ENTERGY

SUMMARY OF THE ANO-2 CRITICALITY SAFETY ANALYSES FOR FUEL ENRICHMENTS UP TO 5.0 WT. % U-235

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1. SUMMARY

The Arkansas Nuclear One Unit 2 (ANO–2) spent fuel racks were originally designed by Westinghouse for the storage of fuel containing up to 4.1 wt. percent U^{235}. Currently, unrestricted storage is allowed in Region 1 of the storage racks since a fixed poison (Boraflex) is included in the rack structure. Two storage configurations are allowed in Region 2 which utilize checkerboarding and burnup credit. Two additional storage areas, the new fuel storage rack and the containment temporary storage rack, also exist at ANO–2.

This report describes calculations used to determine acceptable fuel storage configurations to allow for enrichments up to 5.0 wt. percent at ANO–2. Uncertainties and biases due to method and manufacturing tolerances are addressed in determining the 95/95 upper limit k_{eff} for each rack. The results for all configurations are consistent with the requirements outlined in NUREG–0800 [Reference 14].

In the Region 1 calculations, conservative assumptions are made in considering the increase in reactivity due to Boraflex gapping or shrinkage. Additionally, the analysis contains significant conservatisms to compensate for potential long term surface degradation effects. All Boraflex panels are modeled with shrinkage or gapping losses. The shrinkage/gapping is determined based on EPRI reported blackness test data for Westinghouse racks [Reference 12]. To allow storage of 5.0 wt. percent assemblies in the Region 1 racks, cross–hatching (three of four cells contain assemblies) and burnup credit are utilized. All configurations assume no credit for soluble boron and yield 95/95 k_{eff} values less than 0.95.

In the Region 2 calculations, checkerboarding is used to allow storage of undepleted 5.0 wt. percent fuel assemblies. Two configurations assume burnup credit to allow storage of assemblies with enrichments up to 5.0 wt. %. One configuration allows storage in all cells while the other requires cross–hatching with three of four cells containing assemblies (the fourth cell is a water hole). No soluble boron credit is assumed in the analysis of the Region 2 storage configurations.

In the new storage fuel rack calculations, both possible and optimum moderation conditions were analyzed. The 95/95 k_{eff} values were determined to be less than 0.95 when moderated with water at a density of 1.00 gm/cc and less than 0.98 at optimum moderation conditions (0.065 gm/cc). Calculations were also performed to verify 5.0 wt. percent assemblies can be loaded into the fuel transfer upender and stored in the containment temporary storage rack.

With increasing cycle lengths, higher enrichments are needed to meet cycle energy demands. This criticality analysis demonstrates that fuel assemblies with enrichments up to 5.0 wt. percent U^{235} can be safely stored in the ANO–2 fuel storage racks. Both nominal and accident conditions are analyzed. The results of these analyses are summarized in Table 1–1.

Table 1–1. Final reactivities for ANO-2 fuel storage areas

Storage area description	Acceptance criterion	Determined 95/95 k_{eff}
Spent fuel pool Region 1		
Configuration A (cross–hatch)	0.95	0.938
Configuration B (undepleted)	0.95	0.937
Configuration B (burnup credit)	0.95	0.942
Spent fuel pool Region 2		
Configuration A (checkerboard)	0.95	0.926
Configuration B (burnup credit/cross–hatch)	0.95	0.944
Configuration C (burnup credit)	0.95	0.9498
New fuel storage rack		
Possible moderation (1.00 gm/cc)	0.95	0.916
Optimum moderation (0.065 gm/cc)	0.98	0.976
Upender	0.95	0.94997
Containment temporary storage rack	0.95	0.92

2. METHODOLOGY

Computer codes

All rack criticality calculations are performed with the widely accepted SCALE–4 code package [Reference 1]. The SCALE–4 system includes the CSAS25 Control Sequence of the ORNL Criticality Safety Analysis Sequence No. 4 (CSAS4). The functional modules sequentially executed by the CSAS25 control module are the BONAMI-S code, the NITAWL-S code, and the KENO V.a code. The benchmarking of SCALE–4 is discussed in Appendix A. Unless otherwise noted, the calculated eigenvalue for each case is based on 500,000 neutron histories.

The CASMO–3 two–dimensional integral transport code was used to evaluate the rack and fuel design tolerances and perform reactivity equivalencing calculations [Reference 8]. This code is widely accepted by the industry for these applications.

SIMULATE–3 is an advanced 3D nodal simulator which uses the nodal expansion solution method [Reference 9]. It has been previously qualified for application to Entergy Operations, Inc. PWR cores [Reference 13]. Its use in this study is limited to providing data for the evaluation of burnup distribution and spectral history effects.

Fuel assembly description

The base fuel assembly is a Combustion Engineering 16 by 16 assembly as shown in Figure 2–1. In the rack calculations, nominal values are used for all fuel dimensions and design tolerances are treated as uncertainties. The fuel parameters are listed in Table 2–1. Axial dimensions were determined using the debris resistant ABB–CE Guardian Grid lower grid design. Consistent with the analysis in Reference 18, the neutron absorption by U^{234} is credited.

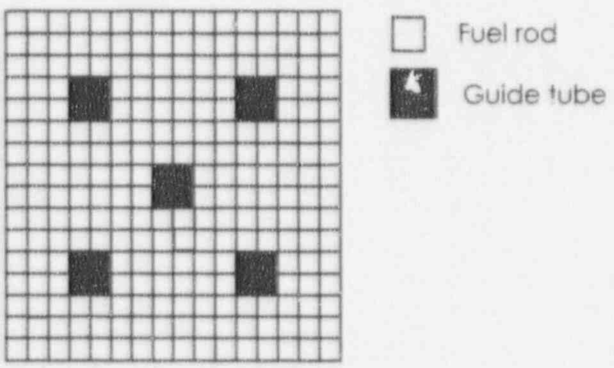


Figure 2–1. Combustion Engineering 16 by 16 fuel assembly

Table 2–1. ANO-2 base fuel assembly parameters

Description	Parameter
Fuel enrichment (wt. % U^{235})	up to 5.0
Number of fuel rods (per assembly)	236
Fuel rod Zirc-4 clad OD (inch)	0.382
Clad thickness (inch)	0.025
Fuel pellet OD (inch)	0.325
Stack density (gm/cc)	10.25
Maximum U–235 loading per unit length (gm/inch)	0.614108
Rod pitch (inch)	0.506
Number of Zirc-4 guide tubes (per assembly)	5
Guide tube OD (inch)	0.98
Guide tube thickness (inch)	0.04
Active fuel height (inch)	150.0

Fuel assembly uncertainties

Uncertainties or tolerance factors for the fuel and rack design parameters are evaluated by performing sensitivity studies to determine the reactivity impact of each factor. The rack design tolerances are discussed in the rack specific portions of this report. The following fuel tolerance factors were analyzed:

1. **Fuel enrichment:** In cases considering fuel with enrichments less than 5.0 wt. % or depleted fuel, an increased loading of +0.05 wt. % U^{235} is assumed. No uncertainty is assumed for 5.0 wt. % cases since this is the maximum allowed enrichment.
2. **Fuel pellet density:** The maximum value is assumed in the base calculations; therefore, no tolerance analysis is necessary.
3. **Form factor:** The maximum form factor increases the fuel loading.
4. **Fuel pellet diameter:** A larger fuel pellet diameter increases the fuel loading.
5. **Fuel clad inner diameter:** A larger fuel clad inner diameter decreases the absorption in the fuel cladding.
6. **Fuel clad outer diameter:** A small fuel clad outer diameter reduces parasitic absorption and increases moderation.
7. **Guide tube thickness:** A smaller guide tube thickness reduces the parasitic absorption and increases moderation.

Burnup credit using reactivity equivalencing

For burnup credit, reactivity calculations are performed to generate initial enrichment–fuel assembly burnup combinations which yield equivalent reactivity when stored in the fuel storage racks. Depletion calculations are performed for various initial fuel assembly enrichments using CASMO. The fuel assembly is depleted using hot full power operating conditions. A conservative boron history is assumed to enhance the buildup of plutonium and make the assembly more reactive when stored in the spent fuel storage racks. An additional spectral history adjustment factor is also included to account for higher boron levels which may occur if Entergy elects to implement 24 month fuel cycles. The most reactive time after shutdown of the reactor is conservatively approximated by removing Xe^{135} and I^{135}.

Following depletion in core geometry, the assembly is reanalyzed in rack geometry, using CASMO, to determine reactivity as a function of burnup. An initial enrichment to burnup curve is then established based on a constant reactivity criteria. Multiple pairs are used to establish a burnup curve which bounds the possible initial enrichment range (up to 5.00 wt. percent) of the spent fuel storage rack. This burnup–initial enrichment curve is converted to a burnup–initial U^{235} loading curve. When this conversion is performed, reactivity effects due to variations in fuel density and geometry are considered. Potential changes in reactivity due to increases in nominal pellet volume and density while conserving the same U^{235} loading were evaluated. The most limiting combination of parameters over the expected range was used to determine the burnup requirement. Each burnup–U^{235} loading combination was confirmed to be equivalent to or less reactive than the base configuration.

The effects of the axial burnup distribution on an assembly's reactivity is considered for each rack geometry. Axial burnup distributions determined from core follow calculations based on SIMULATE–3 [Reference 9] are modeled in the rack geometry. Assemblies are sorted based on average burnup and a typical exposure distribution is determined based on assemblies with similar average burnup. The burnup of the upper and lower axial regions are then reduced by 10% to produce a more severe distribution. The effects of the axial distribution is rack specific and is discussed in the appropriate sections. If the axially dependent exposure distribution is determined to be more reactive than the uniform distribution, a limiting axial burnup distribution adjustment is established based on the reactivity difference between the uniform and axially distributed cases. This adjustment is included when determining 95/95 k_{eff} values.

Two factors are included to account for the uncertainties associated with burnup credit: the depletion history uncertainty and the isotopic calculational uncertainty. The depletion history uncertainty accounts for nodal variations in depletion history such as different moderator densities and inter–assembly burnup tilts. The established uncertainty was confirmed to bound any axially dependent bias. The calculational isotopic uncertainty was determined from previously approved physics methods [Reference 13].

Uncertainties in fuel and rack materials and geometries

Fuel assembly and rack geometry mechanical tolerances are evaluated using CASMO. The difference between the base case k_{inf} and the tolerance case k_{inf} is the reactivity effect of a tolerance. Negative values are set equal to zero. The Δk values are statistically combined by taking the square root of the sum of the squares of each contributing uncertainty [Reference 8].

Treatment of bias and uncertainty

The KENO calculated eigenvalue for each analyzed storage rack configuration is combined with the appropriate tolerance and method uncertainties using the following equation [Reference 6]. This 95/95 treatment is the same as that used in previously approved analyses by Entergy [Reference 18]. The method bias and method uncertainty are discussed in Appendix A. The 95/95 tolerance factors for each case are determined from Reference 7.

When considering racks containing Boraflex poison, various Boraflex configuration assumptions are evaluated. For each set of Boraflex assumptions, several cases, each containing randomly generated panel gap and/or end shrinkage configurations are analyzed. The KENO k_{eff}'s of each randomly generated case are combined to obtain an average k_{eff} value. The uncertainty due to

variations between Boraflex cases is combined with t[illegible]ertainty (σ_{total}) and used to determine the degrees–of–freedom and the 95/95 tole[illegible] (κ) to yield the 95/95 k_{eff} value.

Equation for determining 95/95 probability/confidence reactivities

$$\text{CASE } k_{eff(95/95)} = k_{keno} + \Delta k_{method} + \Delta k_{tolerances} + \kappa \times \sigma_{total} + \Delta k_{adj-spect} + \Delta k_{adj-axial}$$

where

k_{keno} = KENO k_{eff} (case dependent)

$\Delta k_{method} = 0.007600$

$\Delta k_{tolerances}$ = Overall tolerance uncertainty

$$\sigma_{total} = \sqrt{\sigma^2_{keno} + \sigma^2_{Boraflex} + \sigma^2_{method}} = \sqrt{\sigma^2_{keno} + \sigma^2_{Boraflex} + 0.001464^2}$$

$$f = \frac{\sigma^4_{total}}{\dfrac{\sigma^4_{keno}}{((500-1)+2)} + \dfrac{\sigma^4_{Boraflex}}{((X-1)+2)} + \dfrac{\sigma^4_{method}}{((21-1)+2)}} - 2$$

Note: 500 generations, X Boraflex cases, and 21 critical experiments were analyzed.

κ = 95/95 tolerance factor for f degrees-of-freedom

$\Delta k_{adj-spect}$ = Spectral history adjustment

$\Delta k_{adj-axial}$ = Axial burnup distribution adjustment

3. SPENT FUEL POOL STORAGE RACK: REGION 1

It was shown in a previous analysis that assemblies with enrichments up to 4.1 wt. % U^{235} may be safely stored in the Region 1 spent fuel pool storage racks [Reference 10]. This work shows that assemblies with enrichments up to 5.0 wt. % U^{235} may be safely stored in these racks. Conservative assumptions are made to consider the reactivity effects of Boraflex panel gapping and shrinkage. A significant margin to the acceptance criteria and other conservatisms are reserved for the potential long term effects of surface degradation. The requirements of NUREG–0800 [Reference 14] and ANSI/ANS–57.2–1983 [Reference 15] are met by this analysis.

3.1 Modeling

Base models

The ANO–2 spent fuel racks were designed by Westinghouse Electric Corporation. The Region 1 rack is an array of cells with stainless steel walls. Stainless steel wrapper plates retain Boraflex sheets on each side of the storage cells. This configuration is illustrated in Figure 3–1. Three–dimensional KENO calculations were performed using a four by four array of rack cells which includes a total of 64 Boraflex panels. The end shrinkage for each Boraflex panel is randomly determined for the upper and lower edges from the distribution shown in Figure 3–2. The maximum allowed total shrinkage in a single panel is 4.1% of the panel length, the maximum value determined from EPRI testing [Reference 12].

Boraflex configuration

The ANO–2 spent fuel pool Region 1 racks contain Boraflex panels held in place by a stainless steel wrapper plate. The edges of the wrapper plates are welded to the stainless rack cell. This configuration allows minimal water flow around the Boraflex panels unlike other rack designs which allow a large volume of water to interact with the panels.

In this work, EPRI reported blackness test results of Westinghouse racks were used to determine the impact of Boraflex panel shrinkage. The testing was performed on panels which have been exposed to gamma radiation in excess of 1×10^{10} rad, the dose level where shrinkage reaches a saturation condition of 4.1% of its pre–irradiation length [Reference 12].

Of the five tested plants, no gaps were detected in the Boraflex panels at two of the plants. At these plants, the shrinkage reduced the length of the Boraflex at the ends of the panels. To determine the most conservative assumption for the ANO–2 rack design, calculations were performed assuming 1) all panels have gaps, 2) all panels have end shrinkage, and 3) 65% of panels have gaps and 45% have end shrinkage.

The gap distribution or end shrinkage in each panel was determined based on random sampling of gap/shrinkage probability distributions. The location and size of the gaps and/or end shrinkage

were determined using probability distributions from Reference 12. The most limiting configuration for the ANO–2 rack design was determined to be the case where all panels have end shrinkage. The most limiting end shrinkage distribution from Reference 12 was used and is shown in Figure 3–2.

Additional dimensions and characteristics of the Boraflex panels are shown in Table 3–1. The minimum design B^{10} loading and physical dimensions are assumed. Also, the maximum predicted shrinkage of Boraflex (4.1%) is assumed in the panel width to conservatively account for radiation induced shrinkage. The corresponding increase in density is conservatively not included.

Tolerance analysis

The fuel tolerance factors are described in Section 2. The additional storage rack tolerance factors (8–13) are discussed below.

8. **Fuel storage area:** A larger area increases the neutron moderation around the fuel assembly.
9. **Rack wall thickness on the Boraflex side:** A thinner wall reduces the absorption in structural material.
10. **Rack wall thickness on the fuel assembly side:** A thinner wall reduces the absorption in structural material.
11. **Stainless steel wrapper plate thickness:** A thinner wrapper plate reduces the absorption in structural material.
12. **Minimum separation distance between cell wrapper plates:** A reduction in the distance between the cell wrapper plates decreases moderation between rack cells.
13. **Lateral assembly position:** Off–center positioning of the fuel assembly in the storage cell increases the interaction between assemblies.

The tolerance factor results are shown in Table 3–2. The tolerances were combined using the methodology described in Section 2. Tolerance factors were determined for each storage configuration which are described in detail below.

3.2 Storage configurations

Two different fuel storage configurations were evaluated using the previously described approach.

Configuration A

Configuration A utilizes cross–hatching to allow storage of assemblies with enrichments up to 5.00 wt. percent as shown in Figure 3–3. Each fuel assembly must be adjacent to two water holes or located diagonally from four water holes as shown. No credit is assumed to burnable poisons or soluble boron. The 95/95 k_{eff} value for this configuration is 0.938 as shown in Table 3–3.

Configuration B

Credit for assembly burnup is taken to allow storage of assemblies with enrichments up to 5.0 wt. % in an arrangement with fuel assemblies located in all rack cells as shown in Figure 3–3. The 95/95 k_{eff} values are shown in Table 3–3 and the exposure–initial U^{235} loading per unit length curve generated using reactivity equivalencing is shown in Figure 3–4. Variations in the assembly reactivity due to changes in fuel density and geometry were considered. If an assembly's fuel loading is less than the analyzed loading, the loading used to determine the assembly's burnup requirement is conservatively considered to be the analyzed loading.

The effects of the axial burnup distribution on assembly reactivity are considered in the determination of the curve. The axial exposure distribution corresponding to the 0.614108 gm U^{235} per inch (5.00 wt. %) statepoint was converted to an equivalent reactivity assembly by determining the equivalent initial enrichment for each axial segment. This assembly was then analyzed in 10 KENO cases containing randomly generated Boraflex configurations as previously discussed. An assembly with the same average burnup, which was uniformly distributed, was also evaluated using this same process. The distributed burnup case was determined to be limiting. The differences between these cases were used to establish an axial burnup distribution adjustment which was applied to lower burnup configurations. This approach is conservative because exposure shapes are more uniformly distributed at lower burnups. Other enrichment–burnup combinations were evaluated using uniformly distributed burnup assumptions with reactivity equivalent to the 5.0 wt. % statepoint. These evaluations were performed with the adjustment included to account for the axial burnup shape bias.

Interface effects between configurations

Cases were evaluated to consider interface effects between various orientations of Configurations A and B. In each case the assembly storage constraints of each configuration were met. For example, the Configuration A 5.00 wt. % assembly was always adjacent to two water holes or diagonal to four water holes. The 95/95 k_{eff} values for these cases were less than or equal to the values determined for the limiting configuration shown in Table 3–3.

Region 1 – Region 2 interface

Region 1–Region 2 racks are not separated from each other by additional water spacing. The Region 1 cells at the interface contain a Boraflex panel on the cell wall adjacent to the Region 2 cells. Calculations were performed to determine if any limitations exist for the Region 1 storage cells at the Region 2 interface since one Boraflex panel is present between the Region 1 and Region 2 assemblies.

These calculations determined that 5.00 wt. % assemblies should be restricted from storage in the first row of Region 1 cells at the Region 1–Region 2 rack interface. Configuration B assemblies may be placed in the first row. Therefore, no restrictions are placed on the storage of Region 1 assemblies which meet the exposure–initial U^{235} loading requirements of Configuration B.

3.3 Fuel handling accidents

For accident conditions, the double contingency principle applies which states it shall require two unlikely, independent, concurrent events to produce a criticality accident. Therefore, for accidents, the presence of soluble boron in the storage pool water can be assumed as a realistic initial condition. The accidents which must be considered are listed below:

- **Fuel assembly dropped on top of the rack**: The rack structure is such that an assembly positioned horizontally on top of the rack is approximately 30 inches away from the upper end of the active fuel region of the stored assemblies. This distance precludes interaction between the dropped assembly and the stored fuel.
- **Fuel assembly dropped between rack modules or next to the pool wall**: This accident cannot occur since the distance between all the rack modules and to the pool walls is less than the width of a fuel assembly.
- **Misplaced fuel assembly**: The misplacement of a fuel assembly in a rack configuration was considered. This accident is considered by placing a 5.0 wt. percent assembly from Configuration A in a Configuration B position. The soluble boron concentration was assumed to be 1000 ppm. The 95/95 k_{eff} value is 0.80 which is well below 0.95.

3.4 Analysis conservatisms

The following conservatisms are included in the analysis of the Region 1 spent fuel storage racks:

1. Minimum as–designed Boraflex dimensions and the minimum areal B^{10} loading are used. Additionally, maximum poison shrinkage of 4.1% is assumed in the panel width. The boron loading is not increased to account for the densification which occurs as a result of the shrinkage. The end shrinkage assumptions are more conservative than gap formation assumptions for the ANO–2 rack geometry.
2. The statistical uncertainty associated with the evaluation of a limited number of Boraflex configurations (10 KENO cases) is considered in the determination of the total uncertainty.
3. No neutron leakage in the x–y directions is assumed.
4. Water is set to the maximum density of 1.00 gm/cc.
5. The assembly is modeled at its most reactive condition after shutdown when assuming burnup credit.
6. U^{235} loading–burnup combinations for assemblies less than 5.0 wt. % for Configuration B conservatively assume the axial burnup distribution adjustment of the 5.0 wt. % case. The axial exposure shapes are more uniform for assemblies with burnups less than that required for a 5.0 wt. % assembly.
7. No credit is assumed for burnable poison in the fuel assemblies.
8. Much stainless steel structure is not modeled.
9. Credit for soluble boron is assumed only for accident cases consistent with the double contingency principle.

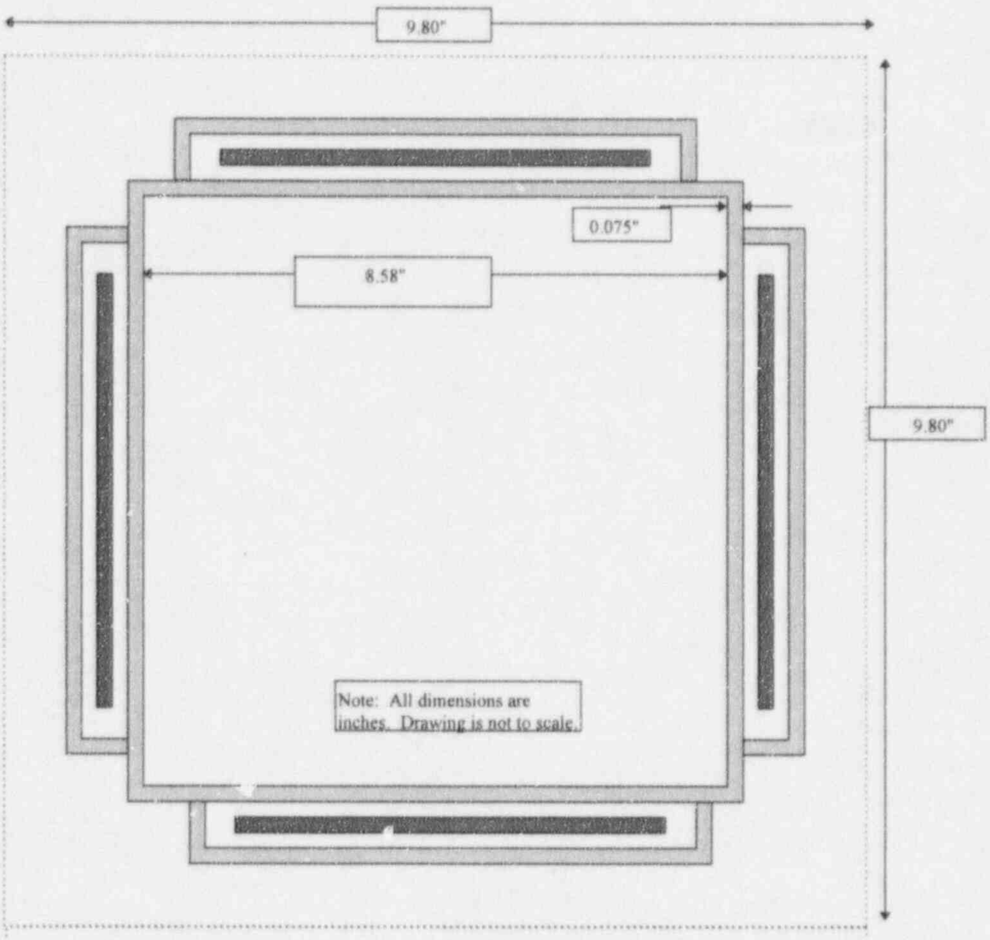


Figure 3–1. Radial view of the Region 1 spent fuel pool storage rack

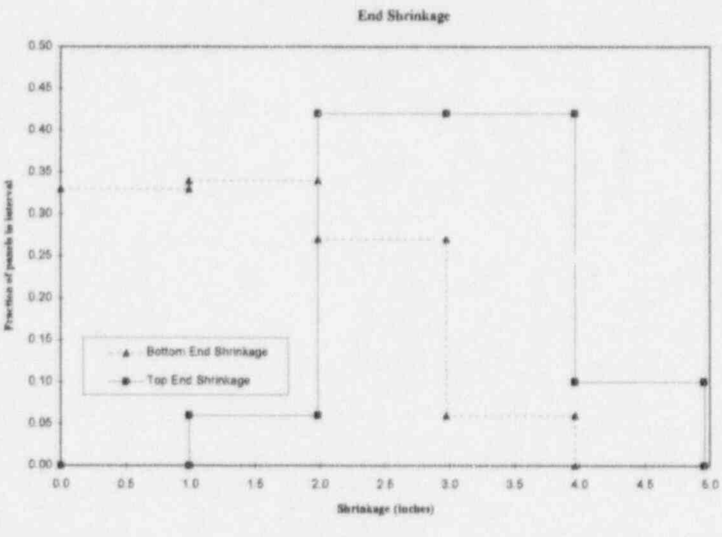


Figure 3–2. End panel shrinkage based on blackness test data for Westinghouse racks

Table 3–1. Boraflex panel characteristics used in the Region 1 analysis

Parameter	Design specification	Modeled value
Minimum B^{10} loading ($gm\ B^{10}/cm^2$ for 0.100 inch thickness)	0.026	0.026
Height (inch)	144.00±0.25	143.75[a]
Width (inch)	7.500±0.075	7.1206
Thickness (inch)	0.100±0.007	0.093

[a] Changes in the axial dimensions of the Boraflex panels due to shrinkage are discussed in the text.

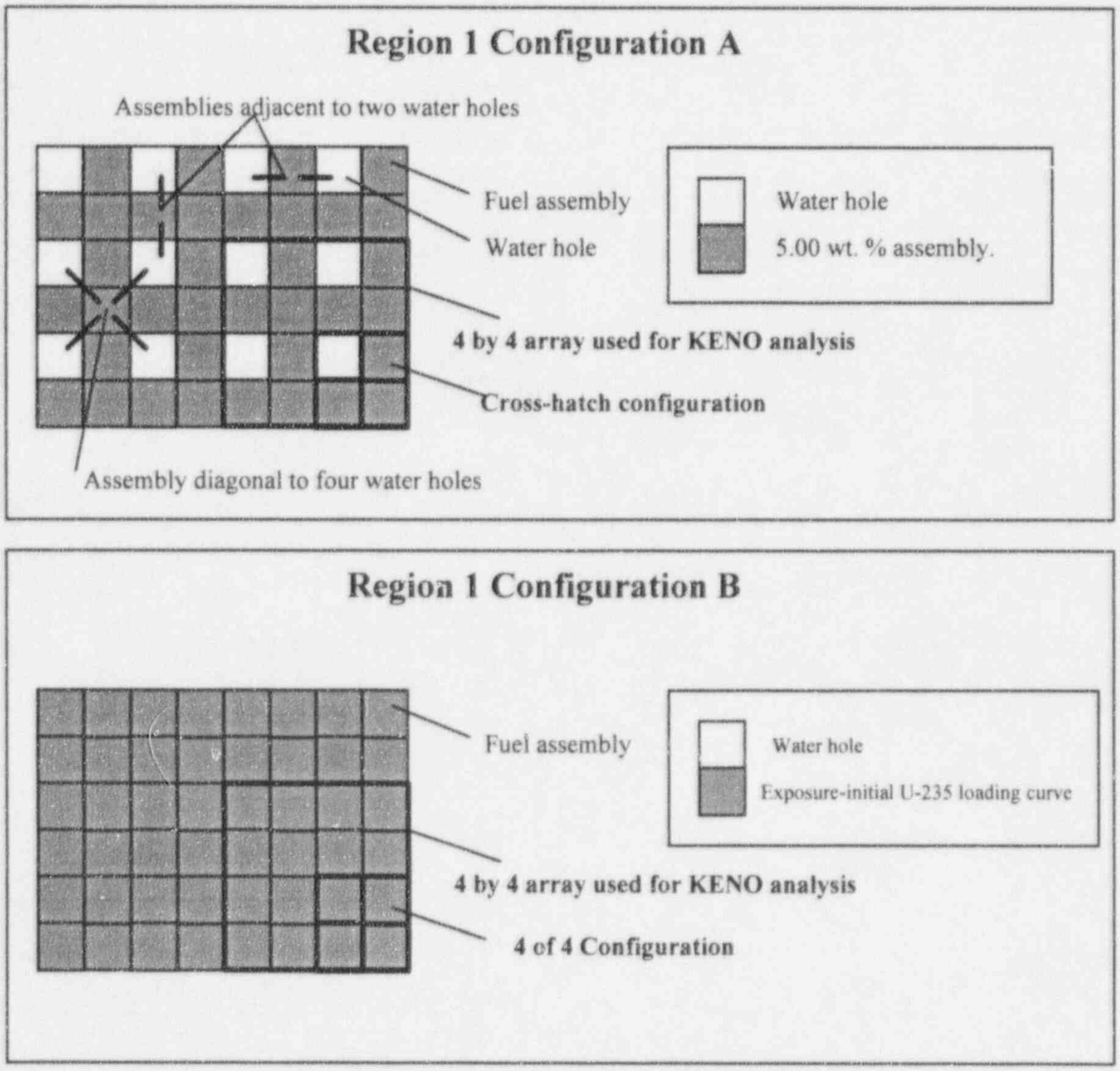


Figure 3–3. Region 1 storage configurations

Table 3–2. Tolerance factor results for Region 1 configurations

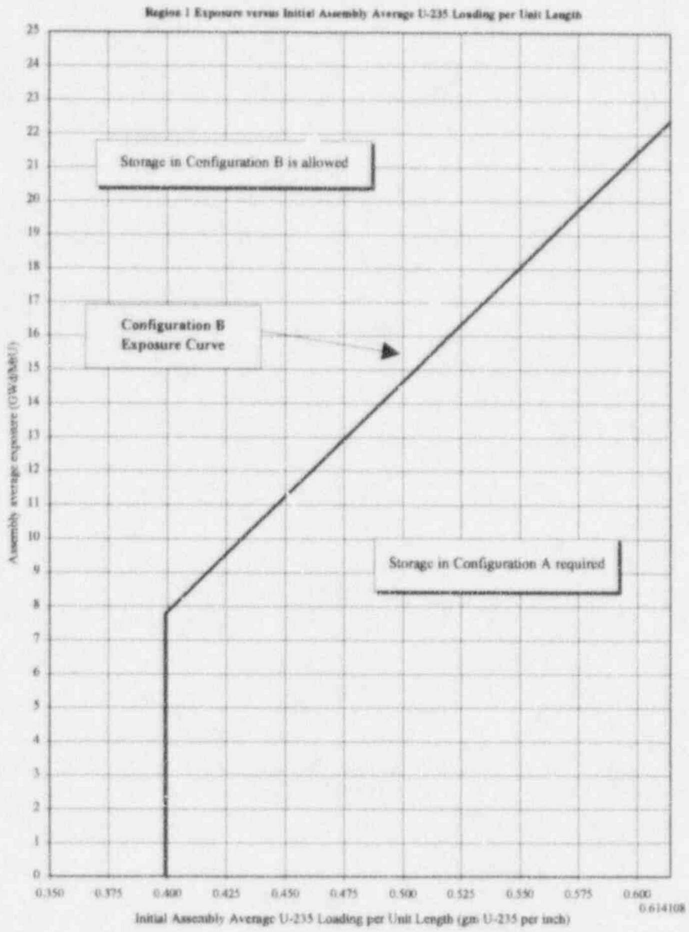
	Configuration		
	A	B Undepleted assembly	B Depleted assembly
Tolerance number	Delta k_{inf}'s		
1[a]	N/A	0.00311	0.00444
2	N/A	N/A	N/A
3	0.00118	0.00144	0.00161
4	0.00029	0.00036	0.00041
5	0.00000	0.00002	0.00003
6	0.00263	0.00246	0.00232
7	0.00057	0.00052	0.00049
8	0.00056	0.00092	0.00109
9	0.00000	0.00000	0.00000
10	0.00000	0.00000	0.00000
11	0.00000	0.00000	0.00000
12	0.00048	0.00043	0.00040
13	0.00186	0.00067	0.00000
Isotopic calc. uncert.	N/A	N/A	0.00495
Depletion hist. uncert.	N/A	N/A	0.00425
Overall tolerance uncertainty	**0.00357**	**0.00444**	**0.00849**

[a] see Section 2 for the description of tolerances 1–7 and this section for tolerances 8–13.

Table 3–3. Final reactivities for Region 1 configurations

Parameter	Configuration A	Configuration B Undepleted assembly	Configuration B Depleted assembly
Statistical average of the KENO k_{eff}'s	0.92154	0.91841	0.91483
Method bias	0.007600	0.007600	0.007600
Tolerances	0.00357	0.00444	0.00849
Spectral history	n/a[a]	n/a[a]	0.0050
Total uncertainty	0.002396	0.002565	0.002605
95/95 factor	2.092	2.176	2.179
Final 95/95 k_{eff}	**0.938**	**0.937**	**0.942**

[a] Undepleted fuel is considered in these configurations; therefore, no spectral history bias must be included.



Curve = 68.008x – 19.366 when x > 0.399181

Figure 3–4. Region 1 Configuration B exposure versus initial assembly average U–235 loading curve

4. SPENT FUEL POOL RACK: REGION 2

It was shown in a previous analysis that assemblies with enrichments up to 4.1 wt. % U^{235} may be safely stored in the Region 2 spent fuel storage racks [Reference 10]. This work shows that assemblies with enrichments up to 5.0 wt. % U^{235} may be safely stored in these racks. The requirements of NUREG–0800 [Reference 14] and ANSI/ANS–57.2–1983 [Reference 15] are met by this analysis.

4.1 Modeling

Base models

The Region 2 rack is an array of cells with stainless steel walls. This configuration is illustrated in Figure 4–1. The three–dimensional KENO model used in the Region 2 calculations includes a four by four array of rack cells. The fuel assembly dimensions are given in Section 2.

Tolerance analysis

The fuel tolerance factors are described in Section 2. The additional storage rack tolerance factors (8–12) are discussed below.

8. **Fuel storage area:** A smaller area increases the neutron moderation between rack cells.
9. **Rack wall thickness on the outer wall side:** A thinner wall reduces the absorption in structural material.
10. **Rack wall thickness on the fuel assembly side:** A thinner wall reduces the absorption in structural material.
11. **Minimum separation distance between cell walls:** A reduction in the distance between the cell walls decreases moderation between rack cells.
12. **Lateral assembly position:** Off–center positioning of the fuel assembly in the storage cell increases the interaction between assemblies.

The tolerance factor results for each configuration are shown in Table 4–1. The tolerances were combined using the methodology described in Section 2. Tolerance factors were determined for each storage configuration. Each storage configuration is discussed below.

4.2 Storage configurations

Configuration A

This configuration utilizes checkerboarding to allow storage of assemblies with fuel enrichments up to 5.0 wt. %. Each fuel assembly must be adjacent to four water holes as shown in Figure 4–

2. This configuration is modeled using a 4 by 4 array of rack cells with fuel assemblies in every other cell. The 95/95 k_{eff} value is 0.926 as shown in Table 4–2.

Configurations B and C

Credit for assembly burnup is taken to allow storage of enrichments up to 5.0 wt. % in these configurations. Configuration B requires cross–hatching where each fuel assembly to be adjacent to two water holes or located diagonally from four water holes as shown in Figure 4–2. Configuration C defines the requirements which must be met for an assembly to be stored in any Region 2 rack location.

Reactivity equivalencing is used to generate an assembly exposure–initial U^{235} loading curve which determines if fuel assemblies can be stored in these configurations. Variations in the assembly reactivity due to changes in fuel density and geometry were considered. If an assembly's fuel loading is less than the analyzed loading, the loading used to determine the assembly's burnup requirement is conservatively considered to be the analyzed loading.

Both uniform and axially distributed burnup distributions were considered. The uniform distribution was determined to be more limiting. This is due to the fact that the racks do not contain fixed poison (Boraflex) and the axial leakage effects offset the burnup distribution effects for the range of exposures considered in this analysis. The 95/95 k_{eff} value for Configurations B and C are 0.944 and 0.9498, respectively. The exposure–initial U–235 loading curves are shown in Figure 4–3.

Interface effects between configurations

Cases were evaluated to consider interface effects between various orientations of Configurations A, B, and C. In each case the assembly storage constraints of each configuration were met. For example, the Configuration A 5.00 wt. % assembly was always adjacent to four water holes. The 95/95 k_{eff} values for all cases were equal to or less than the values determined for the limiting configuration shown in Table 4–2.

4.3 Fuel handling accidents

For accident conditions, the double contingency principle applies which states it shall require two unlikely, independent, concurrent events to produce a criticality accident. Therefore, for accidents, the presence of soluble boron in the storage pool water can be assumed as a realistic initial condition. The accidents which must be considered are listed below:

- **Fuel assembly dropped on top of the rack**: The rack structure is such that an assembly positioned horizontally on top of the rack is approximately 30 inches away from the upper end of the active fuel region of the stored assemblies. This distance precludes interaction between the dropped assembly and the stored fuel.
- **Fuel assembly dropped between rack modules or next to the pool wall**: This accident cannot occur since the distance between all the rack modules and to the pool walls is less than the width of a fuel assembly.
- **Misplaced fuel assembly**: The misplacement of a fuel assembly in a rack configuration was considered. This accident is considered by placing a 5.0 wt. percent assembly from Configuration A in a Configuration C position which requires burnup credit. The soluble

boron concentration was assumed to be 1000 ppm. The 95/95 k_{eff} value is 0.84 which is well below 0.95.

4.4 Analysis conservatisms

The following conservatisms are included in the analysis of the Region 2 spent fuel storage racks:

1. No neutron leakage in the x–y directions is assumed.
2. Water is set to the maximum density of 1.00 gm/cc.
3. The assembly is modeled at its most reactive condition after shutdown when assuming burnup credit.
4. No credit is assumed for burnable poison in the fuel assemblies.
5. Much stainless steel structure is not modeled.
6. Credit for soluble boron is assumed only for accident cases consistent with the double contingency principle.

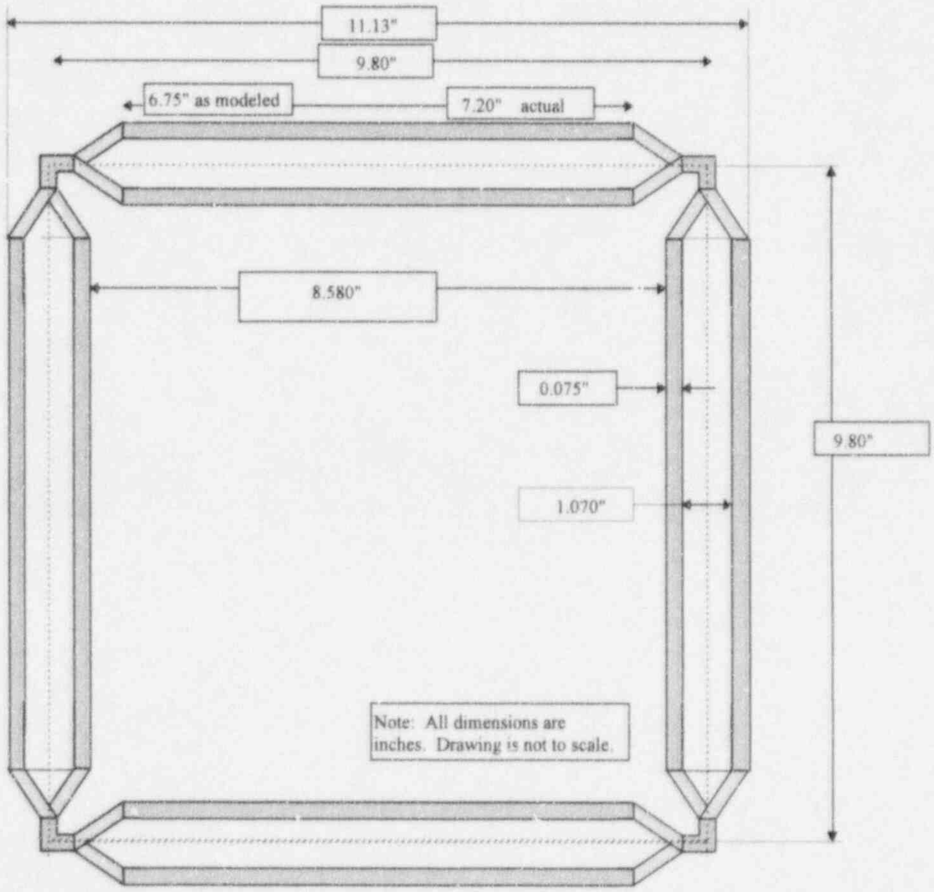


Figure 4–1. Radial view of the Region 2 spent fuel pool storage rack

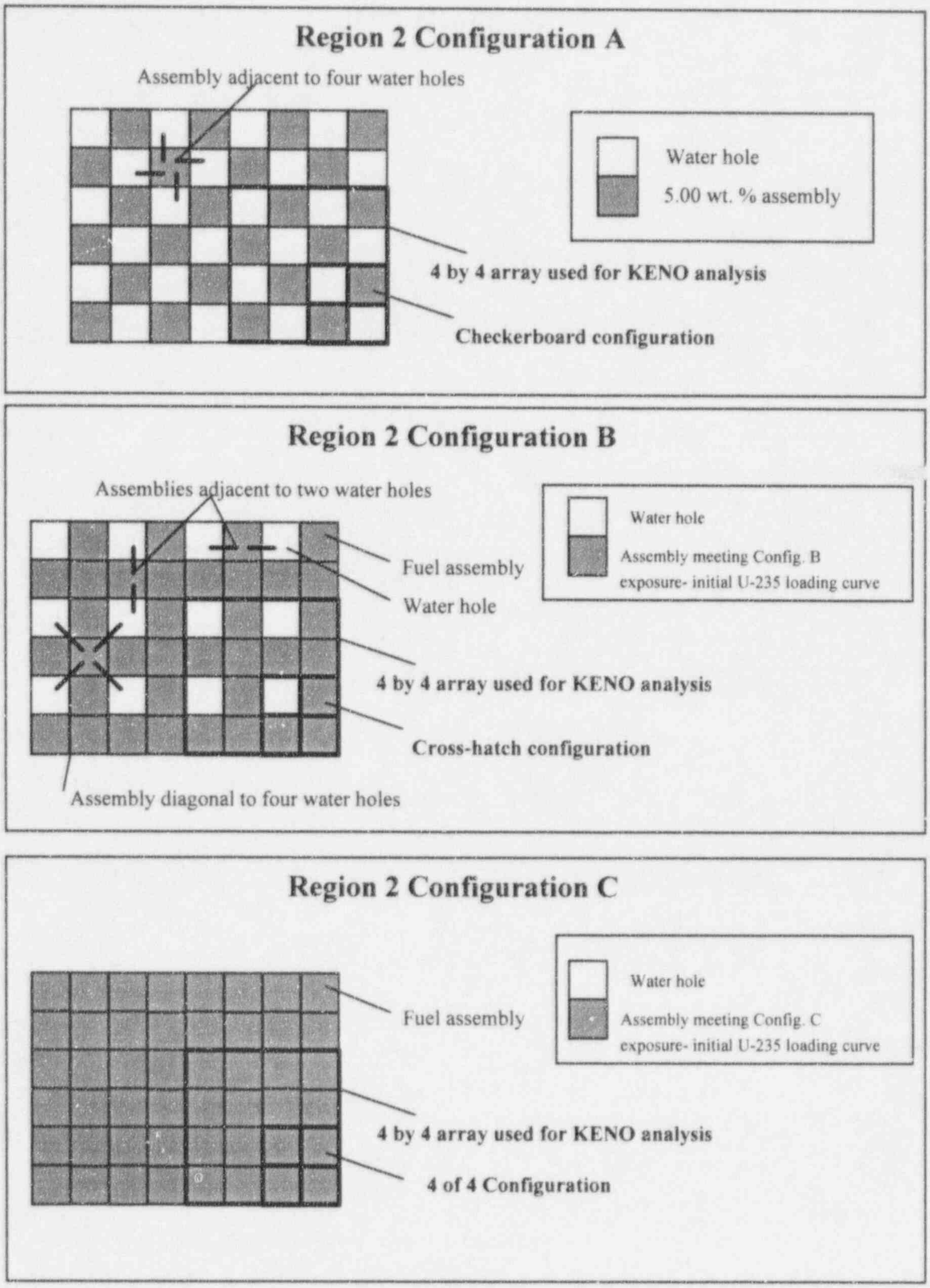


Figure 4–2. Region 2 storage configurations

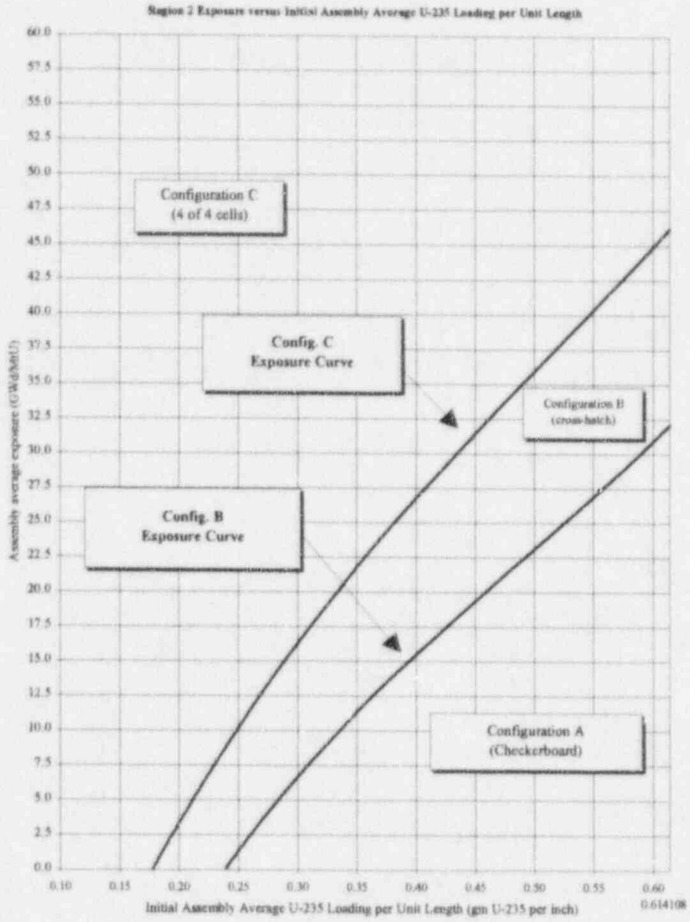
Table 4–1. Tolerance factor results for Region 2 configurations

	Configuration		
	A	B	C
Tolerance number	Delta k_{inf}'s		
1[a]	N/A	0.00760	0.01143
2	N/A	N/A	N/A
3	0.00106	0.00169	0.00188
4	0.00026	0.00044	0.00048
5	0.00003	0.00022	0.00030
6	0.00163	0.00099	0.00072
7	0.00035	0.00021	0.00015
8	0.00004	0.00016	0.00000
9	0.00256	0.00283	0.00286
10	0.00257	0.00282	0.00284
11	0.00000	0.00000	0.00001
12	0.00207	0.00060	0.00159
Isotopic calc. uncert.	N/A	0.00642	0.00642
Depletion hist. uncert.	N/A	0.00586	0.00752
Overall tolerance uncertainty	**0.00463**	**0.01240**	**0.01586**

[a] see Section 2 for the description of tolerances 1–7 and this section for tolerances 8–12

Table 4–2. Final reactivities for Region 2 configurations

	Configuration		
	A	B	C
KENO k_{eff}	0.90937	0.91088	0.91418
Biases			
Method	0.007600	0.007600	0.007600
Spectral history	0.00000	0.00850	0.00850
Uncertainty			
KENO	0.00114	0.00088	0.00078
Method	0.001464	0.001464	0.001464
Tolerance	0.00463	0.01240	0.01586
Total	0.00186	0.00171	0.00166
Degrees–of–freedom	54	39	34
95/95 factor	2.046	2.133	2.176
(95/95 factor)×Total	0.00380	0.00364	0.00361
Case 95/95 k_{eff}	**0.926**	**0.944**	**0.9498**



$$\text{Config. B curve} = 239.01\mathbf{x}^3 - 347.75\mathbf{x}^2 + 243.18\mathbf{x} - 41.452$$

$$\text{Config. C curve} = -714.35\mathbf{x}^4 + 1335.80\mathbf{x}^3 - 946.44\mathbf{x}^2 + 394.52\mathbf{x} - 47.040$$

Figure 4–3. Region 2 exposure versus initial assembly average U–235 loading curve

5. NEW FUEL STORAGE RACKS

In a previous analysis, assemblies with enrichments up to 4.1 wt. % U^{235} show significant margin to the criticality acceptance criteria [Reference 11]. This work shows that assemblies with enrichments up to 5.0 wt. % U^{235} may be safely stored in these racks. The requirements of NUREG–0800 [Reference 14] and ANSI/ANS–57.3–1983 [Reference 16] are met by this analysis.

Tolerance analysis

The fuel tolerance factors are described in Section 2. The uncertainty in the lateral position of the fuel assembly in the rack cavity is considered as a tolerance by reducing the assembly pitch to minimize the separation between assemblies.

The tolerance results for the optimum moderation (0.065 gm/cc) and possible moderation (1.00 gm/cc) cases are shown in Table 5–1. The tolerances were combined using the methodology described in Section 2.

Base model

The following assumptions were used in the development of the base KENO model. The nominal fuel assembly dimensions are described in Section 2. Scoping calculations to determine the optimum moderator density were performed using 250,000 particles. All other calculations used 500,000 particles.

1. The new fuel rack is filled with unirradiated fuel assemblies containing 5.0 wt. % U^{235}. The UO_2 density of the fuel stack is 10.25 gm/cc. The nominal assembly spacing of 26.0" is assumed.
2. The rack is moderated by pure water at various uniform densities.
3. No burnable poison, control element assembly, or other fixed poison is stored with the fuel assembly.
4. The pit walls and the floor are modeled using concrete followed by a reflective boundary condition. The area above the rack is modeled as water moderator followed by a reflective boundary condition.
5. No rack structural material is modeled.

SCALE cases were run to determine the optimum moderator density. The optimum density was determined to be 0.065 gm/cc as shown in Figure 5–1. The 95/95 k_{eff} values for the 0.065 and

1.00 gm/cc cases are shown in Table 5–2. The 95/95 k_{eff} is 0.916 for the possible moderation case (1.0 gm/cc) and 0.976 for the optimum moderation case (0.065 gm/cc).

Fuel handling accidents

For accident conditions, the double contingency principle applies which states it shall require two unlikely, independent, concurrent events to produce a criticality accident. Therefore, 'dry' conditions are assumed in the evaluation of the accident where an assembly drops on top of the new fuel rack. The dropped assembly and all assemblies in the rack are assumed to contain 5.0 wt. % fuel. The dropped assembly accident case yields a 95/95 k_{eff} of 0.52 which is well below 0.95.

Analysis conservatisms

The following conservatisms are included in the analysis of the new fuel storage racks:

1. No neutron leakage in the x–y directions is assumed.
2. Water is set to the maximum density of 1.00 gm/cc. The optimum moderation condition is also evaluated.
3. None of the rack structure is modeled.
4. No credit is assumed for burnable poison in the fuel assemblies.

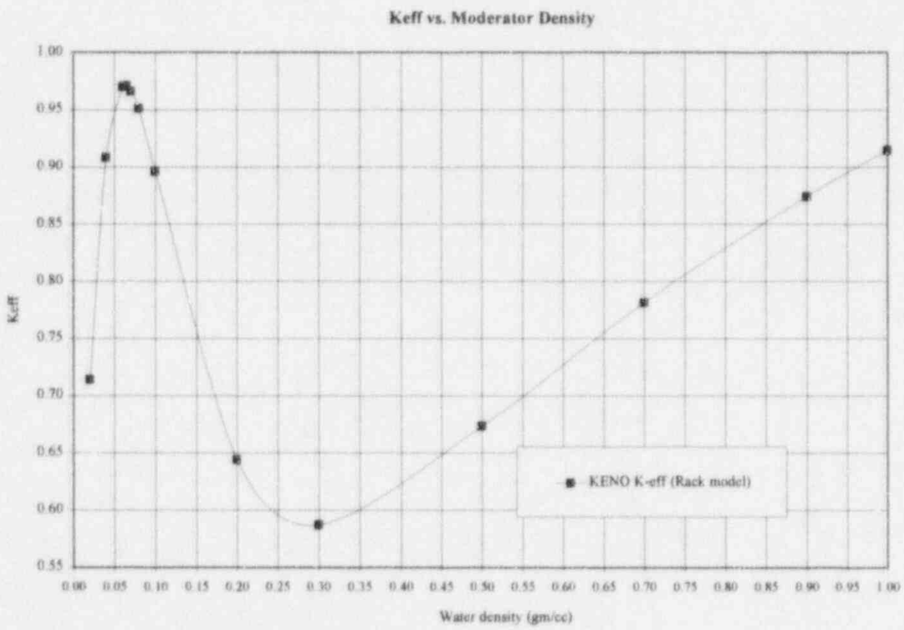


Figure 5–1. Determination of optimum moderator density for the new fuel storage rack

Table 5–1. Tolerance factor results for the new fuel storage rack

	Moderator density (gm/cc)	
	1.00	0.065
Tolerance number	Delta k_{inf}'s	
1[a]	N/A	N/A
2	N/A	N/A
3	0.00115	0.00036
4	0.00029	0.00010
5	0.00000	0.00053
6	0.00215	0.00074
7	0.00053	0.00012
Lateral assembly position	0.00011	0.00703
Overall tolerance uncertainty	**0.00251**	**0.00710**

[a] see Section 2 for the description of tolerances 1–7

Table 5–2. Final reactivities for the new fuel storage rack

	Moderator density (gm/cc)	
	1.00	0.065
KENO k_{eff}	0.90113	0.95725
Biases		
Method	0.007600	0.007600
Uncertainty		
KENO	0.00113	0.00105
Method	0.001464	0.001464
Tolerance	0.00251	0.00710
Total	0.00185	0.00180
Degrees–of–freedom	53	48
95/95 factor	2.051	2.075
(95/95 factor)×Total	0.00379	0.00374
Case 95/95 k_{eff}	**0.916**	**0.976**

6. FUEL TRANSFER UPENDER

This work shows that two assemblies with enrichments up to 5.0 wt. % U^{235} may be safely transported using the fuel upender. It is shown that k_{eff} is less than the 0.95 limit assuming no credit for soluble boron.

Tolerance analysis

The fuel tolerance factors are described in Section 2. Worst case lateral assembly position is assumed in the base model. The tolerance results are shown in Table 6–1. The tolerances were combined using the methodology described in Section 2.

Base model

The following assumptions were used in the development of the base KENO model. The nominal fuel assembly dimensions are described in Section 2. Calculations were also performed to model the presence of a single assembly in the upender.

1. Both upender assembly positions contain unirradiated fuel assemblies with 5.0 wt. % U^{235} fuel. The UO_2 density of the fuel stack is 10.25 gm/cc.
2. Water is set to the maximum density of 1.00 gm/cc.
3. No burnable poison, control element assembly, or other fixed poison is stored with the fuel assembly.
4. Three cases were examined. Case 1 assumed the two assemblies are completely outside the canal (infinite moderator), Case 2 assumed the assemblies are centered in the transfer canal, and Case 3 assumed half of the assembly is in the canal and half is outside the canal. Case 1 yielded the highest 95/95 k_{eff} value.

The final 95/95 eigenvalue is 0.94997 as shown in Table 6–2 which is based on 1,500,000 neutron histories. This value is less than the 0.95 limit. The 95/95 eigenvalue for a single assembly in infinite moderator is 0.92. The minimum allowed separation distance between the loaded upender and a third assembly adjacent to the upender was determined to be 12 inches (assembly edge to assembly edge). At this separation distance, the final 95/95 eigenvalue is less than 0.95 assuming 0 ppm soluble boron.

Fuel handling accidents

For accident conditions, the double contingency principle applies which states it shall require two unlikely, independent, concurrent events to produce a criticality accident. Therefore, credit for soluble boron can be assumed in the evaluation of the accident where an assembly drops next to

the upender. The dropped assembly and the two assemblies in the upender are assumed to contain 5.0 wt. % fuel. The dropped assembly accident case yields a 95/95 k_{eff} of 0.87 when assuming credit for 1000 ppm soluble boron. The soluble boron concentration during refueling operations is maintained at a much higher level.

Analysis conservatisms

The following conservatisms are included in the analysis of the fuel transfer upender:

1. The base model assumes the fuel assemblies are in the most reactive geometry (smallest possible separation distance).
2. Water is set to the maximum density of 1.00 gm/cc.
3. The stainless steel upender structure is not modeled.
4. No credit is assumed for burnable poison in the fuel assemblies.
5. No credit is assumed for soluble boron in the water.

Table 6–1. Tolerance factor results for the fuel transfer upender

Tolerance number	Delta k_{inf}'s
1[a]	N/A
2	N/A
3	0.00114
4	0.00029
5	0.00011
6	0.00203
7	0.00049
Lateral assembly position[b]	N/A
Overall tolerance uncertainty	**0.00240**

[a] see Section 2 for the description of tolerances 1–7

[b] The base model assumes worst case positioning.

Table 6–2. Final reactivity for the fuel transfer upender

KENO k_{eff}	0.93640
Biases	
Method	0.007600
Uncertainty	
KENO	0.00063
Method	0.001464
Tolerance	0.00240
Total	0.00159
Degrees–of–freedom	29
95/95 factor	2.232
(95/95 factor)×Total	0.00356
Case 95/95 k_{eff}	**0.94997**

7. CONTAINMENT TEMPORARY STORAGE RACK

This work shows that assemblies with enrichments up to 5.0 wt. % U^{235} may be safely stored in the containment temporary storage racks. It is shown that k_{eff} is less than 0.95 for both normal and accident conditions.

Tolerance analysis

The fuel tolerance factors are described in Section 2. The uncertainty in the lateral position of the fuel assembly in the rack cavity is considered as a tolerance by reducing the assembly pitch.

The tolerance results are shown in Table 7–1. The tolerances were combined using the methodology described in Section 2.

Base model

The following assumptions were used in the development of the base KENO model. The nominal fuel assembly dimensions are described in Section 2.

1. All four positions in the rack contain unirradiated fuel assemblies with 5.0 wt. % U^{235} fuel. The UO_2 density of the fuel stack is 10.25 gm/cc. The nominal value of 17.812" is assumed for spacing between assemblies.
2. Water is set to the maximum density of 1.00 gm/cc.
3. No burnable poison, control element assembly, or other fixed poison is stored with the fuel assembly.
4. The wall supporting the storage rack is modeled as concrete followed by a reflective boundary condition. The upper, lower, and other sides of the rack are modeled as water followed by reflective boundary conditions.
5. No rack structural material is modeled.

The final 95/95 eigenvalue is 0.92 as shown in Table 7–2. This value is less than the 0.95 limit.

Fuel handling accidents

For accident conditions, the double contingency principle applies which states it shall require two unlikely, independent, concurrent events to produce a criticality accident. Therefore, credit for soluble boron can be assumed in the evaluation of the accident where an assembly drops next to the containment temporary storage rack. The dropped assembly and all assemblies in the rack are assumed to contain 5.0 wt. % fuel. The dropped assembly accident case yields a 95/95 k_{eff} of 0.83 when assuming credit for 1000 ppm soluble boron. The soluble boron concentration during refueling operations is maintained at a much higher level.

Analysis conservatisms

The following conservatisms are included in the analysis of the containment temporary fuel storage racks:

1. No neutron leakage in the x–y directions is assumed.
2. Water is set to the maximum density of 1.00 gm/cc.
3. None of the stainless steel rack structure is modeled.
4. No credit is assumed for burnable poison in the fuel assemblies.
5. Credit for soluble boron is assumed only for accident cases consistent with the double contingency principle.

Table 7–1. Tolerance factor results for the containment temporary storage rack

Tolerance number	Delta k_{inf}'s
1[a]	N/A
2	N/A
3	0.00114
4	0.00029
5	0.00000
6	0.00214
7	0.00053
Lateral assembly position	0.00087
Overall tolerance uncertainty	**0.00265**

[a] see Section 2 for the description of tolerances 1–7

Table 7–2. Final reactivities for the containment temporary storage rack

KENO k_{eff}	0.90537
Biases	
Method	0.007600
Uncertainty	
KENO	0.00118
Method	0.001464
Tolerance	0.00265
Total	0.00188
Degrees–of–freedom	57
95/95 factor	2.034
(95/95 factor)×Total	0.0382
Case 95/95 k_{eff}	**0.92**

8. REFERENCES

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APPENDIX A: BENCHMARK OF SCALE–4

A benchmarking of the SCALE–4 system of codes against critical experiments is performed in order to qualify and validate its use for performing fuel storage rack criticality safety analyses at Entergy Operations, Inc. plants.

The benchmarked SCALE–4 codes includes the CSAS25 Control Sequence of the ORNL Criticality Safety Analysis Sequence No. 4 (CSAS4). The functional modules sequentially executed by the CSAS25 control module are the BONAMI-S code, the NITAWL-S code, and the KENO V.a code [Reference 1].

A total of twenty-one critical experiments are used to benchmark these codes. These criticals are selected from a list of seventy-five critical experiments conducted by Babcock and Wilcox and Pacific Northwest Laboratory [References 2, 3, and 4]. The twenty-one criticals are chosen because their fuel characteristics, lattice geometry's water gap spacing and materials are reasonably representative of those found in Entergy Operations, Inc. fuel storage rack arrays.

An evaluation of the 218 group cross section library benchmarking results identifies one significant bias in the SCALE calculated k_{eff}'s. The bias is an observed trend toward over-prediction of reactivity and increasing Boron loading in the Boral plates for four of the B&W cores, as also reported for the 123 group library in Reference 5. These four cases are corrected for the Boron loading bias before further data reduction is performed. For conservatism, this credit is not taken in analyzing fuel storage racks.

Statistical analysis of the twenty–one calculated k_{eff}'s, using Criterion 2 [Reference 6], gives a mean k_{eff} of 0.992402 with a Monte Carlo uncertainty of ±0.000987, a method bias of 0.007600, and a method uncertainty of ±0.001464. Table A–1 provides a summary of the benchmark statistics.

Table A–1. Summary of SCALE–4 benchmark

Case number	Case name	Enrichment (wt. % U^{235})	SCALE k_{eff}	Standard deviation	Corrected k_{eff}	Number of generations	Number of neutrons per generation
1	BWII	2.46	0.99141	0.00082	0.99141	500	1000
2	BWIII	2.46	0.98996	0.00086	0.98996	500	1000
3	BWXI	2.46	0.98837	0.00091	0.98837	500	1000
4	BWXIII	2.46	0.99761	0.00095	0.99292	500	1000
5	BWXIV	2.46	0.99522	0.00096	0.99209	500	1000
6	BWXVII	2.46	0.99233	0.00088	0.99364	500	1000
7	BWXIX	2.46	0.98988	0.00089	0.99181	500	1000
8	PNL5	2.35	0.99329	0.00099	0.99329	500	1000
9	PNL26	2.35	0.99340	0.00095	0.99340	500	1000
10	PNL28	2.35	0.99384	0.00093	0.99384	500	1000
11	PNL32	2.35	0.99392	0.00092	0.99392	500	1000
12	PNL33	2.35	0.99486	0.00098	0.99486	500	1000
13	PNL38	2.35	0.99276	0.00102	0.99276	500	1000
14	PNL39	2.35	0.99487	0.00096	0.99487	500	1000
15	PNL8	4.29	0.99075	0.00110	0.99075	500	1000
16	PNL9	4.29	0.99254	0.00111	0.99254	500	1000
17	PNL10	4.29	0.99491	0.00106	0.99491	500	1000
18	PNL11	4.29	0.98996	0.00112	0.98996	500	1000
19	PNL12	4.29	0.99137	0.00104	0.99137	500	1000
20	PNL13	4.29	0.99243	0.00110	0.99243	500	1000
21	PNL32	4.29	0.99169	0.00109	0.99169	500	1000

Avg. Corrected Keff = ***0.992402***
Monte Carlo Uncertainty = ***0.000987***
Method Bias = ***0.007600***
Method Uncertainty= ***0.001464***