Westinghouse Non-Proprietary Class 3

WCAP-16518-NP
Revision 2

July 2007

Beaver Valley Unit 2 Spent Fuel Pool Criticality Analysis

WCAP-16518-NP, Revision 2

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1.0 Introduction

1.1 Objective

This report presents the results of criticality analyses for the Beaver Valley Unit 2 spent fuel pool racks with credit for burnup, integral fuel burnable absorber (IFBA), ^{241}Pu decay and soluble boron, where applicable. The primary objectives of this report are as follows:

1. To determine the fuel assembly burnup versus initial enrichment limits required for safe storage of fuel assemblies in the "All-Cell," "1-out-of-4 5.0 w/o at 15,000 MWD/MTU," and "1-out-of-4 3.85 w/o Fresh with IFBA" storage configurations.
2. To determine the burnup versus initial enrichment limits required for safe storage of fuel assemblies in the "3x3" configuration with credit for 5, 10, 15, and 20 years of ^{241}Pu decay.
3. To determine the number of IFBA pins versus initial enrichment limits required for safe storage of fuel assemblies in the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration. These limits will be derived based on 1.5X boron loading levels [ ]^{a,c}.
4. To demonstrate that fuel rod storage canisters (FRSCs) containing fuel rods with a maximum enrichment of 5.0 w/o ^{235}U may be safely stored in any storage configuration.
5. To determine the assembly loading requirements at the interface between storage configurations.
6. To determine the amount of soluble boron required to maintain k_{eff} less than or equal to 0.95 in the spent fuel pools, including all biases and uncertainties, assuming the most limiting plausible reactivity accident.

The methodology used in this analysis for soluble boron credit is analogous to that of Reference 1 and employs analysis criteria consistent with those cited in the Safety Evaluation by the Office of Nuclear Reactor Regulation, Reference 2. Reference 1 was reviewed and approved by the U.S. Nuclear Regulatory Commission (NRC). [

]^{a,c}.

The analysis/evaluations done to support this report comply with 10 CFR Part 50, Appendix B requirements and Westinghouse's Quality Management System program which has been reviewed and approved by the NRC.

1.2 Design Criteria

The design criteria are consistent with General Design Criterion (GDC) 62, Reference 4, and NRC guidance given in Reference 5. Section 1.3 describes the analysis methods including a description of the computer codes used to perform the criticality safety analysis. A brief summary of the analysis approach and criteria follows.

1. Determine the fresh and spent fuel storage configurations using no soluble boron conditions such that the 95/95 upper tolerance limit value of k_{eff}, including applicable biases and uncertainties, is less than 0.995. This is accomplished with infinite arrays of either fresh or spent fuel assembly

configurations. Note that the actual NRC k_{eff} limit for this condition is 1.0. Therefore, an additional margin of 0.005 Δk_{eff} units is included in the analysis results.

2. Determine the amount (ppm) of soluble boron necessary to reduce the k_{eff} value of all storage configurations by at least 0.05 Δk_{eff} units. [

] [a, c]. As an example, storage configurations which contain depleted fuel assemblies (and represented by depleted isotopics) are less reactivity-sensitive to changes in soluble boron concentration than a fuel assembly represented by zero burnup and relatively low initial fuel enrichment.

3. Determine the amount of soluble boron necessary to compensate for 5% of the maximum burnup credited in any storage configuration. In addition, determine the amount of soluble boron necessary to account for a reactivity depletion uncertainty of 1.0% Δk_{eff} per 30,000 MWD/MTU of credited fuel burnup. This is accomplished by multiplying this derivative by the maximum burnup credited in any storage configuration and converting to soluble boron using the data generated in Step 2.

4. Determine the largest increase in reactivity caused by postulated accidents and the corresponding amount of soluble boron needed to offset this reactivity increase.

An alternative form of expressing the soluble boron requirements is given in Reference 2. The final soluble boron credit (SBC) requirement is determined from the following summation.

$$SBC_{TOTAL} = SBC_{95/95} + SBC_{RE} + SBC_{PA}$$

Where,

SBC_{TOTAL} = total soluble boron credit requirement (ppm)

$SBC_{95/95}$ = soluble boron requirement for 95/95 k_{eff} less than or equal to 0.95 (ppm)

SBC_{RE} = soluble boron required to account for burnup and reactivity uncertainties (ppm)

SBC_{PA} = soluble boron required to offset accident conditions (ppm)

For purposes of the analyses, minimum burnup limits established for fuel assemblies to be stored in the storage configurations racks include burnup credit established in a manner that takes into account approximations to the operating history of the fuel assemblies. [

] [a, c]. Also, the axial reactivity effects associated with the "cut-back" of the IFBA at both ends of the fuel assembly were included in this analysis.

1.3 Design Approach

The soluble boron credit methodology provides additional reactivity margin in the spent fuel storage analyses which may then be used to implement added flexibility in storage criteria and to eliminate the need to credit any of the degraded Boraflex.

The square storage cell pitch modeled for fuel assembly storage configurations is 10.4375 inches. No credit is taken for Boraflex in any of the storage configurations.

The fuel assembly type used for all the analyses is the Westinghouse 17x17 Standard design. The most reactive spent fuel pool temperature (with full moderator density of 1 g/cc) is used for each fuel assembly storage configuration such that the analysis results are valid over the nominal spent fuel temperature range (50° to 185°F) (Reference 6).

The reactivity characteristics of the storage racks were evaluated using infinite lattice analyses; this environment was used in the evaluation of the burnup limits versus initial enrichment as well as the evaluation of physical tolerances and uncertainties. [

]^{a,c}.

1.4 Methodology

This section describes the methodology used to assure the criticality safety of the Beaver Valley Unit 2 spent fuel pool and to define limits placed on fresh and depleted fuel assembly storage configurations. The analysis methodology employs: (1) SCALE-PC, a personal computer version of the SCALE-4.4a code system, as documented in Reference 7 with the updated SCALE-4.4a version of the 44 group Evaluated Nuclear Data File, Version 5 (ENDF/B-V) neutron cross section library, and (2) the two-dimensional Discrete Integral Transport (DIT) code (Reference 8) with an Evaluated Nuclear Data File, Version 6 (ENDF/B-VI) neutron cross section library.

SCALE-PC was used for calculations involving infinite arrays for all the storage configurations in the spent fuel pool. [

]^{a,c}.

SCALE-PC, used in both the benchmarking and the fuel assembly storage configurations, includes the control module CSAS25 and the following functional modules: BONAMI, NITAWL-II, and KENO V.a. All references to KENO in this report refer to the KENO V.a module.

The DIT code is used for simulation of in-reactor fuel assembly depletion. The following sections describe the application of these codes in more detail.

1.4.1 SCALE-PC

The SCALE system was developed for the NRC to satisfy the need for a standardized method of analysis for evaluation of nuclear fuel facilities and shipping package designs. SCALE-PC is a version of the SCALE code system that runs on personal computers.

1.4.2 Validation of SCALE-PC

Validation of SCALE-PC for purposes of fuel storage rack analyses is based on the analysis of selected critical experiments from two experimental programs: the Babcock & Wilcox (B&W) experiments in support of Close Proximity Storage of Power Reactor Fuel (Reference 10) and the Pacific Northwest Laboratory (PNL) Program in support of the design of Fuel Shipping and Storage Configurations. References 11 and 12, as well as several of the relevant thermal experiment evaluations in Reference 13 were found to be useful in updating pertinent experimental data for the PNL experiments.

The validation of SCALE-PC was limited to the 44-group library provided with the SCALE-PC version 4.4a package. The 238-group library, which is utilized for the off-nominal temperature cases, was further validated by comparing the results from identical cases performed with the 44-group library and confirming that the results agreed within the statistical uncertainty.

Nineteen experimental configurations were selected from the B&W experimental program; these consisted of the following experimental cores: Core X, the seven measured configurations of Core XI, Cores XII through XXI, and Core XIIIA. These analyses used measured critical data, rather than the extrapolated configurations to a fixed critical water height reported in Reference 10, to avoid introducing possible biases or added uncertainties associated with the extrapolation techniques. In addition to the active fuel region of the core, the full environment of the latter region, including the dry fuel above the critical water height, was represented explicitly in the analyses.

The B&W group of experimental configurations used variable spacing between individual rod clusters in the nominal 3x3 array. In addition, the effects of placing either SS-304 or Borated Aluminum (B/Al) plates of different boron contents in the water channels between rod clusters were measured. Table 1-1 summarizes the results of these analyses performed with both the 44-group and 238-group libraries.

Eleven experimental configurations were selected from the PNL experimental program. These experiments included unpoisoned uniform arrays of fuel pins and 2x2 arrays of rod clusters with and without interposed SS-304 or B/Al plates of different blackness. As in the case of the B&W experiments, the full environment of the active fuel region was represented explicitly. Table 1-2 summarizes the results of these analyses performed with both the 44-group and 238-group libraries.

The approach used for the determination of the mean calculational bias and the mean calculational variance is based on Criterion 2 of Reference 15. For a given KENO-calculated value of k_{eff} and associated one sigma uncertainty, the magnitude of $k_{95/95}$ is computed by the equation below. By this definition, there is a 95 percent confidence level that in 95 percent of similar analyses the validated calculational model will yield a multiplication factor less than $k_{95/95}$.

$$k_{95/95} = k_{keno} + \Delta k_{bias} + M_{95/95}\left(\sigma_m^2 + \sigma_{KENO}^2\right)^{1/2}$$

Where,

k_{keno} is the KENO-calculated multiplication factor,

Δk_{bias} is the mean calculational method bias,

$M_{95/95}$ is the 95/95 multiplier appropriate to the degrees of freedom for the number of validation analyses, and is obtained from the tables of Reference 16,

σ_m^2 is the mean calculational method variance deduced from the validation analyses,

σ_{KENO}^2 is the square of the KENO standard deviation.

The equation for the mean calculational methods bias is as follows:

$$\Delta k_{bias} = \frac{1}{n}\sum_{i=1}^{n}\left(1 - k_i\right)$$

Where,

k_i is the i^{th} value of the multiplication factor for the validation lattices of interest.

The equation for the mean calculational variance of the relevant validating multiplication factors is as follows:

$$\sigma_m^2 = \frac{n\sum_{1}^{n}\frac{\left(k_i - k_{ave}\right)^2}{\sigma_i^2}}{(n-1)\sum_{1}^{n}\frac{1}{\sigma_i^2}} - \sigma_{ave}^2$$

where k_{ave} is given by the following equation:

$$k_{ave} = \frac{\sum_{1}^{n}\frac{k_i}{\sigma_i^2}}{\sum_{1}^{n}\frac{1}{\sigma_i^2}},$$

σ_{ave}^2 is given by the following equation:

$$\sigma_{ave}^2 = \frac{\sum_{1}^{n}\sigma_i^2 G_i}{\sum_{1}^{n} G_i},$$

G_i is the number of generations.

For purposes of this bias evaluation, the data points of Table 1-1 and Table 1-2 are pooled into a single group from the 44-group library calculations. With this approach, the mean calculational methods bias,

Δk_{bias}, and the mean calculational variance, σ_m^2, calculated by the equations given above, were determined to be [ ] [a, c], respectively. The magnitude of $M_{95/95}$ is obtained from Reference 16 for the total number of pooled data points, 30.

The magnitude of $k_{95/95}$ is given by the following equation for SCALE 4.4a KENO analyses employing the 44-group ENDF/B-V neutron cross section library and for analyses where these experiments are a suitable basis for assessing the methods bias and calculational variance:

[ ] a, c

Based on the above analyses, the mean calculational bias, the mean calculational variance, and the 95/95 confidence level multiplier for the 44-group library were deduced as [ ] [a, c] and 2.22, respectively.

1.4.3 Application to Fuel Storage Pool Calculations

As noted above, the CSAS25 control module was used to execute the functional modules within SCALE-PC. The CSAS25 control module was used to analyze either infinite arrays of single or multiple storage cells [ ] [a, c].

Standard material compositions were used in the SCALE-PC analyses consistent with the design input given in Section 2.0; these data are listed in Table 1-3. For fresh fuel conditions, the fuel nuclide number densities were derived within the CSAS25 module using input consistent with the data in Table 1-3. For burnt fuel representations, the fuel isotopics were derived from the DIT code as described below.

1.4.4 The DIT Code

The DIT code performs a heterogeneous multigroup transport calculation for an explicit representation of a fuel assembly. The neutron transport equations are solved in integral form within each pin cell. The cells retain full heterogeneity throughout the discrete integral transport calculations. The multigroup spectra are coupled between cells through the use of multigroup interface currents. The angular dependence of the neutron flux is approximated at cell boundaries by a pair of second order Legendre polynomials. Anisotropic scattering within the cells, together with the anisotropic current coupling between cells, provide an accurate representation of the flux gradients between dissimilar cells.

The multigroup cross sections are based on the ENDF/B-VI. Cross sections have been collapsed into an 89-group structure that is used in the assembly spectrum calculation. Following the multigroup spectrum calculation, the region-wise cross sections within each heterogeneous cell are collapsed to a few groups (usually 4 broad groups), for use in the assembly flux calculation. [

]^{a,c}.

The DIT code and its cross section library are used in the design of initial and reload cores and have been extensively benchmarked against operating reactor history and test data.

For the purpose of spent fuel pool criticality analysis calculations, the DIT code is used to generate the detailed fuel isotopic concentrations as a function of fuel burnup and initial feed enrichment. Each complete set of fuel isotopics is reduced to a smaller set of burnt fuel isotopics at specified time points after discharge. [

]^{a,c}.

[

]^{a,c}.

1.5 Assumptions

- The Westinghouse 17x17 Standard fuel was modeled as the design basis fuel assembly to conservatively represent all fuel assemblies residing in all the storage configurations. The model bounds Westinghouse fuel products with a 0.3740-inch fuel pin, such as the Westinghouse Standard design, the V5H product, as well as the Robust Fuel Assembly (RFA) and RFA-2 products.

- Fresh fuel assemblies were conservatively modeled with a UO_2 density of 10.686 g/cm^3 (97.5% of theoretical density). This translates into a pellet density equal 98.6% of theoretical density with a 1.1% dishing (void) fraction.

- All fuel assemblies, fresh and depleted, were conservatively modeled as containing solid right cylindrical pellets and uniformly enriched over the entire length of the fuel stack height. This conservative assumption bounds fuel assembly designs that incorporate lower enrichment blanket or annular pellets.

- All of the Boraflex poison material residing in the storage racks was conservatively omitted for this analysis.

- In addition, the IFBA pins were modeled as annular cylinders 120 inches in length and centered about the midplane of the active fuel. Therefore, the IFBA coating is modeled with a 12-inch "cut-back" on the total length of the fuel (blanket and non-IFBA section). Also, [ ] [a, c] on the 1.5X IFBA loading [ ] [a, c] is assumed to cover manufacturing uncertainty and tolerances.

- The design basis limit for k_{eff} at the zero soluble boron condition was conservatively reduced from 1.0 to 0.995 for this analysis.

Table 1-1
Calculational Results for Cores X Through XXI of the B&W Close Proximity Experiments

a, c

[

]

[1] Entry indicates metal separating unit assemblies.
[2] Entry indicates spacing between unit assemblies in units of fuel rod pitch.

Table 1-2
Calculational Results for Selected Experimental PNL Lattices,
Fuel Shipping and Storage Configurations

a, c

[

]

Table 1-3
Standard Material Compositions Used in Criticality Analysis of the Beaver Valley Unit 2 Spent Fuel Storage Racks

Material	Element	Weight Fraction
Zircaloy[1], Density = 6.578 g/cm^3 @ 293.15 K	Zr	0.9824
	Sn	0.0145
	Fe	0.0021
	Cr	0.0010
Water	SCALE Standard Composition Library Density = 1.0 g/cm^3 @ 293.15 K	
Stainless Steel	SCALE Standard Composition Library Density = 7.94 g/cm^3 @ 293.15 K	
Fresh UO_2	Fraction of Theoretical Density = 0.975 Enrichment = 5.0 w/o ^{235}U @ 293.15 K	
Regular Concrete	SCALE Standard Composition Library Density = 2.3 g/cm^3 @ 293.15 K	
	Element or Isotope	**Isotopics (atoms/barn/cm^2)**
IFBA (ZrB_2) 1.5X [ ]^{a,c}	[ ]^{a,c}	[ ]^{a,c}
	[ ]^{a,c}	[ ]^{a,c}
	[ ]^{a,c}	[ ]^{a,c}

[1] Beaver Valley Unit 2 also uses ZIRLO™ cladding; however, the fuel rod, guide tube, and instrumentation tube claddings are modeled with Zircaloy in this analysis. This is conservative with respect to the Westinghouse ZIRLO™ product, which is a zirconium alloy containing additional elements including niobium. Niobium has a small absorption cross section, which causes more neutron capture in the cladding regions resulting in a lower reactivity. Therefore, this analysis is conservative with respect to fuel assemblies containing ZIRLO™ cladding in fuel rods, guide tubes, and the instrumentation tube.

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2.0 Design Input

This section provides a brief description of the Beaver Valley Unit 2 spent fuel storage racks with the objective of establishing a basis for the analytical models used in the criticality analyses described in Section 3.0.

2.1 Design Input from FENOC

Design data related to the Beaver Valley Unit 2 that were required to develop the KENO models were obtained from Reference 6. Drawing 80E7670 (Reference 17) was used to develop the KENO model for the entire spent fuel pool.

2.2 Spent Fuel Pool Storage Configuration Description

Beaver Valley Unit 2 pool has an inside dimension of 473.5 inches in the west to east direction and 263.5 inches in the north to south direction at the east side, and 353.5 inches at the west side. Seventeen rack modules, each with 64 (8x8) cell locations occupy the spent fuel pool. Rack modules measure 422.3125 inches in the west to east direction at the north side, and 168.25 inches at the south side, 252.9375 inches in the north-to-south direction at the east side, and 337.625 inches at the west side of the pool. Rack modules are separated from each other by a 1.125 inch gap. Rack modules are located 6.5 inches from the north wall and 9.375 inches from the south wall, 36.4375 inches from the west wall, and 14.75 inches from the east wall of the spent fuel pool. They are also located 4.0624 inches from the transfer canal wall on the south side.

Figure 2-1 shows the spent fuel pool and the storage rack modules. Table 2-1 summarizes the overall geometry data for the Beaver Valley Unit 2 spent fuel pool.

2.3 Individual Storage Cell Descriptions

Beaver Valley Unit 2 spent fuel pool storage cells are centered on a pitch of 10.4375 ± 0.0278 inches. Each storage cell consists of an inner stainless steel canister, which has a nominal inside dimension of 8.9375 ± 0.0469 inches and is 0.090 ± 0.010-inches thick. Each Boraflex poison panel is held in place and is centered on the surface of the stainless steel canister by an outer stainless steel sheathing panel. The sheathing contacts the outside face of the Boraflex poison panel. The sheathing surfaces of two adjacent storage cells are separated only by pool water. The dimensions of the Boraflex poison panel are 7.5 ± 0.0625 inches in width by 0.078 inch in thickness. The sheathing panels are included as 0.0293 ± 0.005 inch in thickness and are located at the outside surface of the nominal Boraflex poison panel position. Note that no credit is taken for the presence of the neutron absorbing, Boraflex material in the analysis. Table 2-2 and Figure 2-2 summarize the storage cell dimensions used for the Beaver Valley Unit 2 analyses.

2.4 Fuel Rod Storage Canister Description

Figure 2-3 shows the "IFE" design (Reference 18) fuel rod storage canister (FRSC). The FRSC is designed to accommodate individual spent and/or fresh fuel rods in a fixed array. The nominal dimensions are depicted on Figure 2-3. Fifty-two tubes are stored in the IFE canister, 48 of them are of Type 1 and four are of Type 2. The tubes are centered on a pitch of 0.9374 inches. Type 1 tubes have an outer diameter of 0.625 inches with a wall thickness of 0.035 inches, and Type 2 tubes have an outer diameter of 0.75 inches with a wall thickness of 0.049 inches. Peripheral tubes are centered at half-pitch distance from the canister walls. Canister wall thickness is 0.593 inches.

Table 2-1
Spent Fuel Pool Dimensions
(All dimensions in inches)

Parameter	Value
Pool Length	473.5
Pool Width	353.5
Wall Thickness	24
Reflector	24

Table 2-2
Storage Cell Description
(All dimensions in inches)

Parameter	Dimension
Cell Pitch	10.4375 ± 0.0278
Cell ID	8.9375 ±0.0469
Cell Wall Thickness	0.090 ± 0.010
Cell Wall Material	SS-304
Boraflex[1] Width	7.5 ± 0.0625
Total Gap	0.078
Wrapper Thickness	0.0293 ± 0.005
Wrapper Material	SS-304

[1] Boraflex is replaced with water in Region 2 racks.

a, c

Figure 2-1
Beaver Valley Unit 2 Spent Fuel Pool Showing Storage Rack Modules

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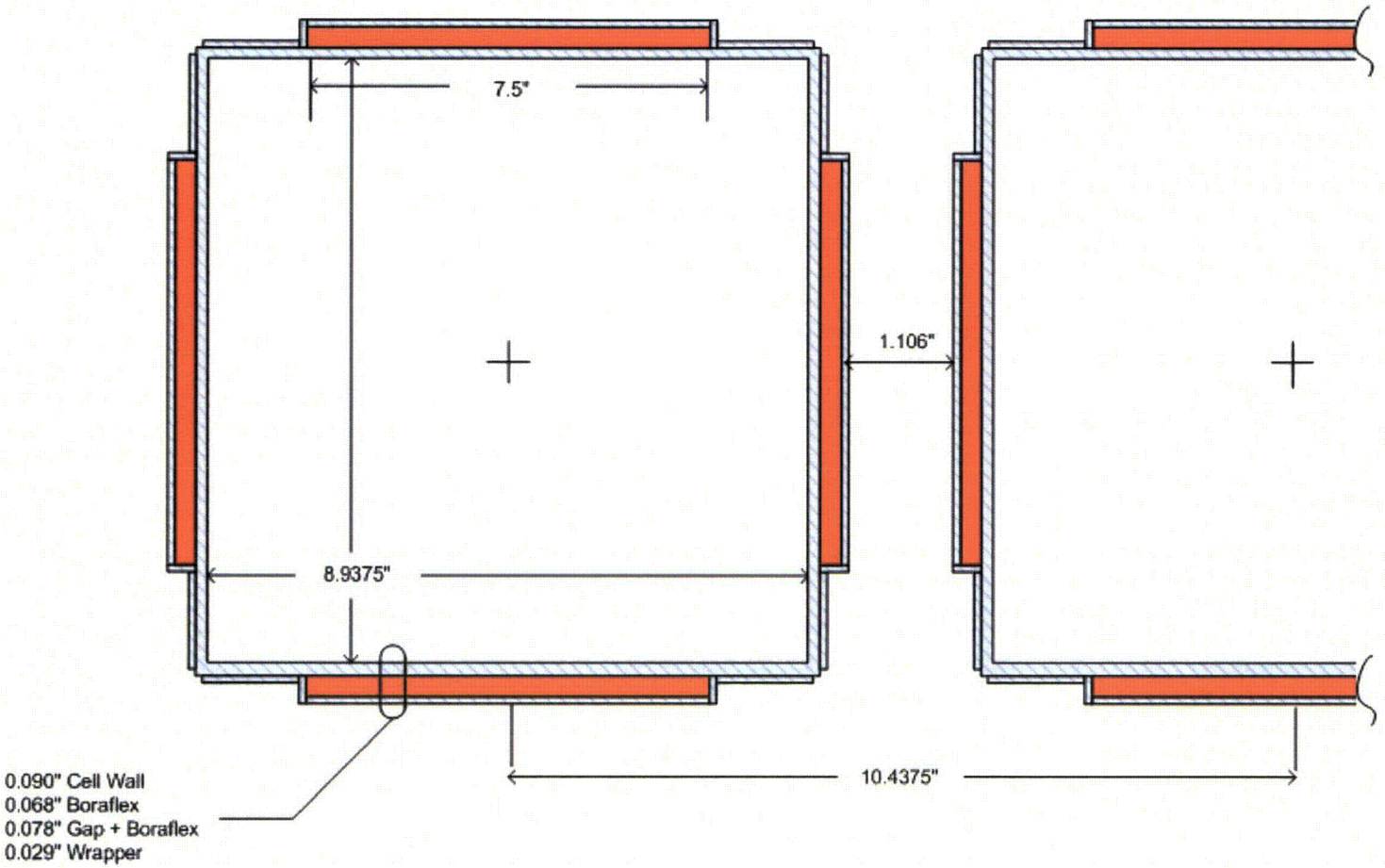

Figure 2-2
Beaver Valley Unit 2 Storage Cell

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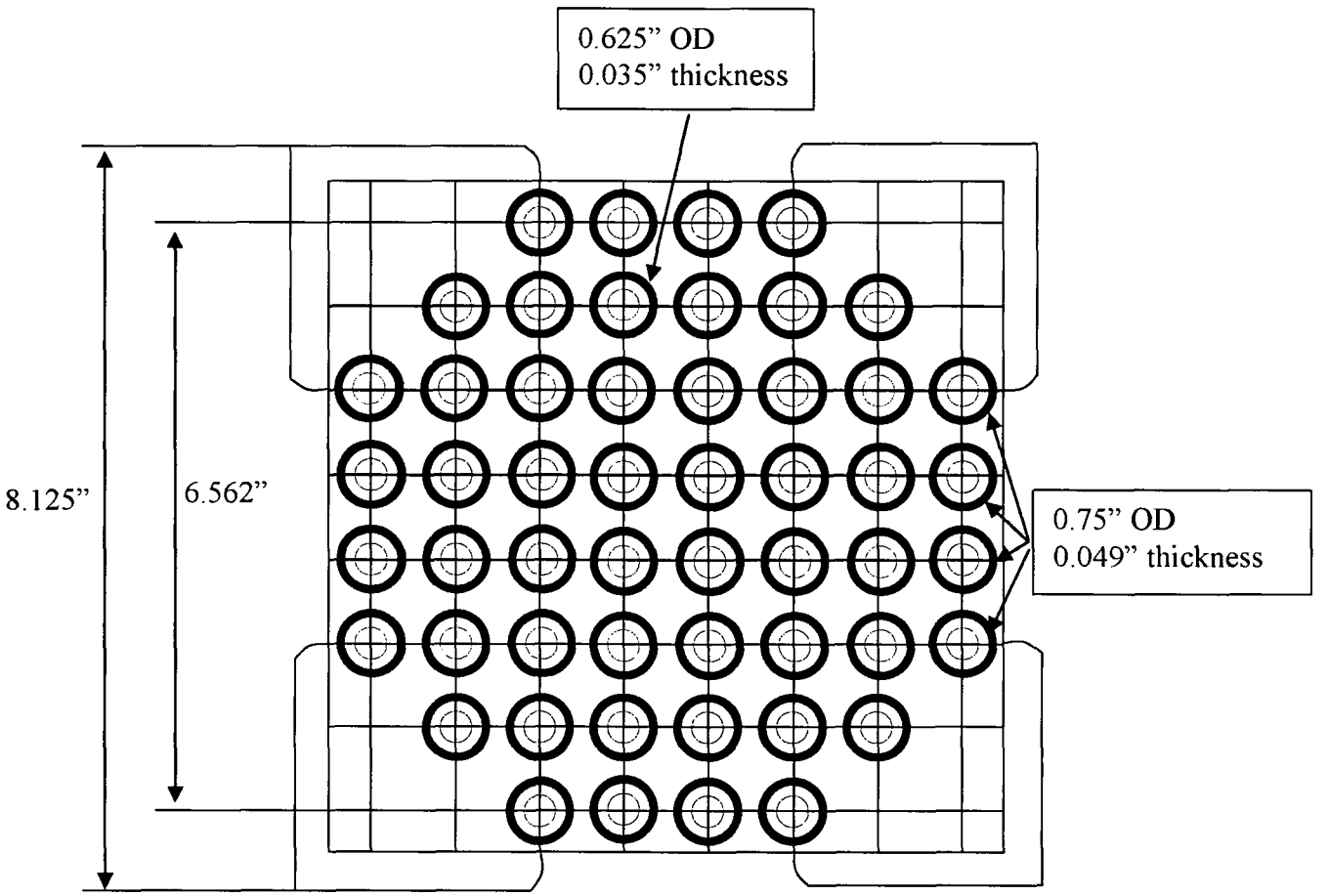

Figure 2-3
"IFE" Fuel Rod Storage Canister

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3.0 Analysis

3.1 KENO Models for the Spent Fuel Pool Storage Configurations

The Beaver Valley Unit 2 spent fuel storage racks employ four different fuel assembly storage configurations: "All-Cell," "3x3," "1-out-of-4 5 w/o at 15,000 MWD/MTU," and "1-out-of-4 3.85 w/o Fresh with IFBA." KENO models of these storage configurations are provided in the following sections. [ ]^{a,c}.

The fuel assembly modeled by KENO represents the Westinghouse standard 17x17 design. Note that the enrichment of fresh fuel pellets is up to 5.0 w/o ^{235}U and the UO_2 density is 97.5% of theoretical density. The fuel pellets in a fuel rod are modeled as a fully enriched right solid cylinder that is 144 inches tall. This assumption conservatively bounds fuel rod designs that incorporate annular and or lower enrichment fuel pellets such as those used for axial blankets.

Each of the storage cell locations is modeled in KENO as a square cell with a pitch of 10.4375 inches. The stainless steel canister, which controls the fuel assembly position within the array, is modeled with an inside dimension of 8.9375 inches and is 0.090-inches thick. (Dimensions are taken from Table 2-2.) The Boraflex poison panels are modeled centered on the surface of the stainless steel canisters by an outer stainless steel sheathing panel. The sheathing surfaces of two adjacent storage cells are separated by pool water. The dimensions of the Boraflex poison panel are 7.5 inch in width by 0.078 inch in thickness. The sheathing panels are included as 0.0293 inch in thickness and are located at the outside surface of the nominal Boraflex poison panel position. The active fuel, storage rack box and sheathing heights are modeled in KENO as 144 inches tall. The geometry of the Boraflex poison is represented as water in the KENO model, thus no credit is taken for the presence of the neutron absorbing, Boraflex material.

Reflective boundary conditions are applied to the X and Y surfaces of either 2x2 or 3x3 array, thus simulating an infinitely repeating array. A 2-foot water reflector is modeled above and below the storage cell geometry. The pool water is simulated to be full density (1 g/cm^3) at room temperature (20 °C). The top and bottom surfaces of the water reflector have reflected boundary conditions.

3.1.1 KENO Model for the "All-Cell" Storage Configuration

An "All-Cell" storage configuration is modeled in KENO as a repeating 2x2 array of storage cells that contain depleted fuel assemblies as shown below.

Depleted Fuel	Depleted Fuel
Depleted Fuel	Depleted Fuel

A KENO-produced plot of an "All-Cell" storage configuration is shown in Figure 3-1.

3.1.2 KENO Model for the "3x3" Storage Configuration

The "3x3" storage configuration is modeled in KENO as a repeating 3x3 array with eight storage cell locations containing a ring of depleted fuel assemblies that surround a 5.0 w/o ^{235}U fresh fuel assembly, as shown below.

Depleted Fuel	Depleted Fuel	Depleted Fuel
Depleted Fuel	5.0 w/o Fresh Fuel	Depleted Fuel
Depleted Fuel	Depleted Fuel	Depleted Fuel

Note that ^{241}Pu decay credit (up to 20 years) is assumed for this storage configuration. A KENO-produced plot of a single "3x3" storage configuration is shown in Figure 3-2.

3.1.3 KENO Model for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

The "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration is modeled in KENO as a repeating 2x2 array with a 5.0 w/o initial enrichment fuel assembly at 15,000 MWD/MTU occupying a storage cell location and depleted fuel assemblies occupying the remaining locations.

5.0 w/o at 15,000 MWD/MTU	Depleted Fuel
Depleted Fuel	Depleted Fuel

A KENO-produced plot of a single "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration is shown in Figure 3-3.

3.1.4 KENO Model for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

The "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration is modeled in KENO as a repeating 2x2 array with a fresh 3.85 w/o ^{235}U fuel assembly occupying a storage cell location and depleted fuel assemblies occupying the remaining locations. Note that the fresh fuel assembly with enrichments greater than 3.85 w/o contains IFBA rods.

3.85 w/o Fresh	Depleted Fuel
Depleted Fuel	Depleted Fuel

A KENO-produced plot of a single "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration is shown in Figure 3-4. IFBA rods were modeled for this configuration using the layouts from Figure 3-5. A 1.5X ^{10}B poison loading [ ]$^{a, c}$ was considered for the analyses. Also note that a 12-inch IFBA cutback was assumed on both top and bottom sections of the active fuel length.

3.1.5 KENO Model for the Fuel Rod Storage Canister with 5.0 w/o ^{235}U Fuel

The Fuel Rod Storage Canister (FRSC) is modeled as a stainless steel box containing a fixed array of 52 stainless-steel tubes. Each tube contains a fresh 5.0 w/o ^{235}U fuel pin. The tubes are modeled in KENO according to the design as described in Section 2.3.

The fuel pins, the stainless steel tubes and FRSC are modeled in KENO as 144-inches tall. The FRSC is inserted in a storage configuration by replacing one of the assemblies in that configuration.

Figure 3-6 shows, as an example, an FRSC in an "All-Cell" configuration. Periodic boundary conditions are applied to the X and Y surfaces of the 2x2 array, thus simulating an infinitely repeating array. A 2-foot water reflector is modeled above and below the storage cell geometry. The pool water is simulated to be full density (1 g/cm^3) at room temperature (20 °C). The top and bottom surfaces of the water reflector have reflected boundary conditions.

The fuel rods in FRSC are modeled by KENO as the Westinghouse standard 17x17 design with no burnable absorber. The UO_2 density is 97.5% of theoretical density for the fresh fuel. Note that the fuel pellets in the fuel rods are modeled as a solid cylinder that is 144 inches tall. This assumption

conservatively bounds fuel rod designs that incorporate annular and or lower enrichment fuel pellets such as those used for axial blankets.

3.1.6 KENO Model for Entire Spent Fuel Pool

The Beaver Valley Unit 2 spent fuel pool is modeled in KENO as a rectangular water cell that is 473.5-inches long and 353.5-inches wide on the long side. Seventeen storage rack modules (8x8 cell array) along with an empty refueling transfer canal surrounded by 2-feet thick concrete walls occupy the pool. Storage rack modules span a region that is 422.3125 inches in the west to east direction at the north side and 168.25 inches at the south side, 252.9375 inches in the north-to-south direction at the east side, and 337.625 inches at the west side of the pool. The floor and walls of the spent fuel pool are modeled by surrounding the rectangular water cell with two feet of concrete on the bottom and sides. A 1.125-inch intra module water gap was modeled. The pool dimensions are shown in Table 2-1. The pool water was modeled at room temperature conditions, 20 °C, and full density (1.0 g/cm^3). Figure 3-7 shows a KENO-produced plot of the spent fuel pool.

3.2 Design Basis Fuel Assembly

Figure 3-8 shows the Westinghouse standard 17x17 fuel assembly with the standard assembly parameters given in Table 3-1. The Westinghouse standard fuel assembly design was modeled as the design basis fuel assembly to represent fresh and depleted fuel assemblies residing in all of the fuel assembly storage configurations.

The design basis fuel assemblies are modeled with the fresh fuel pellets as a solid right cylinder with a UO_2 density of 10.686 g/cm^3 (97.5% of theoretical density). No credit is taken for the nominal 1.1 void fraction percentage that is associated with dishing or chamfering. In addition, no credit is taken for any natural or reduced enrichment pellets, even for the blanketed assemblies. This assumption results in conservative calculations of reactivity for all fuel assemblies stored in the racks. No credit is taken for any spacer grids or sleeves.

Figure 3-5 shows the IFBA patterns for [ ]^{a,c} IFBA rods in the Westinghouse Standard 17x17 fuel assembly used in this analysis. A 12-inch IFBA cutback is applied to the top and bottom sections of the active fuel length. Note that ^{10}B loading is modeled as 1.5X [ ]^{a,c}.

3.3 Modeling of Axial Burnup Distributions

A key aspect of the burnup credit methodology used in this analysis is the inclusion of an axial burnup profile correlated with feed enrichment and discharge burnup of the depleted fuel assemblies. This effect is important in the analysis of the spent fuel pool characteristics since the majority of spent fuel

assemblies stored in the pool have a discharge burnup well beyond the limit for which the assumption of a uniform axial burnup shape is conservative. Therefore, it is necessary to represent the burnt fuel assembly with a representative axial burnup profile.

[

]^{a,c}.

[

]^{a,c}.

Input to this analysis is based on the limiting axial burnup profile data provided in the Department of Energy (DOE) Topical Report, as documented in Reference 20. The burnup profile in the DOE Topical Report is based on a database of 3,169 axial-burnup profiles for Pressurized Water Reactor (PWR) fuel assemblies compiled by Yankee Atomic. This profile is derived from the burnups calculated by utilities or vendors based on core-follow calculations and in-core measurement data. [

]^{a,c}.

The DIT code was used to generate the isotopic concentrations for each segment of the axial burnup profile. Table 3-2 lists the fuel and moderator temperatures used in the spectral calculations for the fuel assembly average burnup model and each node of the [ ]^{a,c} axial burnup models. The fuel temperatures for each axial zone are calculated based on a representative fuel temperature correlation while the moderator temperatures are based on a linear relationship with axial position. These node dependent moderator and fuel temperature data and power profile data were used in DIT to deplete the fuel to the desired burnup for each initial enrichment and each axial zone.

[

]^{a,c}.

The values of assembly average burnups versus feed enrichment for which depleted fuel assemblies were simulated are presented in Table 3-3.

[

] ^{a,c}. The k_∞ and the isotopic number densities were then extracted for the KENO model development at these assembly conditions.

3.3.1 Impact of Beaver Valley Unit 2 Power Ratings on the Spent Fuel Pool Criticality

The Beaver Valley Power Station Unit 2 originally operated at 2652 MW_{th} and it currently operates at 2689 MW_{th}. Studies for an extended power uprate (9.4%) were in progress at the time this report was issued. The uprated power projects an average assembly power of 18.47 MW. The isotopics generated for this analysis were based on a 19.96 MW/assembly average power, which conservatively covers the original and the uprated power levels and any other power level in-between.

Another aspect of the power uprate impact on the spent fuel pool criticality is the 3-D reactivity effect dominated by the difference between the average fuel burnup and burnup at the top section of the fuel. As mentioned in the previous section, this difference is mostly driven by the difference between the average fuel/moderator temperature and temperature at the top region of the fuel. As long as this temperature difference between the bottom and top regions of the core is represented, "end-effects" can be adequately captured. The current core average coolant and outlet temperatures are 580.3 °F and 615.1 °F, respectively. With the planned power uprate, the core average temperature is expected to be in the range of 570.6 °F - 584.6 °F, and the outlet temperature between 608.6 °F - 621.4 °F. From Table 3-2, the temperatures used in the current analysis to generate the isotopics are very similar to the original and the uprated values; therefore it is concluded that the analysis results will be valid for both the current and uprated power ratings.

3.4 Tolerance / Uncertainty Calculations

Using the input described above, analytical models were developed to perform the quantitative evaluations necessary to demonstrate that the effective multiplication factor for the spent fuel pool is less than 0.995 with zero soluble boron present in the pool water. Applicable biases factored into this evaluation are: 1) the methodology bias deduced from the validation analyses of pertinent critical experiments, and 2) any reactivity bias, relative to the reference analysis conditions, associated with operation of the spent fuel pool over a temperature range of 50 °F to 185 °F. Note that cases for nominal conditions were run with a full moderator density (1 g/cc), which actually corresponds to 40 °F, which is less than the normal operating range and more conservative.

A second allowance is based on a 95/95 confidence level assessment of tolerances and uncertainties. The following are included in the summation of variances:

a. The 95/95 confidence level methods variance,
b. The 95/95 confidence level calculational uncertainty,
c. Fuel rod manufacturing tolerance,
d. Storage rack fabrication tolerances,
e. Tolerance due to positioning the fuel assembly in the storage cell,
f. Burnup and IFBA manufacturing uncertainty.

Items a. and b. are based on the calculational methods validation analyses described in subsection 1.4.2. For item c., the fuel rod manufacturing tolerance for the reference design fuel assembly is assumed to consist of an increase in fuel enrichment of 0.05w/o ^{235}U. An increase in UO_2 density is not assumed since all calculations are performed using 97.5% of theoretical density, which is the highest credible density for PWR fuel. The individual contributions of each change are combined by taking the square root of the sum of the squares of each component.

For item d., the following uncertainty components were evaluated. The inner stainless steel canister ID was decreased from 8.9375 inches to 8.8906 inches and the thickness of the canister was decreased from 0.090 inches to 0.080 inches. The storage cell pitch was decreased from 10.4375 inches to 10.4097 inches. The wrapper thickness was decreased from 0.0293 inches to 0.0243 inches.

In the case of the tolerance due to positioning of the fuel assembly in the storage cells (item e.), all nominal calculations were carried out with fuel assemblies conservatively centered in the storage cells. Cases were run to investigate the effect of off-center position of the fuel assemblies for each of the fuel assembly storage configurations. These cases positioned the assemblies as close as possible in four adjacent storage cells. In the case of the "3x3" storage configuration, all the peripheral assemblies were positioned as close as possible to the central fresh fuel assembly.

For item f., a [

]^{a,c}.

Table 3-4 through Table 3-7 provide a summary of the KENO results used in the calculation of biases and uncertainties for the fuel assembly storage configurations.

3.5 No Soluble Boron 95/95 k_{eff} Calculational Results

The following subsections present the KENO-calculated multiplication factors for the Beaver Valley Unit 2 spent fuel pool storage configurations.

The KENO calculations reported in this section were performed at 68 °F, with maximum water density of 1.0 g/cm^3, to maximize the array reactivity, and with an axially distributed burnup profile. The relative axial burnup profile used for these calculations is discussed in Section 3.3. The resulting k_{eff} data were then used to determine the burnup versus initial enrichment limits for a target k_{eff} value at zero soluble boron. The target value of k_{eff} was selected to be less than 0.995 by an amount sufficient to cover the magnitude of the analytical biases and uncertainties in these analyses.

The fuel assembly modeled in these analyses is the Westinghouse Standard 17x17 fuel assembly design.

3.5.1 "All-Cell" Storage Configuration

As described in subsection 3.1.1, the "All-Cell" storage configuration consists of a repeating 2x2 array of storage cells that contain depleted fuel assemblies.

The k_{eff} values were calculated for an infinite array of "All-Cell" storage configurations over a range of initial enrichment values up to 5.0 w/o ^{235}U and assembly average burnups up to 35,000 MWD/MTU. From Table 3-4, the sum of the biases and uncertainties is 0.03043 Δk_{eff} units. Therefore, the target k_{eff} value for the "All-Cell" storage configuration is 0.96457 (0.995-0.03043).

Table 3-8 lists the k_{eff} values for the "All-Cell" storage configuration versus initial enrichment and average burnups. The first entry in Table 3-8 lists the initial enrichment for no burnup. Based on the target k_{eff} value, the fresh enrichment for no burnup is 1.856 w/o ^{235}U. The derived burnup limits, for enrichments greater than 1.856 w/o ^{235}U, are based on the k_{eff} values for 3.0, 4.0, and 5.0 w/o ^{235}U. For each of these three enrichments, KENO calculations were performed at three assembly average burnup values with an axially distributed burnup profile. A second degree fit of the burnup versus k_{eff} data was then used to determine the burnup required to meet the target k_{eff} value of 0.96457. The resulting burnup

versus initial enrichment storage limits are provided in Table 3-9. The limiting burnups as a function of initial enrichment was fitted to a third degree polynomial. This polynomial is given below Table 3-9 and will be used to determine the burnup as a function of initial enrichment of "All-Cell" configuration. The data in Table 3-9 are plotted in Figure 4-11.

3.5.2 "3x3" Storage Configuration

As described in subsection 3.1.2, the "3x3" storage configuration is modeled in KENO as a repeating 3x3 array, with a 5.0 w/o fresh fuel assembly occupying the central storage cell location and depleted fuel assemblies occupying the remaining eight locations.

The k_{eff} values were calculated for an infinite array of "3x3" storage configurations over a range of initial enrichment values up to 5.0 w/o ^{235}U and average burnups up to 65,000 MWD/MTU. From Table 3-5, the sum of the biases and uncertainties is 0.02423 Δk_{eff} units. Therefore, the target k_{eff} value for the "3x3" storage configuration is 0.97077 (0.995-0.02423).

Table 3-10 lists the k_{eff} values for the "3x3" storage configuration versus initial enrichment and average burnups with an axially distributed burnup profile (for 0, 5, 10, 15, and 20 years of decay time). The first entry in Table 3-10 lists the initial enrichment for no burnup. Based on the target k_{eff} value, the fresh enrichment for no burnup is 1.194 w/o ^{235}U. The derived burnup limits, for enrichments greater than 1.194 w/o ^{235}U, are based on the k_{eff} values for 3.0, 4.0, and 5.0 w/o ^{235}U. For each of these three enrichments, KENO calculations were performed at three average burnup values for an axially distributed burnup profile. A second degree fit of the burnup versus k_{eff} data was then used to determine the burnup required to meet the target k_{eff} value of 0.97077. The resulting burnup versus initial enrichment storage limits for 0, 5, 10, 15, and 20 years of decay time are provided in Table 3-11. The limiting burnups as a function of initial enrichment were fitted to a third degree polynomial for each of the decay period. These polynomials are given below Table 3-11 and will be used to determine the burnup as a function of initial enrichment for the "3x3" storage configuration. The data contained in Table 3-11 are plotted in Figure 4-12.

3.5.3 "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

As described in subsection 3.1.3, the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration consists of a repeating 2x2 array, with a fuel assembly at 5.0 w/o initial enrichment and 15,000 MWD/MTU in a storage cell location and depleted fuel assemblies in the remaining locations.

The k_{eff} values were calculated for an infinite array of "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configurations over a range of initial enrichment values up to 5.0 w/o ^{235}U and average burnups up to 45,000 MWD/MTU. From Table 3-6, the sum of the biases and uncertainties is 0.02758. Therefore, the

target k_{eff} value for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration is 0.96742 (0.995-0.02758).

Table 3-12 lists the k_{eff} values for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration versus initial enrichment and average burnups with an axially distributed burnup profile. The first entry in Table 3-12 lists the initial enrichment for no burnup. Based on the target k_{eff} value, the interpolated enrichment for no burnup is 1.569 w/o ^{235}U. The derived burnup limits, for enrichments greater than 1.569 w/o ^{235}U, are based on the k_{eff} values for 3.0, 4.0, and 5.0 w/o ^{235}U. For each of these three enrichments, KENO calculations were performed at three assembly average burnup values for an axially distributed burnup profile. A second degree fit of the burnup versus k_{eff} data was then used to determine the burnup required to meet the target k_{eff} value of 0.96742. The resulting burnup versus initial enrichment storage limits are provided in Table 3-13. The limiting burnups as a function of initial enrichment were fitted to a third degree polynomial. This polynomial is given below Table 3-13 and will be used to determine the burnup as a function of initial enrichment for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration. The data in Table 3-13 are plotted in Figure 4-13.

3.5.4 "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

As described in subsection 3.1.4, the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration consists of a repeating 2x2 array, with a 3.85 w/o ^{235}U Fresh fuel assembly in a storage cell location and depleted fuel assemblies in the remaining locations. For the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration, burnup limits have been evaluated for the depleted fuel assemblies and IFBA requirements have been determined for the fresh fuel assembly with enrichments greater than 3.85 w/o ^{235}U.

3.5.4.1 Burnup Requirements of the Depleted Fuel Assemblies

The k_{eff} values were calculated for an infinite array of "1-out-of-4 3.85 w/o Fresh with IFBA" storage configurations over a range of initial enrichment values up to 5.0 w/o ^{235}U and average burnups up to 65,000 MWD/MTU. From Table 3-7, the sum of the biases and uncertainties is 0.02217. Therefore, the target k_{eff} value for the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration is 0.97283 (0.995-0.02217).

Table 3-14 lists the k_{eff} values for the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration versus initial enrichment and average burnups with an axially distributed burnup profile. The first entry in Table 3-14 lists the initial enrichment for no burnup. Based on the target k_{eff} value, the interpolated enrichment for no burnup is 1.279 w/o ^{235}U. The derived burnup limits, for enrichments greater than 1.279 w/o ^{235}U, are based on the k_{eff} values for 3.0, 4.0, and 5.0 w/o ^{235}U. For each of these three enrichments, KENO calculations were performed at three assembly average burnup values for an axially distributed burnup profile. A second degree fit of the burnup versus k_{eff} data was then used to determine

the burnup required to meet the target k_{eff} value of 0.97283. The resulting burnup versus initial enrichment storage limits are provided in Table 3-15. The limiting burnups as a function of initial enrichment were fitted to a third degree polynomial. This polynomial is given below Table 3-15 and will be used to determine the burnup as a function of initial enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration. The data in Table 3-15 are plotted in Figure 4-14.

3.5.4.2 IFBA Requirements for the Fresh Fuel Assembly

Table 3-16 to Table 3-18 list the k_{eff} values versus the number of IFBA pins contained in the fresh fuel assembly with 4.0 w/o, 4.5 w/o and 5.0 w/o ^{235}U enrichments, respectively. For each fresh fuel enrichment and number of IFBA pins, k_{eff} was evaluated for different burnups of the depleted fuel assemblies with an initial enrichment of 5.0 w/o ^{235}U. [

]^{a,c}.

From these tables, fuel assembly burnup versus k_{eff} data was fitted to a second degree polynomial using the target k_{eff} value of 0.97283. Note that this was the target k_{eff} value used to determine the burnup requirements for the depleted fuel assemblies. The resulting polynomials were then used to determine the required number of IFBA pins to meet the fuel assembly burnup requirement of 52,205 MWD/MTU with 5.0 w/o initial enrichment. Note that using the burnup requirement for the 5.0 w/o ^{235}U initial enrichment resulted in the most conservative number of IFBA pins.

Table 3-19 contains the required number of IFBA pins versus initial enrichment for the fresh fuel assemblies with enrichments greater than 3.85 w/o. The required number of IFBA pins as a function of initial enrichment was fitted to a third degree polynomial. This polynomial is given below Table 3-19 and will be used to determine the number of IFBA pins as a function of initial enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration. The data in Table 3-19 are plotted in Figure 4-15. [ ]^{a,c}. Also note that any IFBA length 120 inches or greater is acceptable.

3.5.4.3 Early Discharge Requirements for IFBA Fuel

Analysis have shown that reactivity at any point in the burnup history of a 17x17 Standard fuel assembly with 5.0 w/o enrichment and [ ]^{a,c} IFBA pins is less than the BOC reactivity. Therefore, in the case of an early discharge part way through a cycle, the discharged fuel assembly with IFBA can be stored in the "1-out-of-4 3.85 w/o Fresh with IFBA" storage configuration, provided that it meets the storage requirements of that configuration.

3.5.5 Interface Requirements

Table 3-20 shows the entire spent fuel pool k_{eff} results for the interface configurations in the Beaver Valley Unit 2 storage racks. These interface configurations result in KENO-calculated multiplication factors that are less than the maximum of the infinite array multiplication factors for the involved storage configurations. As an example, the first analyzed interface involves the "3x3" configuration surrounded by the "All-Cell" storage configuration. From Table 3-8, the infinite array k_{eff} value for the "All-Cell" storage configuration is 0.96455 and from Table 3-10, the infinite array k_{eff} value for the "3x3" storage configuration is 0.97072. The maximum of these two values is 0.97072. From Table 3-20, the multiplication factor for the interface configuration was then compared to this maximum value to verify that the interface meets the storage requirements.

The KENO models constructed to analyze the interface effects follow the description of the entire spent fuel pool from subsection 3.1.6. The assembly loading requirements at the interface between different storage configurations are provided in Table 3-21. As seen from this table and the Table 3-20 results, it is required that for storage configurations involving high and low reactivity assemblies (i.e., 1-out-of 4 configurations), the assemblies with lower reactivity must be placed at the interface. These interface requirements are depicted in Figure 4-5 to Figure 4-10. Note that it is acceptable to leave a storage cell empty.

3.5.6 Burnup Requirements for Intermediate Decay Time Points

For the "3x3" storage configuration that credits ^{241}Pu decay, burnup requirements for intermediate decay time points should be determined using at least a second order polynomial.

3.5.7 Empty Cells

For all configurations at Beaver Valley Unit 2, an empty cell is permitted in any location of the spent fuel pool to replace an assembly since the water cell will not cause any increase in reactivity in the spent fuel pool. Non-fissile material and debris canisters may be stored in empty cells of All-Cell storage configuration provided that the canister does not contain fissile materials.

3.5.8 Non-Fissile Equipment

Non fissile equipment, such as UT cleaning equipment is permitted on top of the fuel storage racks, as these equipments will not cause any increase in reactivity in the spent fuel pool.

3.5.9 Fuel Rod Storage Canister with 5.0 w/o ^{235}U Fuel

As described in subsection 3.1.5, the FRSC contains a fixed array of 52 fresh 5.0 w/o ^{235}U fuel rods in stainless steel tubes.

Table 3-22 lists the k_{eff} values for the storage configurations with one of the depleted fuel assemblies replaced with an FRSC containing fresh 5.0 w/o ^{235}U fuel rods. The calculations were performed at 68 °F, with maximum water density of 1.0 g/cm^3 to maximize the array reactivity. As seen from Table 3-22, the resulting k_{eff} values were less than the nominal k_{eff} values of the storage configurations. Therefore, FRSCs filled with fresh fuel rods with a maximum enrichment of 5.0 w/o ^{235}U and no burnable absorbers can be stored in any storage configuration.

3.6 Soluble Boron

The NRC Safety Evaluation Report (SER) for Westinghouse report WCAP-14416-P is given in Reference 2. Page 9 of the enclosure to Reference 2 defines the total soluble boron requirement as the sum of three quantities:

$$SBC_{TOTAL} = SBC_{95/95} + SBC_{RE} + SBC_{PA}$$

where,

SBC_{TOTAL} is the total soluble boron credit requirement (ppm),

$SBC_{95/95}$ is the soluble boron requirement for 95/95 k_{eff} less than or equal to 0.95 (ppm),

SBC_{RE} is the soluble boron required to account for burnup and reactivity uncertainties (ppm),

SBC_{PA} is the soluble boron required to offset accident conditions (ppm).

Each of these terms is discussed in the following subsections.

3.6.1 Soluble Boron Requirement to Maintain k_{eff} Less Than or Equal to 0.95

Table 3-23 contains the KENO-calculated k_{eff} values for the spent fuel pool from 0 to 600 ppm of soluble boron, in increments of 200 ppm. These KENO models assume that the pool is filled with the "3x3" storage configuration containing depleted fuel at 55,000 MWD/MTU with 5.0 w/o ^{235}U initial enrichment. The initial enrichment and burnup chosen to represent the storage configuration was based on minimizing the soluble boron worth. The soluble boron worth decreases as burnup increases. The reactivity worth, Δk_{eff}, of the soluble boron was determined by subtracting the k_{eff} value, for a given soluble boron concentration, from the k_{eff} value for zero soluble boron. The soluble boron concentration and reactivity worth data was then fitted to a third degree polynomial, which is shown on the bottom of Table 3-23. This polynomial was then used to determine the amount of soluble boron required to reduce k_{eff} by 0.05 Δk_{eff} units, which is 291.7 ppm.

3.6.2 Soluble Boron Requirement for Reactivity Uncertainties

The soluble boron credit, in units of ppm, required for reactivity uncertainties was determined by converting the uncertainty in fuel assembly reactivity and the uncertainty in absolute fuel burnup values to a soluble boron concentration, in units of ppm, necessary to compensate for these two uncertainties. The first term, uncertainty in fuel assembly reactivity, is calculated by employing a depletion reactivity uncertainty of 0.010 Δk_{eff} units per 30,000 MWD/MTU of burnup (obtained from Reference 2) and multiplying by the maximum amount of burnup credited in a storage configuration. For this analysis, the maximum amount of burnup credited is 56,000 MWD/MTU for the "3x3" storage configuration. Therefore, the depletion reactivity uncertainty is 0.018667 Δk_{eff}.

The uncertainty in absolute fuel burnup values is conservatively calculated as 5% of the maximum fuel burnup credited in a storage configuration analysis. The maximum fuel burnup credited in the various storage configurations, the 5% uncertainty in these burnup values, and the corresponding reactivity values are given in Table 3-24.

The maximum reactivity change associated with a 5% change in burnup is 0.00877 Δk_{eff} units and occurs for the "All-Cell" storage configuration.

The total of the uncertainties in fuel assembly reactivity and burnup effects is 0.027437 Δk_{eff}. By applying the polynomial at the bottom of Table 3-23, the soluble boron concentration (ppm) necessary to compensate for this reactivity is found to be of 150.1 ppm.

3.6.3 Soluble Boron Required to Mitigate Accidents

The soluble boron concentration, in units of ppm, to mitigate accidents is determined by first surveying all possible events that increase the k_{eff} value of the spent fuel pool. The accident event which produced the largest increase in spent fuel pool k_{eff} value is used to determine the required soluble boron concentration necessary to mitigate this and all less severe accident events. The list of accident cases considered includes:

- Dropped fresh fuel assembly on top of the storage racks,
- Misloaded fresh fuel assembly into an incorrect storage rack location, or outside the racks,
- Intramodule water gap reduction due to seismic event,
- Spent fuel pool temperature greater than 185°F.

Several fuel mishandling events were simulated using the KENO model to assess the possible increase in the k_{eff} value of the spent fuel pool. The fuel mishandling events all assumed that a fresh Westinghouse standard 17x17 fuel assembly enriched to 5.0 w/o ^{235}U (and no burnable poisons) was misloaded into a

storage rack or between the racks and the walls of the spent fuel pool. These cases were simulated with the KENO model [ ] [a, c].

It is possible to drop a fresh fuel assembly on top of the spent fuel pool storage racks. In this case the physical separation between the fuel assemblies in the spent fuel pool storage racks and the assembly lying on top of the racks is sufficient to neutronically decouple the accident. In other words, dropping the fresh fuel assembly on top of the storage racks does not produce a positive reactivity increase. Note that the design of the spent fuel racks and fuel handling equipment is such that it precludes the insertion of a fuel assembly between the rack modules.

For the accident of a misloaded fresh fuel assembly, two scenarios were analyzed:

- A depleted fuel assembly was replaced with a fresh fuel assembly in a storage configuration;
- A fresh fuel assembly was placed between the racks and the spent fuel pool wall, face adjacent to either a depleted fuel or fresh fuel assembly of a storage configuration.

The k_{eff} values for the accident scenarios described above are summarized in Table 3-25. Note that the nominal cases were developed by filling up the pool with one of the storage configurations and then the accident scenarios, as described above, were applied. This process was repeated for all the storage configurations. Note also that both the nominal cases and the accident scenarios were simulated at zero ppm boron. As seen in Table 3-25, the accident event that produced the largest increase in the spent fuel pool k_{eff} value is the misloaded fresh fuel assembly (5.0 w/o ^{235}U enrichment) in an incorrect storage rack location (for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" configuration). As seen in Table 3-26, the required soluble boron concentration necessary to mitigate this and all less severe accident events was then calculated as 382.3 ppm using the Table 3-23 equation.

3.6.4 Total Soluble Boron Requirement

Soluble boron in the spent fuel pool coolant is used in this criticality safety analysis to offset the reactivity allowances for calculational uncertainties in modeling, storage rack fabrication tolerances, fuel assembly design tolerances, and postulated accidents.

The magnitude of each soluble boron requirement is as follows:

$$SBC_{95/95} = 291.7 \text{ ppm}$$
$$SBC_{RE} = 150.1 \text{ ppm}$$
$$SBC_{PA} = 382.3 \text{ ppm}$$
$$SBC_{TOTAL} = 824.1 \text{ ppm}$$

Therefore, without considering an accident, the soluble boron (with 19.9% ^{10}B abundance) necessary to maintain k_{eff} less than or equal to 0.95 (including all biases and uncertainties) is:

$$SBC_{95/95} + SBC_{RE} = 291.7 \text{ ppm} + 150.1 \text{ ppm} = 441.8 \text{ ppm}.$$

The soluble boron concentration required for a ^{10}B atom percent equal to 19.6 (expected lowest pool value crediting ^{10}B depletion) is 448.6 ppm.

A total of 824.1 ppm of soluble boron (with 19.9% ^{10}B abundance) is required to maintain k_{eff} less than or equal to 0.95 (including all biases and uncertainties) and assuming the most limiting single accident. The soluble boron concentration required for a ^{10}B atom percent equal to 19.6 (expected lowest pool value crediting ^{10}B depletion) is 836.7 ppm. The recommended minimum boron level is 836.7 ppm and is sufficient to accommodate all the design requirements.

Table 3-1

Fuel Assembly Data Used in Criticality Analysis of the Beaver Valley Unit 2 Spent Fuel Storage Racks

a, c

[

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Table 3-2
Relative Power and Fuel/ Moderator Temperatures
for the Average and [ ] [a, c] **a, c**

[

]

Table 3-3
Burnup and Initial Enrichment Combinations Used to Determine the Isotopic Number Densities

3.0 w/o ^{235}U (MWD/MTU)	4.0 w/o ^{235}U (MWD/MTU)	5.0 w/o ^{235}U (MWD/MTU)
0	0	0
5,000	5,000	5,000
15,000	15,000	15,000
25,000	25,000	25,000
35,000	35,000	35,000
45,000	45,000	45,000
55,000	55,000	55,000
65,000	65,000	65,000

Table 3-4
K_{eff} Values for the Tolerance/Uncertainty Cases for the "All-Cell" Storage Configuration

a, c

[ ]

a, c

[ ]

Table 3-5
K_{eff} Values for the Tolerance/Uncertainty Cases for the "3x3" Storage Configuration

a, c

[ ]

a, c

[ ]

Table 3-6
K_{eff} Values for the Tolerance/Uncertainty Cases for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

a, c

[

]

a, c

[

]

Table 3-7
K_{eff} Values for the Tolerance/Uncertainty Cases for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

a, c

[redacted]

a, c

[redacted]

Table 3-8
K_{eff} Values versus Initial Enrichment and Assembly Burnup for the "All-Cell" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Assembly Burnup (MWD/MTU)	k_{eff} Value
1.856	0	0.96455 ± 0.00034
3.000	5,000	1.03844 ± 0.00034
3.000	15,000	0.94970 ± 0.00034
3.000	25,000	0.88372 ± 0.00035
4.000	15,000	1.02947 ± 0.00035
4.000	25,000	0.95716 ± 0.00036
4.000	35,000	0.90355 ± 0.00033
5.000	25,000	1.01616 ± 0.00035
5.000	35,000	0.96161 ± 0.00035
5.000	45,000	0.91593 ± 0.00035

Table 3-9
Fuel Assembly Burnup versus Initial Enrichment for the "All-Cell" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.856	0
3.000	13,049
4.000	23,792
5.000	34,404

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $78.116e^3 - 1002.647e^2 + 14871.032e - 24649.599$

Table 3-10
K_{eff} Values versus Initial Enrichment and Assembly Burnup for the "3x3" Storage Configuration (for 0 to 20 Years Decay)

Initial Enrichment (w/o ^{235}U)	Burnup (MWD/ MTU)	k_{eff} Value				
		0 year decay	5 years decay	10 years decay	15 years decay	20 years decay
1.194	0	0.97072 ± 0.00050	0.97072 ± 0.00050	0.97072 ± 0.00050	0.97072 ± 0.00050	0.97072 ± 0.00050
3.000	25,000	0.98572 ± 0.00049	0.98062 ± 0.00048	0.97797 ± 0.00051	0.97579 ± 0.00052	0.97409 ± 0.00053
3.000	35,000	0.96635 ± 0.00051	0.96177 ± 0.00054	0.95771 ± 0.00052	0.95553 ± 0.00056	0.95317 ± 0.00053
3.000	45,000	0.95431 ± 0.00056	0.94989 ± 0.00053	0.94676 ± 0.00051	0.94452 ± 0.00050	0.94190 ± 0.00048
4.000	35,000	0.99069 ± 0.00050	0.98428 ± 0.00046	0.98005 ± 0.00051	0.97738 ± 0.00050	0.97571 ± 0.00054
4.000	45,000	0.97052 ± 0.00052	0.96503 ± 0.00053	0.96127 ± 0.00052	0.95903 ± 0.00050	0.95681 ± 0.00053
4.000	55,000	0.95653 ± 0.00056	0.95437 ± 0.00052	0.94881 ± 0.00051	0.94772 ± 0.00049	0.94535 ± 0.00051
5.000	45,000	0.99128 ± 0.00049	0.98460 ± 0.00051	0.98110 ± 0.00046	0.97734 ± 0.00051	0.97586 ± 0.00054
5.000	55,000	0.97195 ± 0.00048	0.96694 ± 0.00055	0.96384 ± 0.00054	0.96059 ±0.00049	0.95828 ± 0.00052
5.000	65,000	0.95932 ± 0.00047	0.95482 ± 0.00051	0.95137 ± 0.00053	0.949 01 ±0.00052	0.94757 ± 0.00050

Table 3-11
Fuel Assembly Burnup versus Initial Enrichment for the "3x3" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)				
	0 yr decay	5 yr decay	10 yr decay	15 yr decay	20 yr decay
1.194	0	0	0	0	0
3.000	32,060	29,330	27,291	26,465	25,845
4.000	44,847	40,936	39,182	37,717	36,835
5.000	55,821	52,374	50,452	48,296	47,077

Note that the assembly burnups as a function of initial enrichment for each decay period are described by the following polynomials:

Assembly Burnup (0 yr decay) = 226.346 e^3 – 3622.515 e^2 + 29770.012 e – 30759.089
Assembly Burnup (5 yr decay) = 411.594 e^3 – 5022.911 e^2 + 31537.071 e – 31188.090
Assembly Burnup (10 yr decay) = 219.829 e^3 – 2948.038 e^2 + 24392.920 e – 25290.545
Assembly Burnup (15 yr decay) = 229.788 e^3 – 3094.064 e^2 + 24408.298 e – 25117.773
Assembly Burnup (20 yr decay) = 212.385 e^3 – 2922.606 e^2 + 23590.057 e – 24355.76

Table 3-12
K_{eff} Values versus Initial Enrichment and Assembly Burnup for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Assembly Burnup (MWD/MTU)	k_{eff} Value
1.569	0	0.96707 ± 0.00037
3.000	5,000	1.04895 ± 0.00033
3.000	15,000	0.99002 ± 0.00037
3.000	25,000	0.94866 ± 0.00035
4.000	15,000	1.04387 ± 0.00036
4.000	25,000	0.99320 ± 0.00035
4.000	35,000	0.95745 ± 0.00036
5.000	25,000	1.03256 ± 0.00032
5.000	35,000	0.99322 ± 0.00034
5.000	45,000	0.96386 ± 0.00035

Table 3-13
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.569	0
3.000	20,160
4.000	31,967
5.000	43,673

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $259.098e^3 - 3159.653e^2 + 24337.852e - 31412.160$

Table 3-14
K_{eff} Values versus Initial Enrichment and Assembly Burnup for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Assembly Burnup (MWD/MTU)	k_{eff} Value
1.279	0	0.97254 ± 0.00046
3.000	25,000	0.98370 ± 0.00039
3.000	35,000	0.95662 ± 0.00044
3.000	45,000	0.93919 ± 0.00045
4.000	35,000	0.98826 ± 0.00045
4.000	45,000	0.96249 ± 0.00045
4.000	55,000	0.94402 ± 0.00042
5.000	45,000	0.99117 ± 0.00041
5.000	55,000	0.96686 ± 0.00043
5.000	65,000	0.94846 ± 0.00047

Table 3-15
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.279	0
3.000	28,205
4.000	40,434
5.000	52,205

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $349.431e^3 - 4422.547e^2 + 30258.629e - 32203.081$

Table 3-16
K_{eff} Values versus Number of IFBA Pins (1.5X) Contained in the 4.0 w/o ^{235}U Fresh Fuel of the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Enrichment of Fresh Fuel (w/o ^{235}U)	Burnup of Depleted Fuel (MWD/MTU)	Number of IFBA Pins [ ] a, c	k_{eff}
4.000	35,000		1.02511 ± 0.00038
4.000	35,000		1.01446 ± 0.00038
4.000	35,000		1.00618 ± 0.00036
4.000	35,000		1.00193 ± 0.00038
4.000	45,000		0.99455 ± 0.00040
4.000	45,000		0.98392 ± 0.00043
4.000	45,000		0.97705 ± 0.00038
4.000	45,000		0.97226 ± 0.00038
4.000	55,000		0.97187 ± 0.00044
4.000	55,000		0.96034 ± 0.00042
4.000	55,000		0.95267 ± 0.00041
4.000	55,000		0.94885 ± 0.00040

Table 3-17
K_{eff} Values versus Number of IFBA Pins (1.5X) Contained in the 4.5 w/o ^{235}U Fresh Fuel of the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Enrichment of Fresh Fuel (w/o ^{235}U)	Burnup of Depleted Fuel (MWD/MTU)	Number of IFBA Pins [ ] a, c	k_{eff}
4.500	45,000		1.00810 ± 0.00042
4.500	45,000		0.99671 ± 0.00043
4.500	45,000		0.98912 ± 0.00040
4.500	45,000		0.98356 ± 0.00043
4.500	55,000		0.98458 ± 0.00040
4.500	55,000		0.97518 ± 0.00044
4.500	55,000		0.96609 ± 0.00044
4.500	55,000		0.96077 ± 0.00043
4.500	65,000		0.96790 ± 0.00046
4.500	65,000		0.95549 ± 0.00048
4.500	65,000		0.94866 ± 0.00044
4.500	65,000		0.94203 ± 0.00042

Table 3-18
K_{eff} Values versus Number of IFBA Pins (1.5X) Contained in the 5.0 w/o ^{235}U Fresh Fuel of the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Enrichment of the Fresh Fuel (w/o ^{235}U)	Burnup of the Depleted Fuel (MWD/MTU)	Number of IFBA Pins [ ] a, c	k_{eff}
5.000	45,000		1.01949 ± 0.00042
5.000	45,000		0.99930 ± 0.00038
5.000	45,000		0.99334 ± 0.00045
5.000	45,000		0.98843 ± 0.00041
5.000	55,000		0.99669 ± 0.00044
5.000	55,000		0.97697 ± 0.00048
5.000	55,000		0.97237 ± 0.00041
5.000	55,000		0.96692 ± 0.00045
5.000	65,000		0.98055 ± 0.00047
5.000	65,000		0.96088 ± 0.00047
5.000	65,000		0.95341 ± 0.00045
5.000	65,000		0.94989 ± 0.00047

Table 3-19
Required Number of IFBAs versus Initial Enrichment for the Fresh Fuel Assembly in the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Number of IFBAs
3.850	0
4.000	7
4.500	30
5.000	63

Required Number of IFBA pins as a function of enrichment is given by the following polynomials:

Number of IFBA Pins = $15.444e^3 - 187.380e^2 + 800.538e - 1185.967$

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Table 3-20
Entire Spent Fuel Pool k_{eff} Results for the Interface Configurations

	All-Cell		3x3		1-out-of-4 5.0 w/o at 15,000 MWD/MTU		1-out-of-4 3.85 w/o Fresh with IFBA	
	k_{eff}	Max. Infinite Array k_{eff}	k_{eff}	Max. Infinite Array k_{eff}	k_{eff}	Max. Infinite Array k_{eff}	k_{eff}	Max. Infinite Array k_{eff}
All-Cell								
3x3	0.96996	0.97072						
1-out-of-4 5.0 w/o at 15,000 MWD/MTU	0.96691	0.96707	0.97028	0.97072				
1-out-of-4 3.85 w/o Fresh with IFBA	0.96598	0.97254	0.97026	0.97254	0.96643	0.97254		

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Table 3-21
Assembly Loading Requirements at the Interface between Different Storage Configurations

Configuration	Assembly that Must be Loaded at the Interface with Another Configuration[1]
"All-Cell"	Any
"3x3"	Only Depleted Fuel Assemblies
"1-out-of-4 5.0 w/o at 15,000 MWD/MTU"	Only Depleted Fuel Assemblies
"1-out-of-4 3.85 w/o Fresh with IFBA"	Only Depleted Fuel Assemblies

Instructions:
1. Identify which storage configurations will be interfaced.
2. Look up the assembly loading requirements for both storage configurations.

[1] An empty storage location is always permitted.

Table 3-22
K_{eff} Values for the Fuel Rod Storage Canister with 5.0 w/o ^{235}U Fresh Fuel in Beaver Valley Unit Spent Fuel Pool Storage Configurations

Configuration in which FRSC is Inserted	k_{eff} with FRSC	k_{eff} without FRSC
All-Cell	0.90648 ± 0.00035	0.96455 ± 0.00034
3x3	0.96845 ± 0.00052	0.97072 ± 0.0005
1-out-of-4 with 5.0 w/o at 15,000 MWD/MTU	0.93287 ± 0.00042	0.96707 ± 0.00037
1-out-of-4 with 3.85 w/o Fresh with IFBA	0.95595 ± 0.00043	0.97254 ± 0.00046

Table 3-23
K_{eff} Values as a Function of Soluble Boron Concentration for the Spent Fuel Pool with Depleted Fuel Assemblies in 3x3 Storage Configuration

Configuration	k_{eff}			
	0 ppm	200 ppm	400 ppm	600 ppm
Depleted Fuel (5.0 w/o, 55,000 MWD/MTU)	0.97102 ± 0.00032	0.93533 ± 0.00031	0.90529 ± 0.00032	0.87873 ± 0.00030

Note that the following polynomial describes an amount of boron as a function of Δk_{eff} for the entire spent fuel pool:

$$\mathbf{ppm = -6747.975\Delta k_{eff}^3 + 16719.356\Delta k_{eff}^2 + 5015.692\Delta k_{eff}}$$

Table 3-24
Summary of Burnup Reactivity Uncertainties for the Storage Configurations

Configuration	Maximum Burnup (MWD/MTU)	5% Burnup Uncertainty	Δk_{eff}
All-Cell	35,000	1,750	0.00877
3x3	56,000	2,800	0.00429
1-out-of-4 5.0 w/o at 15,000 MWD/MTU	44,000	2,200	0.00558
1-out-of-4 3.85 w/o with IFBA	53,000	2,650	0.00597

Table 3-25
K_{eff} Values for Various Accident Scenarios in the Spent Fuel Pool

	All-Cell		3x3		1-out-of-4 5.0 w/o at 15,000 MWD/MTU		1-out-of-4 3.85 w/o Fresh with IFBA	
Accident Scenarios	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}
Misloaded fresh fuel assembly into burnup storage rack location	1.0108 ± 0.00030	0.05505[1]	1.02498 ± 0.00031	0.05620[2]	1.02193 ± 0.00055	0.06323[3]	1.00947 ± 0.00030	0.04323[4]
Misloaded fresh fuel assembly between storage racks and pool wall	0.95722 ± 0.00023	0.00147	0.99688 ± 0.00040	0.02810	0.96149 ± 0.00024	0.00279	0.99754 ± 0.00027	0.03130
Intramodule water gap reduction due to seismic event	0.96266 ± 0.00021	0.00691	0.97039 ± 0.00032	0.00161	0.96493 ± 0.00023	0.00623	0.97216 ± 0.00025	0.00592
Spent fuel pool temperature greater than 185 °F	0.97852 ± 0.00022	0.02603	0.9289 ± 0.00027	-0.03673	0.97399 ± 0.00021	0.01893	0.96164 ± 0.00023	-0.00116

1 Based on the nominal k_{eff} value of 0.95575 for a pool filled with "All-Cell" storage configuration
2 Based on the nominal k_{eff} value of 0.96878 for a pool filled with "3x3" storage configuration
3 Based on the nominal k_{eff} value of 0.95870 for a pool filled with "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage configuration
4 Based on the nominal k_{eff} value of 0.96624 for a pool filled with "1-out-of-4 3.85 with IFBA" storage configuration

Table 3-26
Soluble Boron required to Mitigate Various Accidents in the Spent Fuel Pool

	All-Cell	3x3	1-out-of-4 5.0 w/o at 15,000 MWD/MTU	1-out-of-4 3.85 w/o Fresh with IFBA
Accident Scenarios	**[ppm]**	**[ppm]**	**[ppm]**	**[ppm]**
Misloaded fresh fuel assembly into burnup storage rack location	325.7	333.5	382.3	247.5
Misloaded fresh fuel assembly between storage racks and pool wall	7.4	154.0	14.1	173.2
Intramodule water gap reduction due to seismic event	35.5	8.1	31.9	30.3
Spent fuel pool temperature greater than 185 °F	141.8	-	100.9	-

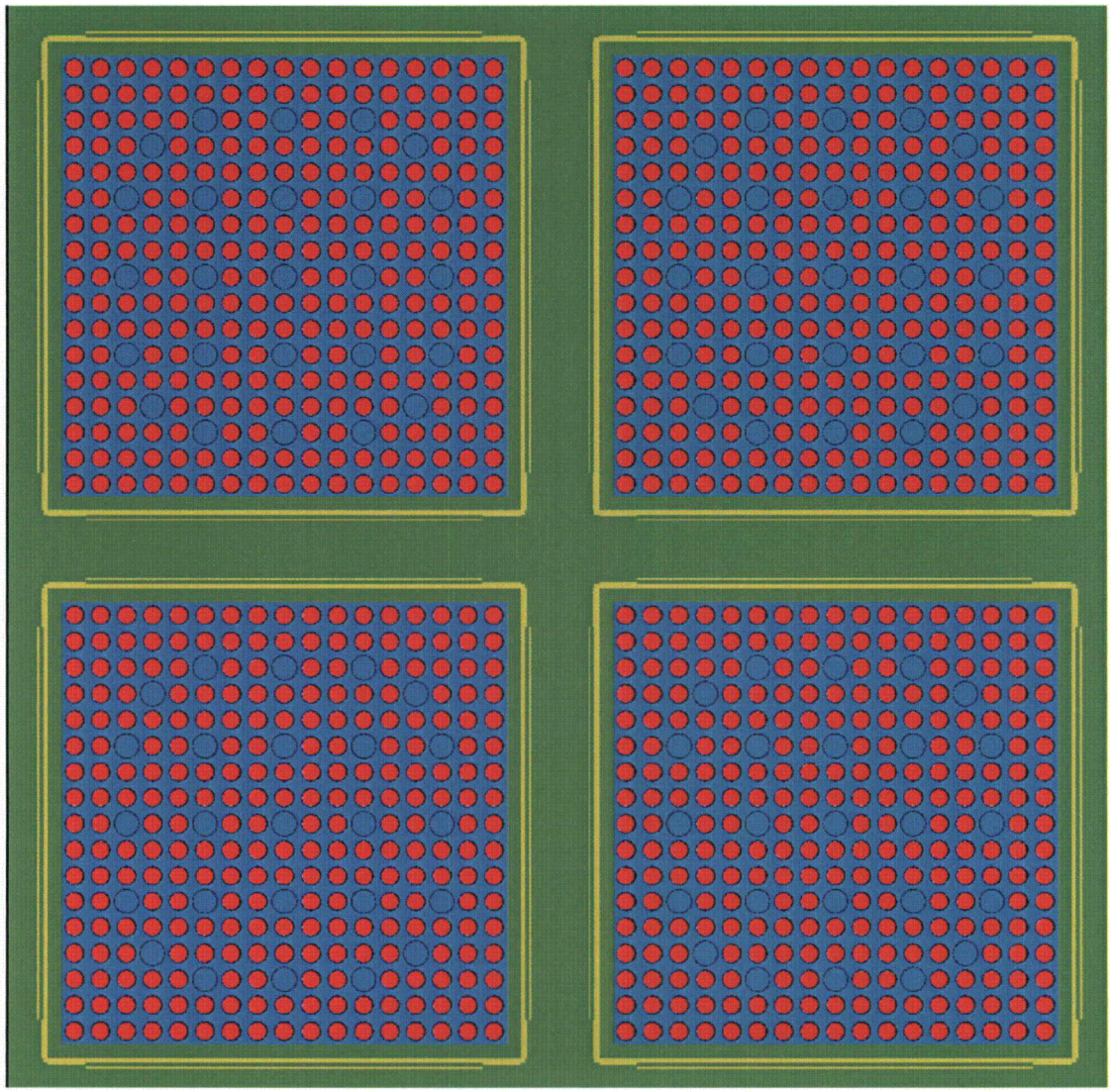

Figure 3-1
KENO Output Plot for the "All-Cell" Storage Configuration

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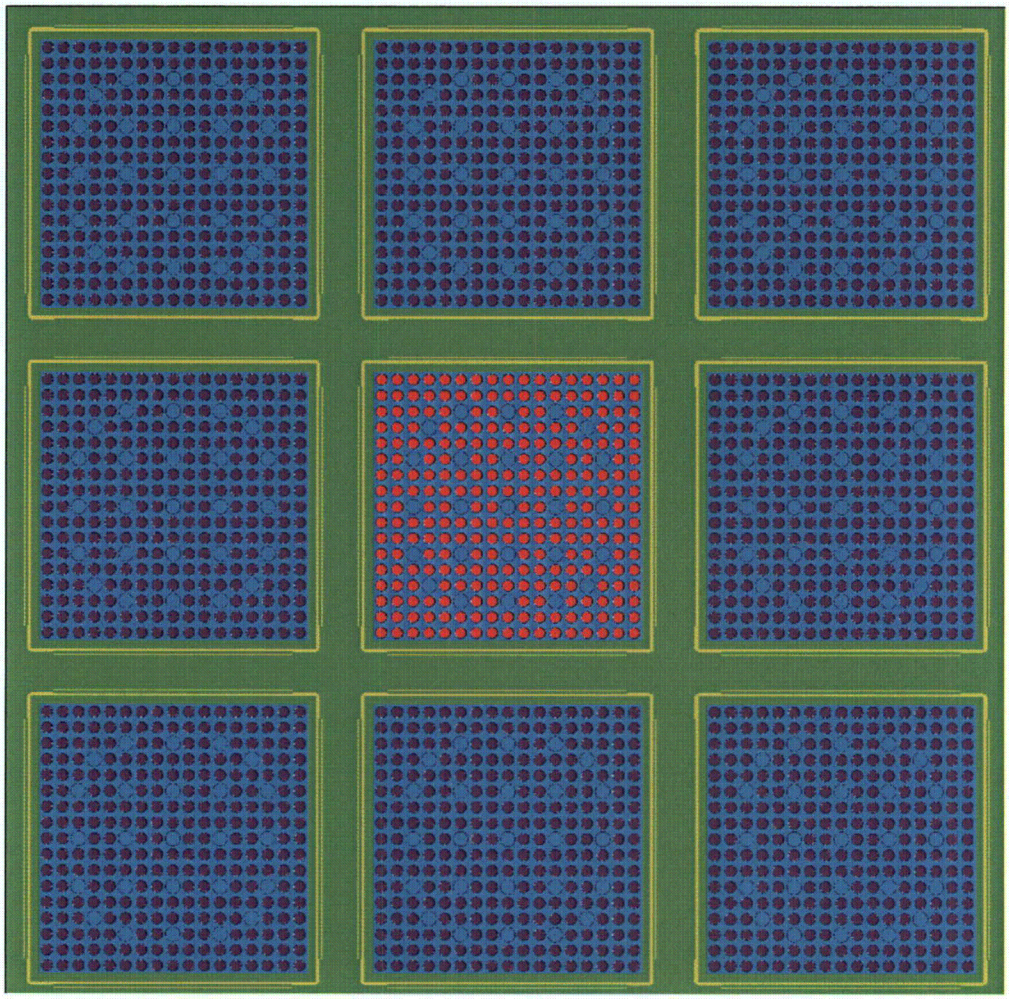

Figure 3-2
KENO Output Plot for the "3x3" Storage Configuration

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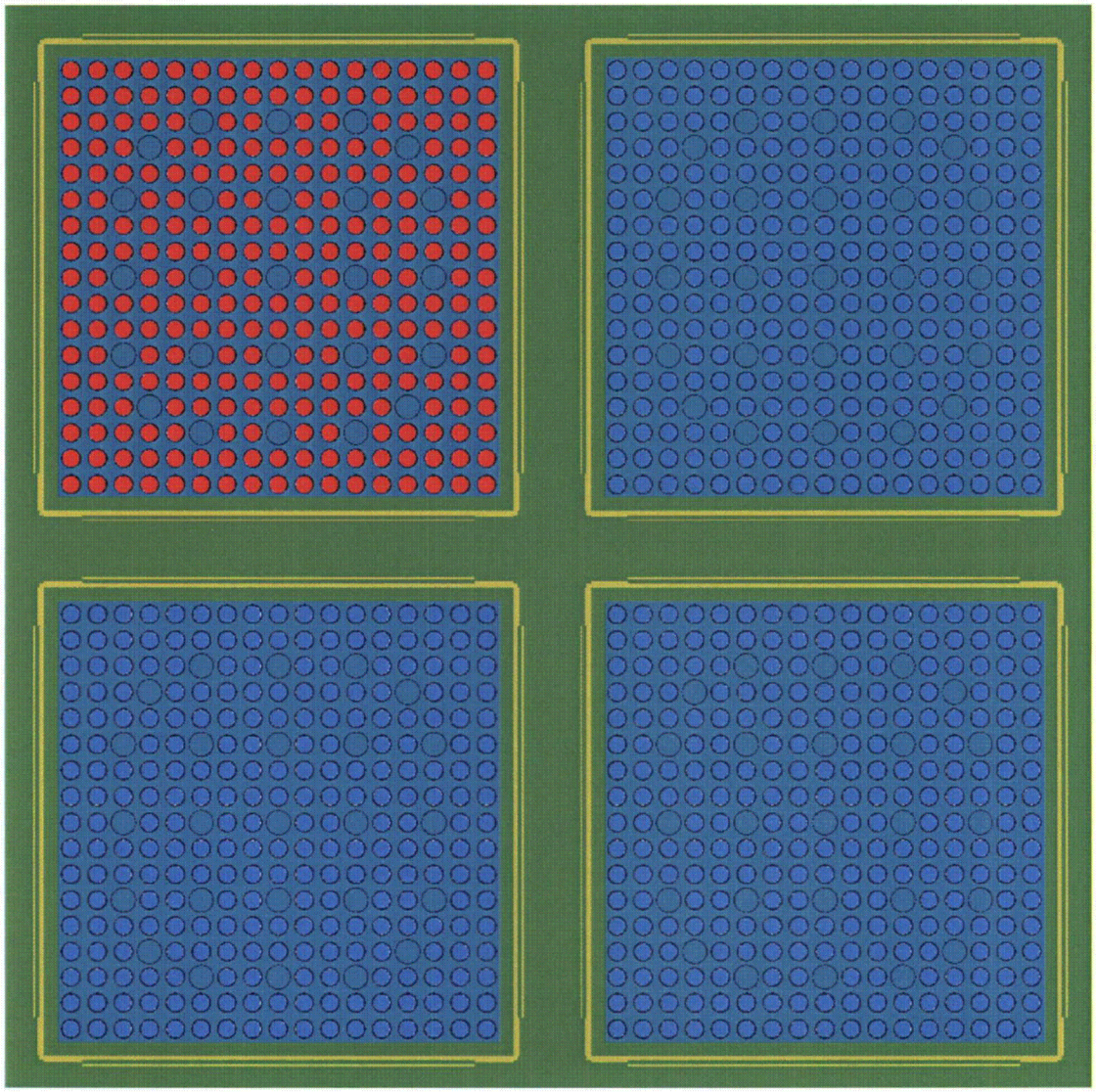

Figure 3-3
KENO Output Plot for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

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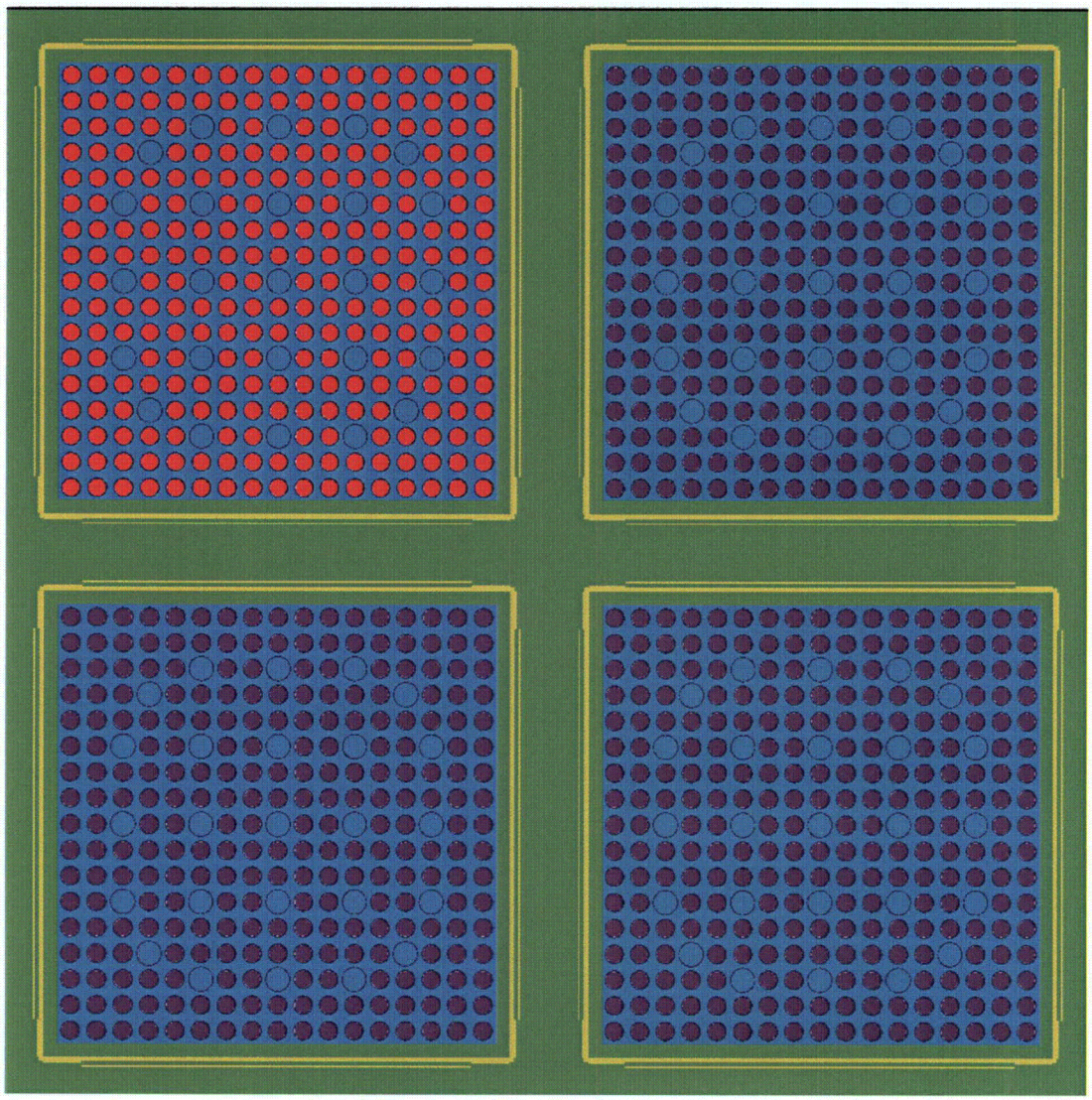

Figure 3-4
KENO Output Plot for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

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a, c

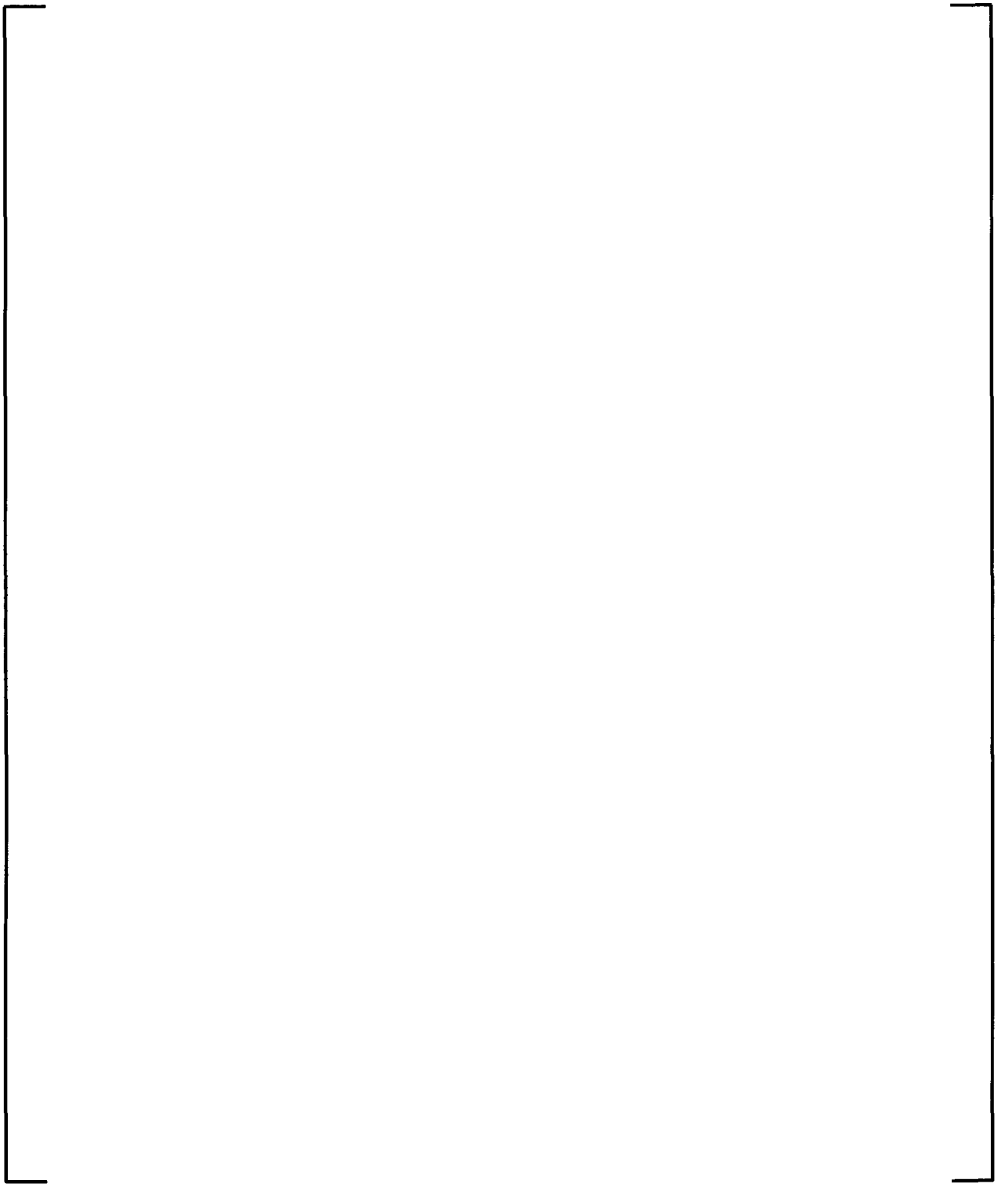

Figure 3-5
IFBA Patterns Assumed for the BVPS Unit 2 Criticality Analysis

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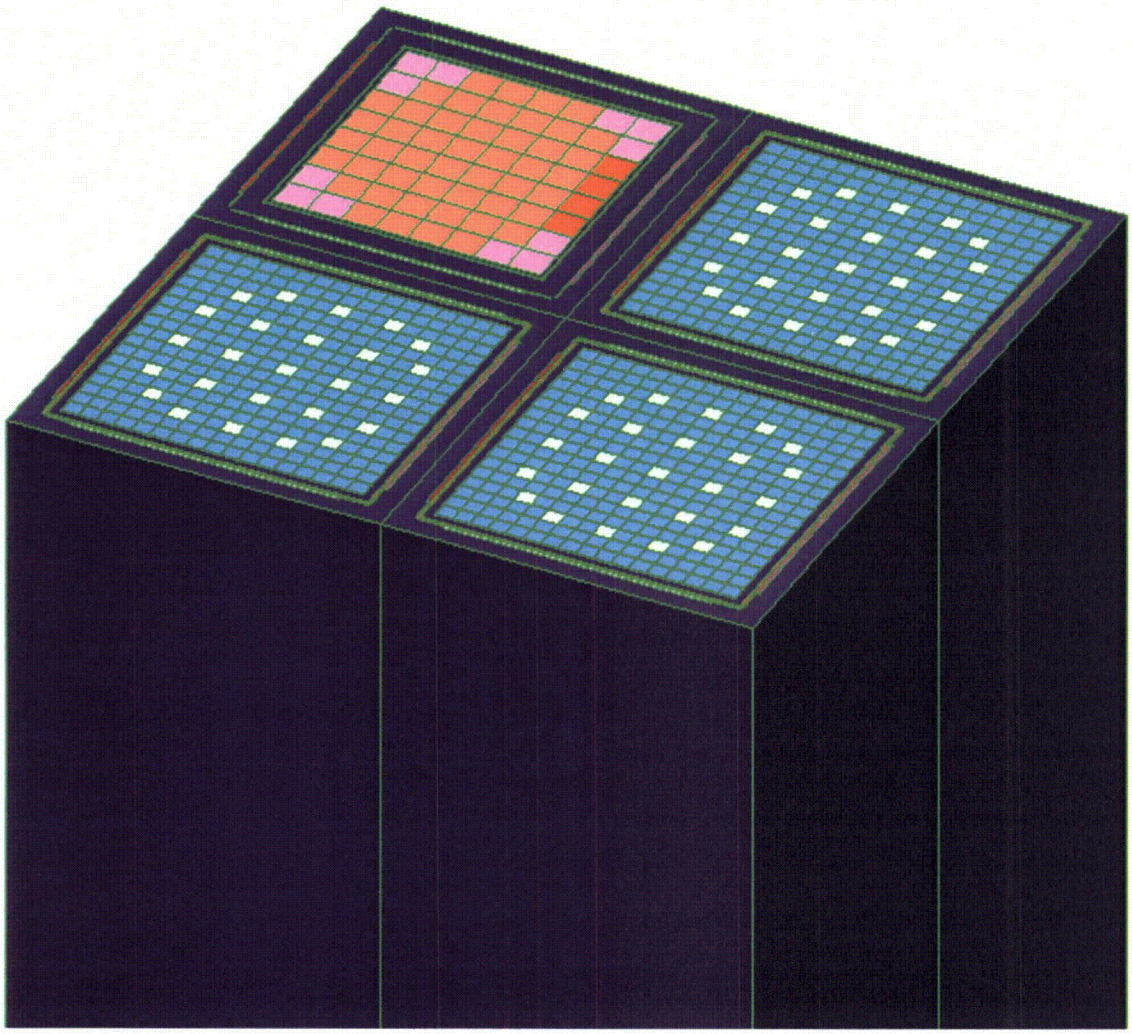

Figure 3-6
KENO Output Plot for the Fuel Rod Storage Canister in the "All-Cell" Storage Configuration

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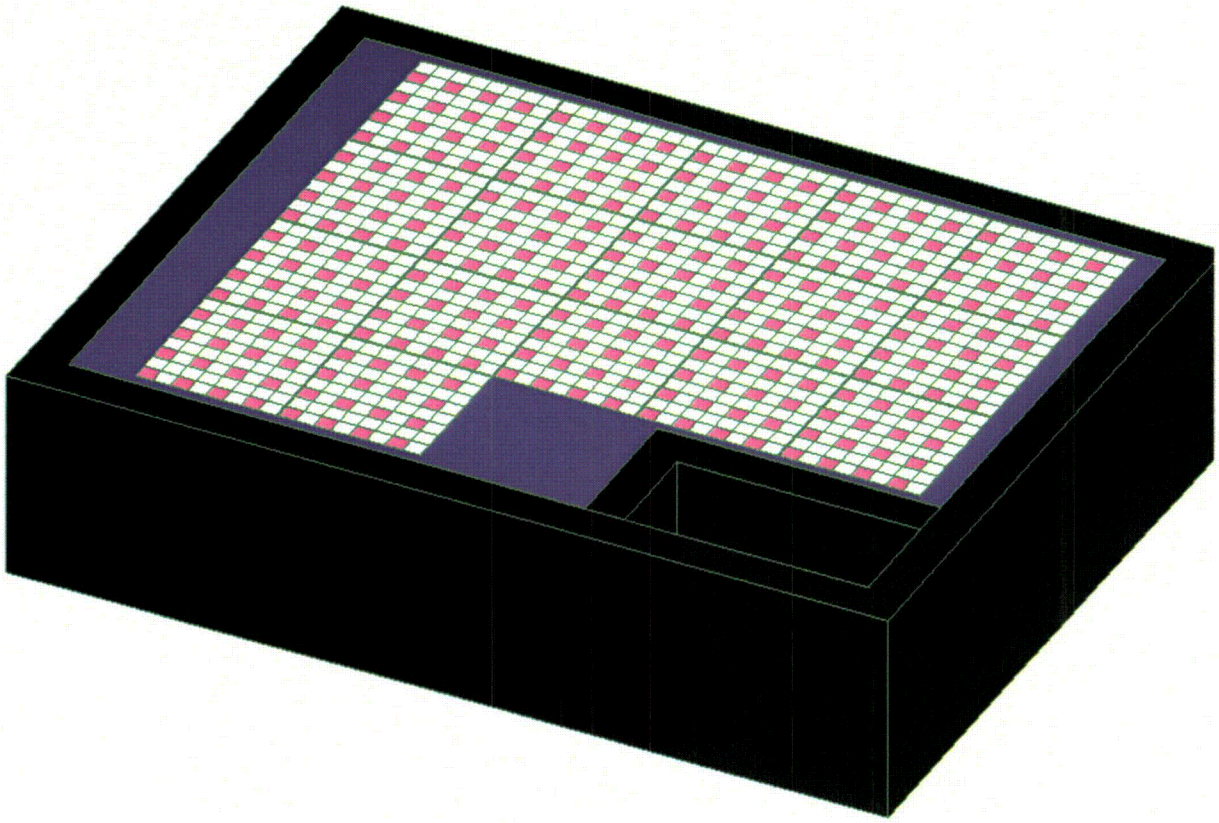

Figure 3-7
KENO Output Plot for the Spent Fuel Pool Loaded with the "1-out-of 4 3.85 w/o Fresh with IFBA" Storage Configurations

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a, c

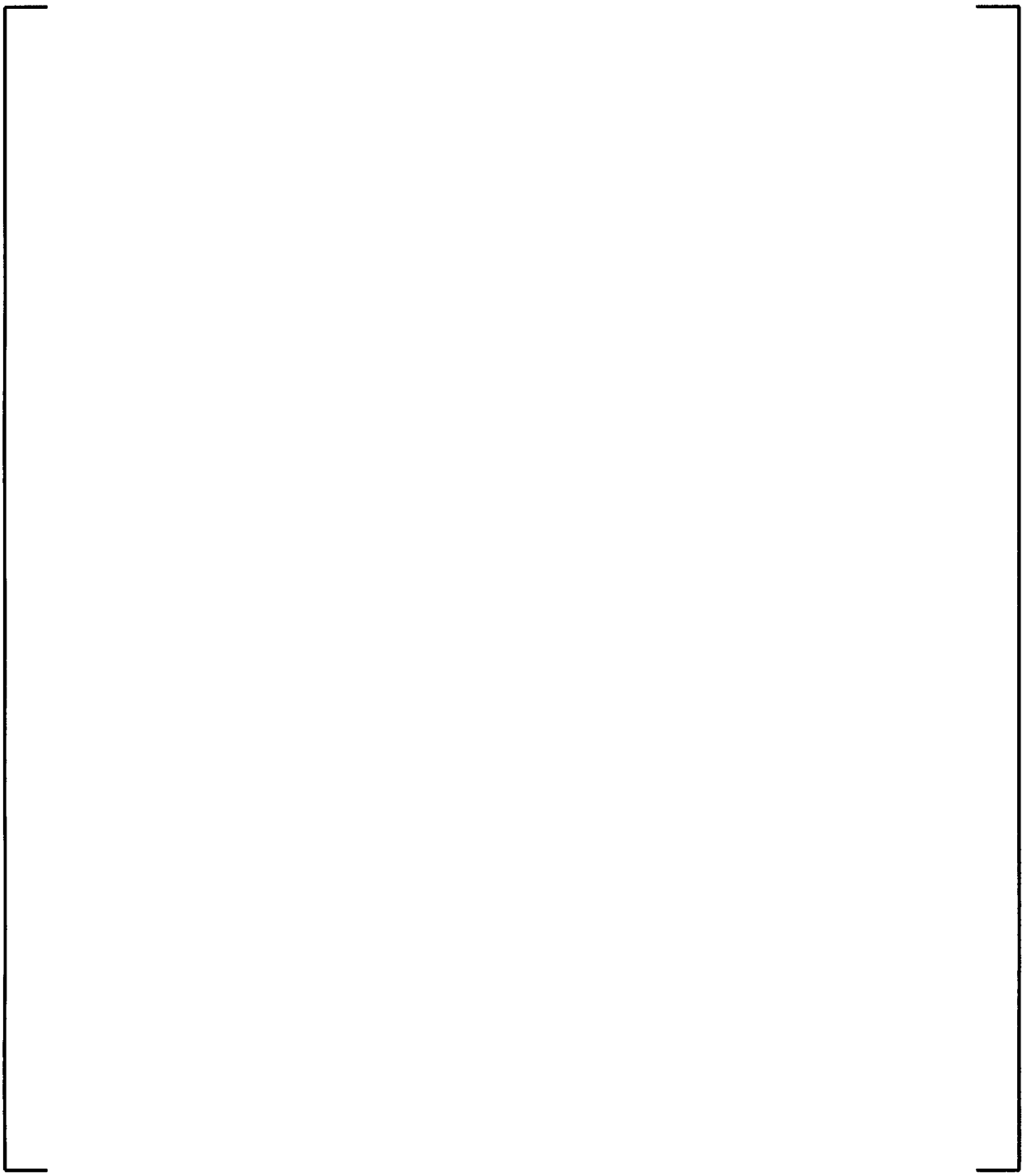

Figure 3-8
Westinghouse Standard 17x17 Fuel Assembly Dimensions

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a, c

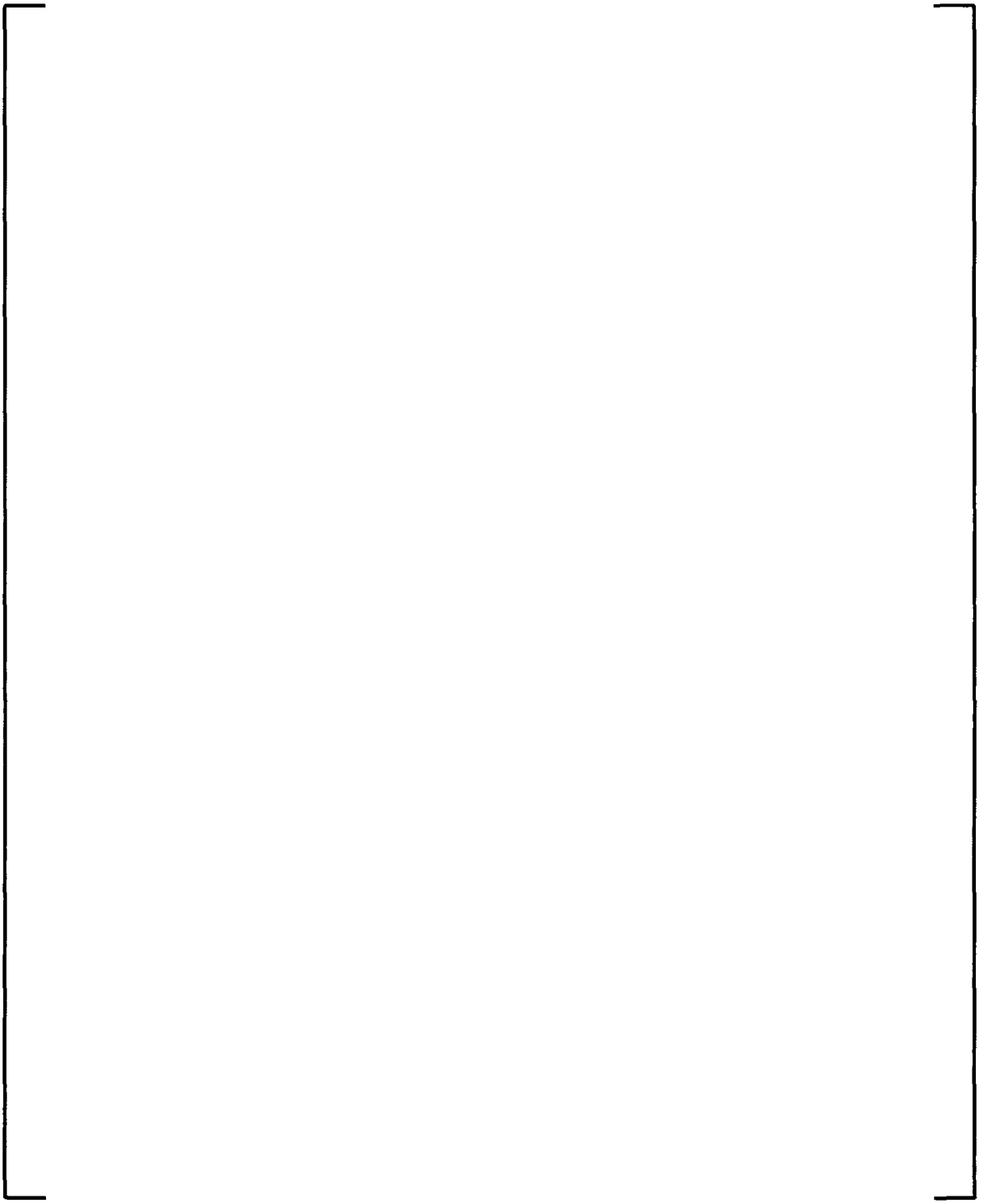

Figure 3-9
Sketch of Axial Zones Used in Fuel Assembly: Four-Zone Model

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4.0 Summary of Results

The following sections contain the criticality analysis results for the Beaver Valley Unit 2 spent fuel pools with soluble boron credit.

4.1 Allowable Storage Configurations

4.1.1 "All-Cell" Storage Configuration

Figure 4-1 displays the allowable storage configurations for the "All-Cell" storage. The "All-Cell" storage rack will be employed to store depleted fuel assemblies which meet the requirements of Table 4-1 and Figure 4-11.

4.1.2 "3x3" Storage Configuration

Figure 4-2 displays the allowable storage configurations for the "3x3" storage. The "3x3"Region storage rack will be employed to store fresh fuel assemblies with enrichments up to 5.0 w/o ^{235}U and depleted fuel assemblies which meet the requirements of Table 4-2 and Figure 4-12.

4.1.3 "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

Figure 4-3 displays the allowable storage configurations for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage. The "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" storage rack will be employed to store assemblies with burnups consistent with once cycle of operation and initial enrichment equal to 5.0 w/o ^{235}U and depleted fuel assemblies which meet the requirements of Table 4-3 and Figure 4-13.

4.1.4 "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Figure 4-4 displays the allowable storage configurations for the "1-out-of-4 3.85 w/o Fresh with IFBA" storage. The "1-out-of-4 3.85 w/o Fresh with IFBA" storage rack will be employed to store fresh fuel assemblies with enrichments up to 3.85 w/o ^{235}U and depleted fuel assemblies which meet the requirements of Table 4-4 and Figure 4-14. The fresh fuel assemblies with enrichments greater than 3.85 w/o ^{235}U and up to 5.0 w/o ^{235}U shall meet the requirements of Table 4-5 and Figure 4-15. [

] [a, c]. Also note that any IFBA length 120 inches or greater is acceptable.

4.2 Interface Requirements in Spent Fuel Pool Storage Racks

Fuel storage patterns used at the interface of storage configurations shall comply with the assembly loading requirements provided in Table 4-6 and Figure 4-5 to Figure 4-10. Note that it is acceptable to leave a storage cell empty.

4.3 Empty Cells

For all configurations at Beaver Valley Unit 2, an empty cell is permitted in any location of the spent fuel pool to replace an assembly since the water cell will not cause any increase in reactivity in the spent fuel pool. Non-fissile material and debris canisters may be stored in empty cells of "All-Cell" storage configuration provided that the canister does not contain fissile materials.

4.4 Non-Fissile Equipment

Non fissile equipment, such as UT cleaning equipment is permitted on top of the fuel storage racks, as these equipments will not cause any increase in reactivity in the spent fuel pool.

4.5 Fuel Rod Storage Canisters

Fuel rod storage canisters, filled with fuel rods with a maximum enrichment equal to 5.0 w/o ^{235}U with no burnable absorbers, can be stored in any storage configuration.

4.6 Total Soluble Boron Requirement

The soluble boron (with 19.9% ^{10}B abundance) necessary to maintain k_{eff} less than or equal to 0.95 (including all biases and uncertainties) is 441.8 ppm. The soluble boron concentration required for a ^{10}B atom percent equal to 19.6 (expected lowest pool value crediting ^{10}B depletion) is 448.6 ppm. A total of 824.1 ppm of soluble boron (with 19.9% ^{10}B abundance) is required to maintain k_{eff} less than or equal to 0.95 (including all biases and uncertainties) and assuming the most limiting single accident. The soluble boron concentration required for a ^{10}B atom percent equal to 19.6 (expected lowest pool value crediting ^{10}B depletion) is 836.7 ppm. The recommended minimum boron level is 836.7 ppm and is sufficient to accommodate all the design requirements.

Table 4-1
Fuel Assembly Burnup versus Initial Enrichment for the "All-Cell" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.856	0
3.000	13,049
4.000	23,792
5.000	34,404

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $78.116e^3 - 1002.647e^2 + 14871.032e - 24649.599$

Table 4-2
Fuel Assembly Burnup versus Initial Enrichment for the "3x3" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)				
	0 yr decay	5 yr decay	10 yr decay	15 yr decay	20 yr decay
1.194	0	0	0	0	0
3.000	32,060	29,330	27,291	26,465	25,845
4.000	44,847	40,936	39,182	37,717	36,835
5.000	55,821	52,374	50,452	48,296	47,077

Note that the assembly burnups as a function of initial enrichment for each decay period are described by the following polynomials:

Assembly Burnup (0 yr decay) = 226.346 e^3 – 3622.515 e^2 + 29770.012 e – 30759.089
Assembly Burnup (5 yr decay) = 411.594 e^3 – 5022.911 e^2 + 31537.071 e – 31188.090
Assembly Burnup (10 yr decay) = 219.829 e^3 – 2948.038 e^2 + 24392.920 e – 25290.545
Assembly Burnup (15 yr decay) = 229.788 e^3 – 3094.064 e^2 + 24408.298 e – 25117.773
Assembly Burnup (20 yr decay) = 212.385 e^3 – 2922.606 e^2 + 23590.057 e – 24355.76

Table 4-3
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.569	0
3.000	20,160
4.000	31,967
5.000	43,673

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $259.098e^3 - 3159.653e^2 + 24337.852e - 31412.160$

Table 4-4
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Limiting Burnup (MWD/MTU)
1.279	0
3.000	28,205
4.000	40,434
5.000	52,205

Note that the assembly burnup as a function of initial enrichment is described by the following polynomial:

Assembly Burnup = $349.431e^3 - 4422.547e^2 + 30258.629e - 32203.081$

Table 4-5
Number of IFBAs versus Initial Enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

Initial Enrichment (w/o ^{235}U)	Number of IFBAs
3.850	0
4.000	7
4.500	30
5.000	63

Required Number of IFBA pins as a function of enrichment is given by the following polynomials:

Number of IFBA Pins = $15.444e^3 - 187.380e^2 + 800.538e - 1185.967$

Table 4-6
Assembly Loading Requirements at the Interface between Different Storage Configurations

Configuration	Assembly that Must be Loaded at the Interface with Another Configuration[1]
"All-Cell"	Any
"3x3"	Only Depleted Fuel Assemblies
"1-out-of-4 5.0 w/o at 15,000 MWD/MTU"	Only Depleted Fuel Assemblies
"1-out-of-4 3.85 w/o Fresh with IFBA"	Only Depleted Fuel Assemblies

Instructions:
1. Identify which storage configurations will be interfaced.
2. Look up the assembly loading requirements for both storage configurations.

[1] An empty storage location is always permitted.

The depleted fuel assemblies shall meet the requirements of Figure 4-11.

Figure 4-1
Allowable Fuel Assemblies in the "All-Cell" Storage Configuration

1.194 w/o	**1.194 w/o**	**1.194 w/o**
1.194 w/o	**5.0 w/o Fresh**	**1.194 w/o**
1.194 w/o	**1.194 w/o**	**1.194 w/o**

The depleted fuel assemblies shall meet the requirements of Figure 4-12.

Figure 4-2
Allowable Fuel Assemblies in the "3x3" Storage Configuration

1.569 w/o	**5.0 w/o at 15,000 MWD/MTU**
1.569 w/o	**1.569 w/o**

The depleted fuel assemblies shall meet the requirements of Figure 4-13.

Figure 4-3
Allowable Fuel Assemblies in the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

1.279 w/o	**3.85 w/o Fresh with IFBA**
1.279 w/o	**1.279 w/o**

The depleted fuel assemblies shall meet the requirements of Figure 4-14.

The fresh fuel assemblies shall meet the requirements of Figure 4-15.

Figure 4-4
Allowable Fuel Assembly Categories in the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

1-out-of-4 5 w/o at 15,000 MWD/MTU

A	A	A	A	A	A	A
A	A	A	A	A	A	A
A	A	A	A	A	A	A
L1	L1	L1	L1	A	A	A
H1	L1	H1	L1	A	A	A
L1	L1	L1	L1	A	A	A
H1	L1	H1	L1	A	A	A

All-Cell

A : Fuel Assembly with 1.856 w/o initial enrichment in the "All-Cell" Configuration

L1 : Fuel Assembly with 1.569 w/o initial enrichment in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

H1 : Fuel Assembly with 5.0 w/o initial enrichment at 15,000 MWD/MTU in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

Figure 4-5
Allowable Interface between "All-Cell" and "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configurations

A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A
L2	L2	L2	L2	L2	L2	A	A	A
L2	H2	L2	L2	H2	L2	A	A	A
L2	L2	L2	L2	L2	L2	A	A	A
L2	L2	L2	L2	L2	L2	A	A	A
L2	H2	L2	L2	H2	L2	A	A	A
L2	L2	L2	L2	L2	L2	A	A	A

3x3

All-Cell

A : Fuel Assembly with 1.856 w/o initial enrichment in the "All-Cell" Configuration

L2 : Fuel Assembly with 1.194 w/o initial enrichment in the "3x3" Configuration

H2 : Fuel Assembly with 5.0 w/o fresh enrichment in the "3x3" Configuration

Figure 4-6
Allowable Interface between "All-Cell" and "3x3" Storage Configurations

1-out-of-4 3.85 w/o Fresh with IFBA

A	A	A	A	A	A	A
A	A	A	A	A	A	A
A	A	A	A	A	A	A
L3	L3	L3	L3	A	A	A
H3	L3	H3	L3	A	A	A
L3	L3	L3	L3	A	A	A
H3	L3	H3	L3	A	A	A

All-Cell

A : Fuel Assembly with 1.856 w/o initial enrichment in the "All-Cell" Configuration

L3 : Fuel Assembly with 1.279 w/o initial enrichment in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

H3 : Fuel Assembly with 3.85 w/o Fresh in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

Figure 4-7
Allowable Interface between "All-Cell" and "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configurations

1-out-of-4 3.85 w/o Fresh with IFBA

L1	L1	L1	L1	L1	L1	L1
L1	H1	L1	H1	L1	H1	L1
L1	L1	L1	L1	L1	L1	L1
L3	L3	L3	L3	L1	H1	L1
H3	L3	H3	L3	L1	L1	L1
L3	L3	L3	L3	L1	H1	L1
H3	L3	H3	L3	L1	L1	L1

1-out-of-4 5 w/o at 15,000 MWD/MTU

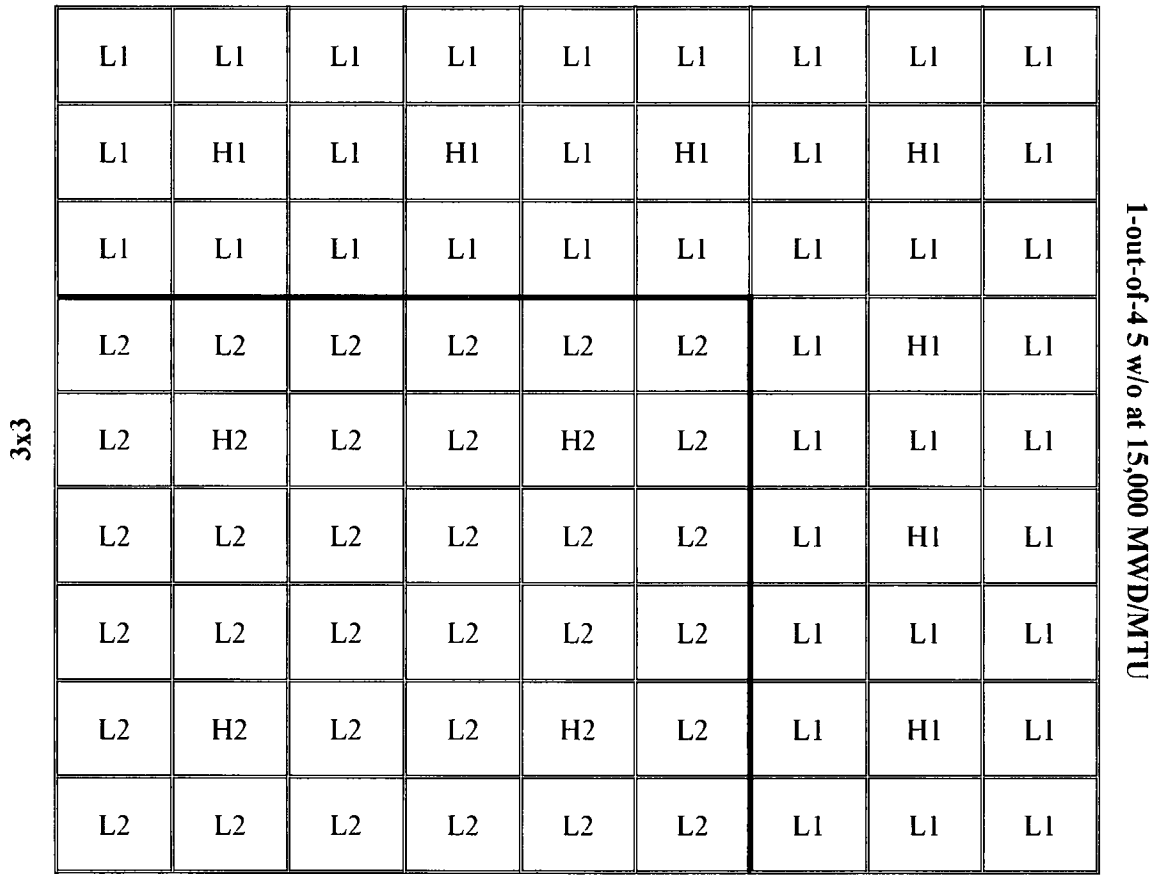
L1 : Fuel Assembly with 1.569 w/o initial enrichment in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

H1 : Fuel Assembly with 5.0 w/o initial enrichment at 15,000 MWD/MTU in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

L3 : Fuel Assembly with 1.279 w/o initial enrichment in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

H3 : Fuel Assembly with 3.85 w/o Fresh in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

Figure 4-8
Allowable Interface between "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" and "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configurations



L1 : Fuel Assembly with 1.569 w/o initial enrichment in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

H1 : Fuel Assembly with 5.0 w/o initial enrichment at 15,000 MWD/MTU in the "1-out-of 4 5.0 w/o at 15,000 MWD/MTU" Configuration

L2 : Fuel Assembly with 1.194 w/o initial enrichment in the "3x3" Configuration

H2 : Fuel Assembly with 5.0 w/o fresh enrichment in the "3x3" Configuration

Figure 4-9
Allowable Interface between "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" and "3x3" Storage Configurations

3x3

L3	L3	L3	L3	L3	L3	L3	L3	L3
L3	H3	L3	H3	L3	H3	L3	H3	L3
L3	L3	L3	L3	L3	L3	L3	L3	L3
L2	L2	L2	L2	L2	L2	L3	H3	L3
L2	H2	L2	L2	H2	L2	L3	L3	L3
L2	L2	L2	L2	L2	L2	L3	H3	L3
L2	L2	L2	L2	L2	L2	L3	L3	L3
L2	H2	L2	L2	H2	L2	L3	H3	L3
L2	L2	L2	L2	L2	L2	L3	L3	L3

1-out-of-4 3.85 w/o Fresh with IFBA

L2 : Fuel Assembly with 1.194 w/o initial enrichment in the "3x3" Configuration

H2 : Fuel Assembly with 5.0 w/o fresh enrichment in the "3x3" Configuration

L3 : Fuel Assembly with 1.279 w/o initial enrichment in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

H3 : Fuel Assembly with 3.85 w/o Fresh in the "1-out-of 4 3.85 w/o Fresh with IFBA" Configuration

Figure 4-10
Allowable Interface between "1-out-of-4 3.85 w/o Fresh with IFBA" and "3x3" Storage Configurations

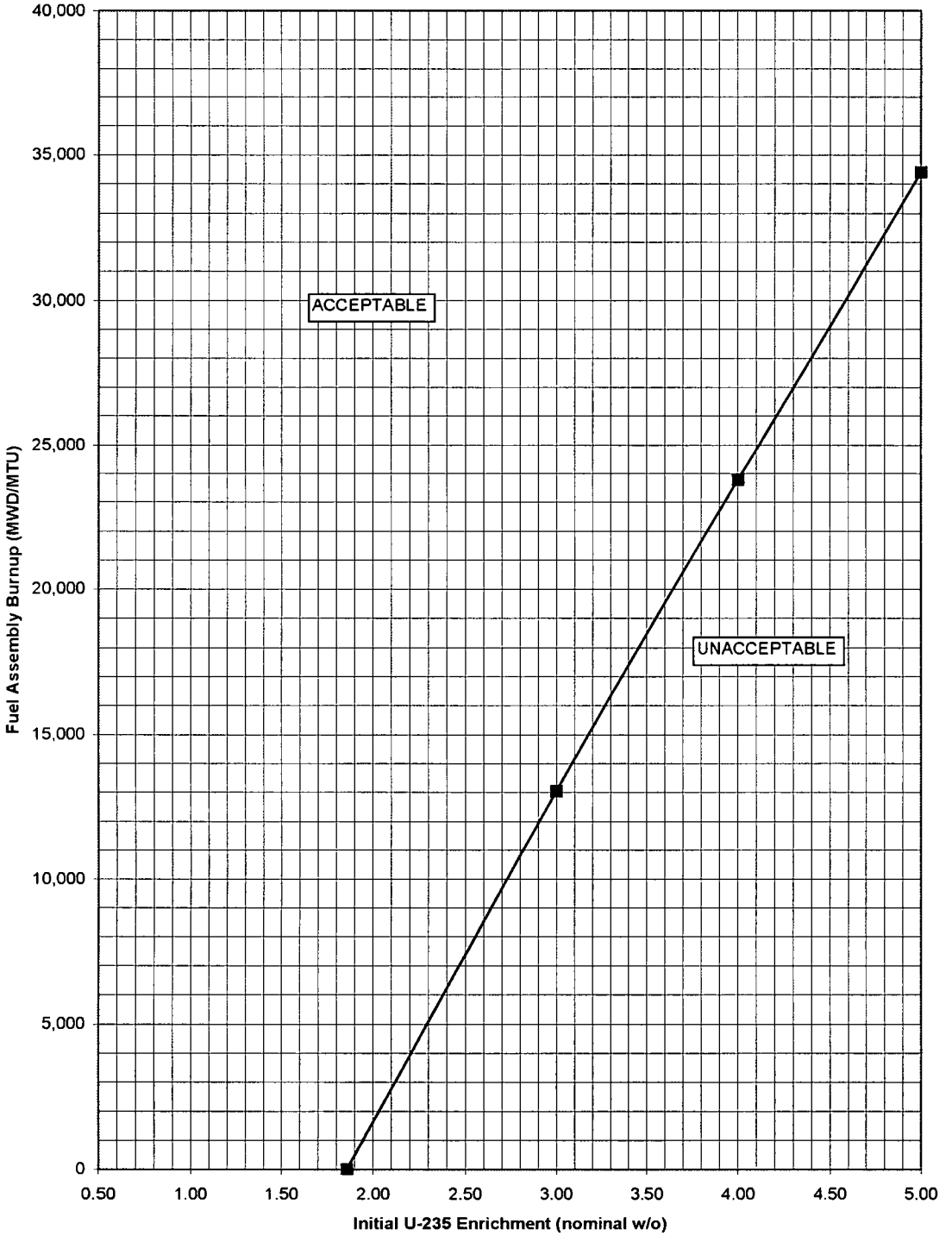


Figure 4-11
Fuel Assembly Burnup versus Initial Enrichment for the "All Cell" Storage Configuration

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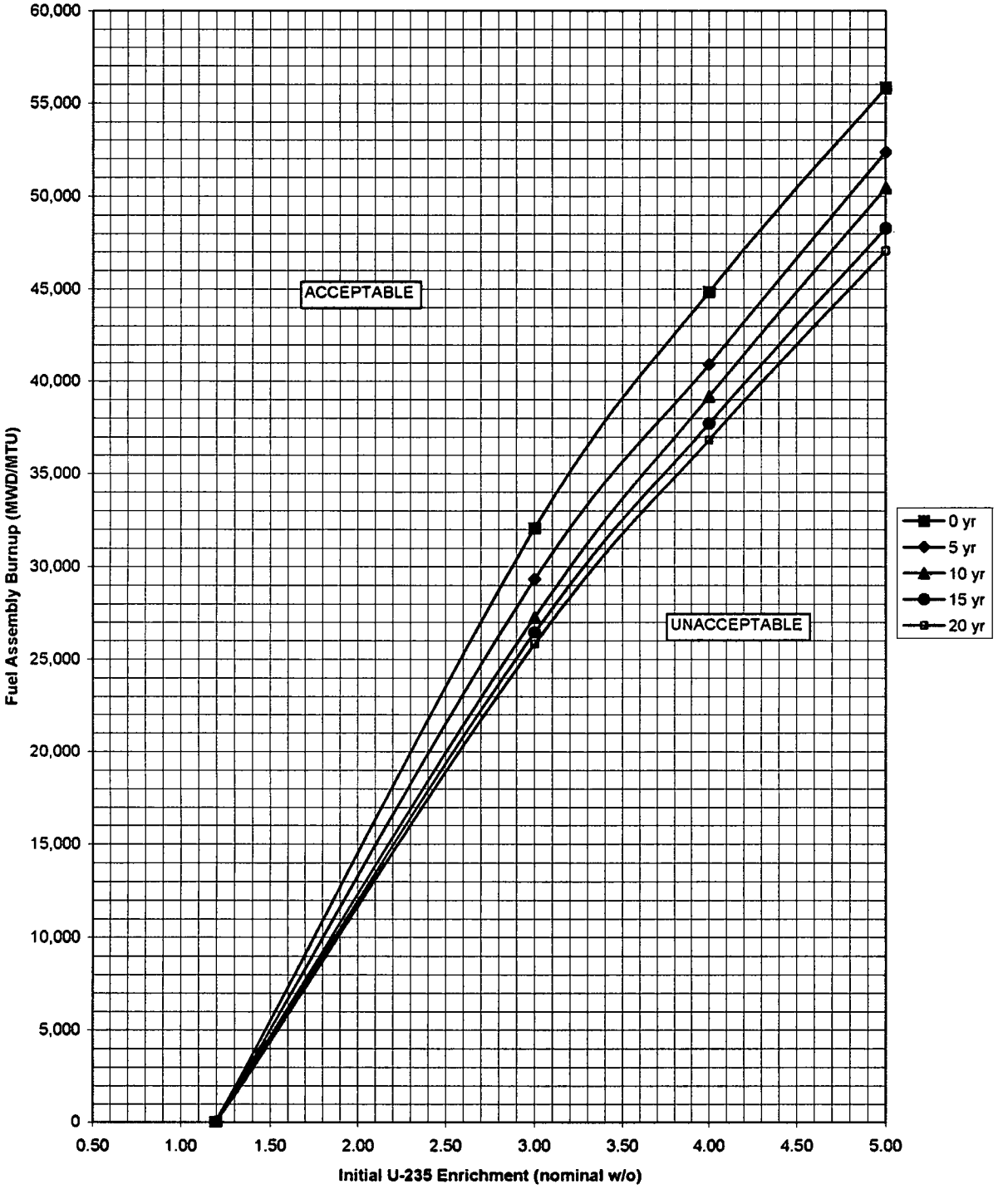

Figure 4-12
Fuel Assembly Burnup versus Initial Enrichment for the "3x3" Storage Configuration

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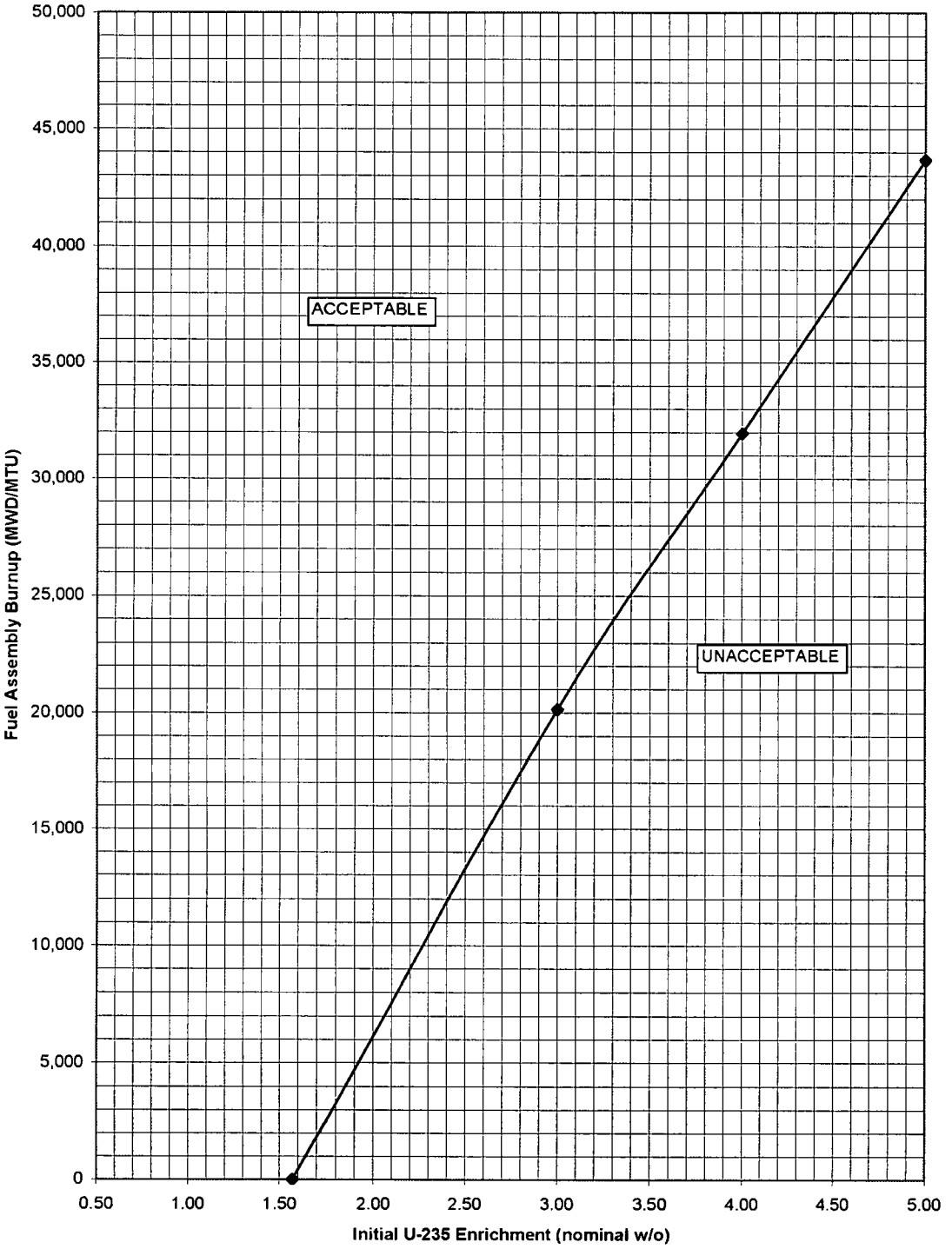

Figure 4-13
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 5.0 w/o at 15,000 MWD/MTU" Storage Configuration

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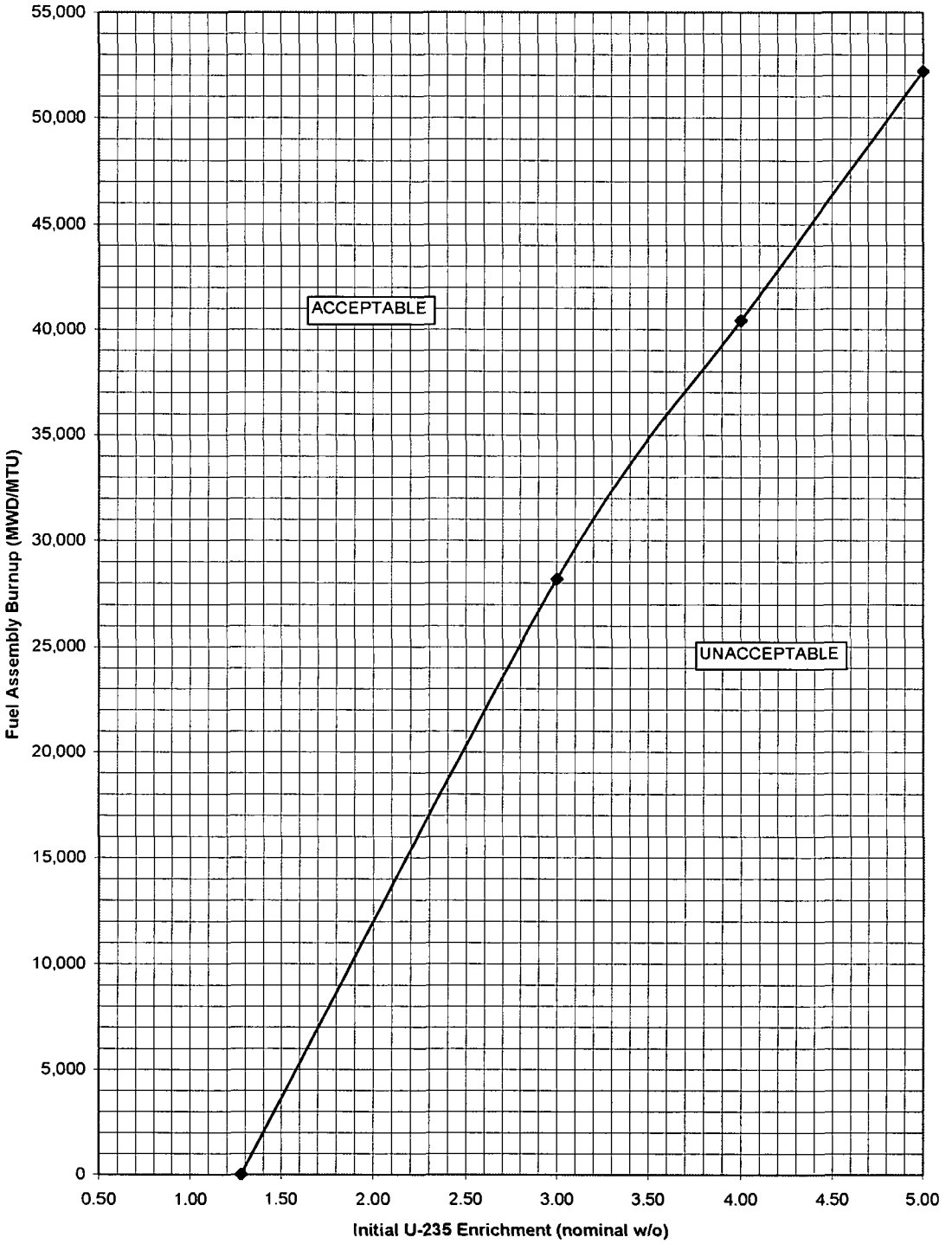

Figure 4-14
Fuel Assembly Burnup versus Initial Enrichment for the "1-out-of-4 3.85 w/o Fresh with IFBA" Storage Configuration

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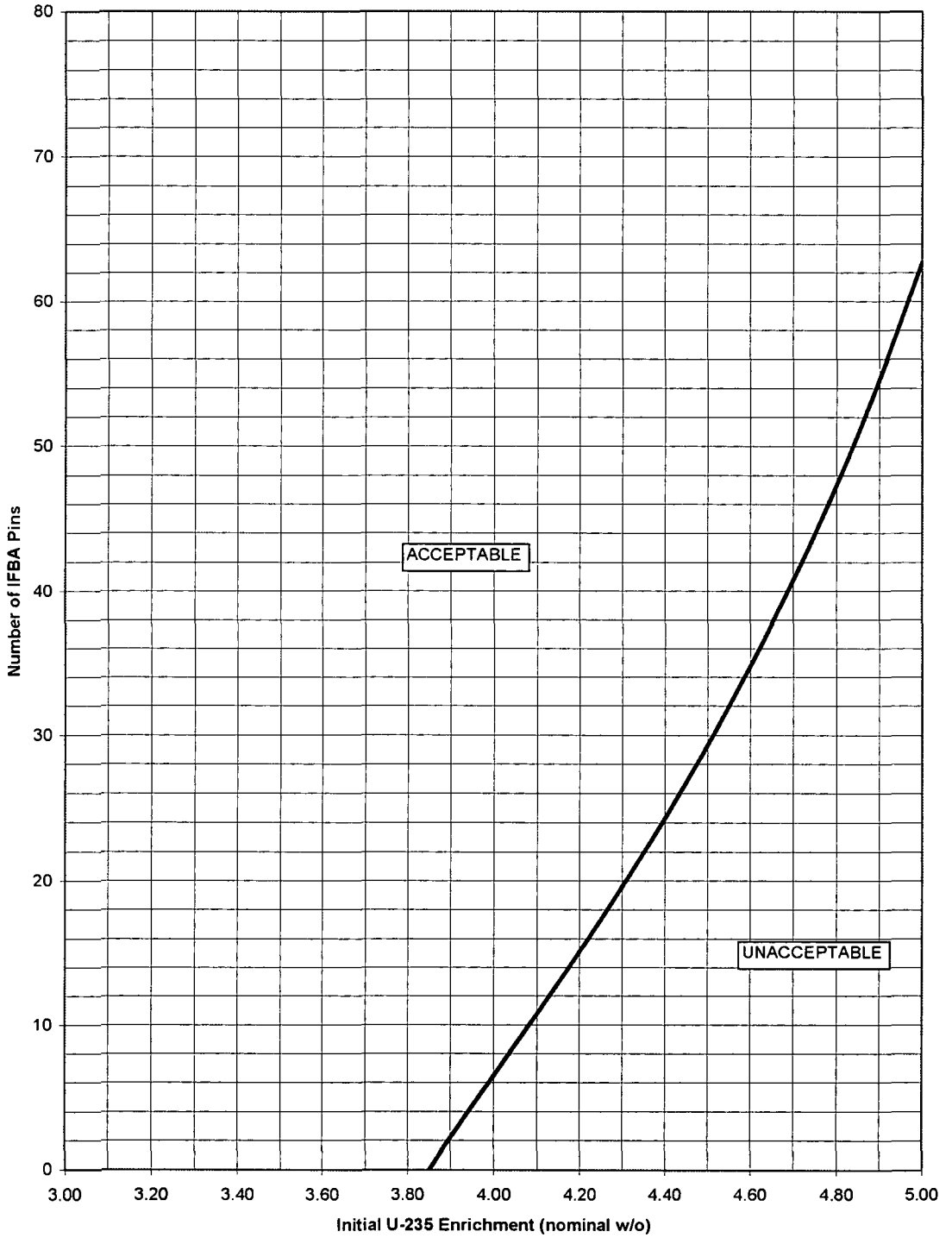

Figure 4-15
IFBA Requirements for the Fresh Fuel Assembly with Enrichments Greater than 3.85 w/o ^{235}U in the "1-out-of-4 3.85 w/o with IFBA" Storage Configuration

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5.0 Computer Codes Used In Calculation

Table 5-1
Summary of Computer Codes Used in Beaver Valley Unit 2 Spent Fuel Pool Criticality Calculations

Code No.	Code Name	Code Version	Verified and Configured (Yes/No) or Configuration Control Reference	Basis (or reference) that supports use of code in current calculation	Outstanding Issues (Yes/No). If Yes, how acceptable?
1	SCALE-PC	4.4a	See Footnote[1]	See Footnote[1]	See Note

Note: There is a recent notification of an error in SCALE associated with the HOLE function. The error is documented in the SCALE notebook, titled "Error in KENO V.a for cylindrical holes with shared boundaries," and dated March 22nd, 2005. In the standard spent fuel pool analysis, none of the input files involve cylindrical holes with shared boundaries; therefore, the analysis is not affected from this code error.

[1] Validation and benchmarking of the SCALE-PC Code package version 4.4a installation was performed as described in subsection 1.4.2. Verification of SCALE-PC Version 4.4a was achieved by running the sample test problems provided in the software package. The output and the listing of differences between the PC installation's results and the reference outputs were previously documented internally. Only differences in the outputs are due to time/date information and the header lines.

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6.0 References

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2. Letter, T. E. Collins (NRC) to T. Greene (WOG), "Acceptance for Referencing of Licensing Topical Report WCAP-14416-P, Westinghouse Spent Fuel Rack Methodology (TAC No. M93254)," October 25, 1996.

3. Not Used.

4. Code of Federal Regulations, Title 10, Part 50, Appendix A, Criterion 62, "Prevention of Criticality in Fuel Storage and Handling."

5. L. Kopp (NRC), "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," February 1998.

6. "Duquesne Light Company, Beaver Valley Power Station Unit 2, Revision 1 to Soluble Boron Credit Analysis," 98DL-G-0043, November 12, 1998.

7. "SCALE 4.4a- Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers," RSICC CODE PACKAGE CCC-545, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2000.

8. "DIT: Discrete Integral Transport Assembly Design Code," CE-CES-11, Revision 4-P, April 1994.

9. Not Used.

10. M. N. Baldwin, et al., "Critical Experiments Supporting Close Proximity Water Storage of Power Reactor Fuel; Summary Report," BAW-1484-7, July 1979.

11. S. R. Bierman and E.D. Clayton, "Critical Experiments with Subcritical Clusters of 2.35 Wt% ^{235}U Enriched UO2 Rods in Water at a Water-to-Fuel Volume Ratio of 1.6," NUREG/CR-1547, PNL-3314, July 1980.

12. S.R. Bierman and E.D. Clayton, "Criticality Experiments with Subcritical Clusters of 2.35 and 4.31 Wt% U-Enriched UO_2 Rods in Water with Steel Reflecting Walls," Nuclear Technology, Vol. 54, pg. 131, August 1981.

13. International Handbook of Evaluated Criticality Safety Benchmark Experiments, Nuclear Energy Agency and Organization for Economic Cooperation and Development.

14. Not Used.

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16. D. B. Owen, "Factors for One-Sided Tolerance Limits and for Variables Sampling Plans," SCR-607, Sandia Corporation Monograph, March 1963.

17. Drawing 80E7670, "Pool Fuel Storage Rack Arrangement," September, 1983.

18. W. D. Newmyer and N.L. Domenico "Fuel Rod Storage Canister Criticality Analysis," October 1994.

19. Not Used.

20. "Recommendations for Addressing Axial Burnup in PWR Burnup Credit Analyses," NUREG/CR-6801, March 2003.