FRSC) which was provided to Farley. This report compared the FRSC, loaded with 5.0 w/o $^{235}U$ fuel rods, to an intact assembly with 5.0 w/o $^{235}U$ fuel rods. The conclusion was that the Fuel Rod Storage Canister is much less reactive than an assembly. However, this analysis was done independent of any rack geometry. Therefore, for the FRSC the location within the spent fuel rack must be able to accept the highest enrichment fuel rod contained in the canister.

# 8.0 Discussion of Postulated Accidents

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

| | |
|---|---|
| **Fuel assembly drop on top of rack** | The rack structure pertinent for criticality is not excessively deformed and the dropped assembly which comes to rest horizontally on top of the rack has sufficient water separating it from the active fuel height of stored assemblies to preclude neutronic interaction. |
| **Fuel assembly drop between rack modules or between rack modules and spent fuel pool wall** | Design of the spent fuel racks is such that it precludes the insertion of a fuel assembly in these locations. |

However, three accidents can be postulated for each storage configuration which would increase reactivity beyond the analyzed condition. The first postulated accident would be a loss of fuel pool cooling system. The second accident would be dropping an assembly into an already loaded cell and the third would be a misload of an assembly into a cell for which the restrictions on location, enrichment, or burnup are not satisfied.

For the loss of fuel pool cooling system accident, calculations were performed for both all cell storage and checkerboard storage to show the reactivity increase caused by a rise in the Farley spent fuel pool water temperature from 180°F to 240°F. The reactivity increase for all cell storage is 0.00408 ΔK for Westinghouse STD fuel assemblies. The reactivity increase for 3-out-of-4 checkerboard storage is 0.00089 ΔK for Westinghouse OFA fuel assemblies. There is no reactivity increase above 180°F for 2-out-of-4 checkerboard storage so the misload accident bounds the loss of cooling accident. The reactivity increase for burned/fresh checkerboard storage is 0.00052 ΔK.

For the accident of dropping of a fuel assembly into an already loaded cell, the upward axial leakage of that cell will be reduced, however the overall effect on the rack reactivity will be insignificant. This is because the total axial leakage in both the upward and downward directions for the entire spent fuel array (over 1400 cells) is worth only 0.003 ΔK. Thus, minimizing the upward-only leakage of just a single cell will not cause any significant increase in rack reactivity (much less than 0.0015 ΔK). Furthermore, the neutronic coupling between the dropped assembly and the already loaded assembly will be low due to several inches of assembly nozzle structure which would separate the active fuel regions. Therefore, this accident would be bounded by the misload accident.

For the misload assembly accident, calculations were performed for the all cell storage and various checkerboard storage configurations to show the largest reactivity increase caused by a 5.0 w/o $^{235}U$ Westinghouse fuel assembly misplaced into a storage cell. The largest reactivity increase for all cell storage is 0.04359 ΔK for Westinghouse STD fuel assemblies. The largest reactivity increase for 3-out-of-4 checkerboard storage is 0.06184 ΔK for Westinghouse OFA fuel

assemblies. The largest reactivity increase for 2-out-of-4 checkerboard storage is 0.11611 $\Delta K$ for Westinghouse OFA fuel assemblies. The largest reactivity increase for burned/fresh checkerboard storage is 0.05129 $\Delta K$.

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 reactivity change due to the presence of soluble boron in the Farley spent fuel pool has been calculated with PHOENIX-P for the all cell storage and the three checkerboard storage configurations. The additional amount of soluble boron needed for accident conditions is shown below:

| Storage Configuration | Limiting Fuel Assembly Type | Reactivity Increase ($\Delta K$) | Soluble Boron Required for Accidents (ppm) | Total Soluble Boron Required (ppm) |
|---|---|---|---|---|
| All Cell Storage | W - STD | 0.04359 | 350 | 750 |
| 3-out-of-4 Checkerboard Storage | W - OFA | 0.06184 | 500 | 800 |
| 2-out-of-4 Checkerboard Storage | W - OFA | 0.11611 | 850 | 850 |
| Burned/Fresh Checkerboard Storage | W - OFA/STD | 0.05129 | 350 | 700 |

Based on the above discussion, should a loss of spent fuel pool cooling accident, a dropped assembly, or a fuel assembly misload occur in the Farley spent fuel racks, $K_{eff}$ will be maintained less than or equal to 0.95 due to the presence of at least 850 ppm of soluble boron in the spent fuel pool water.

# 9.0 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 12 on page 47 summarizes the storage configurations, fuel types and corresponding soluble boron credit requirements.

# 10.0 Storage Configuration Interface Requirements

The Farley spent fuel pool is composed of a single type of rack. The spent fuel pool 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.

Boundaries between different checkerboard zones and between a checkerboarded 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 a fuel assembly at the boundary and ensuring that each 2x2 matrix conforms to the checkerboard restrictions for the given regions.

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

| | | |
|---|---|---|
| A | B | C |
| D | E | F |
| G | H | I |

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

## 10.1 Interface Requirements within Farley Racks

The following interface requirements are applicable to the Farley Spent Fuel Racks:

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

The boundary between all cell storage and 3-out-of-4 storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover uses 3.0 w/o or equivalent fuel assemblies and empty cells. Figure 7 on page 54 illustrates the carryover configuration.

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

The boundary between all cell storage and 2-out-of-4 can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover uses 5.0 w/o fuel assemblies and empty cells. Figure 7 on page 54 illustrates the carryover configuration.

**All Cell Storage Next to Burned/Fresh Storage**

The boundary between all cell storage and Burned/Fresh storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover uses 1.6 w/o or equivalent fuel assemblies. Figure 8 on page 55 illustrates the carryover configuration.

**3-out-of-4 Storage Next to Burned/Fresh Storage**

The boundary between 3-out-of-4 storage and burned/fresh storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover uses 3.0 w/o or equivalent fuel assemblies and empty cells in the 3-out-of 4 zone, and 1.6 w/o or equivalent fuel assemblies in the burned/fresh zone. Figure 8 on page 55 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 uses 3.0 w/o or equivalent fuel assemblies and empty cells in the 3-out-of 4 zone, and 5.0 w/o fuel assemblies and empty cells in the 2-out-of-4 zone. Figure 9 on page 56 illustrates the carryover configuration.

**2-out-of-4 Storage Next to Burned/Fresh Storage**

The boundary between 2-out-of-4 storage and burned/fresh storage can be either separated by a vacant row of cells or the interface must be configured such that the first row of carryover uses 3.9 w/o or equivalent fuel assemblies and alternating empty cells in the burned/fresh zone. Figure 9 on page 56 illustrates the carryover configuration.

**Open Water Cells**

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

**Neutron Source in a Cell**

The placement of a neutron source in the spent fuel pool will not cause any increase in reactivity in the spent fuel pool because the source displaces water, which results in a reduction in reactivity.

# 11.0 Summary of Criticality Results

For the storage of fuel assemblies in the spent fuel storage racks, the acceptance criteria for criticality requires the effective neutron multiplication factor, $K_{eff}$, to be less than or equal to 0.95, including uncertainties. This report shows that the acceptance criterion for criticality is met for the Farley spent fuel racks for the storage of 17x17 fuel assemblies under both normal and accident conditions with soluble boron credit and no credit for the spent fuel rack Boraflex poison panels and the following storage configurations and enrichment limits:

| | |
|---|---|
| **All Cell Storage Enrichment Limits** | Storage of Westinghouse 17x17 OFA, VANTAGE 5, and STD assemblies with nominal enrichments no greater than 2.15 w/o $^{235}U$ in all cell locations. Fuel assemblies with initial nominal enrichments greater than this must satisfy the minimum burnup requirement shown in Figure 3. |
| **3-out-of-4 Checkerboard Enrichment Limits** | Storage of Westinghouse 17x17 OFA, VANTAGE 5, and STD assemblies with nominal enrichments no greater than 3.0 w/o $^{235}U$ in a 3-out-of-4 checkerboard. Fuel assemblies with initial nominal enrichments greater than this must satisfy the minimum burnup requirement shown in Figure 3. |
| **2-out-of-4 Checkerboard Enrichment Limits** | Storage of Westinghouse 17x17 OFA, VANTAGE 5, and STD assemblies with nominal enrichments no greater than 5.0 w/o $^{235}U$ in a 2-out-of-4 checkerboard. |
| **Burned/Fresh Checkerboard Enrichment Limits** | Storage of Westinghouse 17x17 OFA assemblies with nominal enrichments no greater than 3.9 w/o $^{235}U$ and STD assemblies with nominal enrichments no greater than 1.6 w/o $^{235}U$ in a burned/fresh checkerboard. This configuration bounds all combinations of fuel types. Fuel assemblies with initial nominal enrichments greater than 1.6 w/o $^{235}U$ must satisfy the minimum burnup requirement shown in Figure 3. Fuel assemblies with initial nominal enrichments greater than 3.9 w/o $^{235}U$ must satisfy the minimum IFBA number requirement shown in Figure 4. |

The soluble boron credit required for these storage configurations are 400 ppm for normal conditions and 850 ppm for accidents.

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* | Westinghouse 17x17 STD |
|---|---|---|
| Number of Fuel Rods per Assembly | 264 | 264 |
| Fuel Rod Clad O.D. (inch) | 0.360 | 0.374 |
| Clad Thickness (inch) | 0.0225 | 0.0225 |
| Fuel Pellet O.D.(inch) | 0.3088 | 0.3225 |
| Fuel Pellet Density (% of Theoretical) | 95 | 95 |
| Fuel Pellet Dishing Factor (%) | 1.211 | 1.2074 |
| Rod Pitch (inch) | 0.496 | 0.496 |
| Number of Zirc Guide Tubes ** | 24 | 24 |
| Guide Tube O.D. (inch) | 0.474 | 0.482 |
| Guide Tube Thickness (inch) | 0.016 | 0.016 |
| Number of Instrument Tubes | 1 | 1 |
| Instrument Tube O.D. (inch) | 0.474 | 0.482 |
| Instrument Tube Thickness (inch) | 0.016 | 0.016 |

* The 17x17 VANTAGE 5 fuel design parameters relevant to the criticality analysis are the same as the OFA parameters and will yield equivalent results.

** The fuel rod cladding, guide tube and instrumentation tube are modeled with zircaloy. This is conservative with respect to fuel assemblies containing ZIRLO™.

**Table 2. Farley All Cell Storage No Soluble Boron 95/95 $K_{eff}$**

| | W - STD |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.96231** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00760 |
| TOTAL Bias | 0.01530 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00653 |
| $UO_2$ Density Tolerance (±2%) | 0.00309 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00158 |
| Cell Inner Diameter (±0.045 inch) | 0.00009 |
| Cell Pitch (±0.06 inch) | 0.00590 |
| Cell Wall Thickness (±0.012 inch) | 0.00525 |
| Asymmetric Assembly Position | 0.00880 |
| Calculational Uncertainty (95/95) | 0.00195 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01440 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.99201** |

**Table 3. Farley All Cell Storage Soluble Boron Credit 95/95 $K_{eff}$**

| | W - STD |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.90920** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00716 |
| TOTAL Bias | 0.01486 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00661 |
| $UO_2$ Density Tolerance (±2%) | 0.00346 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00178 |
| Cell Inner Diameter (±0.045 inch) | 0.00027 |
| Cell Pitch (±0.06 inch) | 0.00593 |
| Cell Wall Thickness (±0.012 inch) | 0.00371 |
| Asymmetric Assembly Position | 0.00761 |
| Calculational Uncertainty (95/95) | 0.00188 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01335 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.93741** |

**Table 4. Farley 3-out-of-4 Checkerboard Storage No Soluble Boron 95/95 $K_{eff}$**

| | W - OFA |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.97212** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00268 |
| TOTAL Bias | 0.01038 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00384 |
| $UO_2$ Density Tolerance (±2%) | 0.00283 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00166 |
| Cell Inner Diameter (±0.045 inch) | 0.00009 |
| Cell Pitch (±0.06 inch) | 0.00420 |
| Cell Wall Thickness (±0.012 inch) | 0.00430 |
| Asymmetric Assembly Position | 0.00981 |
| Calculational Uncertainty (95/95) | 0.00205 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01308 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.99558** |

**Table 5. Farley 3-out-of-4 Checkerboard Storage Soluble Boron Credit 95/95 $K_{eff}$**

| | W - OFA |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.92351** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00360 |
| TOTAL Bias | 0.01130 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00381 |
| $UO_2$ Density Tolerance (±2%) | 0.00298 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00174 |
| Cell Inner Diameter (±0.045 inch) | 0.00028 |
| Cell Pitch (±0.06 inch) | 0.00447 |
| Cell Wall Thickness (±0.012 inch) | 0.00321 |
| Asymmetric Assembly Position | 0.00939 |
| Calculational Uncertainty (95/95) | 0.00219 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01260 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.94741** |

**Table 6. Farley 2-out-of-4 Checkerboard Storage No Soluble Boron 95/95 $K_{eff}$**

| | W - OFA |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.92764** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00011 |
| TOTAL Bias | 0.00781 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00152 |
| $UO_2$ Density Tolerance (±2%) | 0.00239 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00135 |
| Cell Inner Diameter (±0.045 inch) | 0.00017 |
| Cell Pitch (±0.06 inch) | 0.00080 |
| Cell Wall Thickness (±0.012 inch) | 0.00247 |
| Asymmetric Assembly Position | 0.00485 |
| Calculational Uncertainty (95/95) | 0.00238 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.00740 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.94285** |

**Table 7. Farley Burned/Fresh Checkerboard Storage No Soluble Boron 95/95 $K_{eff}$**

| | W - OFA/STD |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.96905** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00379 |
| TOTAL Bias | 0.01149 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00519 |
| $UO_2$ Density Tolerance (±2%) | 0.00284 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00167 |
| Cell Inner Diameter (±0.045 inch) | 0.00011 |
| Cell Pitch (±0.06 inch) | 0.00462 |
| Cell Wall Thickness (±0.012 inch) | 0.00446 |
| Asymmetric Assembly Position | 0.00965 |
| Calculational Uncertainty (95/95) | 0.00203 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01361 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.99415** |

**Table 8. Farley Burned/Fresh Checkerboard Storage Soluble Boron Credit 95/95 $K_{eff}$**

| | W - OFA/STD |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.91704** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00308 |
| TOTAL Bias | 0.01078 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00501 |
| $UO_2$ Density Tolerance (±2%) | 0.00321 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00188 |
| Cell Inner Diameter (±0.045 inch) | 0.00024 |
| Cell Pitch (±0.06 inch) | 0.00451 |
| Cell Wall Thickness (±0.012 inch) | 0.00311 |
| Asymmetric Assembly Position | 0.00852 |
| Calculational Uncertainty (95/95) | 0.00200 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01243 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.94025** |

**Table 9. Summary of the Burnup Requirements**

| Nominal Enrichment (w/o $^{235}U$) | All Cell Burnup (MWD/MTU) | 3-out-of-4 Checkerboard Burnup (MWD/MTU) | Burned/Fresh Checkerboard Burnup (MWD/MTU) |
|---|---|---|---|
| 1.60 | 0 | 0 | 0 |
| 2.00 | 0 | 0 | 8567 |
| 2.15 | 0 | 0 | 10662 |
| 2.20 | 755 | 0 | 11349 |
| 2.40 | 3436 | 0 | 14043 |
| 2.60 | 5706 | 0 | 16656 |
| 2.80 | 7720 | 0 | 19196 |
| 3.00 | 9602 | 0 | 21668 |
| 3.20 | 11451 | 1560 | 24080 |
| 3.40 | 13335 | 3108 | 26440 |
| 3.60 | 15294 | 4643 | 28753 |
| 3.80 | 17341 | 6165 | 31028 |
| 4.00 | 19460 | 7674 | 33271 |
| 4.20 | 21606 | 9170 | 35489 |
| 4.40 | 23705 | 10654 | 37689 |
| 4.60 | 25658 | 12125 | 39879 |
| 4.80 | 27333 | 13583 | 42064 |
| 5.00 | 28573 | 15028 | 44253 |

**Table 10. Summary of Minimum IFBA Requirements for Fresh Fresh Assembly in Burned/Fresh Checkerboard Storage**

| Nominal Enrichment (w/o $^{235}U$) | Burned/Fresh Checkerboard IFBA Requirement** | | | |
|---|---|---|---|---|
| | 1.0X* | 1.25X* | 1.5X* | 2.0X* |
| 3.90 | 0 | 0 | 0 | 0 |
| 4.20 | 14 | 11 | 9 | 7 |
| 4.40 | 24 | 19 | 15 | 12 |
| 4.60 | 34 | 27 | 21 | 17 |
| 4.80 | 42 | 34 | 27 | 21 |
| 5.00 | 52 | 42 | 34 | 26 |

* Denotes nominal IFBA loadings of 1.5 mg-$^{10}$B/in (1.0X), 1.88 mg-$^{10}$B/in (1.25X), 2.25 mg-$^{10}$B/in (1.5X), and 3.0 mg-$^{10}$B/in (2.0X)

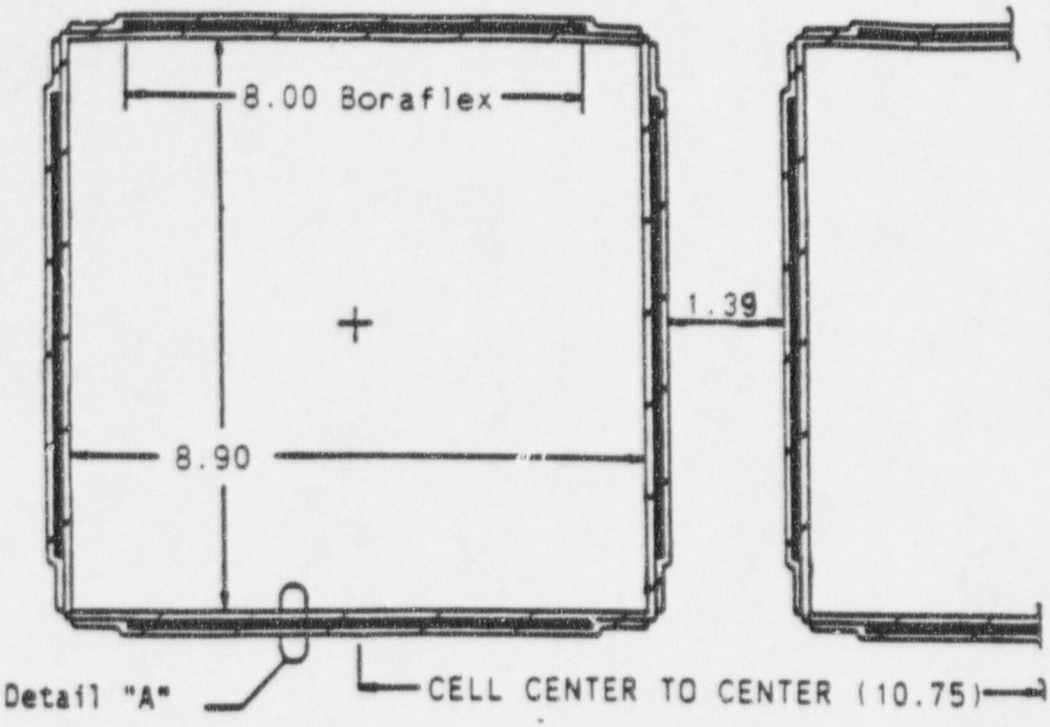
** These IFBA limits bound the nominal IFBA loadings for Standard fuel of 1.57 mg-$^{10}$B/in (1.0X), 1.96 mg-$^{10}$B/in (1.25X), 2.35 mg-$^{10}$B/in (1.5X), and 3.14 mg-$^{10}$B/in (2.0X)

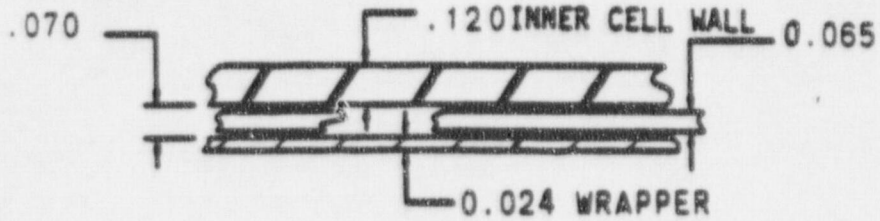
**Table 11. Farley Damaged Assembly Storage No Soluble Boron 95/95 $K_{eff}$**

| | W - STD |
|---|---|
| **Nominal KENO-Va Reference Reactivity:** | **0.95152** |
| **Calculational & Methodology Biases:** | |
| Methodology (Benchmark) Bias | 0.00770 |
| Pool Temperature Bias (50°F - 180°F) | 0.00821 |
| TOTAL Bias | 0.01591 |
| **Tolerances & Uncertainties:** | |
| $UO_2$ Enrichment Tolerance (±0.05 w/o $^{235}U$) | 0.00414 |
| $UO_2$ Density Tolerance (±2%) | 0.00265 |
| Fuel Pellet Dishing Variation (0 to 2X) | 0.00132 |
| Cell Inner Diameter (±0.045 inch) | 0.00020 |
| Cell Pitch (±0.06 inch) | 0.00612 |
| Cell Wall Thickness (±0.012 inch) | 0.00534 |
| Asymmetric Assembly Position | 0.00880 |
| Calculational Uncertainty (95/95) | 0.00195 |
| Methodology Bias Uncertainty (95/95) | 0.00300 |
| TOTAL Uncertainty (statistical) | 0.01350 |
| $\sqrt{\sum_{i=1}^{9}((tolerance_i \ldots or \ldots uncertainty_i)^2)}$ | |
| **Final 95/95 $K_{eff}$ Including Uncertainties & Tolerances:** | **0.98093** |

Table 12. Summary of the Soluble Boron Credit Requirements

| Storage Configuration | Limiting Fuel Assembly Type | 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) |
|---|---|---|---|---|---|---|
| All Cell Storage | W - STD | 200 | 200 | 400 | 350 | 750 |
| 3-out-of-4 Checkerboard Storage | W - OFA | 200 | 100 | 300 | 500 | 800 |
| 2-out-of-4 Checkerboard Storage | W - OFA | 0 | 0 | 0 | 850 | 850 |
| Burned/Fresh Checkerboard Storage | W - OFA/STD | 200 | 150 | 350 | 350 | 700 |

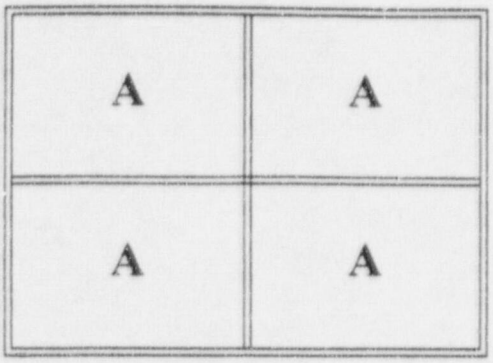


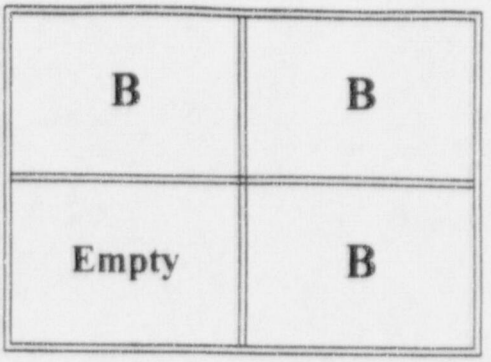

DETAIL "A"

Note: There are two thicknesses of inner cell wall: 0.120" and 0.135". The thickness of 0.120" is chosen for this analysis since it is conservative when no Boraflex is present.

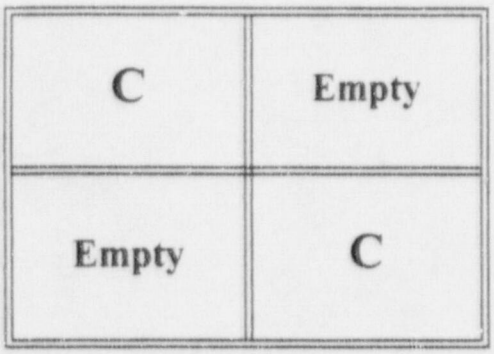
**Figure 1. Farley Spent Fuel Pool Storage Cell Nominal Dimensions**



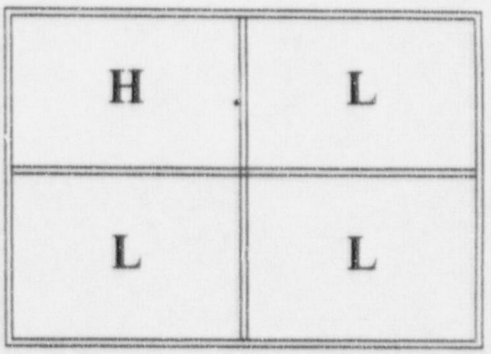

All Cell Storage




3-out-of-4 Storage




2-out-of-4 Storage




Burned/Fresh Storage

Note:
A = All Cell Enrichment
B = 3-Out-Of-4 Enrichment
C = 2-Out-Of-4 Enrichment
L = Low Enrichment of Burned/Fresh
H = High Enrichment of Burned/Fresh
Empty = Empty Cell

**Figure 2. Farley Spent Fuel Storage Configurations**

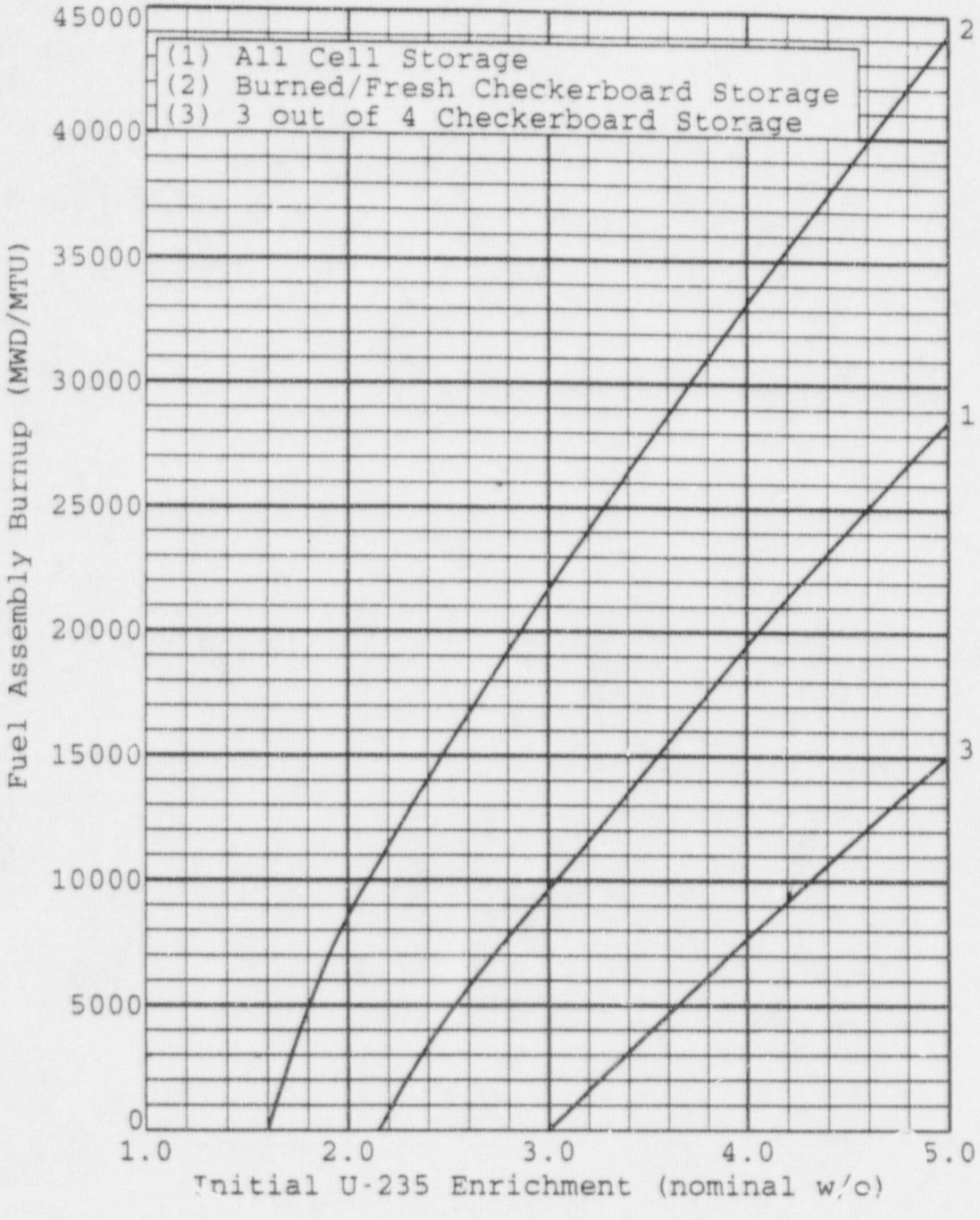



**Figure 3. Farley Burnup Credit Requirements**

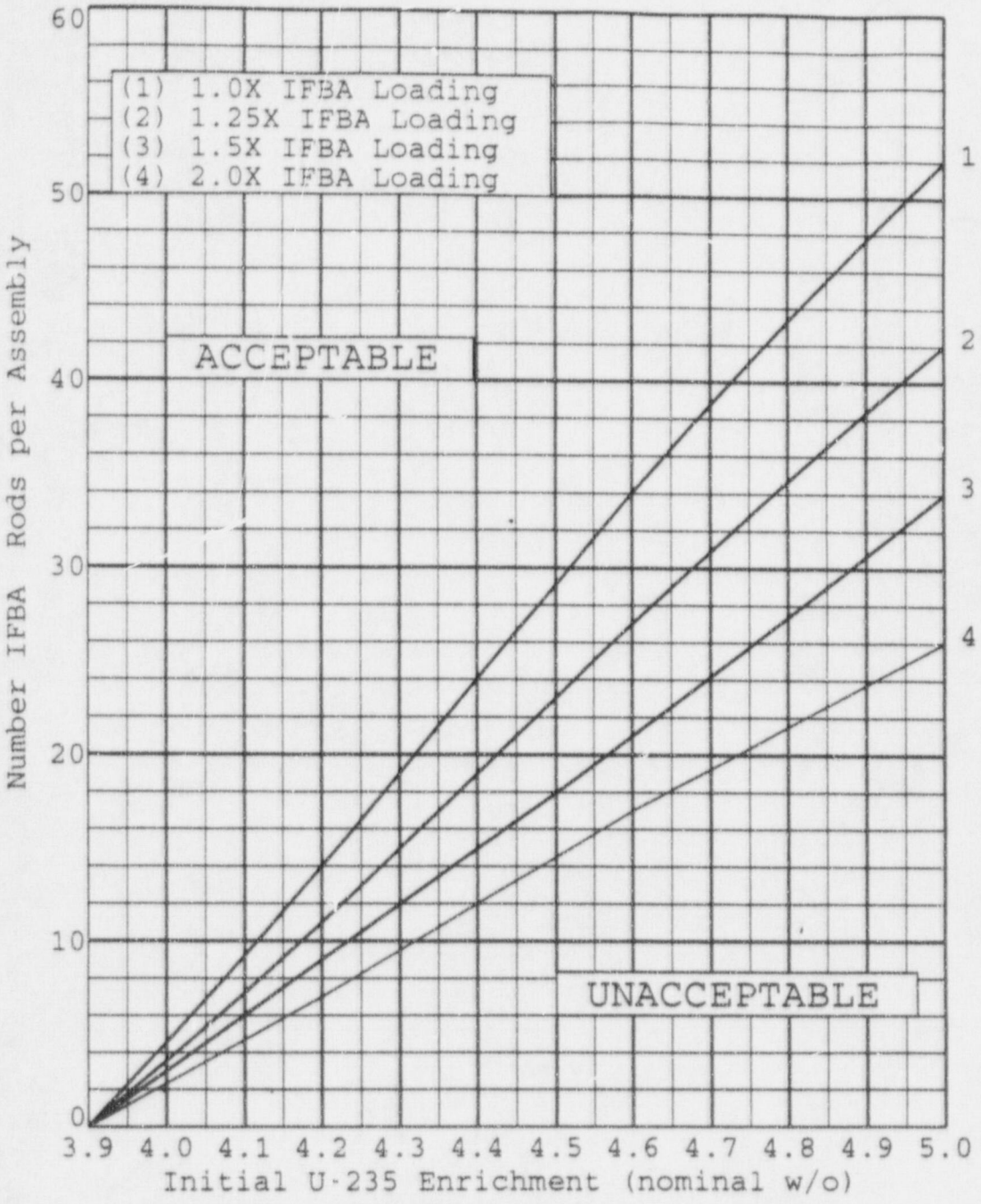



**Figure 4. Farley Minimum IFBA Requirements for Fresh Assembly in Burned/Fresh Checkerboard Storage**

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | F31<br>7516 | Empty | F30<br>7341 | F06<br>7441 | |
| | F18<br>7407 | F17<br>7423 | F19<br>7487 | F02<br>7329 | |
| | F15<br>7227 | F20<br>7522 | F05<br>7444 | F32<br>7356 | |
| | | | | WATER | |

**Note: All assemblies are 3.0 w/o $^{235}U$ nominal enrichment**

**All burnups shown in MWD/MTU**

**Figure 5. Farley Damaged Fuel Assembly Configuration and Assembly Burnups**

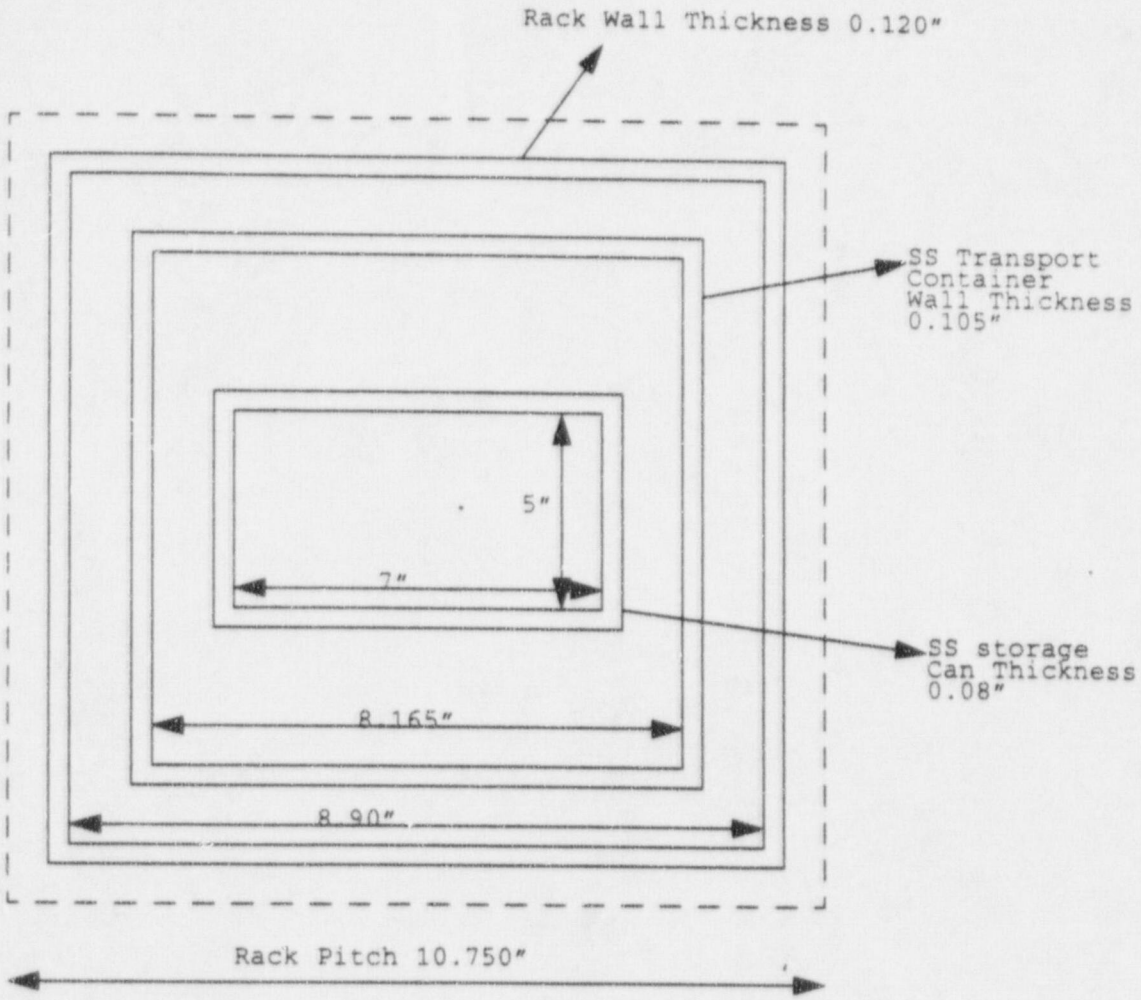
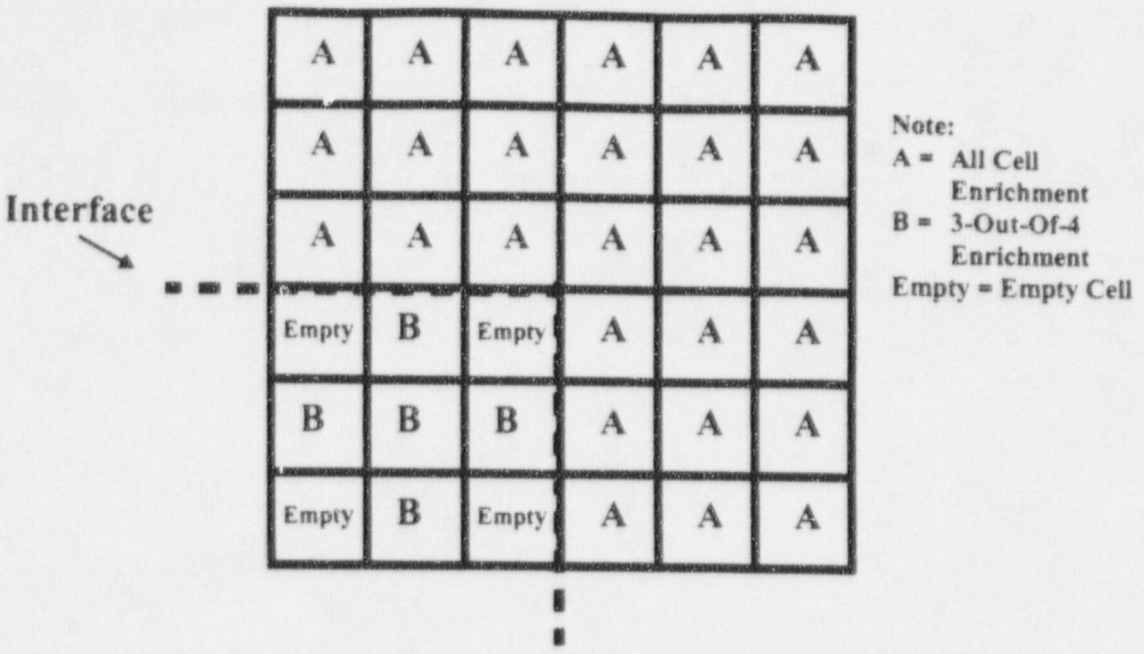



**Figure 6. Farley Loose Pellet Transport Container Dimensions in Spent Fuel Rack**



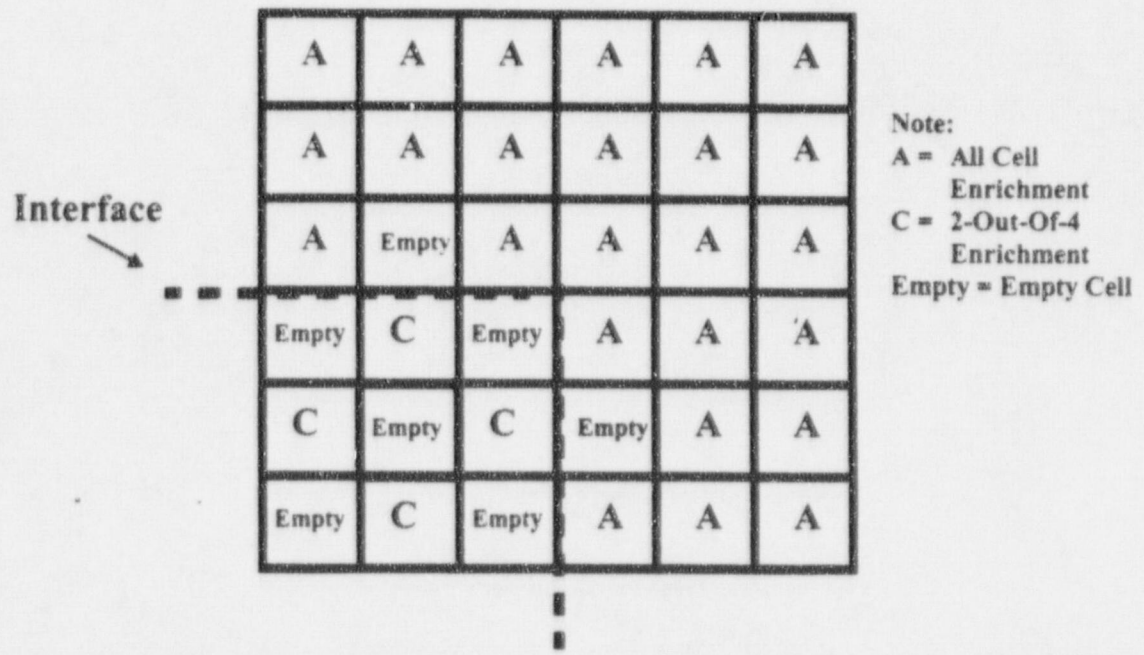
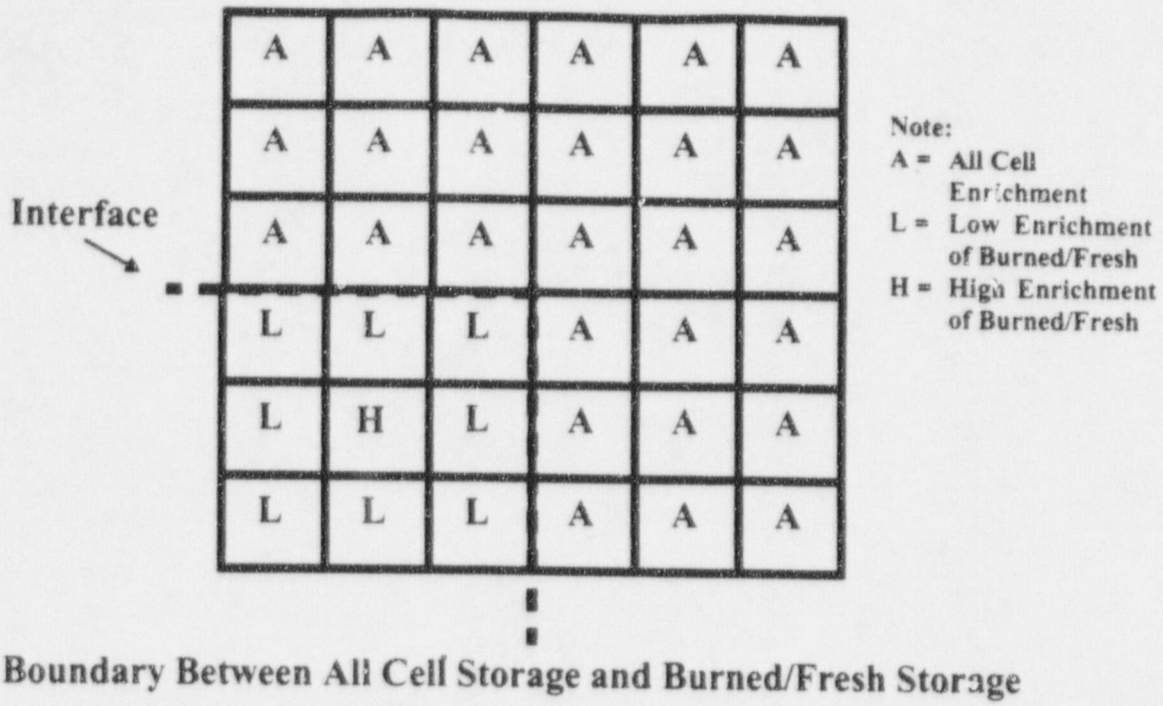




**Figure 7. Farley Interface Requirements (Part 1)**



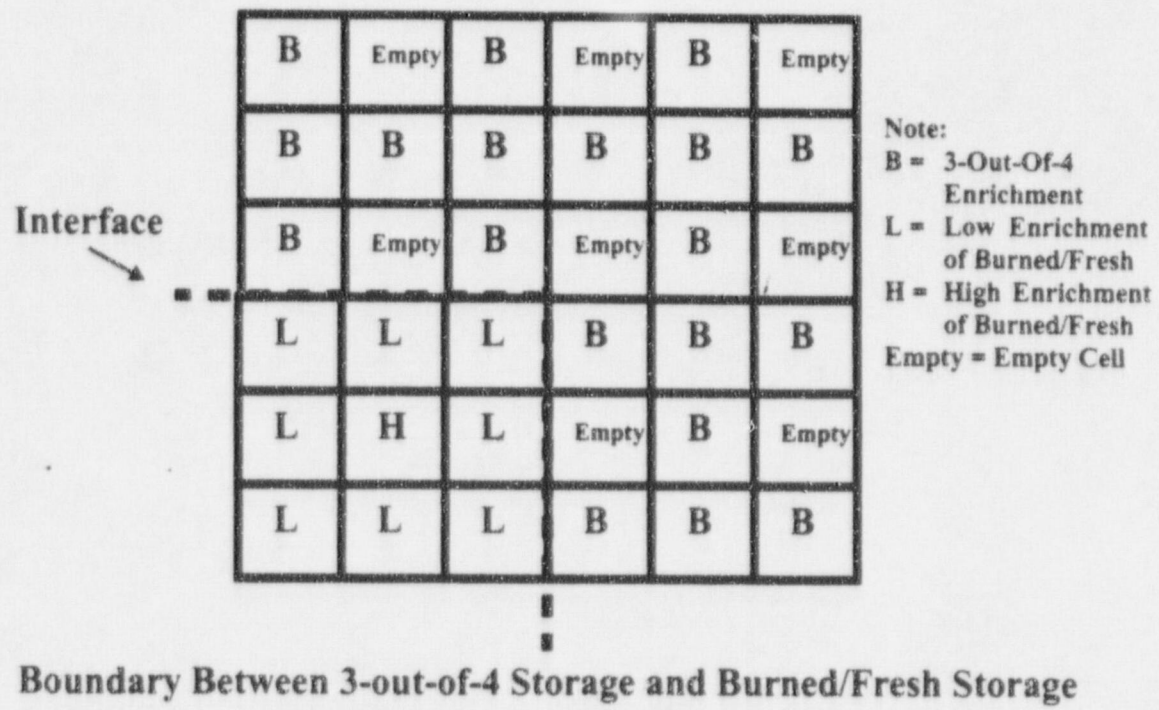
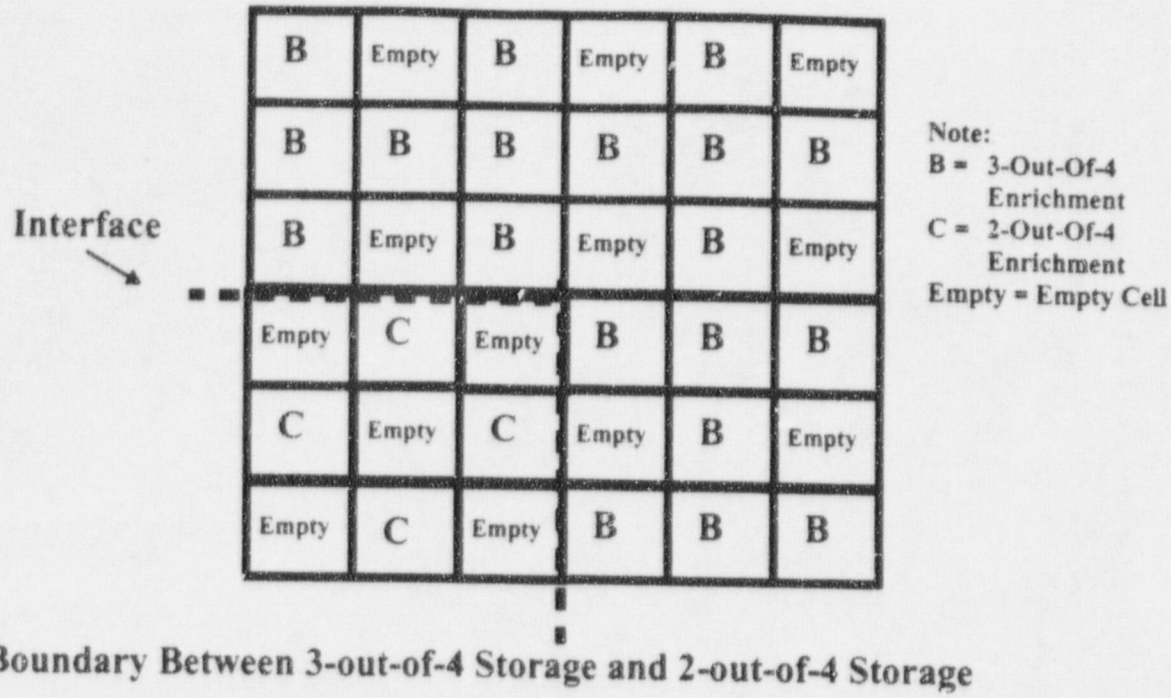
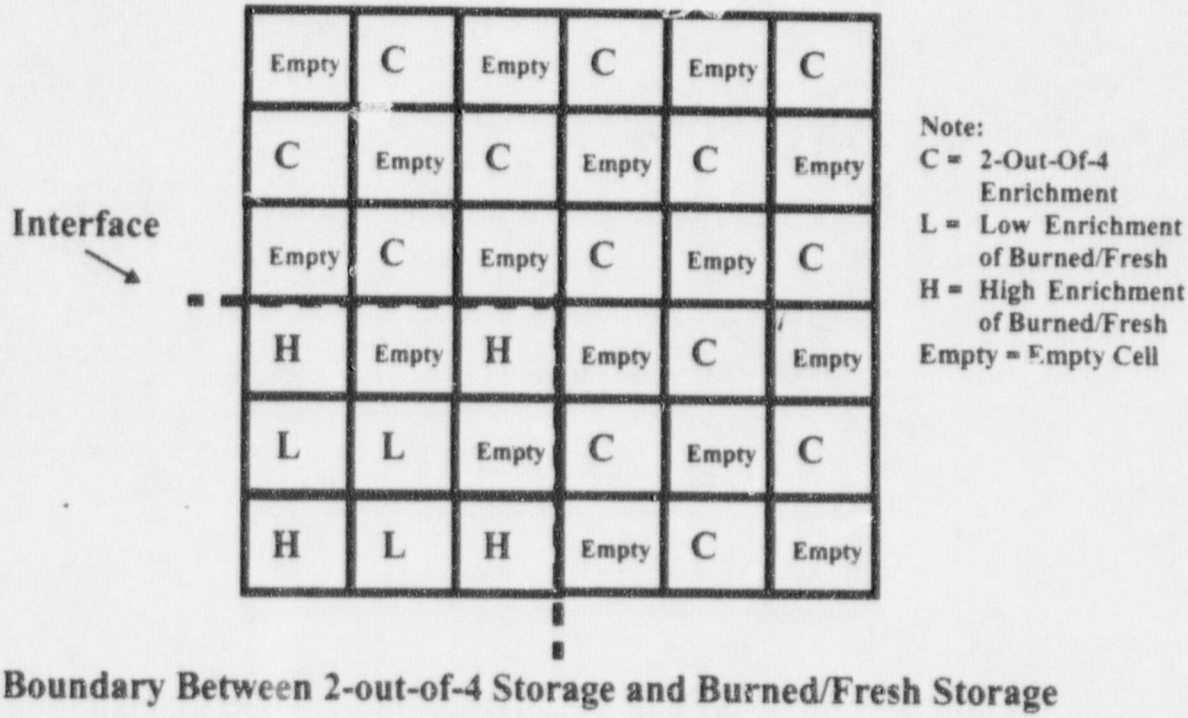




**Figure 8. Farley Interface Requirements (Part 2)**




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




**Boundary Between 2-out-of-4 Storage and Burned/Fresh Storage**

**Figure 9. Farley Interface Requirements (Part 3)**

# Bibliography


1. Newmyer, W.D., Westinghouse Spent Fuel Rack Criticality Analysis Methodology, WCAP-14416-NP-A, November 1995.
2. Fecteau, M. W., *Criticality Analysis of the Farley Units 1 & 2 Fresh and Spent Fuel Racks*, March 1991.
3. Davidson, S. L., et al, *VANTAGE 5 Fuel Assembly Reference Core Report, Addendum 1, WCAP-10444-PA*, March 1986.
4. Newmyer. W.D., *Fuel Rod Storage Canister Criticality Analysis*, October 1994.

# ATTACHMENT V

FARLEY NUCLEAR PLANT

TECHNICAL SPECIFICATIONS CHANGE REQUEST

SPENT FUEL POOL SOLUBLE BORON CREDIT

BORON DILUTION ANALYSIS

FARLEY

SPENT FUEL POOL BORON DILUTION ANALYSIS

Table of Contents

## 1.0 INTRODUCTION

A boron dilution analysis has been performed for crediting boron in the Farley spent fuel pool (SFP) rack criticality analysis. The boron dilution analysis includes an evaluation of the following plant specific features:

- Dilution Sources and Flowrates
- 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 performed 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 SFP and its related systems and features.

### 2.1 Spent Fuel Pool

The design purpose of the SFP is to provide for safe storage of irradiated fuel assemblies. The pool is filled with borated water. The water functions to remove decay heat, provide shielding for personnel handling the fuel, and to reduce 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 remove boron. Evaporation actually increases the boron concentration in the pool.

Each unit has one SFP. The pools are identical in size and are physically separated (in separate rooms and not in communication). The SFP is a reinforced concrete structure with a welded steel liner. The concrete structure has formed leak chases that can be drained by opening sample valves that are located in the Auxiliary building. The pool structure is designed to meet seismic requirements. The pool is approximately 40.5 feet deep. The top of the pool is approximately 6 inches above grade level.

The transfer canal is located adjacent to the SFP. The transfer canal connects the SFP with the transfer tube and the cask loading area. Leaktight gates separate the SFP from the transfer canal and the transfer canal from the cask loading area. Both gates are normally installed thus isolating the SFP from the transfer canal and the cask loading area. The total volume of water in the SFP is conservatively calculated to be approximately 300,000 gallons when allowance is made for the materials in the SFP with all rack cells containing fuel elements.

## 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 structural strength 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

There are two trains of spent fuel pool cooling. 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.

The system is designed to remove an amount of decay heat in excess of that produced by the number of spent fuel assemblies that are stored in the pool following a normal refueling plus any fuel assemblies that may remain in the pool from previous refuelings. System piping is so arranged that failure of any pipeline does not drain the SFP below the top of the stored spent fuel assemblies.

## 2.4 Spent Fuel Pool Cleanup System

The SFP cleanup system is designed to maintain water clarity and to control borated water chemistry. The cleanup system is connected to the SFP cooling system. A portion of the SFP cooling pump(s) discharge flow can be diverted to the cleanup loop, which includes the SFP demineralizer and filter. The filter removes particulates from the SFP water and the SFP demineralizer removes ionic impurities.

The refueling water cleanup loop also uses the SFP demineralizer and filters to clean up the refueling water storage tank after refueling operations.

To assist further in maintaining spent fuel pool water clarity, the water surface is cleaned by a skimmer loop. The system consists of one strainer, pump and filter. The skimmer pump is a centrifugal pump with a 100 gpm design flow rate. The pump discharge flow passes through the filter to remove particulates, then returns to the SFP at three locations remote from the skimmers.

## 2.5 Dilution Sources

### 2.5.1 Chemical and Volume Control System (CVCS)

The Chemical and Volume Control System (CVCS) connects with the SFP via temporary tygon hose routed from a connection at the discharge of the boric acid blender to the SFP. This connection is used as an alternate method to supply water (reactor makeup water blended with borated water) at a specific boron concentration to the SFP. The connection is on the down stream side of the boric acid blender and is isolated by a manual valve and is blind flanged. The supply from the blender to the SFP cooling system can have a boron concentration from 0 to 7,700 ppm depending on the control setting for the blender. The expected maximum flowrate using this line is 120 gpm.

### 2.5.2 Reactor Makeup Water System

The reactor makeup water (RMW) system connects to the SFP cooling system indirectly through the boric acid blender (Section 2.5.1) and through a connection to the SFP demineralizer. The connection to the demineralizer is designed to be used to flush the SFP demineralizer resin.

There is also a RMW line in the SFP room adjacent to the SFP to allow for direct makeup to the SFP. Using this supply line, the contents of the reactor makeup water tank can be transferred via the reactor makeup water pumps directly to the SFP via a temporary hose. The line is isolated from the SFP area by a locked closed manual valve. This is used as a source of makeup water in case of a loss of both trains of SFP cooling.

The reactor makeup water system consists of reactor makeup water tank and two reactor makeup water pumps for each unit. The reactor makeup water tank contains approximately 200,000 gallons of non-borated reactor grade water. Each pump provides a design flowrate of 150 gpm at 275 feet of head. The tank can be filled via manual operator action from the water treatment plant. The treatment plant can provide flowrates of up to 360 gpm.

### 2.5.3 Demineralized Water System

A local demineralized water system line is located adjacent to the SFP. The line is isolated from the pool area by a closed manual valve. Demineralized water also connects to the SFP cooling return line and is used as the normal source for SFP makeup as a result of evaporative losses. This line is isolated by a locked closed manual valve.

The demineralized water system consists of a 200,000 gallon tank with 3 pumps each delivering a design flow of 300 gpm at a head of 275 feet. One of these pumps normally runs. One of the non running pumps is placed in automatic and the other is placed in "off". The pump placed in automatic starts on low system pressure. The tank is automatically filled from the water treatment plant. The treatment plant can provide flowrates of up to 360 gpm.

### 2.5.4 Component Cooling

Component cooling water is the cooling medium for the SFP cooling system heat exchangers. There is no direct connection between the component cooling system and the SFP cooling system. If however, a leak were to develop in a heat exchanger that is in service, the connection would be made. In case of a leak, the CCW water would be expected to leak into the SFP cooling system because the CCW system normally operates at a slightly higher pressure than the SFP cooling system.

It would be expected that the flow rate of any leakage of component cooling water into the SFP 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 system to the SFP, the impact on the SFP boron concentration would be minimal because the component cooling water system volume is approximately 37,000 gallons (35,000 gallons for the system and 2,000 gallons for the surge tank). Any loss of water from the component cooling system surge tank would be manually replaced which could increase the amount of water available to dilute the pool. However, the need to makeup to the surge tank along with alarms and control room indications would alert the control room operators to any significant loss of water from the component cooling system.

A dilution resulting from an addition of 37,000 gallons would be approximately 230 ppm resulting in a final SFP boron concentration of approximately 1770 ppm from an initial concentration of 2000 ppm (see section 3.1 for calculation of boron dilution times and volumes). Because of the limited amount of water available from the component cooling water system, and the mechanisms available to operators to help identify such leakage, a SFP heat exchanger leak cannot result in any significant dilution of the SFP and is not considered further in this analysis.

### 2.5.5 SFP Demineralizer Resin Fill Connection / Resin Sluice Line

The SFP demineralizer has a resin fill line in which demineralized water is used to assist in resin addition. This is a blind flanged connection. Only a small amount of water is used during resin addition. The resin sluice line is connected through a normally closed manual valve to a spent resin header which in turn connects to the spent resin storage tank. Resin addition and sluicing are procedurally controlled, infrequently performed evolutions. Misalignment of multiple valves would have to occur to start a dilution. Since neither of these paths can provide a significant dilution rate, they are not considered further in this analysis.

### 2.5.6 Fire Protection System

The spent fuel pool area has a 3 inch fire protection water supply line running in the overhead (4 inch for Unit 2) and a 2.5 inch sprinkler system supply line. The fire protection system consists of two 300,000 gallon tanks with 1 engine driven fire pump and 2 diesel driven fire pumps. The design flowrate for each pump is 2500 gpm at 289 feet of head.

Any planned addition of fire system water to the SFP 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 SFP boron concentration would be addressed.

The fire protection system contains instrumentation which would alarm in the control room should unplanned flow develop in the fire protection system.

### 2.5.7 Recycle Holdup Tank Discharge to SFP Transfer Canal

A line runs from the outlet of the Recycle Holdup Tanks (RHT) to the SFP transfer canal (SFPTC) to allow for filling of the transfer canal from the RHTs. There are 3 RHTs each with a volume of approximately 28,000 gallons. Each tank is sampled for appropriate boron concentration prior to transferring its contents to the SFPTC. If all three RHTs were full of dilute water and transferred to

the SFPTC, the total amount of water transferred would be approximately 84,000 gallons. The transfer canal holds approximately 46,000 gallons. If this evolution was to occur with the transfer canal full, a maximum of 84,000 gallons of water could enter the SFP. A dilution of approximately 500 ppm would occur resulting in a final boron concentration of 1500 ppm from an initial concentration of 2000 ppm (see section 3.1 for calculation of boron dilution times and volumes). An addition of three RHTs cannot result in any significant dilution of the SFP and is not considered further in this analysis.

### 2.5.8 Dilution Source and Flow Rate Summary

Based on the evaluation of potential SFP dilution sources summarized above, the following dilution sources where determined to be capable of providing a significant amount of non-borated water to the SFP. The potential for these sources to dilute the SFP boron concentration down to the design basis boron concentration (400 ppm) will be evaluated in Section 3.0.

| SOURCE | APPROXIMATE FLOW RATE | SECTION |
|---|---|---|
| **Reactor Makeup Water System** | | |
| - SFP Demineralizer flush connection | 100 gpm | 3.2.1 |
| - SFP area | 150 gpm | 3.2.1 |
| | 380 gpm (pipe break) | 3.2.4 |
| **Chemical and Volume Control System** | | |
| - Connection to SFP (CVCS Blender) | 120 gpm | 3.2.2 |
| **Demineralized Water System** | | |
| - SFP Cooling connection | 300 gpm | 3.2.3 |
| - SFP Area | 200 gpm | 3.2.3 |
| | 1300 gpm (pipe break) | 3.2.4 |
| **Fire Protection Supply Lines** | 2000 gpm (pipe break) | 3.2.4 |

## 2.6 Boration Sources

The normal source of borated water to the SFP is from the RWST through the Refueling Water Purification pump. An alternate source of borated water to the SFP is from the CVCS via a temporary hose connection. It is also possible to borate the SFP by the addition of dry boric acid directly to the SFP water.

### 2.6.1 Refueling Water Storage Tank

The refueling water storage tank connects to the SFP through separate inlet and outlet lines. These connections are normally used to purify the RWST water when the purification loop is isolated from the SFP cooling system. If necessary, this connection can supply approximately 110 gpm of borated water to the SFP via the refueling water purification pump to the inlet to the SFP cooling system purification loop. The RWST is required by Technical Specifications to be kept at a minimum boron concentration of 2300 ppm and volume of 471,000 gallons during modes one through four.

### 2.6.2 Chemical and Volume Control System

The Chemical and Volume Control System (CVCS) is an alternate borated makeup source for the SFP. The CVCS blender is connected to the SFP cooling system by a temporary hose connection near the discharge of the blender. This connection is used to supply water at a specific boron concentration to the SFP. Concentrated boric acid is supplied to the CVCS blender from boric acid tanks via the boric acid transfer pumps. Reactor makeup water is supplied to the CVCS blender from the reactor makeup water tanks via the reactor makeup pumps. Flow controllers are used to control the boric acid and demineralized water flow to the blender and to establish the desired boron concentration in the water being sent to the SFP. The rate of addition through this connection is approximately 120 gpm when providing blended flow. The supply from the blender to the SFP cooling system can have a boron concentration of anywhere from 0 to 7,700 ppm depending on-the control setting for the blender.

### 2.6.3 Direct Addition of Boric Acid

If necessary, the boron concentration of the SFP can be increased by depositing dry boric acid directly into the SFP. The dry boric acid will dissolve into the SFP water and will be mixed throughout the pool by the SFP cooling system flow and by the thermal convection created by the spent fuel decay heat.

## 2.7 Spent Fuel Pool Instrumentation

Instrumentation is available to monitor SFP water level and temperature, and the radiation levels in the SFP enclosure. Additional instrumentation is provided to monitor the pressure, flow and temperature of the SFP cooling and cleanup system.

The instrumentation provided to monitor the temperature of the water in the SFP is locally indicated as well as 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 SFP area, provides high radiation alarms locally in the SFP area and in the control room.

A change of 1 inch in SFP level requires approximately 750 gallons of water. If a dilution event caused the pool level to rise from the low level alarm point to the high level alarm (6 inch span), a dilution of approximately 4,500 gallons could occur before an alarm would be received in the control room. If the SFP boron concentration were at 2000 ppm initially, such a dilution would only result in a reduction of the pool boron concentration of approximately 30 ppm.

## 2.8 Administrative Controls

The following administrative controls will be in place to control the SFP 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 nonborated sources only be used as a last resort.

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

4. Administrative controls are placed on some of the potential dilution paths.

5. The proposed Technical Specifications associated with the use of soluble boron credit will require the SFP boron concentration to be verified every seven days.

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

## 2.9 Piping

The piping located inside the SFP room consists of a 2.5 inch and 4 inch fire protection line, a 4 inch demineralized water line, and a 2 inch reactor makeup water line. The fire protection lines and reactor makeup water line are seismically qualified.

## 2.10 Loss of Offsite Power Impact

Of the dilution sources listed in Section 2.5.7, only the fire protection system is capable of providing non-borated water to the SFP during a loss of offsite power.

The SFP level instrumentation is powered from batteries.

The loss of offsite power would affect the ability to respond to a dilution. The normal source of borated water to the SFP would not be available upon a loss of offsite power. The temporary CVCS blender connection could be established as well as manual addition of dry boric acid to the SFP if it became necessary to increase the SFP boron concentration during a loss of offsite power.

The SFP cooling pumps are not automatically restarted following a loss of offsite power but are supplied by power supplies backed by the emergency diesel generators. These pumps can be manually loaded on the emergency diesel generators following a loss of offsite power.

## 3.0 SPENT FUEL POOL DILUTION EVALUATION

### 3.1 Calculation of Boron Dilution Times and Volumes

For the purposes of evaluating SFP dilution times and volumes, the total pool volume available for dilution is conservatively assumed to be 300,000 gallons. This is the total volume of the SFP when it is filled to the elevation associated with the pool low level alarm and taking into account the volume displaced by SFP racks and fuel.

The transfer canal is normally isolated from the SFP. Therefore, the dilution analysis will only concern the SFP. For Farley, the boron concentration currently maintained in the SFP is greater than 2000 ppm. Based on the Farley criticality analysis (Reference 1), the soluble boron concentration required to maintain the spent fuel boron concentration at $K_{eff} \leq 0.95$, including uncertainties and burnup, with a 95% probability at a 95% confidence level (95/95) is 400 ppm.

For the purposes of the evaluating dilution times and volumes, the initial SFP boron concentration is assumed to be at the proposed Technical Specification limit of 2000 ppm. The evaluations are based on the SFP boron concentration being diluted from 2000 ppm to 400 ppm. To dilute the pool volume of 300,000 gallons from 2000 ppm to 400 ppm would conservatively require 480,000 gallons of non-borated water.

This analysis assumes thorough mixing of all the non-borated water added to the SFP. It is likely, with cooling flow and convection from the spent fuel decay heat, that thorough mixing would occur. However, if mixing was not adequate, a localized pocket of non-borated water could form somewhere in the SFP. 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 SFP filled with non-borated water. Thus, even if a pocket of non-borated water formed in the SFP, $K_{eff}$ would not be expected to exceed 1.0 anywhere in the pool, since the entire pool would be less than 1.0 at 0 ppm.

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

$$t_{end} = \ln (C_0 / C_{end})V/Q \qquad \text{(Equation 1)}$$

Where:

$t_{end}$ = time to dilute

$C_0$ = the boron concentration of the pool volume at the beginning of the event

$C_{end}$ = the boron endpoint concentration

Q = dilution rate (gallons of water/minute)

V = volume (gallons) of SFP.

### 3.2 Evaluation of Boron Dilution Events

The potential SFP dilution events that could occur at Farley are evaluated below:

#### 3.2.1 Dilution From Reactor Makeup Water Tank

While the normal configuration of the reactor makeup water system would limit the amount of water available to dilute the SFP to the contents of one reactor makeup water tank (200,000 gallons), the contents of the reactor makeup water tank can be manually replenished from the water treatment system.

The following events assume that the RMW tank is manually replenished.

There is a RMW line in the SFP room to allow for direct makeup to the SFP during a loss of both trains of spent fuel pool cooling. This connection is isolated from the SFP by a locked closed manual valve. The operator would connect a temporary hose connection to the RMW piping. The RMW valve would then be unlocked and opened to provide water to the SFP. In order to reach the dilution endpoint of 400 ppm, the RMW tank would have to be manually replenished to allow for over 2 tank

volumes (480,000 gallons) of dilute reactor makeup water to enter the pool area. At an estimated flowrate of 150 gpm, the dilution would take over 53 hours to reach the dilution endpoint.

The indirect connection (CVCS blender discharge) from the RMW pumps to the SFP can provide approximately 120 gpm of non-borated water to the SFP. The dilution event is described in section 3.2.2.

There is a RMW line that connects to the SFP demineralizer. This 1 inch line is designed for use in flushing the SFP demineralizer. Assuming the reactor makeup water valve is left open following flushing and the spent fuel pool purification system is placed back in service, with the line supplying an estimated 100 gpm it would take approximately 80 hours to reduce the spent fuel pool boron concentration from 2000 ppm to 400 ppm. While the normal configuration of the reactor makeup water system would limit the amount of water available to dilute the SFP to the contents of one reactor makeup water tank (200,000 gallons), the contents of the reactor makeup water tank can be manually replenished from the water treatment system.

### 3.2.2 Dilution From CVCS Blender

Makeup to the SFP (reactor makeup water blended with concentrated boric acid) may be provided via the CVCS blender. This manual connection is used to supply water at a specific boron concentration from the CVCS blender to the SFP cooling system. The connection is on the down stream side of the boric acid blender and is isolated by a manual valve and blind flanged.

When delivering blended flow, this connection is expected to deliver a maximum flow rate of approximately 120 gpm to the SFP.

Assuming the CVCS blender controls were set to provide unlimited non-borated water, the temporary hose line connected and routed to the spent fuel pool, and the reactor makeup water tank was repeatedly manually replenished, the 120 gpm flow from the CVCS blender to the SFP would take over 67 hours to reduce the pool boron concentration from 2000 ppm to 400 ppm.

This scenario assumes that the water supplied by the CVCS blender is non-borated. If the blender controls are set to provide borated water, the SFP 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 amount of dilution of the SFP would be reduced.

### 3.2.3 Dilution From Demineralized Water System

A local demineralized water system line is located adjacent to the SFP. The line is isolated from the pool area by a closed manual valve. Demineralized water also connects to the SFP cooling return line and is used as the normal source for SFP makeup as a result of evaporative losses. This line is isolated by a locked closed manual valve.

The local demineralized water line is used for washing spent fuel casks and equipment. The line provides a 2 inch connection for attachment of temporary hose. Assuming that the valve was left open following use and that the line was directed in the SFP, 480,000 gallons of demineralized water would have to be put in the SFP to reduce the boron concentration from 2000 ppm to 400 ppm. Assuming a conservative flowrate of 200 gpm, it would take approximately 40 hours to achieve the dilution.

Non-borated water can be provided from the demineralized water system directly to the SFP cooling system through a line that is isolated by a locked closed manual valve. If the valve was to be left open following a SFP makeup evolution, it is possible that a dilution event could take place. Assuming a makeup flowrate of 300 gpm, the dilution event would take over 26 hours. The demineralized water storage tank contains approximately 200,000 gallons. In order to achieve the dilution, the tank would have to be replenished by the water treatment facility. The water treatment facility provides makeup water to each unit's Condensate Storage tank (automatically) as well as each unit's RMW storage tank (manually added). The maximum flowrate of the treatment plant is 360 gpm and must be adjusted to meet demand by a technician.

### 3.2.4 Dilution Resulting From Random Pipe Breaks or Seismic Events

**Random Pipe Breaks**

This accident scenario is that a pipe randomly breaks in the vicinity of the SFP. The maximum flow expected from these lines is 2000 gpm (4" fire protection line), 1300 gpm (4" demineralized water line), and 380 gpm (2" reactor makeup water line).

There are 2 Diesel Driven Fire Pumps. The pumps start on low system pressure and each provides 2500 gpm at 289 feet of head. The flowrate from a broken 4 inch fire protection line is estimated to be 2000 gpm. At this flowrate, it would take approximately 4 hours to dilute the pool to the 400 ppm concentration. Each fire protection tank contains 300,000 gallons. The tanks are connected so that the total amount of water available would be 600,000 gallons. Since only 480,000 gallons of dilute water is necessary to dilute to the 400 ppm concentration, the fire protection system is a potential dilution source.

There are 3 Demineralized Water Transfer Pumps. One of these pumps normally runs. One of the non running pumps is placed in automatic and the other is placed in "off". The pump placed in automatic starts on low system pressure. Each pumps design flow is 300 gpm at 150 psi. The piping layout will allow approximately 1300 gpm flowrate assuming two pumps are running. Assuming that the demineralized water storage tank is full (200,000 gallons) and the water treatment plant (the demineralized water tank's makeup source) is making up to the tank at its maximum flowrate of 360 gpm, the 1300 gpm flowrate could last for approximately 3.5 hours prior to emptying the tank and deliver approximately 275,000 gallons to the spent fuel pool. This amount of water is well below the 480,000 gallons required to dilute the spent fuel pool to the 400 ppm concentration.

There are two Reactor Makeup Water pumps. Each pump provides a design flowrate of 150 gpm at 275 feet of head. If both reactor makeup water pumps were running, the flowrate would be approximately 380 gpm. At this flowrate it would take approximately 21 hours to dilute the spent fuel pool to the 400 ppm concentration. However, the RMWST volume is 200,000 gallons, therefore,

unless the tank was being manually filled from the water treatment plant, the tank would empty in approximately 8.8 hours.

**Seismic Events**

A seismic event could cause piping ruptures in the vicinity of the SFP in piping that is not seismically qualified. The only piping within the immediate vicinity of the SFP that could result in dilution of the SFP if it ruptures during a seismic event is the 4" demineralized water line discussed above.

For a seismic event at Farley, if offsite power is available, rupture of the 4" demineralized water piping located inside the SFP room would result in flow of approximately 1300 gpm flow rate.

If offsite power is not available, the demineralized water system would not operate and thus there would be no dilution source. The effects of a SFP dilution related to the normal flow from the demineralized water line in the SFP enclosure is discussed in Section 3.2.3.

### 3.2.5 Dilution From Spent Fuel Pool Demineralizer

When the SFP demineralizer is first placed in service after being recharged with fresh resin it can initially remove boron from the water passing through it. The demineralizer normally utilizes a mixed bed of anion and cation resin which would remove a small amount of boron before saturating. Because of the small amount of boron removed by the demineralizer, it is not considered a credible dilution source for the purposes of this evaluation.

### 3.3 Evaluation of Infrequent Spent Fuel Pool Configurations

The most limiting SFP configuration at Farley for the boron dilution analysis is when filling of the spent fuel transfer canal is in progress. Procedurally, the operator is to ensure that the level in the SFP does not fall below a depth of 151'6". The low level alarm is at level 153'4". In this configuration, the SFP volume decreases from 300,000 gallons to 283,500 gallons. For the worst case dilution rate (2000 gpm due to a fire protection line break) the dilution time is reduced from 4 hours to 3.8 hours and the amount of dilute water required for the dilution event decreases from 480,000 gallons to 455,000 gallons. Both the normal configuration and this infrequent configuration maintain the SFP isolated from the transfer canal.

### 3.4 Summary of Dilution Events

| SCENARIO | FLOWRATE (GPM) | TIME TO DILUTION (HRS) | COMMENTS |
|---|---|---|---|
| Reactor Makeup Water to SFP | 150 | 53 | Requires RMW tank manual replenishment for event to occur |
| Reactor Makeup Water to CVCS blender | 120 | 67 | Requires RMW tank manual replenishment for event to occur |
| Reactor Makeup Water to SFP demineralizer | 100 | 80 | Requires RMW tank manual replenishment for event to occur |
| Demineralized Water to Cask Wash area | 200 | 40 | Requires demineralized water tank replenishment for event to occur |
| Demineralized Water to SFP cooling loop (normal makeup) | 300 | 26 | Requires demineralized water tank replenishment for event to occur |
| Random Reactor Makeup Water pipebreak | 380 | 21 | Requires RMW tank manual replenishment for event to occur |
| Random Demineralized Water pipebreak | 1300 | 6.2 | With maximum Water Treatment Plant flow of 360 gpm, tank would empty after 3.5 hours |
| Random Fire Protection supply line pipebreak | 2000 | 4.0<br>3.8 for reduced SFP level | Requires 480,000 gallons of possible 600,000 gallons |
| Demineralized Water pipebreak due to seismic event | 1300 | 6.2 | With maximum Water Treatment Plant flow of 360 gpm, tank would empty after 3.5 hours |

The evaluation of SFP dilution events in Sections 3.2 and 3.3 eliminated from consideration all but nine of the of the dilution scenarios evaluated.

Four dilution scenarios involve the transfer of non-borated water from the reactor makeup water system to the SFP cooling system, cleanup systems or the pool itself at a maximum rate of approximately 380 gpm. The reactor makeup water system is not capable of supplying the approximately 480,000 gallons of water necessary to dilute the SFP from 2000 ppm to 400 ppm unless the reactor makeup water tank is manually replenished from the water treatment system. Based on the analysis in Section 3.2 the least amount of time for response allowed by any of these scenarios is 21 hours.

Four dilution scenarios involve the transfer of non-borated water from the demineralized water system to the SFP cooling system or pool area itself. The flowrates vary from 200 gpm to a maximum rate of approximately 1300 gpm. The demineralized water system is capable of supplying the approximately 480,000 gallons of water necessary to dilute the SFP from 2000 ppm to 400 ppm if the demineralized water tank is repeated replenished from the water treatment system. Based on the analysis in Section 3.2 the least amount of time for response allowed by these scenarios is 26 hours. Note that the 1300 gpm scenarios empty the demineralized water tank in approximately 3.5 hours. With the pumps no longer able to run, the event is terminated prior to achieving dilution to 400 ppm.

The remaining event is the transfer of non-borated water from the fire protection tanks to the SFP area as a result of a random pipe rupture. The maximum flowrate is estimated to be 2000 gpm resulting in a dilution from 2000 ppm to 400 ppm in approximately 4.0 hours. Under conditions where the SFP is at a reduced level, the event could take place in approximately 3.8 hours.

For any one of these scenarios to successfully result in the dilution of the SFP from 2000 ppm to 400 ppm, the addition of 480,000 gallons of water to the SFP would have to go unnoticed. The first indication of such an event would be high level alarms in the control room from the spent fuel 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. In the random fire protection line

break case, alarms for a fire pump running and fire protection tank low level would alert operators of this condition. In cases where tanks require makeup from the water treatment plant, the water treatment plant technician would be expected to investigate the continuous supply of large quantities of water to plant systems. In addition, because the time required to reach a boron concentration of 400 ppm from 2000 ppm is significantly longer than eight hours in all but one case, it can be assumed that the operator rounds through the SFP area that occur once per eight hours will detect the increase in the pool level even if alarms other than the high level alarm fail and the flooding isn't detected.

For any one of these dilution scenarios to successfully add 480,000 gallons of water to the SFP, plant operators would have to fail to question or investigate the continuous makeup of water to the reactor makeup water tank or demineralized water tank, and fail to recognize that the need for 480,000 gallons of makeup was unusual.

## 4.0 CONCLUSIONS

A boron dilution analysis has been completed for the Farley SFP. As a result of this SFP boron dilution analysis, it is concluded that an event which would result in the dilution of the SFP boron concentration from 2000 ppm to 400 ppm is not a credible event. This conclusion is based on the following:

1. In order to dilute the SFP to the design $K_{eff}$ of 0.95, a substantial amount of water (nearly 480,000 gallons) is needed.

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

3. Evaluations indicate that based on the flow rates of non-borated water normally available to the SFP, even when significantly higher flow rates are assumed, sufficient time is available to detect and respond to such an event.

It should be noted that this boron dilution evaluation was conducted by evaluating the time and water volumes required to dilute the SFP from 2000 ppm to 400 ppm. The 400 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 Farley 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 SFP were diluted to zero ppm, which would take significantly more water than evaluated above, the fuel in the racks would be expected to remain subcritical and the health and safety of the public would be protected.

## 5.0 REFERENCES

1. Farley Units 1 and 2 Spent Fuel Rack Criticality Analysis Using Soluble Boron Credit, Westinghouse Commercial Nuclear Fuel Division, April 1997.