V. C. SUMMER SPENT FUEL RACK
CRITICALITY ANALYSIS
CONSIDERING BORAFLEX SHRINKAGE & GAPS

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1.0 INTRODUCTION

This report presents the results of the criticality re-analysis of the V. C. Summer Spent Fuel Storage Racks with consideration of Boraflex shrinkage and gaps.

The spent rack designs considered herein are existing arrays of poisoned and unpoisoned racks, previously qualified for storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 5.0 w/o U^{235}. Occurrences of absorber panel shrinkage and gaps were not considered in the previous criticality analyses for these racks.

In this analysis, each of the three unique storage configurations in the V. C. Summer Spent Fuel Rack will be re-analyzed with consideration of Boraflex shrinkage and gap development. To provide for future fuel management flexibility, storage limits will be developed for enrichments up to and including 5.0 w/o by employing credit for Integral Fuel Burnable Absorbers (IFBA) and accumulated fuel assembly burnup.

The following storage configurations and enrichment limits are considered in this analysis:

Region 1   Storage of fresh fuel assemblies with nominal enrichments up to 4.0 w/o U^{235} utilizing all available storage cells. Fresh fuel assemblies with higher initial enrichments can also be stored in this region provided a minimum number of IFBAs are present in each fuel assembly. IFBAs consist of neutron absorbing material applied as a thin ZrB_2 coating on the outside of the UO_2 fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

Region 2   Storage of fresh fuel assemblies with nominal enrichments up to 2.5 w/o U^{235} utilizing all available storage cells. Burned fuel assemblies with higher initial enrichments can also be stored in this region provided the minimum requirements for enrichment/burnup are satisfied.

Region 3   Storage of fresh fuel assemblies with nominal
                            enrichments up to 1.4 w/o U^{235} utilizing all available
                            storage cells. Burned fuel assemblies with higher initial
                            enrichments can also be stored in this region provided the
                            minimum requirements for enrichment/burnup are satisfied.

In addition to the analyses described above, relaxed limits will also be developed for each storage region assuming the presence of a minimum soluble boron concentration of 300 ppm. Since the spent fuel pool is nominally maintained at a boron concentration of 2000 ppm, the considerable reactivity conservatism present in the spent fuel storage pool is not compromised.

The V. C. Summer Spent Fuel Rack criticality analysis described in this report is based on maintaining $K_{eff} \leq 0.95$ for storage of all Westinghouse 17x17 fuel assembly products, including STANDARD, OFA, VANTAGE 5, VANTAGE 5H, VANTAGE+ and PERFORMANCE+. For each region, the most reactive or limiting fuel assembly type is analyzed to establish the reference K_{eff} and confirm that the 0.95 limit is not exceeded.

The V. C. Summer Fresh Fuel Racks have been previously analyzed[1] for storage of Westinghouse 17x17 fuel assemblies with enrichments up to 5.0 w/o U^{235}. Since the previous analysis remains valid and applicable, the Fresh Fuel Racks are not re-analyzed in this evaluation.

1.1 DESIGN DESCRIPTION

The V. C. Summer spent fuel rack Regions 1, 2, and 3 storage cell designs are depicted schematically in Figure 1 on page 46 through Figure 3 on page 48, respectively. Nominal dimensions are provided on each figure. Axial feature drawings for each region are provided in Figure 4 on page 49 through Figure 6 on page 51. The layout of the racks within the V. C. Summer spent fuel storage pool is shown in Figure 7 on page 52.

The fuel parameters relevant to this analysis are given in Table 1 on page 35. With the simplifying assumptions employed in this analysis (no grids, sleeves, axial blankets, etc.), the various types of Westinghouse 17x17 fuel assemblies can be categorized into two basic designs: 17x17 STANDARD (STD), which utilizes a 0.374 inch OD fuel rod, and 17x17 OFA, which utilizes a 0.360 inch OD fuel rod. The advanced features of the improved fuel assembly designs (V5, V5H, V+, and P+) are beneficial in terms of extending burnup capability and improving fuel reliability, but do not contribute to any meaningful increase in the basic assembly reactivity. Therefore, for this analysis, only the Westinghouse 17x17 STD and OFA fuel assembly types are analyzed since these designs will yield equivalent or conservative reactivity results.

1.2 DESIGN CRITERIA

Criticality of fuel assemblies in a fuel storage rack is prevented by the design of the rack which limits fuel assembly interaction. This is done by fixing the minimum separation between assemblies and inserting neutron poison between assemblies.

The design basis for preventing criticality outside the reactor is that, including uncertainties, there is a 95 percent probability at a 95 percent confidence level that the effective neutron multiplication factor, K_{eff}, of the fuel assembly array will be less than 0.95 as recommended by ANSI 57.2-1983 and NRC guidance[2].

2.0 ANALYTICAL METHODS

2.1 CRITICALITY CALCULATION METHODOLOGY

The criticality calculation method and cross-section values are verified by comparison with critical experiment data for fuel assemblies similar to those for which the racks are designed. This benchmarking data is sufficiently diverse to establish that the method bias and uncertainty will apply to rack conditions which include strong neutron absorbers, large water gaps and low moderator densities.

The design method which insures the criticality safety of fuel assemblies in the fuel storage rack uses the AMPX[3, 4] system of codes for cross-section generation and KENO Va[5] for reactivity determination.

The 227 energy group cross-section library that is the common starting point for all cross-sections used for the benchmarks and the storage rack is generated from ENDF/B-V[3] data. The NITAWL[4] program includes, in this library, the self-shielded resonance cross-sections that are appropriate for each particular geometry. The Nordheim Integral Treatment is used. Energy and spatial weighting of cross-sections is performed by the XSDRNPM[4] program which is a one-dimensional S_n transport theory code. These multigroup cross-section sets are then used as input to KENO Va[5] which is a three dimensional Monte Carlo theory program designed for reactivity calculations.

A set of 44 critical experiments has been analyzed using the above method to demonstrate its applicability to criticality analysis and to establish the method bias and uncertainty. The benchmark experiments cover a wide range of geometries, materials, and enrichments, ranging from relatively low enriched (2.35, 2.46, and 4.31 w/o), water moderated, oxide fuel arrays separated by various materials ($B4C$, aluminum, steel, water, etc) that simulate LWR fuel shipping and storage conditions to dry, harder spectrum, uranium metal cylinder arrays at high enrichments (93.2 w/o) with various interspersed materials (Plexiglas and air). Comparison with these experiments demonstrates the wide range of applicability of the method. Details of the experiments are provided in References 6 through 10. Table 2 on page 36 summarizes these experiments.

The highly enriched benchmarks show that the criticality code sequence can correctly predict the reactivity of a hard spectrum environment, such as the optimum moderation condition often considered in fresh rack and shipping cask analyses. However, the results of the 12 highly enriched benchmarks are not incorporated into the criticality method bias because the enrichments are well above any encountered in commercial nuclear power applications. Basing the method bias solely on the 32 low enriched benchmarks results in a more appropriate and more conservative bias.

The 32 low enriched, water moderated experiments result in an average KENO Va K_{eff} of 0.9933. Comparison with the average measured experimental K_{eff} of 1.0007 results in a method bias of 0.0074. The standard deviation of the bias value is 0.0013 ΔK. The 95/95 one-sided tolerance limit factor for 32 values is 2.20. Thus, there is a 95 percent probability with a 95 percent confidence level that the uncertainty in reactivity, due to the method, is not greater than 0.0029 ΔK. This KENO Va bias and uncertainty are consistent with the previous Westinghouse bias and uncertainty calculated for KENO IV[11].

2.2 REACTIVITY EQUIVALENCING FOR BURNUP AND IFBA CREDIT

Storage of spent fuel assemblies with initial enrichments higher than that allowed by the methodology described in Section 2.1 is achievable by means of the concept of reactivity equivalencing. Reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion or the addition of IFBA fuel rods. A series of reactivity calculations is performed to generate a set of enrichment-burnup or enrichment-IFBA ordered pairs which all yield an equivalent K_{eff} when the fuel is stored in the V. C. Summer spent fuel racks.

The data points on the reactivity equivalence curve are generated with a transport theory computer code, PHOENIX[12]. PHOENIX is a depletable, two-dimensional, multigroup, discrete ordinates, transport theory code. A 25 energy group nuclear data library based on a modified version of the British WIMS[13] library is used with PHOENIX.

A study was done to examine fuel reactivity as a function of time following discharge from the reactor. Fission product decay was accounted for using CINDER[14]. CINDER is a point-depletion computer code used to determine fission product activities. The fission products were permitted to decay for 30 years after discharge. The fuel reactivity was found to reach a maximum at approximately 100 hours after discharge. At this time, the major fission product poison, Xe^{135}, has nearly completely decayed away. Furthermore, the fuel reactivity was found to decrease continuously from 100 hours to 30 years following discharge. Therefore, the most reactive time for a fuel assembly after discharge from the reactor can be conservatively approximated by removing the Xe^{135}.

The PHOENIX code has been validated by comparisons with experiments where the isotopic fuel composition has been examined following discharge from a reactor. In addition, an extensive set of benchmark critical experiments has been analyzed with PHOENIX. Comparisons between measured and predicted uranium and plutonium isotopic fuel compositions are shown in Table 3 on page 37. The measurements were made on fuel discharged from Yankee Core 5[15]. The data in Table 3 on page 37 shows that the agreement between PHOENIX predictions and measured isotopic compositions is good.

The agreement between reactivities computed with PHOENIX and the results of 81 critical benchmark experiments is summarized in Table 4 on page 38. Key parameters describing each of the 81 experiments are given in Table 5 on page 39. These reactivity comparisons again show good agreement between experiment and PHOENIX calculations.

Uncertainties associated with the burnup and IFBA dependent reactivities computed with PHOENIX are accounted for in the development of the individual reactivity equivalence limits. For burnup credit, an uncertainty is applied to the PHOENIX calculational results which starts at zero for zero burnup and increases linearly with burnup, passing through 0.01 ΔK at 30,000 MWD/MTU. This bias is considered to be very conservative and is based on consideration of the good agreement between PHOENIX predictions and measurements and on conservative estimates of fuel assembly reactivity variances with depletion history. For IFBA credit applications, an uncertainty of approximately 10% of the total number of IFBA rods is accounted for in the development of the IFBA requirements. Additional information concerning the specific uncertainties included in each of the V. C. Summer burnup credit and IFBA credit limits is provided in the individual sections of this report.

2.3 BORAFLEX SHRINKAGE AND GAP METHODOLOGY

As a result of blackness testing measurements performed at V. C. Summer, the presence of shrinkage and gaps in some of the Boraflex absorber panels has been noted. The effects of Boraflex shrinkage and gaps will be considered in the spent fuel rack criticality evaluations performed for this report.

Previous generic studies of Boraflex shrinkage and gap reactivity effects have been performed [16] for storage rack geometries which resemble the V. C. Summer spent fuel racks. The results of these studies (and experience gained in performing similar studies for other rack geometries) indicate that:

■ When absorber panel shrinkage occurs evenly and uniformly (equal pull-back is experienced at both ends and the panel remains axially centered and intact), meaningful increases in rack reactivity will not occur until more than 7.0 inches of total active fuel length is exposed (3.5 inches on each end). Assuming a conservative 4% shrinkage scenario, combined top and bottom fuel exposure will reach 10.56 inches given the initial V. C. Summer Boraflex panel length of 139 inches. For this level of uniform top and bottom exposure, generic study data indicates that reactivity will increase by less than 0.015 ΔK.

■ When absorber panel shrinkage occurs all at one end, experience has shown that the reactivity impact will remain approximately constant even when an identical length of exposure is added to the opposite end. For the one-end scenario, generic data indicates that reactivity will increase by well over 0.06 ΔK when 4% uniform, one-end shrinkage is assumed in the V. C. Summer racks.

- When absorber panel shrinkage is assumed to result in the formation of a single large gap in every panel, and all panel gaps are conservatively positioned at the vertical centerline of the active fuel, generic study data indicates that reactivity will increase dramatically once a gap size of 1 inch has been exceeded. For an assumed 4% shrinkage at V. C. Summer, the data indicates that reactivity will increase by more than $0.06 \Delta K$ if all shrinkage is modeled as a single, large (5.56 inch) gap at the centerline.

These generic study results indicate that Boraflex shrinkage and gap formation will result in extremely large reactivity impacts for the conservative scenarios of single-end exposure and mid-plane gap development. Accommodating this level of impact in the V. C. Summer rack limits would cause an unreasonable and unacceptable loss of enrichment storage capability. Therefore, a conservative, but more realistic treatment of shrinkage and gap formation will be considered in this criticality evaluation.

To conservatively bound the current measured data and future development of additional shrinkage and gaps, the following assumptions will be employed in the criticality evaluations performed for each of the V. C. Summer storage regions which utilize Boraflex absorbers:

1. All absorber panels will be modeled with 4% width shrinkage.

2. All absorber panels will be modeled with 4% length shrinkage (5.56 inches) which will be assumed to occur either uniformly (where the panel remains intact over its entire length) or non-uniformly (where a conservative, single 4 inch gap develops somewhere along the panel length).

3. For those panels which are modeled with a gap, the remainder of the 4% length shrinkage not accounted for by the single 4 inch gap will be conservatively applied as bottom end shrinkage.

4. Gaps will be distributed randomly with respect to axial position for the absorber panels which are modeled with gaps.

5. Shrinkage will be conservatively applied to the bottom end for those absorber panels which are modeled with uniform shrinkage (the bottom end results in more active fuel exposure than the top end). Applying all shrinkage to the bottom is very conservative since it ignores the realistic possibilities of uniform top/bottom shrinkage or random distribution of top or bottom shrinkage among the many absorber panels.

6. Determination of which panels experience shrinkage and which experience gaps will be based on random selection. Several scenarios will be considered to cover the complete spectrum of shrinkage and gap combinations:

    - 100% of the panels experience non-uniform shrinkage (random gaps).

    - 75% of the panels experience non-uniform shrinkage (random gaps) and the remaining 25% of panels experience uniform shrinkage (pull-back) from the bottom-end.

- 50% of the panels experience non-uniform shrinkage (random gaps) and the remaining 50% of panels experience uniform shrinkage (pull-back) from the bottom-end.

- 25% of the panels experience non-uniform shrinkage (random gaps) and the remaining 75% of panels experience uniform shrinkage (pull-back) from the bottom-end.

- 100% of the panels experience uniform shrinkage (pull-back) from the bottom-end.

7. A criticality model which simulates 16 storage cells and 64 individual absorber panels will be employed to provide sufficient problem size and flexibility for considering gaps and shrinkage on a random basis.

8. All absorber material which is lost to shrinkage or gaps will be conservatively removed from the model. In reality, the absorber material is not lost -- it is simply repositioned by shrinkage to the remaining intact areas of the panel.

The above assumptions are conservative and bounding with respect to the actual shrinkage/gaps measurements taken at V. C. Summer. The use of 4% shrinkage and maximum 4 inch gap bounds the measured shrinkage/gaps at V. C. Summer and is consistent with the upper bound values recommended by EPRI.

3.0 REGION 1 FUEL STORAGE RACKS

This section develops and describes the analytical techniques and models em-
ployed to perform the criticality analysis and reactivity equivalencing evaluations
for the V. C. Summer Region 1 spent fuel racks.

Section 3.1 describes the analyses performed to show that storage of
Westinghouse 17x17 fuel assemblies with nominal enrichments up to 4.0 w/o
U^{235} is acceptable in all cell locations. Section 3.2 describes the reactivity
equivalencing analysis which establishes the minimum Integral Fuel Burnable
Absorber (IFBA) requirements for assemblies with nominal enrichments above
4.0 w/o. Finally, Section 3.3 presents the results of calculations performed to
show the reactivity sensitivity caused by variations in enrichment, center-to-
center spacing, and absorber poison loading.

3.1 REACTIVITY CALCULATIONS

To show that Region 1 storage of Westinghouse 17x17 fuel assemblies with
nominal enrichments up to 4.0 w/o satisfies the 0.95 K_{eff} criticality acceptance
criteria, KENO is used to establish a nominal reference reactivity and PHOENIX
is used to assess the effects of material and construction tolerance variations.
A final 95/95 K_{eff} is developed by statistically combining the individual tolerance
impacts with the calculational and methodology uncertainties and summing this
term with the nominal KENO reference reactivity.

The following assumptions are used to develop the nominal case KENO model
for the Region 1 fuel storage rack evaluation:

1. The fuel assembly parameters relevant to the criticality analysis are based
    on the Westinghouse 17x17 OFA design (see Table 1 on page 35 for fuel
    parameters). At the enrichment level being considered for this application,
    and with the simplified assembly modeling assumptions (no grids, sleeves,
    axial blankets, etc.), the 17x17 OFA design yields equivalent or bounding
    reactivity results relative to the other Westinghouse 17x17 fuel types.

2. All fuel rods contain uranium dioxide at a nominal enrichment of 4.0 w/o
    over the entire length of each rod.

3. The fuel pellets are modeled assuming nominal values for theoretical den-
    sity and dishing fraction.

4. No credit is taken for any natural enrichment axial blankets.

5. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken
    for the build up of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.

7. No credit is taken for any burnable absorber in the fuel rods.

8. The moderator is pure water (no boron) at a temperature of 68°F and a density of 1.0 gm/cm^3.

9. A nominal Boraflex poison material loading of 0.0264 grams B^{10} per square centimeter is used throughout the array, based on asbuilt measurements provided by the Boraflex material vendor.

10. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent. This allows neutron leakage from only the axial direction.

11. All available storage cells are loaded with fresh fuel assemblies.

With the above assumptions, the KENO calculation for the nominal case (without absorber panel shrinkage/gap effects) results in a K_{eff} of 0.9072 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0051. The nominal case result can be compared to the results from the shrinkage/gap calculations to determine the relative impact of the Boraflex assumptions. The nominal case is also used as the center point for the sensitivity analyses.

To quantify the benefit of axial leakage, a two-dimensional KENO calculation identical to the nominal three-dimensional calculation is performed, except that axial leakage is eliminated. The 2D KENO calculation results in a K_{eff} of 0.9104 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0024. Comparison with the reference 3D result indicates that axial leakage is worth about 0.0032 ±0.0051 ΔK.

To conservatively evaluate the effects of Boraflex shrinkage and gap development, the methodology described in Section 2.3 is employed. Five shrinkage/gap scenarios are examined to cover the spectrum of shrinkage-to-gap ratios from 100% gaps and 0% shrinkage through 0% gaps and 100% shrinkage. Assignment of which panels have gaps or shrinkage, and the axial location of the gap is based on random selection.

The results of the KENO calculations for the various shrinkage/gap scenarios are provided below:

Shrinkage/Gap Scenario	K_{eff} ± 95/95 Uncertainty
100% Random Gaps	0.9170 ±0.0024
75% Random Gaps/25% Bottom Shrinkage	0.9273 ±0.0029
50% Random Gaps/50% Bottom Shrinkage	0.9377 ±0.0024

25% Random Gaps/75% Bottom Shrinkage   0.9580 ±0.0024

100% Bottom Shrinkage   0.9754 ±0.0024

Examination of the trend in reactivity with fraction of gaps/shrinkage indicates that reactivity increases as more of the total absorber shrinkage is positioned at the panel bottom. Positioning all of the absorber shrinkage at the bottom is extremely conservative since it ignores the realistic possibilities of uniform top/bottom shrinkage or random occurrences and positioning of the top/bottom shrinkage. Previous studies performed for racks similar to V. C. Summer indicate that assuming a 50/50 mix of top and bottom shrinkage with random positioning results in a K_{eff} which is significantly reduced from the one-end only scenario.

The results of blackness testing performed in the Region 1 racks has revealed the presence of gaps in 75% of the inspected panels. Based on this data, the K_{eff} from the 75% gap scenario will be used as the reference reactivity for the Region 1 K_{eff} summation. This scenario most closely represents the measured absorber panel shrinkage/gap development experienced to date and will bound future accumulation of even more gaps. Even though a realistic (random) distribution of gaps has been assumed, this calculation is still very conservative due to the assumptions of 4% total width and length shrinkage in every absorber panel; the use of a single, maximum 4 inch gap in every panel with gaps (with the placement of the remaining 1.56 inches of shrinkage at the bottom end); and the placement of the entire 4% of length shrinkage (5.56") at the bottom for those panels without gaps.

Calculational and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases are included:

Methodology: As discussed in Section 2 of this report, benchmarking of the Westinghouse KENO Va methodology resulted in a method bias of 0.0074 ΔK.

B10 Self Shielding: To correct for the modeling assumption that individual B^{10} atoms are homogeneously distributed within the absorber material (versus clustered about each B4C particle), a bias of 0.0010 ΔK is applied.

Water Temperature: To account for the normal range of spent fuel pool water temperatures (40° to 180°F), a reactivity bias of 0.0016 ΔK is applied.

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX perturbation calculations are performed. For the V. C. Summer Region 1 spent fuel storage rack, UO_2 and Boraflex material tolerances are considered along with construction tolerances related to the cell I.D., cell center-to-center spacing, and stainless steel thickness. Uncertainties associated with calculational and methodology accuracy are also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components are considered in the total uncertainty statistical summation:

U^{234} Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o U^{235} about the nominal 4.00 w/o U^{235} reference enrichment was evaluated with PHOENIX and resulted in a reactivity increase of 0.0023 ΔK.

UO_2 Density: A ±2.0% variation about the nominal 95% reference theoretical density was evaluated with PHOENIX and resulted in a reactivity increase of 0.0025 ΔK.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 2.0% (about the nominal 1.2110% reference value) was evaluated with PHOENIX and resulted in a reactivity increase of 0.0015 ΔK.

Storage Cell I.D.: The ±0.032 inch tolerance about the nominal 8.85 inch reference cell I.D. was evaluated with PHOENIX and resulted in a reactivity increase of 0.0008 ΔK.

Center-to-Center Spacing: The ±0.0625 inch tolerance about the nominal 10.4025 inch reference cell center-to-center was evaluated with PHOENIX and resulted in a reactivity increase of 0.0052 ΔK.

Stainless Steel Thickness: The ±0.003/0.004 inch tolerances about the nominal 0.049/0.065 inch reference stainless steel thicknesses were evaluated with PHOENIX and resulted in a reactivity increase of 0.0011 ΔK.

Boraflex Absorber Width: The ±0.0625 inch tolerance about the nominal 8.45 inch Boraflex panel width was evaluated with PHOENIX and resulted in a reactivity increase of 0.0003 ΔK.

Boraflex Absorber Thickness: The ±0.007 inch tolerance about the nominal 0.082 inch Boraflex panel thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0028 ΔK.

Boraflex Absorber Length: An assumed ±0.25 inch tolerance about the nominal 139 inch Boraflex panel length cannot be assessed with PHOENIX due to the 3D nature of the effect. Instead, the impact can be assessed using the results of Westinghouse generic evaluations on this subject[16]. The generic data indicates that removal of 0.25 inches of material from the nominal length will not result in any reactivity increase since the threshold for 3.5" of active fuel exposure on one end is not exceeded. However, for the reference 75% gap/25% shrinkage scenario where bottom fuel exposure does exceed the 3.5" threshold, a 0.25" reduction applied to the bottom end of all absorber panels is conservatively estimated from the generic data to cause a 0.0075 ΔK increase in rack reactivity. This value will be considered in the statistical summation of uncertainty terms.

Boraflex B^{10} Loading: The measured 95/95 minimum B^{10} loading of 0.0255 grams per square centimeter was evaluated with PHOENIX and resulted in a reactivity increase of 0.0011 ΔK.

Assembly Position: The KENO reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells since experience has shown that centered fuel assemblies yield equal or more conservative results in rack K_{eff} than non-centered (asymmetric) positioning. Therefore, no reactivity uncertainty needs to be applied for this tolerance since the most reactive configuration is considered in the calculation of the reference K_{eff}.

Calculation Uncertainty: The KENO calculation for the nominal reference reactivity resulted in a K_{eff} with a 95 percent probability/95 percent confidence level uncertainty of ±0.0029 ΔK.

Methodology Uncertainty: As discussed in Section 2 of this report, comparison against benchmark experiments showed that the 95 percent probability/95 percent confidence uncertainty in reactivity, due to method, is not greater than 0.0029 ΔK.

The maximum K_{eff} for the V. C. Summer Region 1 spent fuel storage rack is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO reference reactivity. The summation is shown in Table 6 on page 41 and results in a maximum K_{eff} of 0.9485.

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the V. C. Summer Region 1 spent fuel rack for storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 4.0 w/o U^{235}.

3.2 IFBA CREDIT REACTIVITY EQUIVALENCING

Storage of fuel assemblies with nominal enrichments greater than 4.0 w/o U^{235} in the V. C. Summer Region 1 spent fuel storage racks is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with the addition of Integral Fuel Burnable Absorbers (IFBA)[17]. IFBAs consist of neutron absorbing material applied as a thin ZrB_2 coating on the outside of the UO_2 fuel pellet. As a result, the neutron absorbing material is a non-removable or integral part of the fuel assembly once it is manufactured.

Two analytical techniques are used to establish the criticality criteria for the storage of IFBA fuel in the fuel storage rack. The first method uses reactivity equivalencing to establish the poison material loading required to meet the criticality limits. The poison material considered in this analysis is a zirconium diboride (ZrB_2) coating manufactured by Westinghouse. The second method uses

the fuel assembly infinite multiplication factor to establish a reference reactivity. The reference reactivity point is compared to the fuel assembly peak reactivity to determine its acceptability for storage in the fuel rack.

3.2.1 IFBA REQUIREMENT DETERMINATION

A series of reactivity calculations are performed to generate a set of IFBA rod number versus enrichment ordered pairs which all yield the equivalent K_{eff} when the fuel is stored in the V. C. Summer Region 1 spent fuel rack. The fuel burnup used in the reactivity calculation is that burnup which yields the highest equivalent K_{eff} when the fuel is stored in the rack. Fuel assembly depletions performed in PHOENIX show that for the number of IFBA rods per assembly considered in this analysis, the maximum reactivity for rack geometry occurs at zero burnup. Although the boron content in the IFBA rods decreases with fuel depletion, the fuel assembly reactivity decreases more rapidly, resulting in a maximum fuel rack reactivity at zero burnup.

The following assumptions were used for the IFBA rod assemblies in the PHOENIX models:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 35 for fuel parameters). At the enrichment level being considered for this application, and with the simplified assembly modeling assumptions (no grids, sleeves, axial blankets, etc.), the 17x17 OFA design yields equivalent or bounding reactivity results relative to the other Westinghouse 17x17 fuel types.

2. The fuel assembly is modeled at its most reactive point in life.

3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.

4. No credit is taken for any natural enrichment axial blankets.

5. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the build up of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.

7. The IFBA absorber material is a zirconium diboride (ZrB_2) coating on the fuel pellet. Each IFBA rod has a nominal poison material loading of 1.50 milligrams B^{10} per inch, which is the minimum standard loading offered by Westinghouse for 17x17 OFA fuel assemblies. This rod and IFBA loading assumption is equivalent to or bounding with respect to the 17x17 STD and other advanced Westinghouse 17x17 fuel assembly designs.

8. The IFBA B^{10} loading is reduced by 5 percent to conservatively account for manufacturing tolerances and then by an additional 25% to conservatively model a minimum poison length of 108 inches.

9. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm^3 .

10. A nominal Boraflex poison material loading of 0.0264 grams B^{10} per square centimeter is used throughout the array, based on asbuilt measurements provided by the Boraflex material vendor.

11. The array is infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.

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

Figure 8 on page 53 shows the constant K$_{eff}$ contour generated for the V. C. Summer Region 1 spent fuel storage rack. Note the endpoint at 0 IFBA rods where the nominal enrichment is 4.0 w/o and at 80 IFBA rods where the nominal enrichment is 5.0 w/o. The interpretation of the endpoint data is as follows: the reactivity of the fuel rack array when filled with fuel assemblies enriched to a nominal 5.0 w/o U^{235} with each containing 80 IFBA rods is equivalent to the reactivity of the rack when filled with fuel assemblies enriched to a nominal 4.0 w/o and containing no IFBAs. The data in Figure 8 on page 53 is also provided on Table 9 on page 44.

It is important to recognize that the curve in Figure 8 on page 53 is based on reactivity equivalence calculations for the specific enrichment and IFBA combinations in actual rack geometry (and not just on simple comparisons of individual fuel assembly infinite multiplication factors). In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered.

The IFBA requirements of Figure 8 on page 53 were developed based on the standard IFBA patterns used by Westinghouse. However, since the worth of individual IFBA rods can change depending on position within the assembly (due to local variations in thermal flux), studies were performed to evaluate this effect and a conservative reactivity margin was included in the development of the IFBA requirement to account for this effect. This assures that the IFBA requirement remains valid at intermediate enrichments where standard IFBA patterns may not be available. In addition, to conservatively account for calculational uncertainties, the IFBA requirements of Figure 8 on page 53 also include a conservatism of approximately 10% on the total number of IFBA rods at the 5.0 w/o end (i.e., about 8 extra IFBA rods for a 5.0 w/o fuel assembly).

Additional IFBA credit calculations were performed to examine the reactivity effects of higher IFBA linear B^{10} loadings (1.5X and 2.0X). These calculations confirm that assembly reactivity remains constant provided the net B^{10} material per assembly is preserved. Therefore, with higher IFBA B^{10} loadings, the required number of IFBA rods per assembly can be reduced by the ratio of the higher loading to the nominal 1.0X loading. For example, using 2.0X IFBA in 5.0 w/o fuel assemblies allows a reduction in the IFBA rod requirement from 80 IFBA rods per assembly to 40 IFBA rods per assembly (80 divided by the the ratio 2.0X/1.0X).

The equivalent K$_{eff}$ for the storage of fuel in the V. C. Summer Region 1 spent fuel rack is determined using the methods described in Section 2.1 of this report. The reference conditions for this are defined by the zero IFBA intercept point in Figure 8 on page 53. The KENO Va computer code was used to calculate the storage rack multiplication factor with an equivalent nominal enrichment of 4.0 w/o and no IFBAs. The reference KENO calculation for this case, including conservative consideration of Boraflex gaps and shrinkage, resulted in a nominal K$_{eff}$ of 0.9273 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0029. After summation with appropriate biases and uncertainties, the final K$_{eff}$ for the V. C. Summer Region 1 spent fuel rack was shown to satisfy the 0.95 K$_{eff}$ limit.

3.2.2 INFINITE MULTIPLICATION FACTOR

The infinite multiplication factor, K$_\infty$, is used as a reference criticality reactivity point, and offers an alternative method for determining the acceptability of fuel assembly storage in the V. C. Summer Region 1 spent fuel storage rack. The reference K$_\infty$ is determined for a nominal fresh 4.0 w/o fuel assembly.

The fuel assembly K$_\infty$ calculations are performed using the Westinghouse licensed core design code PHOENIX-P[18]. The following assumptions were used to develop the infinite multiplication factor model:

1. The Westinghouse 17x17 OFA fuel assembly was analyzed (see Table 1 on page 35 for fuel parameters). The fuel assembly is modeled at its most reactive point in life and no credit is taken for any burnable absorbers in the assembly.

2. All fuel rods contain uranium dioxide at an enrichment of 4.0 w/o U^{235} over the entire length of each rod (this is the maximum nominal enrichment that can be stored in the Region 1 rack without IFBA rods).

3. The fuel array model is based on a unit assembly configuration (infinite in the lateral and axial extent) in V. C. Summer reactor geometry (no rack).

4. The moderator is pure water (no boron) at a temperature of 68° F with a density of 1.0 gm/cm^3.

Calculation of the infinite multiplication factor for the Westinghouse 17x17 OFA fuel assembly in V. C. Summer core geometry resulted in a reference K$_\infty$ of 1.460. This includes a 1% ΔK reactivity bias to conservatively account for calculational uncertainties. This bias is consistent with the standard conservatism included in the V. C. Summer core design refueling shutdown margin calculations.

For IFBA credit, all 17x17 fuel assemblies placed in the V. C. Summer Region 1 spent fuel storage rack must comply with the enrichment-IFBA requirements of Figure 8 on page 53 or have a reference K$_\infty$ less than or equal to 1.460. By

meeting either of these conditions, the maximum rack reactivity will then be less than 0.95, as shown in Section 3.1.

3.3 SENSITIVITY ANALYSIS

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC[2], the variation of the K_{eff} with respect to the following parameters was developed using the PHOENIX computer code:

1. Fuel enrichment, with a 0.50 w/o U^{235} delta about the nominal case enrichment.

2. Center-to-center spacing of storage cells, with a half inch delta about the nominal case center-to-center spacing.

3. Poison loading, with a 0.01 gm-B^{10}/cm^2 delta about the nominal case poison loading.

Results of the sensitivity analysis are shown in Figure 9 on page 54.

4.0   REGION 2 FUEL STORAGE RACKS

This section develops and describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the V. C. Summer Region 2 spent fuel racks.

Section 4.1 describes the analyses performed to show that storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 2.5 w/o U^{235} is acceptable in all cell locations. Section 4.2 describes the reactivity equivalencing analysis which establishes the minimum burnup requirements for assemblies with nominal enrichments above 2.5 w/o. Finally, Section 4.3 presents the results of calculations performed to show the reactivity sensitivity caused by variations in enrichment, center-to-center spacing, and absorber poison loading.

4.1   REACTIVITY CALCULATIONS

To show that Region 2 storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 2.5 w/o satisfies the 0.95 K_{eff} criticality acceptance criteria, KENO is used to establish a nominal reference reactivity and PHOENIX is used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} is developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the nominal KENO reference reactivity.

The following assumptions are used to develop the nominal case KENO model for the Region 2 fuel storage rack evaluation:

1.   The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 35 for fuel parameters). At the enrichment level being considered for this application, and with the simplified assembly modeling assumptions (no grids, sleeves, axial blankets, etc.), the 17x17 OFA design yields equivalent or bounding reactivity results relative to the other Westinghouse 17x17 fuel types.

2.   All fuel rods contain uranium dioxide at a nominal enrichment of 2.5 w/o over the entire length of each rod.

3.   The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.

4.   No credit is taken for any natural enrichment axial blankets.

5.   No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the build up of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.

7. No credit is taken for any burnable absorber in the fuel rods.

8. The moderator is pure water (no boron) at a temperature of 68°F and a density of 1.0 gm/cm^3.

9. A nominal Boraflex poison material loading of 0.0037 grams B^{10} per square centimeter is used throughout the array, based on asbuilt measurements provided by the Boraflex material vendor.

10. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent. This allows neutron leakage from only the axial direction.

11. All available storage cells are loaded with fresh fuel assemblies.

With the above assumptions, the KENO calculation for the nominal case (without absorber panel shrinkage/gap effects) results in a K_{eff} of 0.8845 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0039. The nominal case result can be compared to the results from the shrinkage/gap calculations to determine the relative impact of the Boraflex assumptions. The nominal case is also used as the center point for the sensitivity analyses.

To quantify the benefit of axial leakage, a two-dimensional KENO calculation identical to the nominal three-dimensional calculation is performed, except that axial leakage is eliminated. The 2D KENO calculation results in a K_{eff} of 0.8878 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0037. Comparison with the reference 3D result indicates that axial leakage is worth about 0.0033 ±0.0039 ΔK.

To conservatively evaluate the effects of Boraflex shrinkage and gap development, the methodology described in Section 2.3 is employed. Five shrinkage/gap scenarios are examined to cover the spectrum of shrinkage-to-gap ratios from 100% gaps and 0% shrinkage through 0% gaps and 100% shrinkage. Assignment of which panels have gaps or shrinkage, and the axial location of the gap is based on random selection.

The results of the KENO calculations for the various shrinkage/gap scenarios are provided below:

Shrinkage/Gap Scenario	K_{eff} ± 95/95 Uncertainty
100% Random Gaps	0.8932 ±0.0022
75% Random Gaps/25% Bottom Shrinkage	0.8944 ±0.0021
50% Random Gaps/50% Bottom Shrinkage	0.8987 ±0.0021

25% Random Gaps/75% Bottom Shrinkage   0.9040 ±0.0021

100% Bottom Shrinkage   0.9126 ±0.0046

Examination of the trend in reactivity with fraction of gaps/shrinkage indicates that reactivity increases as more of the total absorber shrinkage is positioned at the panel bottom. Positioning all of the absorber shrinkage at the bottom is extremely conservative since it ignores the realistic possibilities of uniform top/bottom shrinkage or random occurrences and positioning of the top/bottom shrinkage. Previous studies performed for racks similar to V. C. Summer indicate that assuming a 50/50 mix of top and bottom shrinkage with random positioning results in a K_{eff} which is significantly reduced from the one-end only scenario.

Blackness testing performed in the Region 2 racks has failed to find any occurrence of gaps in any of the inspected panels. Based on this data, the K_{eff} from the 0% gap/100% bottom shrinkage scenario is used as the reference reactivity for the Region 2 K_{eff} summation. This scenario will bound future accumulation of gaps since the 100% bottom shrinkage scenario results in the most conservative K_{eff}. It should be noted that this calculation is very conservative due to the assumptions of 4% total width and length shrinkage in every absorber panel and the placement of the entire 4% of length shrinkage (5.56") at the bottom of every absorber panel.

Calculational and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases are included:

   Methodology: As discussed in Section 2 of this report, benchmarking of the Westinghouse KENO Va methodology resulted in a method bias of 0.0074 ΔK.

   B10 Self Shielding: To correct for the modeling assumption that individual B^{10} atoms are homogeneously distributed within the absorber material (versus clustered about each B4C particle), a bias of 0.0053 ΔK is applied.

   Water Temperature: To account for the normal range of spent fuel pool water temperatures (40° to 180°F), a reactivity bias of 0.0016 ΔK is applied.

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX perturbation calculations are performed. For the V. C. Summer Region 2 spent fuel storage rack, UO_2 and Boraflex material tolerances are considered along with construction tolerances related to the cell I.D., cell center-to-center spacing, and stainless steel thickness. Uncertainties associated with calculational and methodology accuracy are also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components are considered in the total uncertainty statistical summation:

U^{235} Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o U^{235} about the nominal 2.50 w/o U^{235} reference enrichment was evaluated with PHOENIX and resulted in a reactivity increase of 0.0046 ΔK.

UO_2 Density: A ±2.0% variation about the nominal 95% reference theoretical density was evaluated with PHOENIX and resulted in a reactivity increase of 0.0028 ΔK.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 2.0% (about the nominal 1.2110% reference value) was evaluated with PHOENIX and resulted in a reactivity increase of 0.0017 ΔK.

Storage Cell I.D.: The ±0.032 inch tolerance about the nominal 8.85 inch reference cell I.D. was evaluated with PHOENIX and resulted in a reactivity increase of 0.0019 ΔK.

Center-to-Center Spacing: The ±0.0625 inch tolerance about the nominal 10.4025/10.1875 inch reference cell center-to-center spacing was evaluated with PHOENIX and resulted in a reactivity increase of 0.0061 ΔK.

Stainless Steel Thickness: The ±0.003/0.004 inch tolerances about the nominal 0.049/0.065 inch reference stainless steel thicknesses were evaluated with PHOENIX and resulted in a reactivity increase of 0.0010 ΔK.

Boraflex Absorber Width: The ±0.0625 inch tolerance about the nominal 8.45 inch Boraflex panel width was evaluated with PHOENIX and resulted in a reactivity increase of 0.0003 ΔK.

Boraflex Absorber Thickness: The ±0.007 inch tolerance about the nominal 0.032 inch Boraflex panel thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0118 ΔK.

Boraflex Absorber Length: An assumed ±0.25 inch tolerance about the nominal 139 inch Boraflex panel length cannot be assessed with PHOENIX due to the 3D nature of the effect. Instead, the impact can be assessed using the results of Westinghouse generic evaluations on this subject[18]. The generic data indicates that removal of 0.25 inches of material from the nominal length will not result in any reactivity increase since the threshold for 3.5" of active fuel exposure on one end is not exceeded. However, for the reference 0% gap/100% shrinkage scenario where bottom fuel exposure does exceed the 3.5" threshold, a 0.25" reduction applied to the bottom end of all absorber panels is conservatively estimated to cause a 0.0031 ΔK increase in rack reactivity. This value will be considered in the statistical summation of uncertainty terms.

Boraflex B^{10} Loading: The measured 95/95 minimum B^{10} loading of 0.0033 grams per square centimeter was evaluated with PHOENIX and resulted in a reactivity increase of 0.0069 ΔK.

Assembly Position: The KENO reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells since experience has shown that centered fuel assemblies yield equal or more conservative results in rack K_{eff} than non-centered (asymmetric) positioning. Therefore, no reactivity uncertainty needs to be applied for this tolerance since the most reactive configuration is considered in the calculation of the reference K_{eff}.

Calculation Uncertainty: The KENO calculation for the nominal reference reactivity resulted in a K_{eff} with a 95 percent probability/95 percent confidence level uncertainty of ± 0.0046 ΔK.

Methodology Uncertainty: As discussed in Section 2 of this report, comparison against benchmark experiments showed that the 95 percent probability/95 percent confidence uncertainty in reactivity, due to method, is not greater than 0.0029 ΔK.

The maximum K_{eff} for the V. C. Summer Region 2 spent fuel storage rack is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO reference reactivity. The summation is shown in Table 7 on page 42 and results in a maximum K_{eff} of 0.9442.

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the V. C. Summer Region 2 spent fuel rack for storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 2.5 w/o U^{235}.

4.2 BURNUP CREDIT REACTIVITY EQUIVALENCING

Storage of burned fuel assemblies in the V. C. Summer Region 2 spent fuel storage rack area is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations are performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 10 on page 55 shows the constant K_{eff} contour generated for close packed storage in the V. C. Summer Region 2 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with fresh fuel at 2.5 w/o U^{235}.

Note in Figure 10 on page 55 the endpoints at 0 MWD/MTU where the enrichment is 2.5 w/o and at 21600 MWD/MTU where the enrichment is 5.0 w/o. The interpretation of this endpoint data is as follows: the reactivity of the spent fuel rack containing 5.0 w/o U^{235} fuel at 21600 MWD/MTU burnup is equivalent to the reactivity of the rack containing fresh fuel having an initial nominal enrichment of 2.5 w/o. The burnup credit curve shown in Figure 10 on page 55 includes a

reactivity uncertainty of 0.0072 ΔK, consistent with the minimum burnup requirement of 21600 MWD/MTU at 5.0 w/o.

It is important to recognize that the curve in Figure 10 on page 55 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered. For convenience, the data from Figure 10 on page 55 is also provided on Table 9 on page 44. The tabulated values have been conservatively reported to allow the use of linear interpolation between the data points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the V. C. Summer Region 2 burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Section 2.2 results in calculations of conservative burnup credit limits[19]. The evaluations show that axial burnup effects can cause assembly reactivity to increase, but the burnup-enrichment combinations required to cause this are well beyond those required by the V. C. Summer Region 2 burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the V. C. Summer Region 2 burnup credit limit is not necessary.

4.3 SENSITIVITY ANALYSIS

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC[2], the variation of the K_{eff} with respect to the following parameters was developed using the PHOENIX computer code:

1. Fuel enrichment, with a 0.50 w/o U^{235} delta about the nominal case enrichment.

2. Center-to-center spacing of storage cells, with a half inch delta about the nominal case center-to-center spacing.

3. Poison loading, with a 0.0037 gm-B^{10}/cm^2 delta about the nominal case poison loading.

Results of the sensitivity analysis are shown in Figure 11 on page 56.

5.0 REGION 3 FUEL STORAGE RACKS

This section develops and describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the V. C. Summer Region 3 spent fuel racks.

Section 5.1 describes the analyses performed to show that storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 1.4 w/o U^{235} is acceptable in all cell locations. Section 5.2 describes the reactivity equivalencing analysis which establishes the minimum burnup requirements for assemblies with nominal enrichments above 1.4 w/o. Finally, Section 5.3 presents the results of calculations performed to show the reactivity sensitivity caused by variations in enrichment, center-to-center spacing, and stainless steel structural material.

5.1 REACTIVITY CALCULATIONS

To show that Region 3 storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 1.4 w/o satisfies the 0.95 K_{eff} criticality acceptance criteria, KENO is used to establish a nominal reference reactivity and PHOENIX is used to assess the effects of material and construction tolerance variations. A final 95/95 K_{eff} is developed by statistically combining the individual tolerance impacts with the calculational and methodology uncertainties and summing this term with the nominal KENO reference reactivity.

The following assumptions are used to develop the nominal case KENO model for the Region 3 fuel storage rack evaluation:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 STD design (see Table 1 on page 35 for fuel parameters). At the enrichment level being considered for this application, and with the simplified assembly modeling assumptions (no grids, sleeves, axial blankets, etc.), the 17x17 STD design yields equivalent or bounding reactivity results relative to the other Westinghouse 17x17 fuel types.

2. All fuel rods contain uranium dioxide at a nominal enrichment of 1.4 w/o over the entire length of each rod.

3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.

4. No credit is taken for any natural enrichment axial blankets.

5. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the build up of fission product poison material.

6. No credit is taken for any spacer grids or spacer sleeves.

7. No credit is taken for any burnable absorber in the fuel rods.

8. The moderator is pure water (no boron) at a temperature of 68°F and a density of 1.0 gm/cm^3 .

9. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent. This allows neutron leakage from only the axial direction.

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

With the above assumptions, the KENO calculation for the nominal case results in a K_{eff} of 0.9183 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0028. The nominal case result is used as the reference reactivity value for the Region 3 K_{eff} summation and is also used as the center point for the sensitivity analyses.

To quantify the benefit of axial leakage, a two-dimensional KENO calculation identical to the nominal three-dimensional calculation is performed, except that axial leakage is eliminated. The 2D KENO calculation results in a K_{eff} of 0.9202 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0050. Comparison with the reference 3D result indicates that axial leakage is worth about 0.0019 ±0.0050 ΔK.

Calculational and methodology biases must be considered in the final K_{eff} summation prior to comparing against the 0.95 K_{eff} limit. The following biases are included:

Methodology: As discussed in Section 2 of this report, benchmarking of the Westinghouse KENO Va methodology resulted in a method bias of 0.0074 ΔK.

Water Temperature: To account for the normal range of spent fuel pool water temperatures (40° to 180°F), a reactivity bias of 0.0045 ΔK is applied.

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX perturbation calculations are performed. For the V. C. Summer Region 3 spent fuel storage rack, UO_2 material tolerances are considered along with construction tolerances related to the cell I.D., cell center-to-center spacing, and stainless steel thickness. Uncertainties associated with calculational and methodology accuracy are also considered in the statistical summation of uncertainty components.

The following tolerance and uncertainty components are considered in the total uncertainty statistical summation:

U^{235} **Enrichment:** The standard DOE enrichment tolerance of ±0.05 w/o U^{235} about the nominal 1.40 w/o U^{235} reference enrichment was evaluated with PHOENIX and resulted in a reactivity increase of 0.0119 ΔK.

UO_2 **Density:** A ±2.0% variation about the nominal 95% reference theoretical density was evaluated with PHOENIX and resulted in a reactivity increase of 0.0033 ΔK.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 2.0% (about the nominal 1.2074% reference value) was evaluated with PHOENIX and resulted in a reactivity increase of 0.0019 ΔK.

Storage Cell I.D.: The ±0.032 inch tolerance about the nominal 8.85 inch reference cell I.D. was evaluated with PHOENIX and resulted in a reactivity increase of 0.0002 ΔK.

Center-to-Center Spacing: The ±0.032 inch tolerance about the nominal 10.1160 inch reference cell center-to-center spacing was evaluated with PHOENIX and resulted in a reactivity increase of 0.0032 ΔK.

Stainless Steel Thickness: The ±0.005 inch tolerance about the nominal 0.090 inch reference stainless steel thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0033 ΔK.

Assembly Position: The KENO reference reactivity calculation assumes fuel assemblies are symmetrically positioned within the storage cells since experience has shown that centered fuel assemblies yield equal or more conservative results in rack K_{eff} than non-centered (asymmetric) positioning. Therefore, no reactivity uncertainty needs to be applied for this tolerance since the most reactive configuration is considered in the calculation of the reference K_{eff}.

Calculation Uncertainty: The KENO calculation for the nominal reference reactivity resulted in a K_{eff} with a 95 percent probability/95 percent confidence level uncertainty of ±0.0028 ΔK.

Methodology Uncertainty: As discussed in Section 2 of this report, comparison against benchmark experiments showed that the 95 percent probability/95 percent confidence uncertainty in reactivity, due to method, is not greater than 0.0029 ΔK.

The maximum K_{eff} for the V. C. Summer Region 3 spent fuel storage rack is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the nominal KENO reference reactivity. The summation is shown in Table 8 on page 43 and results in a maximum K_{eff} of 0.9441.

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met for the V. C. Summer Region 3 spent fuel rack for storage of Westinghouse 17x17 fuel assemblies with nominal enrichments up to 1.4 w/o U^{235}.

5.2 BURNUP CREDIT REACTIVITY EQUIVALENCING

Storage of burned fuel assemblies in the V. C. Summer Region 3 spent fuel storage rack area is achievable by means of the concept of reactivity equivalencing. The concept of reactivity equivalencing is predicated upon the reactivity decrease associated with fuel depletion. For burnup credit, a series of reactivity calculations are performed to generate a set of enrichment-fuel assembly discharge burnup ordered pairs which all yield an equivalent K_{eff} when stored in the spent fuel storage racks.

Figure 12 on page 57 shows the constant K_{eff} contour generated for close packed storage in the V. C. Summer Region 3 spent fuel racks. This curve represents combinations of fuel enrichment and discharge burnup which yield the same rack multiplication factor (K_{eff}) as the rack loaded with fresh fuel at 1.4 w/o U^{235}.

Note in Figure 12 on page 57 the endpoints at 0 MWD/MTU where the enrichment is 1.4 w/o and at 48000 MWD/MTU where the enrichment is 5.0 w/o. The interpretation of this endpoint data is as follows: the reactivity of the spent fuel rack containing 5.0 w/o U^{235} fuel at 48000 MWD/MTU burnup is equivalent to the reactivity of the rack containing fresh fuel having an initial nominal enrichment of 1.4 w/o. The burnup credit curve shown in Figure 12 on page 57 includes a reactivity uncertainty of 0.0160 ΔK, consistent with the minimum burnup requirement of 48000 MWD/MTU at 5.0 w/o.

It is important to recognize that the curve in Figure 12 on page 57 is based on calculations of constant rack reactivity. In this way, the environment of the storage rack and its influence on assembly reactivity is implicitly considered. For convenience, the data from Figure 12 on page 57 is also provided on Table 9 on page 44. The tabulated values have been conservatively reported to allow the use of linear interpolation between the data points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the V. C. Summer Region 3 burnup credit limit. Previous evaluations have been performed to quantify axial burnup reactivity effects and to confirm that the reactivity equivalencing methodology described in Section 2.2 results in calculations of conservative burnup credit limits[19]. The evaluations show that axial burnup effects can cause assembly reactivity to increase, but the burnup-enrichment combinations required to cause this are well beyond those required by the V. C. Summer Region 3 burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the V. C. Summer Region 3 burnup credit limit is not necessary.

5.3 SENSITIVITY ANALYSIS

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC[2], the variation of the K_{eff} with respect to the following parameters was developed using the PHOENIX computer code:

1. Fuel enrichment, with a 0.50 w/o U^{235} delta about the nominal case enrichment.

2. Center-to-center spacing of storage cells, with a half inch delta about the nominal case center-to-center spacing.

3. Stainless steel thickness, with a 0.090 inch delta about the nominal cell wall thickness.

Results of the sensitivity analysis are shown in Figure 13 on page 58.

6.0 SOLUBLE BORON WORTH AND RELAXED LIMITS

During refueling and fuel handling operations, the V. C. Summer spent fuel pool is maintained with a soluble boron concentration of 2000 ppm. After refueling operations have ceased, this level of boron concentration continues to remain in the spent fuel pool since there is no dilution of the concentration. Clean, no boron, makeup water is sometimes added to compensate for evaporation and raise the pool water level back to its nominal level, but this operation does not decrease the minimum concentration of boron which exists in the spent fuel pool.

The concentration of soluble boron in the pool water provides a tremendous degree of reactivity conservatism which is not normally considered in the nominal criticality evaluation. Typically, credit is taken for the existence of boron only under postulated accident conditions with application of the double contingency principle.

This section describes the calculations performed to assess the reactivity worth of the soluble boron concentration which exists in the V. C. Summer spent fuel pool. Relaxed limits are also developed for each storage region by taking credit for a minimum of 300 ppm of soluble boron concentration.

6.1 SOLUBLE BORON WORTH

PHOENIX calculations were performed to evaluate the reactivity worth of soluble boron for the Regions 1, 2, and 3 spent fuel racks. Results of these calculations are shown on Figure 14 on page 59. As the curves show, the presence of soluble boron in the V. C. Summer spent fuel pool provides substantial reactivity conservatism.

6.2 RELAXED LIMITS WITH 300 PPM SOLUBLE BORON

Assuming a nominal concentration of 300 ppm of soluble boron, the reference KENO calculations for the V. C. Summer Regions 1, 2, and 3 spent fuel racks were rerun. These calculations include the same assumptions and conservative treatment of Boraflex gaps and shrinkage as considered in the reference, no-boron calculations. However, the reference enrichment levels considered in each rack calculation were increased consistent with the level of reactivity benefit provided by the 300 ppm of boron concentration.

The following table compares the calculated reference K_{eff} values for the no-boron and with 300 ppm boron assumptions:

Fuel Storage Region	Boron Concentration (ppm)	Reference Enrichment (w/o)	Reference K_{eff} ± 95/95 Uncertainty
Region 1	0	4.0	0.9273 ±0.0029
	300	5.0	0.9243 ±0.0044
Region 2	0	2.5	0.9126 ±0.0046
	300	3.1	0.8951 ±0.0038
Region 3	0	1.4	0.9183 ±0.0028
	300	1.8	0.9122 ±0.0045

The above results show that the reference enrichment limits can be increased because of the presence of 300 ppm soluble boron. For each region, a relaxed, with-boron enrichment limit was established which resulted in an equivalent or reduced reference K_{eff} with respect to the no boron K_{eff}. After summation with the same biases and uncertainties as applied to the no-boron K_{eff} (judged to be conservative since the presence of boron would reduce most of the sensitivities and increase none), the with boron K_{eff} for each region will continue to satisfy the 0.95 K_{eff} limit.

Using the reactivity equivalence methodology described in Section 2.2 of this report, relaxed minimum burnup requirement limits were calculated for the Regions 2 and 3 storage areas, consistent with the relaxed, with-boron enrichment limits. The presence of 300 ppm of boron was considered implicitly in the reactivity equivalence calculations. The results of these calculations are provided in Figure 15 on page 60 and tabulated in Table 10 on page 45. The tabulated values have been conservatively reported to allow the use of linear interpolation between the data points.

7.0 DISCUSSION OF POSTULATED ACCIDENTS

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

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

However, four accidents can be postulated which could cause reactivity to increase beyond the analyzed condition. One such postulated accident would be a loss of the spent fuel pool cooling system. For the Region 1 and 2 racks, this accident would not lead to increased reactivity since the heatup would cause reactivity to decrease. However, for Region 3, this accident could cause a slight increase in reactivity. Calculations for the Region 3 rack show that if the pool water temperature were to increase from 68°F to 248°F (approximate boiling temperature of the bulk coolant at the submerged depth of the fuel racks), reactivity could increase by about 0.008 ΔK. At 248°F, voids resulting from boiling have a negative reactivity effect.

A second postulated accident which could result in increased reactivity would be a "cooldown" event during which the pool temperature would drop below 40°F. This accident would cause reactivity to increase in Regions 1 and 2 only. Based on temperature sensitivities calculated for Regions 1 and 2, reactivity would be expected to increase by about 0.0005 ΔK for a cooldown to 32°F.

A third postulated accident which could result in increased reactivity would be a vertical fuel assembly drop into an already loaded cell. For this accident, the upward axial leakage of that cell would be reduced, however the effect on rack reactivity would be insignificant. This is because the total axial leakage in both the upward and downward directions for the entire spent fuel array is worth only about 0.003 ΔK. Thus, minimizing the upward-only leakage of just a single cell would not cause any significant increase in rack reactivity. Furthermore, the neutronic coupling between the dropped assembly and the already loaded as-

sembly would be very low due to the several inches of assembly nozzle structure which would separate the active fuel regions.

The last postulated accident which could increase reactivity would be a fuel assembly misload into a position for which the restrictions on location, enrichment, minimum IFBA content, or minimum burnup are not satisfied. The reactivity impact of this accident differs for each region due to the unique rack geometries and limits. Calculations were performed for each region to evaluate the effect of misplacing a single, fresh, no IFBA, 5.0 w/o fuel assembly into the center of the fully loaded rack. These calculations indicate that the maximum reactivity effect would occur in Region 3 where this event could cause reactivity to increase by as much as 0.10 ΔK.

For occurrences of any of the above postulated accidents, the double contingency principle of ANSI/ANS 8.1-1983 can be applied. This states that one is not required to assume two unlikely, independent, concurrent events to ensure protection against a criticality accident. Thus, for these postulated accident conditions, the presence of soluble boron in the storage pool water can be assumed as a realistic initial condition since not assuming its presence would be a second unlikely event.

The worth of soluble boron in the V. C. Summer spent fuel pool has been calculated with PHOENIX and is shown in Figure 14 on page 59 for each of the three storage configurations. As the curves show, the presence of soluble boron in the pool water reduces rack reactivity significantly and is more than sufficient to offset the positive reactivity impacts of any of the postulated accidents. To bound the maximum 0.10 ΔK reactivity increase from the most limiting accident (Region 3 assembly misload), it is conservatively estimated that 400 ppm of soluble boron is required. This level of boron is more than sufficient to mitigate the effects of the worst postulated accident in each region.

Since the V. C. Summer spent fuel pool boron concentration is maintained at a minimum of 2000 ppm whenever fuel handling operations are active, and since it is expected this level of boron would remain in the pool between outages, should a postulated accident occur which causes reactivity to increase, K_{eff} will be maintained less than or equal to 0.95 due to the effect of dissolved boron.

Additional evaluations of these postulated accidents were performed assuming the presence of 300 ppm of soluble boron concentration and an initial rack configuration consistent with the 300 ppm relaxed limits. Due to the presence of the boron, the reactivity effects of the accidents were reduced. The results showed the most limiting accident would still be a Region 3 misload, but the maximum reactivity increase would be reduced to no more than 0.065 ΔK. To mitigating this increase, an additional 300 ppm above and beyond the nominal 300 ppm level would be required, bringing the total minimum boron concentration to 600 ppm. Again, since the V. C. Summer spent fuel pool boron concentration is normally 2000 ppm, should a postulated accident occur which cases reactivity to increase, K_{eff} will be maintained less than or equal to 0.95 due to the effect of dissolved boron.

8.0 SUMMARY OF CRITICALITY RESULTS

For the storage of fuel assemblies in the spent fuel storage racks, the acceptance criteria for criticality requires the effective neutron multiplication factor, K_{eff}, to be less than or equal to 0.95, including uncertainties, under all conditions.

This report shows that the acceptance criteria for criticality is met for the V. C. Summer Spent Fuel Storage Racks for the storage of Westinghouse 17x17 fuel assemblies (STANDARD, OFA, VANTAGE 5, VANTAGE 5H, VANTAGE+, and PERFORMANCE+) with the following enrichment limits and IFBA/Burnup requirements:

Region 1   Storage of fresh fuel assemblies with nominal enrichments up to 4.0 w/o U^{235} utilizing all available storage cells. Fresh fuel assemblies with higher initial enrichments can also be stored in this region provided a minimum number of IFBAs are present in each fuel assembly. The minimum IFBA requirements for this region are shown on Figure 8 on page 53 and tabulated in Table 9 on page 44.

Region 2   Storage of fresh fuel assemblies with nominal enrichments up to 2.5 w/o U^{235} utilizing all available storage cells. Burned fuel assemblies with higher initial enrichments can also be stored in this region provided the minimum requirements for enrichment/burnup are satisfied. The minimum burnup requirements for this region are shown on Figure 10 on page 55 and tabulated in Table 9 on page 44.

Region 3   Storage of fresh fuel assemblies with nominal enrichments up to 1.4 w/o U^{235} utilizing all available storage cells. Burned fuel assemblies with higher initial enrichments can also be stored in this region provided the minimum requirements for enrichment/burnup are satisfied. The minimum burnup requirements for this region are shown on Figure 12 on page 57 and tabulated in Table 9 on page 44.

Occurrences of Boraflex shrinkage and gap formation have been considered in the determination of the above Region 1 and 2 rack limits. Conservative assumptions of 4% width and length shrinkage, preferential bottom accumulation of the shrinkage, and use of the EPRI recommended maximum 4 inch single gap size were employed. Various combinations of uniform shrinkage and random axial gaps were examined for each region. The final reference K_{eff} was selected based on the scenario which most closely resembled the measured V. C. Summer

shrinkage/gap data. As supported by the measured shrinkage/gap data, the distribution of gaps within the rack model was based on random assignment.

Additional criticality calculations were performed assuming the presence of a minimum 300 ppm of soluble boron concentration. Relaxed limits were developed for each region, consistent with the reactivity worth of the soluble boron. For Region 1, the maximum enrichment limit is increased to 5.0 w/o with no requirements for minimum IFBA content. For Regions 2 and 3, relaxed burnup credit limits were calculated as presented on Figure 15 on page 60 and tabulated on Table 10 on page 45. The relaxed limits were developed assuming the same conservative treatment of Boraflex shrinkage and gaps as assumed in the no-boron evaluations.

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7, Fuel Handling System; ANSI 57.2-1983, "Design Objectives for LWR Spent Fuel Storage Facilities at Nuclear Power Stations," Section 6.4.2; ANSI N16.9-1975, "Validation of Calculational Methods for Nuclear Criticality Safety"; and the NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage".

Table 1. Fuel Parameters Employed in the Criticality Analysis

Parameter	W 17x17 STD	W 17x17 OFA
Number of Fuel Rods per Assembly	264	264
Rod Zirc-4 Clad O.D. (inch)	0.374	0.360
Clad Thickness (inch)	0.0225	0.0225
Fuel Pellet O.D. (inch)	0.3225	0.3088
Fuel Pellet Density (% of Theoretical)	95	95
Fuel Pellet Dishing Factor (%)	1.2074	1.2110
Rod Pitch (inch)	0.496	0.496
Number of Zirc-4 Guide Tubes	24	24
Guide Tube O.D. (inch)	0.482	0.474
Guide Tube Thickness (inch)	0.016	0.016
Number of Instrument Tubes	1	1
Instrument Tube O.D. (inch)	0.482	0.474
Instrument Tube Thickness (inch)	0.016	0.016

Table 2. Benchmark Critical Experiments

Critical Number	General Description	Enrichment U235 (w/o)	Reflector	Separating Material	Soluble Boron (ppm)	Measured Keff	KENO Reactivity (Keff +/- One Sigma)
1	UO2 Rod Lattice	2.46	water	water	0	1.0002	0.9966 +/- 0.0024
2	UO2 Rod Lattice	2.46	water	water	1037	1.0001	0.9914 +/- 0.0019
3	UO2 Rod Lattice	2.46	water	water	764	1.0000	0.9943 +/- 0.0019
4	UO2 Rod Lattice	2.46	water	B4C pins	0	0.9999	0.9871 +/- 0.0022
5	UO2 Rod Lattice	2.46	water	B4C pins	0	1.0000	0.9902 +/- 0.0022
6	UO2 Rod Lattice	2.46	water	B4C pins	0	1.0097	0.9948 +/- 0.0021
7	UO2 Rod Lattice	2.46	water	B4C pins	0	0.9998	0.9886 +/- 0.0021
8	UO2 Rod Lattice	2.46	water	B4C pins	0	1.0083	0.9973 +/- 0.0021
9	UO2 Rod Lattice	2.46	water	water	0	1.0030	0.9966 +/- 0.0021
10	UO2 Rod Lattice	2.46	water	water	143	1.0001	0.9973 +/- 0.0021
11	UO2 Rod Lattice	2.46	water	stainless steel	514	1.0000	0.9992 +/- 0.0020
12	UO2 Rod Lattice	2.46	water	stainless steel	217	1.0000	1.0031 +/- 0.0021
13	UO2 Rod Lattice	2.46	water	borated aluminum	15	1.0000	0.9939 +/- 0.0022
14	UO2 Rod Lattice	2.46	water	borated aluminum	92	1.0001	0.9882 +/- 0.0022
15	UO2 Rod Lattice	2.46	water	borated aluminum	395	0.9998	0.9854 +/- 0.0021
16	UO2 Rod Lattice	2.46	water	borated aluminum	121	1.0001	0.9848 +/- 0.0022
17	UO2 Rod Lattice	2.46	water	borated aluminum	487	1.0000	0.9892 +/- 0.0021
18	UO2 Rod Lattice	2.46	water	borated aluminum	197	1.0002	0.9944 +/- 0.0022
19	UO2 Rod Lattice	2.46	water	borated aluminum	634	1.0002	0.9956 +/- 0.0020
20	UO2 Rod Lattice	2.46	water	borated aluminum	320	1.0003	0.9893 +/- 0.0022
21	UO2 Rod Lattice	2.46	water	borated aluminum	72	0.9997	0.9900 +/- 0.0022
22	UO2 Rod Lattice	2.35	water	borated aluminum	0	1.0000	0.9980 +/- 0.0024
23	UO2 Rod Lattice	2.35	water	stainless steel	0	1.0000	0.9933 +/- 0.0022
24	UO2 Rod Lattice	2.35	water	water	0	1.0000	0.9920 +/- 0.0024
25	UO2 Rod Lattice	2.35	water	stainless steel	0	1.0000	0.9877 +/- 0.0022
26	UO2 Rod Lattice	2.35	water	borated aluminum	0	1.0000	0.9912 +/- 0.0022
27	UO2 Rod Lattice	2.35	water	B4C	0	1.0000	0.9921 +/- 0.0021
28	UO2 Rod Lattice	4.31	water	stainless steel	0	1.0000	0.9968 +/- 0.0023
29	UO2 Rod Lattice	4.31	water	water	0	1.0000	0.9963 +/- 0.0025
30	UO2 Rod Lattice	4.31	water	stainless steel	0	1.0000	0.9950 +/- 0.0026
31	UO2 Rod Lattice	4.31	water	borated aluminum	0	1.0000	0.9952 +/- 0.0025
32	UO2 Rod Lattice	4.31	water	borated aluminum	0	1.0000	1.0006 +/- 0.0024
33	U-metal Cylinders	93.2	bare	air	0	1.0000	0.9968 +/- 0.0023
34	U-metal Cylinders	93.2	bare	air	0	1.0000	1.0082 +/- 0.0025
35	U-metal Cylinders	93.2	bare	air	0	1.0000	0.9935 +/- 0.0024
36	U-metal Cylinders	93.2	bare	air	0	1.0000	0.9982 +/- 0.0028
37	U-metal Cylinders	93.2	bare	air	0	1.0000	0.9916 +/- 0.0025
38	U-metal Cylinders	93.2	bare	air	0	1.0000	0.9922 +/- 0.0025
39	U-metal Cylinders	93.2	bare	plexiglass	0	1.0000	0.9972 +/- 0.0025
40	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	0.9973 +/- 0.0029
41	U-metal Cylinders	93.2	bare	plexiglass	0	1.0000	1.0019 +/- 0.0027
42	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.0103 +/- 0.0025
43	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.0021 +/- 0.0026
44	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.0022 +/- 0.0029

Table 3. Comparison of PHOENIX Isotopics Predictions to Yankee Core 5
Measurements

Quantity (Atom Ratio)	% Difference
U235/U	-0.67
U236/U	-0.28
U238/U	-0.03
Pu239/U	+3.27
Pu240/U	+3.63
Pu241/U	-7.01
Pu242/U	-0.20
Pu239/U238	+3.24
Mass(Pu/U)	+1.41
FISS-Pu/TOT-Pu	-0.02

Table 4.   Benchmark Critical Experiments PHOENIX Comparison

Description of Experiments	Number of Experiments	PHOENIX k_{eff} Using Experiment Bucklings
UO_2		
Al clad	14	0.9947
SS clad	19	0.9944
Borated H_2O	7	0.9940
Subtotal	40	0.9944
U-Metal		
Al clad	41	1.0012
TOTAL	81	0.9978

Table 5. Data for U Metal and UO₂ Critical Experiments (Part 1 of 2)

Case Number	Cell Type	A/O U-235	H2O/U Ratio	Fuel Density (G/CC)	Pellet Diameter (CM)	Material Clad	Clad OD (CM)	Clad Thickness (CM)	Lattice Pitch (CM)	Boron PPM
1	Hexa	1.328	3.02	7.53	1.5265	Aluminum	1.6916	.07110	2.2050	0.0
2	Hexa	1.328	3.95	7.53	1.5265	Aluminum	1.6916	.07110	2.3590	0.0
3	Hexa	1.328	4.95	7.53	1.5265	Aluminum	1.6916	.07110	2.5120	0.0
4	Hexa	1.328	3.92	7.52	.9855	Aluminum	1.1506	.07110	1.5580	0.0
5	Hexa	1.328	4.89	7.52	.9855	Aluminum	1.1506	.07110	1.6520	0.0
6	Hexa	1.328	2.88	10.53	.9728	Aluminum	1.1506	.07110	1.5580	0.0
7	Hexa	1.328	3.58	10.53	.9728	Aluminum	1.1506	.07110	1.6520	0.0
8	Hexa	1.328	4.83	10.53	.9728	Aluminum	1.1506	.07110	1.8060	0.0
9	Square	2.734	2.18	10.18	.7620	SS-304	.8594	.04085	1.0287	0.0
10	Square	2.734	2.92	10.18	.7620	SS-304	.8594	.04085	1.1049	0.0
11	Square	2.734	3.86	10.18	.7620	SS-304	.8594	.04085	1.1938	0.0
12	Square	2.734	7.02	10.18	.7620	SS-304	.8594	.04085	1.4554	0.0
13	Square	2.734	8.49	10.18	.7620	SS-304	.8594	.04085	1.5621	0.0
14	Square	2.734	10.38	10.18	.7620	SS-304	.8594	.04085	1.6891	0.0
15	Square	2.734	2.50	10.18	.7620	SS-304	.8594	.04085	1.0617	0.0
16	Square	2.734	4.51	10.18	.7620	SS-304	.8594	.04085	1.2522	0.0
17	Square	3.745	2.50	10.27	.7544	SS-304	.8600	.04060	1.0617	0.0
18	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	0.0
19	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	0.0
20	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	456.0
21	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	709.0
22	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1260.0
23	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1334.0
24	Square	3.745	4.51	10.37	.7544	SS-304	.8600	.04060	1.2522	1477.0
25	Square	4.069	2.55	9.46	1.1278	SS-304	1.2090	.04060	1.5113	0.0
26	Square	4.069	2.55	9.46	1.1278	SS-304	1.2090	.04060	1.5113	3392.0
27	Square	4.069	2.14	9.46	1.1278	SS-304	1.2090	.04060	1.4500	0.0
28	Square	2.490	2.84	10.24	1.0297	Aluminum	1.2060	.08130	1.5113	0.0
29	Square	3.037	2.64	9.28	1.1268	SS-304	1.1701	.07163	1.5550	0.0
30	Square	3.037	8.16	9.28	1.1268	SS-304	1.2701	.07163	2.1980	0.0
31	Square	4.069	2.59	9.45	1.1268	SS-304	1.2701	.07163	1.5550	0.0
32	Square	4.069	3.53	9.45	1.1268	SS-304	1.2701	.07163	1.6840	0.0
33	Square	4.069	8.02	9.45	1.1268	SS-304	1.2701	.07163	2.1980	0.0
34	Square	4.069	9.90	9.45	1.1268	SS-304	1.2701	.07163	2.3810	0.0
35	Square	2.490	2.84	10.24	1.0297	Aluminum	1.2060	.08130	1.5113	1677.0
36	Hexa	2.096	2.06	10.38	1.5240	Aluminum	1.6916	.07112	2.1737	0.0
37	Hexa	2.096	3.09	10.38	1.5240	Aluminum	1.6916	.07112	2.4052	0.0
38	Hexa	2.096	4.12	10.38	1.5240	Aluminum	1.6916	.07112	2.6182	0.0
39	Hexa	2.096	6.14	10.38	1.5240	Aluminum	1.6916	.07112	2.9891	0.0
40	Hexa	2.096	8.20	10.38	1.5240	Aluminum	1.6916	.07112	3.3255	0.0
41	Hexa	1.307	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
42	Hexa	1.307	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0

Table 5.   Data for U Metal and UO₂ Critical Experiments   (Part 2 of 2)

Case Number	Cell Type	A/O U-235	H20/U Ratio	Fuel Density (G/CC)	Pellet Diameter (CM)	Material Clad	Clad OD (CM)	Clad Thickness (CM)	Lattice Pitch (CM)	Boron PPM
43	Hexa	1.307	2.02	18.90	1.5240	Aluminum	1.5916	.07112	2.8162	0.0
44	Hexa	1.307	3.01	18.90	1.5240	Aluminum	1.5916	.07112	2.9896	0.0
45	Hexa	1.307	4.02	18.90	1.5240	Aluminum	1.5916	.07112	3.3249	0.0
46	Hexa	1.160	1.01	18.90	1.5240	Aluminum	1.5916	.07112	2.1742	0.0
47	Hexa	1.160	1.51	18.90	1.5240	Aluminum	1.5916	.07112	2.4054	0.0
48	Hexa	1.160	2.02	18.90	1.5240	Aluminum	1.5916	.07112	2.6152	0.0
49	Hexa	1.160	3.01	18.90	1.5240	Aluminum	1.5916	.07112	2.9896	0.0
50	Hexa	1.160	4.02	18.90	1.5240	Aluminum	1.5916	.07112	3.3249	0.0
51	Hexa	1.040	1.01	18.90	1.5240	Aluminum	1.5916	.07112	2.1742	0.0
52	Hexa	1.040	1.51	18.90	1.5240	Aluminum	1.5916	.07112	2.4054	0.0
53	Hexa	1.040	2.02	18.90	1.5240	Aluminum	1.5916	.07112	2.6162	0.0
54	Hexa	1.040	3.01	18.90	1.5240	Aluminum	1.5916	.07112	2.9896	0.0
55	Hexa	1.040	4.02	18.90	1.5240	Aluminum	1.5916	.07112	3.3249	0.0
56	Hexa	1.307	1.00	18.90	.9830	Aluminum	1.1506	.07112	1.4412	0.0
57	Hexa	1.307	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
58	Hexa	1.307	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
59	Hexa	1.307	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
60	Hexa	1.307	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
61	Hexa	1.160	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
62	Hexa	1.160	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
63	Hexa	1.160	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
64	Hexa	1.160	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
65	Hexa	1.160	1.00	18.90	.9830	Aluminum	1.1506	.07112	1.4412	0.0
66	Hexa	1.160	1.52	18.90	.9830	Aluminum	1.1506	.07112	1.5926	0.0
67	Hexa	1.160	2.02	18.90	.9830	Aluminum	1.1506	.07112	1.7247	0.0
68	Hexa	1.160	3.02	18.90	.9830	Aluminum	1.1506	.07112	1.9609	0.0
69	Hexa	1.160	4.02	18.90	.9830	Aluminum	1.1506	.07112	2.1742	0.0
70	Hexa	1.040	1.33	18.90	19.050	Aluminum	2.0574	.07F20	2.8687	0.0
71	Hexa	1.040	1.58	18.90	19.050	Aluminum	2.0574	.07620	3.0086	0.0
72	Hexa	1.040	1.83	18.90	19.050	Aluminum	2.0574	.07620	3.1425	0.0
73	Hexa	1.040	2.33	18.90	19.050	Aluminum	2.0574	.07620	3.3942	0.0
74	Hexa	1.040	2.83	18.90	19.050	Aluminum	2.0574	.07620	3.6284	0.0
75	Hexa	1.040	3.83	18.90	19.050	Aluminum	2.0574	.07620	4.0566	0.0
76	Hexa	1.310	2.02	18.88	1.5240	Aluminum	1.5916	.07112	2.6160	0.0
77	Hexa	1.310	3.01	18.88	1.5240	Aluminum	1.5916	.07112	2.9900	0.0
78	Hexa	1.159	2.02	18.88	1.5240	Aluminum	1.5916	.07112	2.6160	0.0
79	Hexa	1.159	3.01	18.88	1.5240	Aluminum	1.5916	.07112	2.9900	0.0
80	Hexa	1.312	2.03	18.88	.9830	Aluminum	1.1506	.07112	1.7250	0.0
81	Hexa	1.312	3.02	18.88	.9830	Aluminum	1.1506	.07112	1.9610	0.0

Table 6. Spent Fuel Rack Region 1 K_{eff} Summary

	ΔK	K_{eff}
Nominal KENO Reference Reactivity:		0.9273
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	+0.0074	
Boraflex B10 Self Shielding Bias	+0.0010	
Pool Water Temperature Variation	+0.0016	

TOTAL Bias	+0.0100	
Best-Estimate Nominal Keff:		0.9373
Tolerances & Uncertainties:		
UO2 Enrichment Tolerance	+0.0023	
UO2 Density Tolerance	+0.0025	
Fuel Pellet Dishing Variation	+0.0015	
Storage Cell ID Tolerance	+0.0008	
Center-to-Center Tolerance	+0.0052	
Stainless Steel Thickness Tolerance	+0.0011	
Boraflex Absorber Width Tolerance	+0.0003	
Boraflex Absorber Thickness Tolerance	+0.0028	
Boraflex Absorber Length Tolerance	+0.0075	
Boraflex Minimum B10 Content	+0.0011	
Calculational Uncertainty (95/95)	+0.0029	
Methodology Bias Uncertainty (95/95)	+0.0029	

TOTAL Uncertainty (statistical)	+0.0112	
Final Keff Including Uncertainties & Tolerances:		0.9485

Table 7. Spent Fuel Rack Region 2 K_{eff} Summary

	ΔK	K_{eff}
Nominal KENO Reference Reactivity:		0.9126
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	+0.0074	
Boraflex B10 Self Shielding Bias	+0.0053	
Pool Water Temperature Variation	+0.0016	

TOTAL Bias	+0.0143	
Best-Estimate Nominal Keff:		0.9269
Tolerances & Uncertainties:		
U02 Enrichment Tolerance	+0.0046	
U02 Density Tolerance	+0.0028	
Fuel Pellet Dishing Variation	+0.0017	
Storage Cell ID Tolerance	+0.0019	
Center-to-Center Tolerance	+0.0061	
Stainless Steel Thickness Tolerance	+0.0010	
Boraflex Absorber Width Tolerance	+0.0003	
Boraflex Absorber Thickness Tolerance	+0.0118	
Boraflex Absorber Length Tolerance	+0.0031	
Boraflex Minimum B10 Content	+0.0069	
Calculational Uncertainty (95/95)	+0.0046	
Methodology Bias Uncertainty (95/95)	+0.0029	

TOTAL Uncertainty (statistical)	+0 0173	
Final Keff Including Uncertainties & Tolerances:		0.9442

Table 8.   Spent Fuel Rack Region 3 K_{eff} Summary

	ΔK	K_{eff}
Nominal KENO Reference Reactivity:		0.9183
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	+0.0074	
Pool Water Temperature Variation	+0.0045	

TOTAL Bias	+0.0119	
Best-Estimate Nominal Keff:		0.9302
Tolerances & Uncertainties:		
UO2 Enrichment Tolerance	+0.0119	
UO2 Density Tolerance	+0.0033	
Fuel Pellet Dishing Variation	+0.0019	
Storage Cell ID Tolerance	+0.0002	
Center-to-Center Tolerance	+0.0032	
Stainless Steel Thickness Tolerance	+0.0033	
Calculational Uncertainty (95/95)	+0.0028	
Methodology Bias Uncertainty (95/95)	+0.0029	

TOTAL Uncertainty (statistical)	+0.0139	
Final Keff Including Uncertainties & Tolerances:		0.9441

Table 9. Minimum Absorber & Burnup Requirements – No Soluble Boron

Storage Region	Enrichment (w/o)	IFBA Rods In Assembly
Region 1 Rack	4.00	0
	4.20	16
	4.40	32
	4.60	48
	4.80	64
	5.00	80

Storage Region	Enrichment (w/o)	Burnup (MWD/MTU)
Region 2 Rack	2.50	0
	3.00	4700
	3.50	9200
	4.00	13300
	4.50	17500
	5.00	21600
Region 3 Rack	1.40	0
	1.70	6800
	2.00	10900
	2.50	18400
	3.00	24500
	3.50	31100
	4.00	36700
	4.50	42800
	5.00	48000

Note: The IFBA rod requirements shown in this table are based on an IFBA linear B10 loading of 1.50 mg-B10/inch. For higher IFBA linear B10 loadings, the required number of IFBA rods per assembly can be reduced by the ratio of the increased B10 loading to the nominal 1.50 mg-B10/inch loading.

Note: The use of linear interpolation between the minimum burnups reported above is acceptable.

Table 10.   Minimum Absorber & Burnup Requirements – 300 PPM Soluble Boron

Storage Region	Enrichment (w/o)	IFBA Rods In Assembly
Region 1 Rack	5.00	0

Storage Region	Enrichment (w/o)	Burnup (MWD/MTU)
Region 2 Rack	3.10	0
	3.50	3200
	4.00	7400
	4.50	11350
	5.00	15300
Region 3 Rack	1.80	0
	2.00	4400
	2.50	14200
	3.00	21200
	3.50	27000
	4.00	32000
	4.50	37500
	5.00	42700

Note: The use of linear interpolation between the minimum burnups reported above is acceptable.
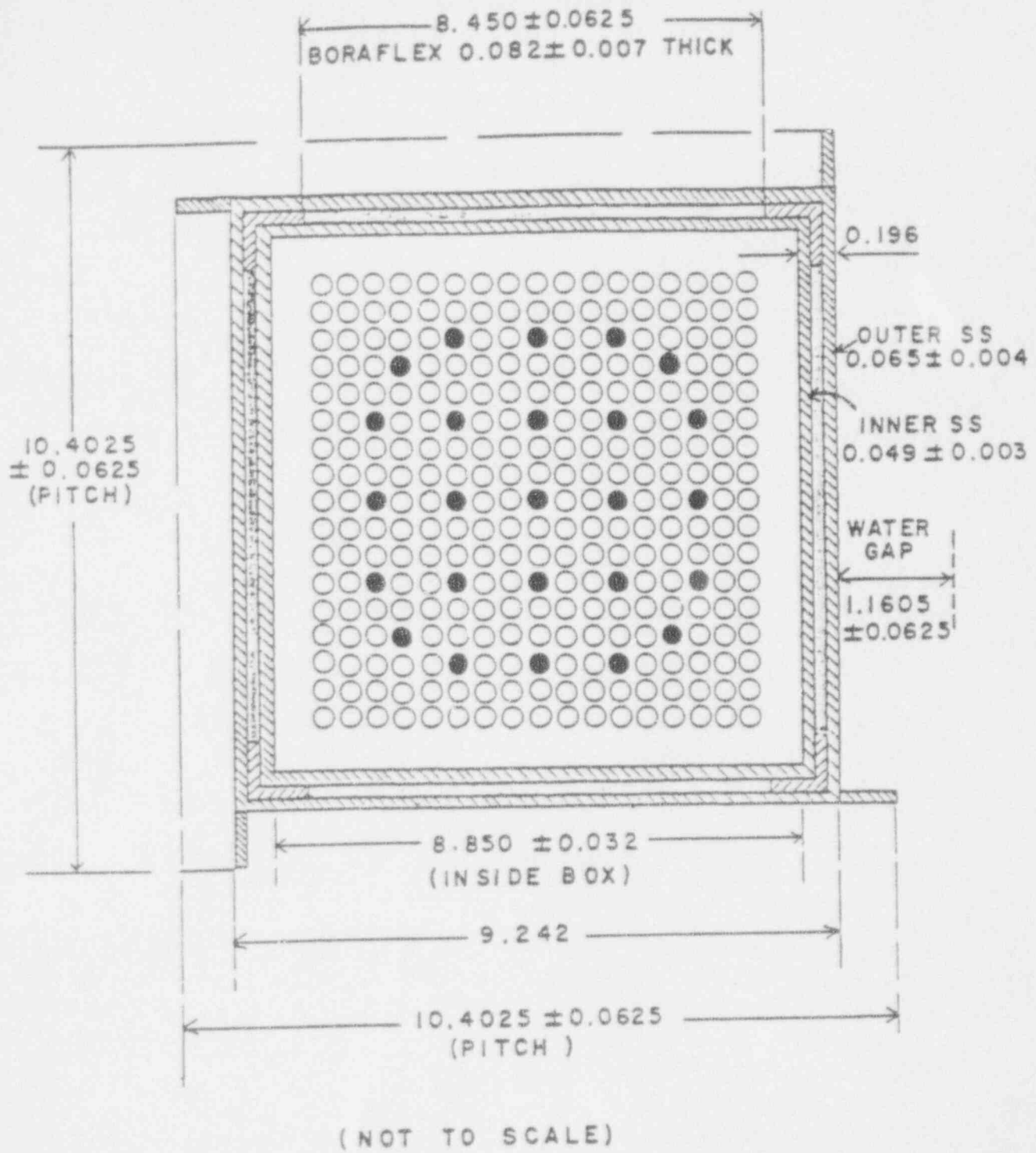
Figure 1   Region 1 Spent Fuel Storage Cell Diagram

46
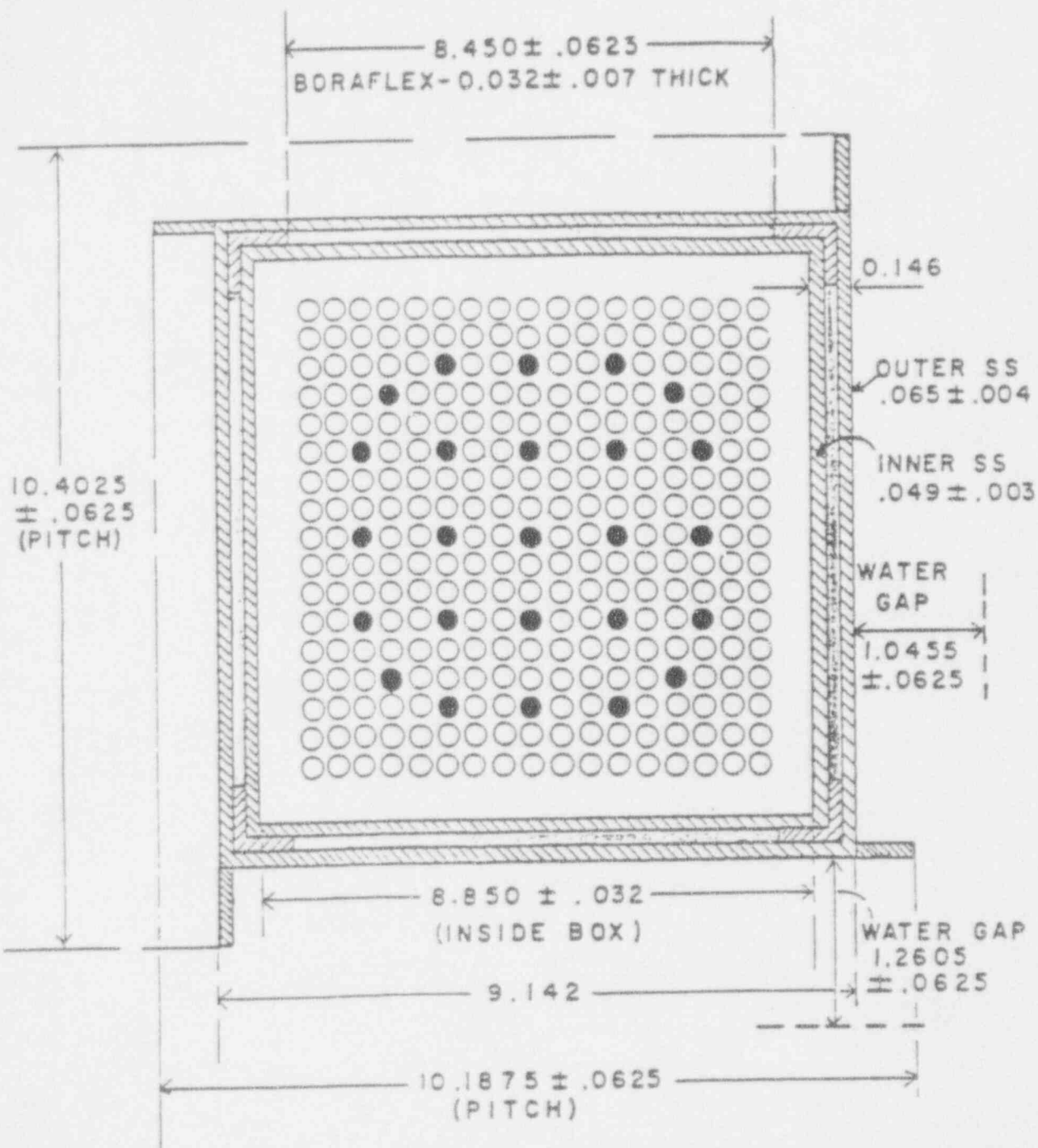
Figure 2   Region 2 Spent Fuel Storage Cell Diagram

WATER GAP

1.086 ±0.032

SS BOX

0.090 ± 0.005

10.116 ±0.032 (PITCH)

8.850 ± 0.032 (INSIDE BOX)

9.030

10.116 ± 0.032 (PITCH)
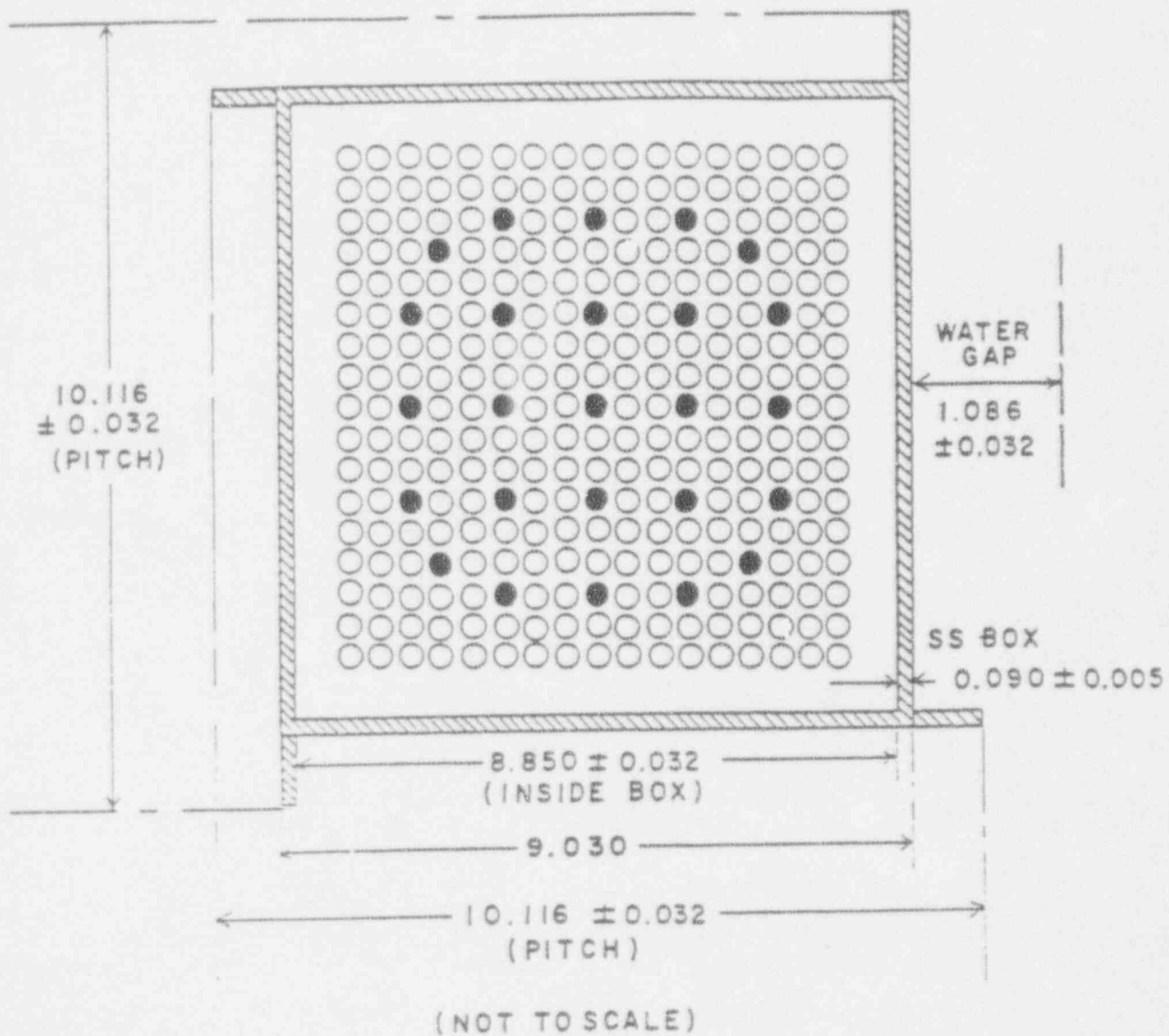
(NOT TO SCALE)

Figure 3   Region 3 Spent Fuel Storage Cell Diagram

48

.083"THK
x 2"x 84¼"

STRIP

8.850"
SQ.(TYP.)

169"
REF.

148"

1"Ø.TYP.
HOLES

2"
2"

¼"

139"
POISON

6¾"

4"
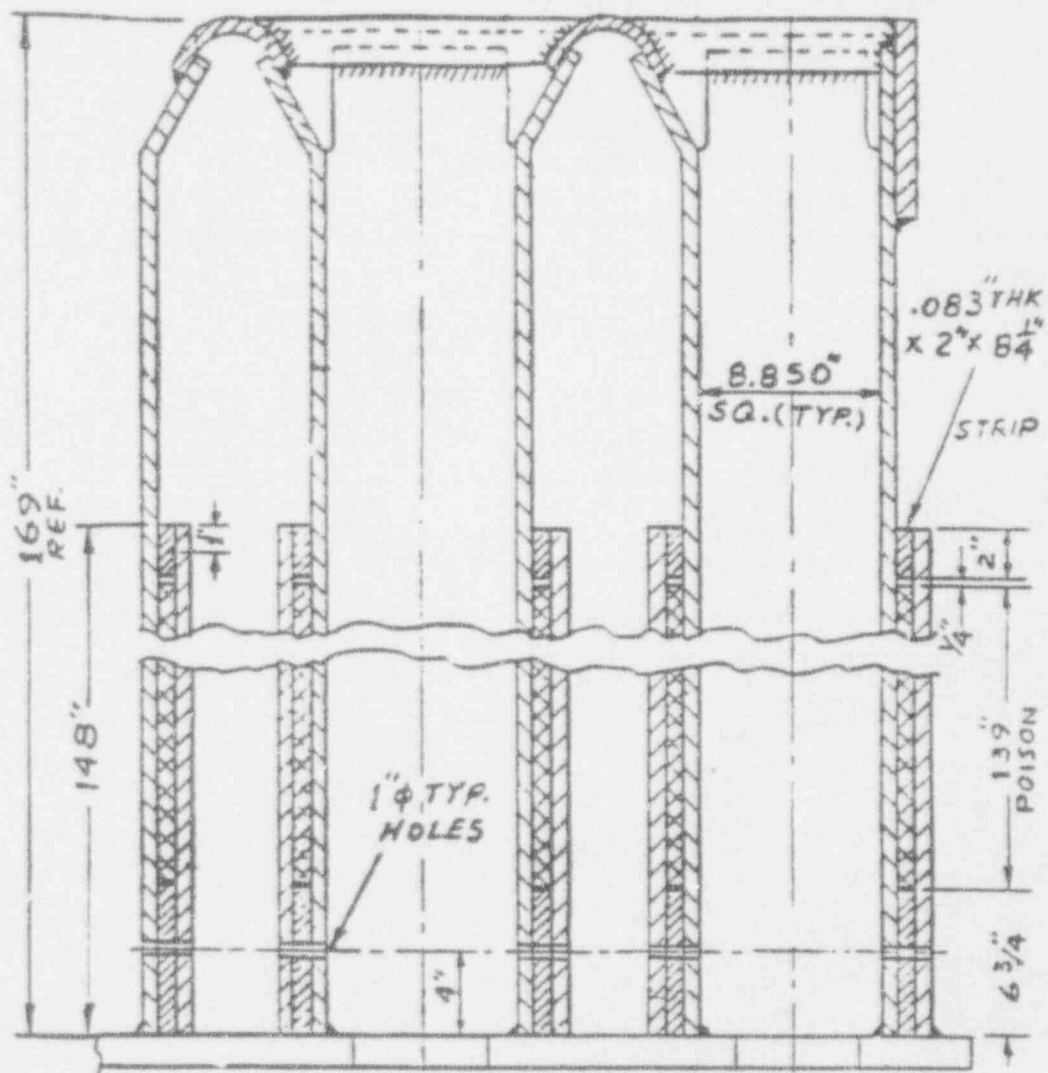
(NOT TO SCALE)

Figure 4   Region 1 Spent Fuel Storage Cell Axial Dimensions

Labels in figure:
- 169" REF.
- 148"
- 0.035" THK. x 2" x 84 1/4" STRIP
- 8.850" SQ. (TYP.)
- 2"
- 1/4"
- 139" POISON
- 1" φ TYP. HOLES
- 4"
- 6 3/4"
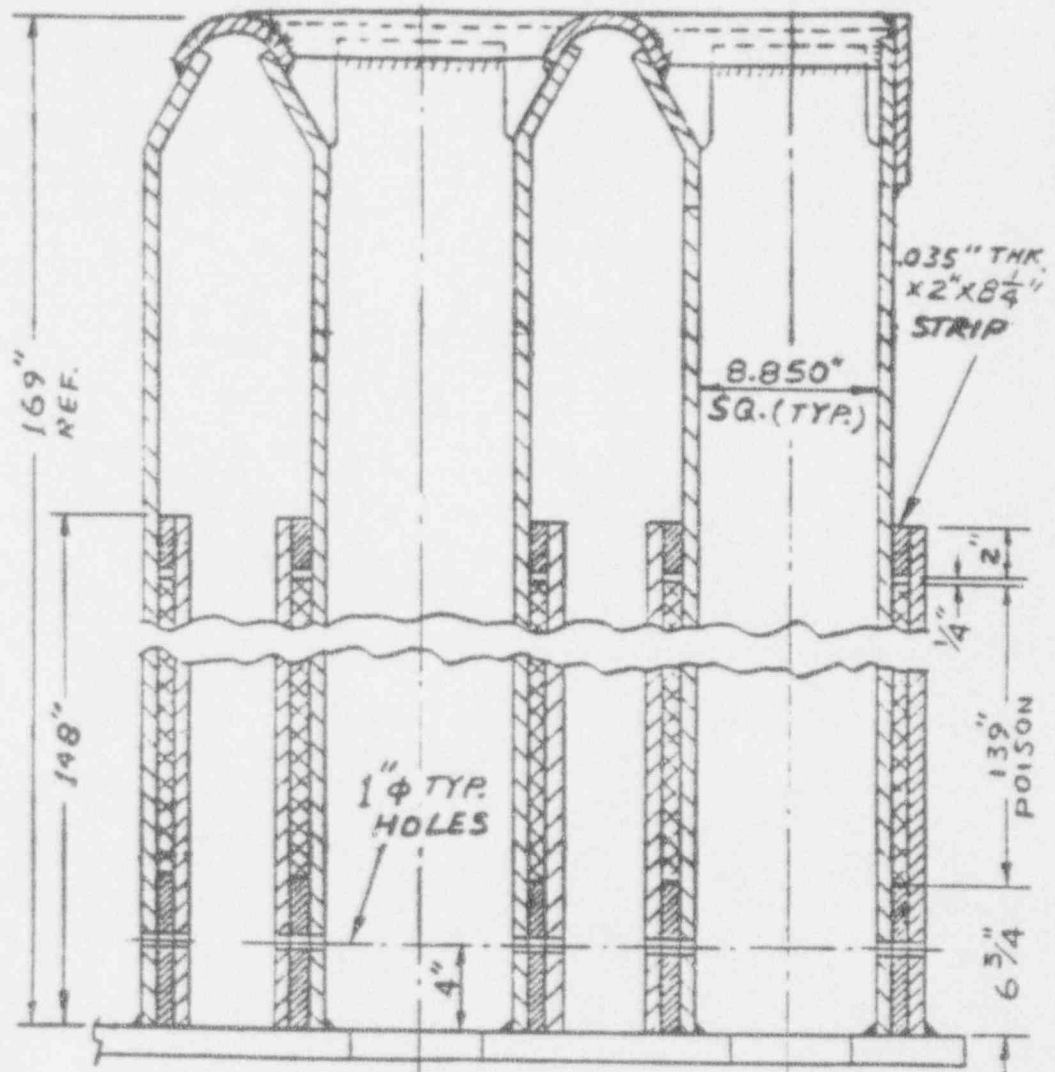
(NOT TO SCALE)

Figure 5   Region 2 Spent Fuel Storage Cell Axial Dimensions

8.850" SQ. (TYP.)

1" φ HOLE (TYP.)

4"

169" REF.
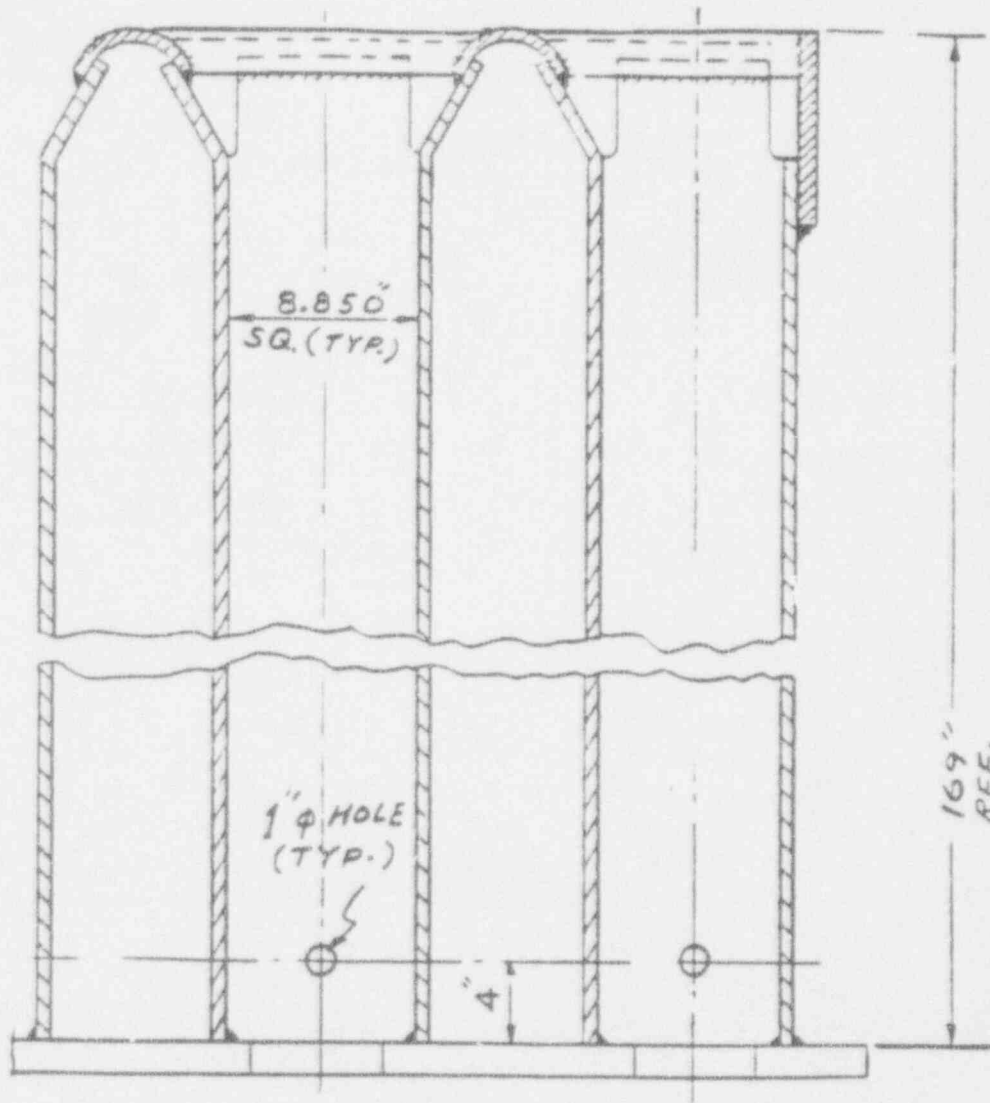
(NOT TO SCALE)

Figure 6   Region 3 Spent Fuel Storage Cell Axial Dimensions

51
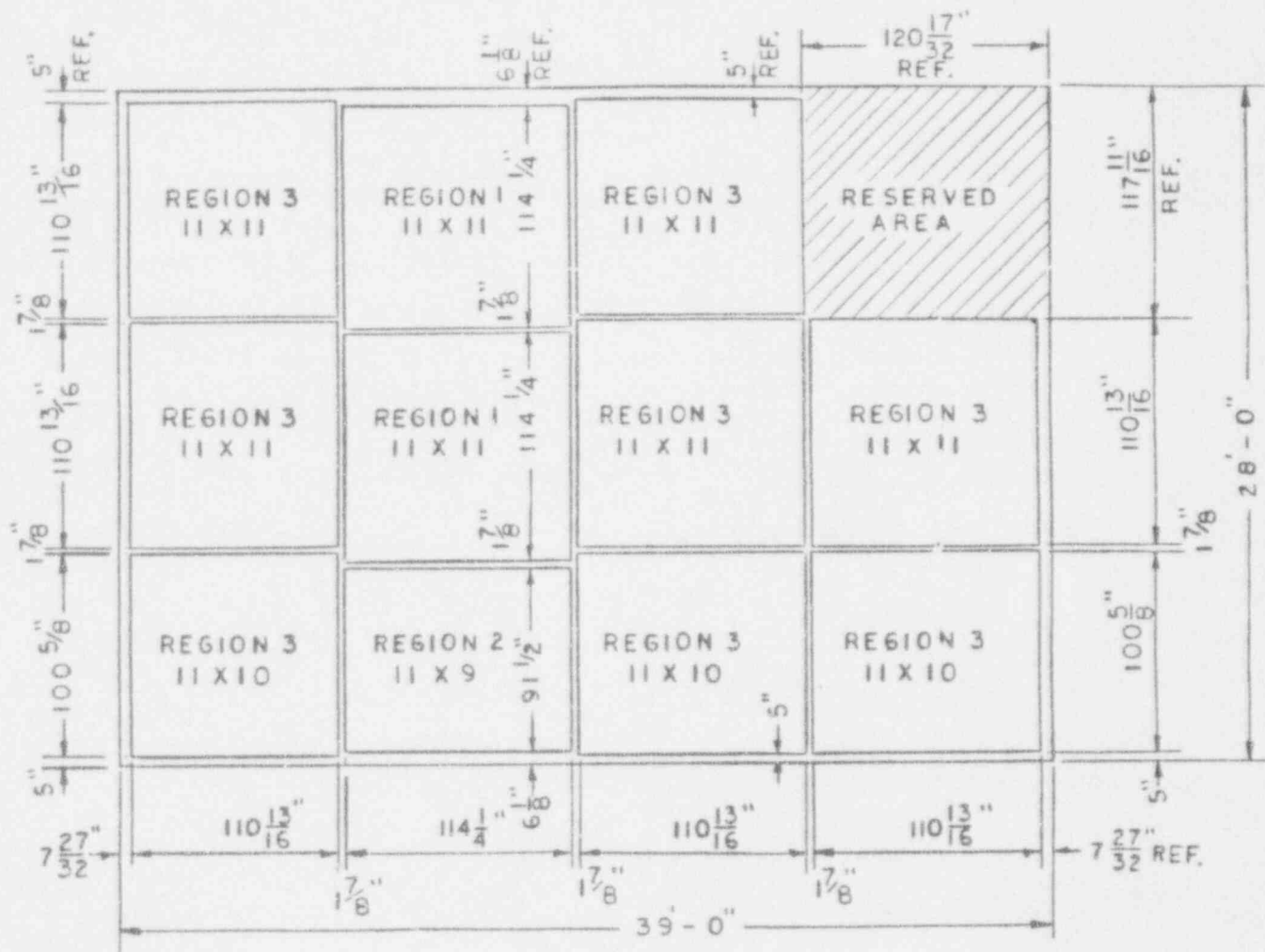
Figure 7   Spent Fuel Storage Rack Layout

52
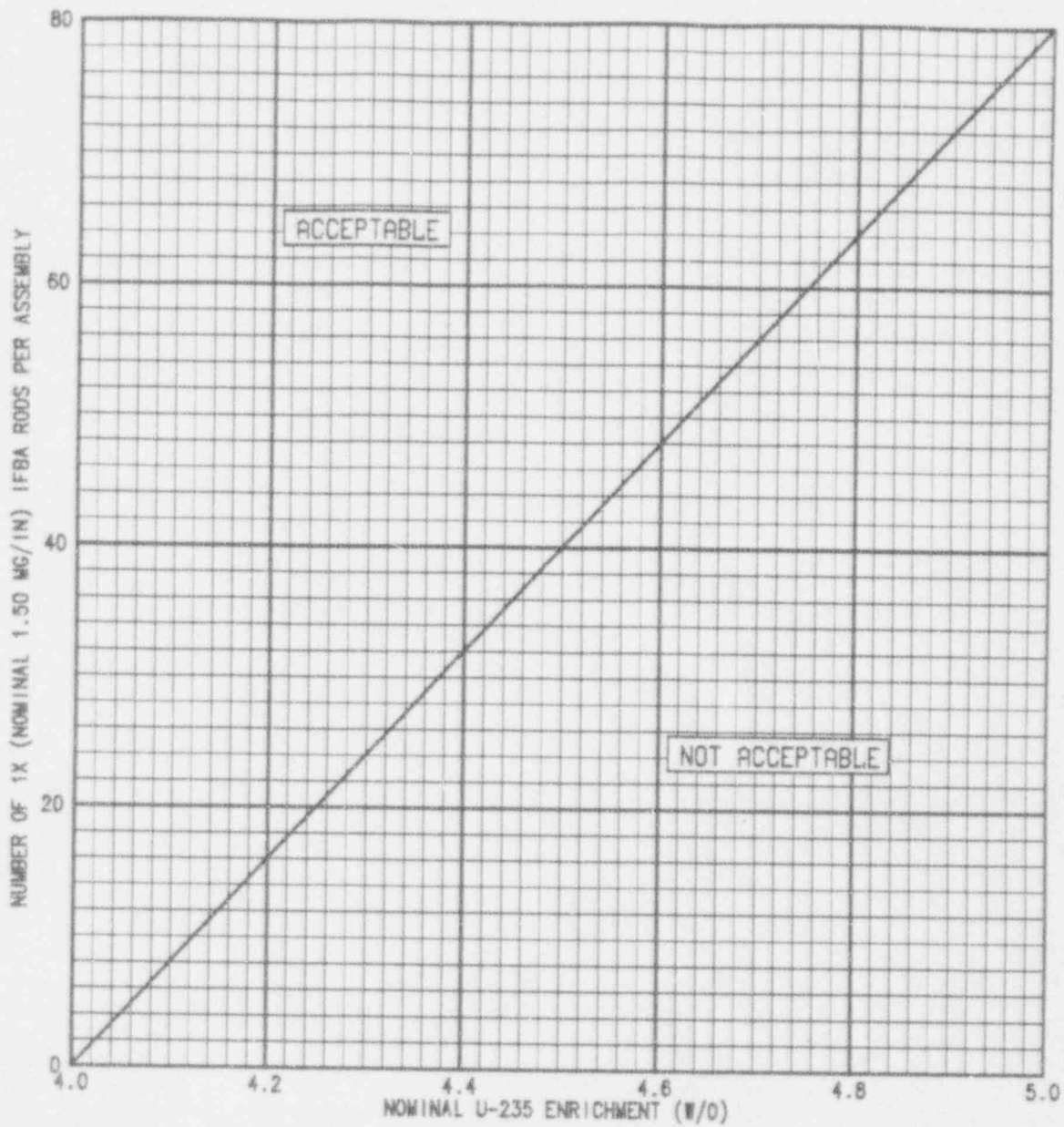
Figure 8   Region 1 Minimum IFBA Requirements
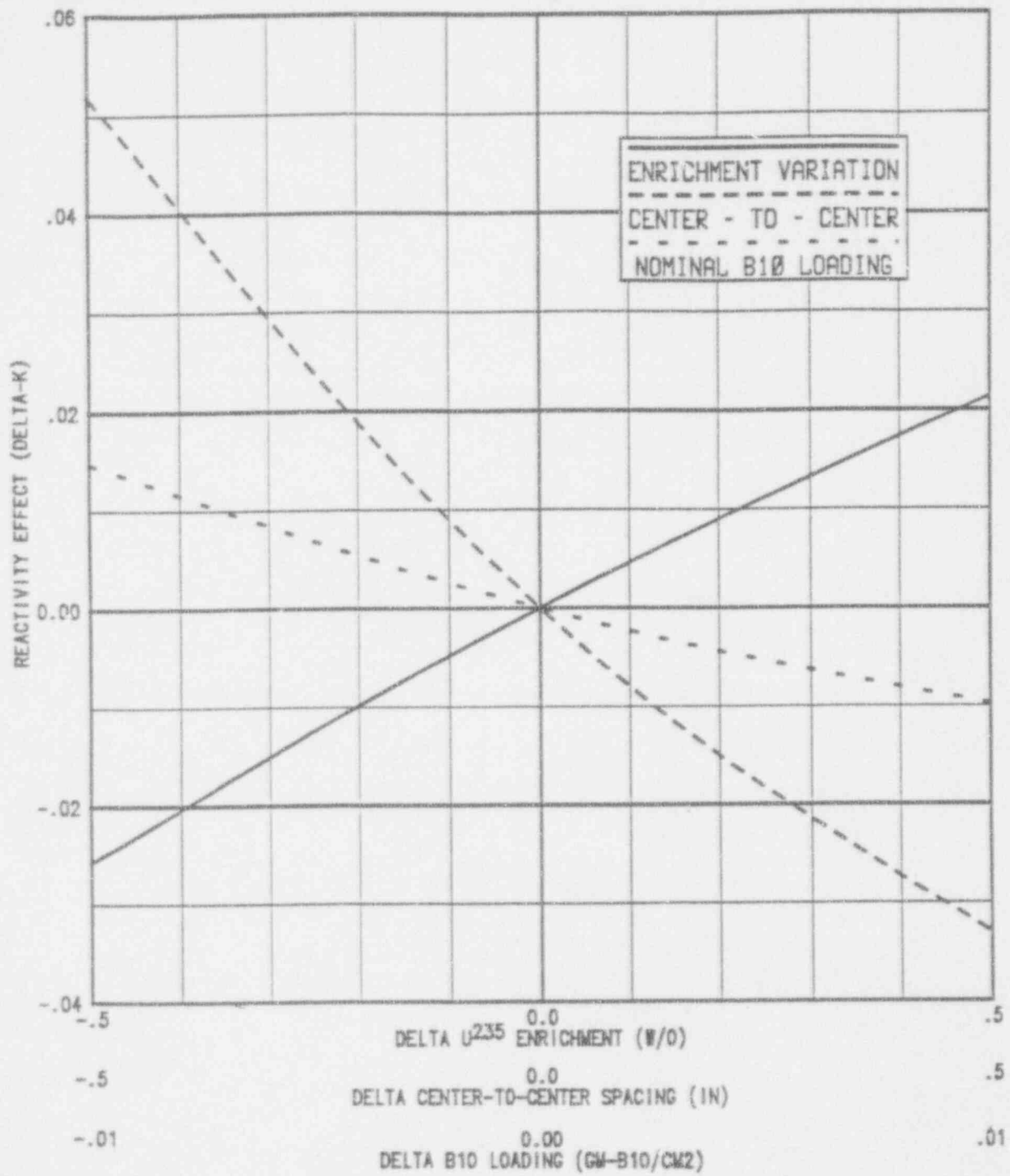
Figure 9   Region 1 Reactivity Sensitivities
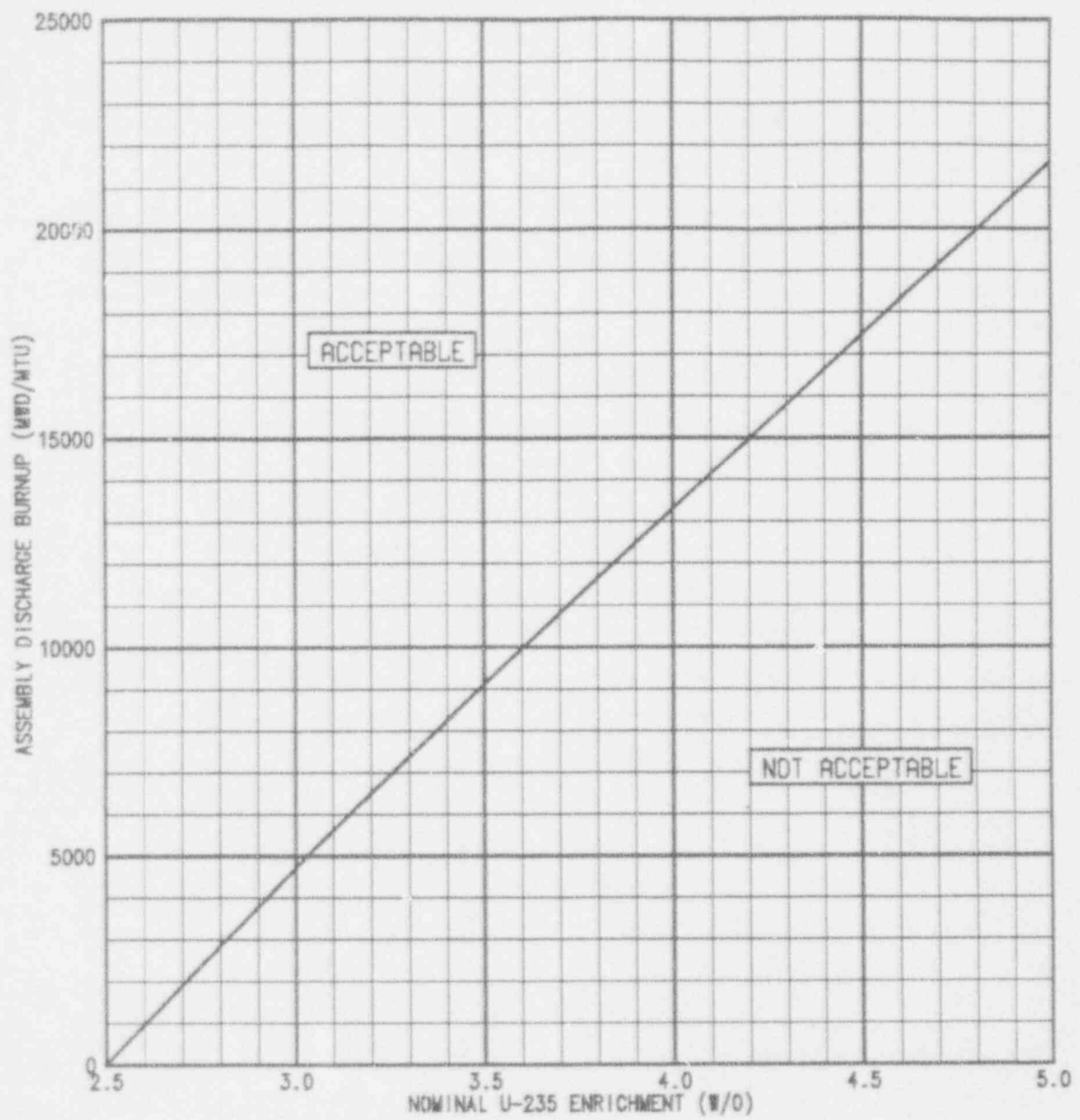
Figure 10   Region 2 Minimum Burnup Requirements
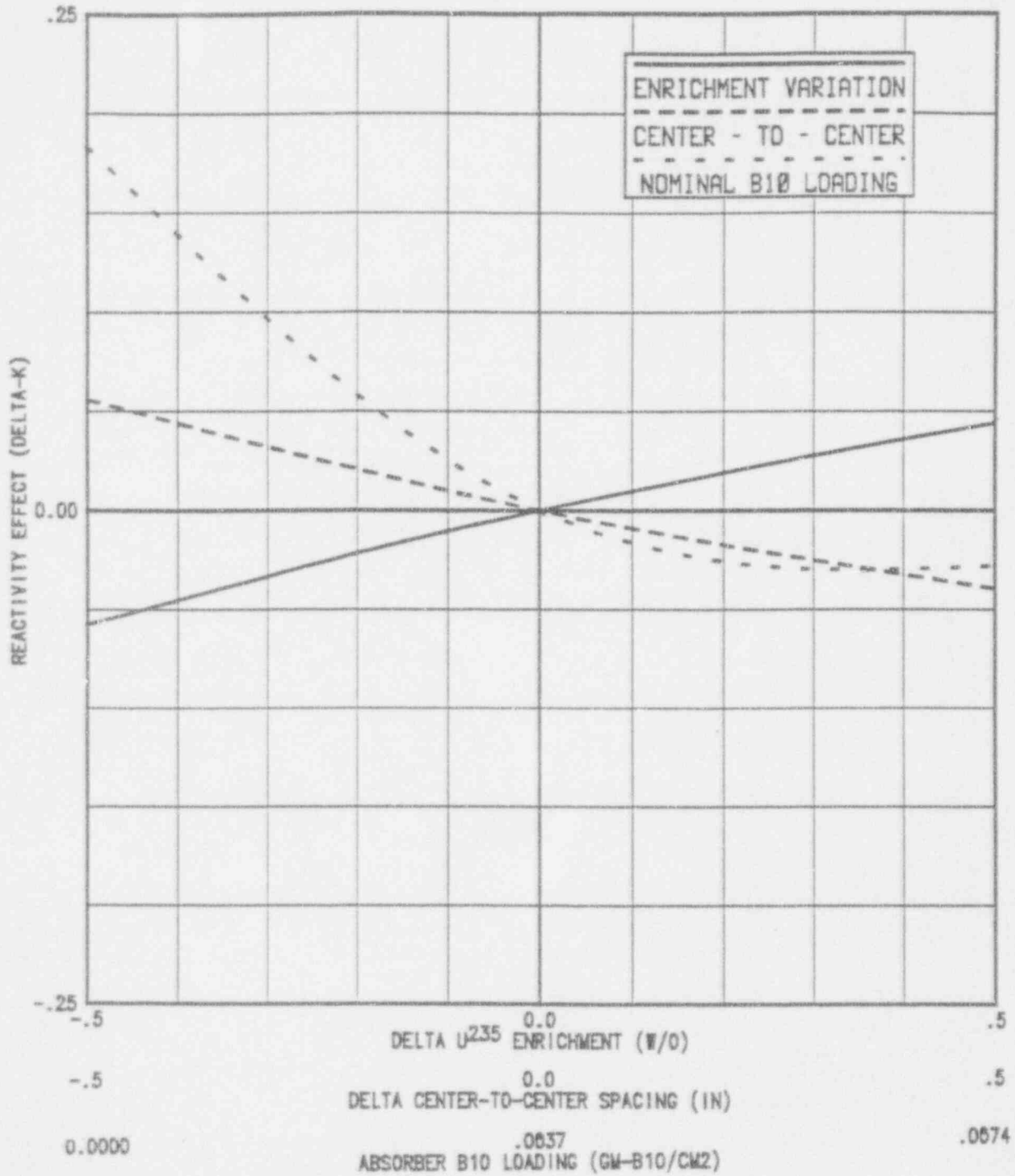
Figure 11   Region 2 Reactivity Sensitivities
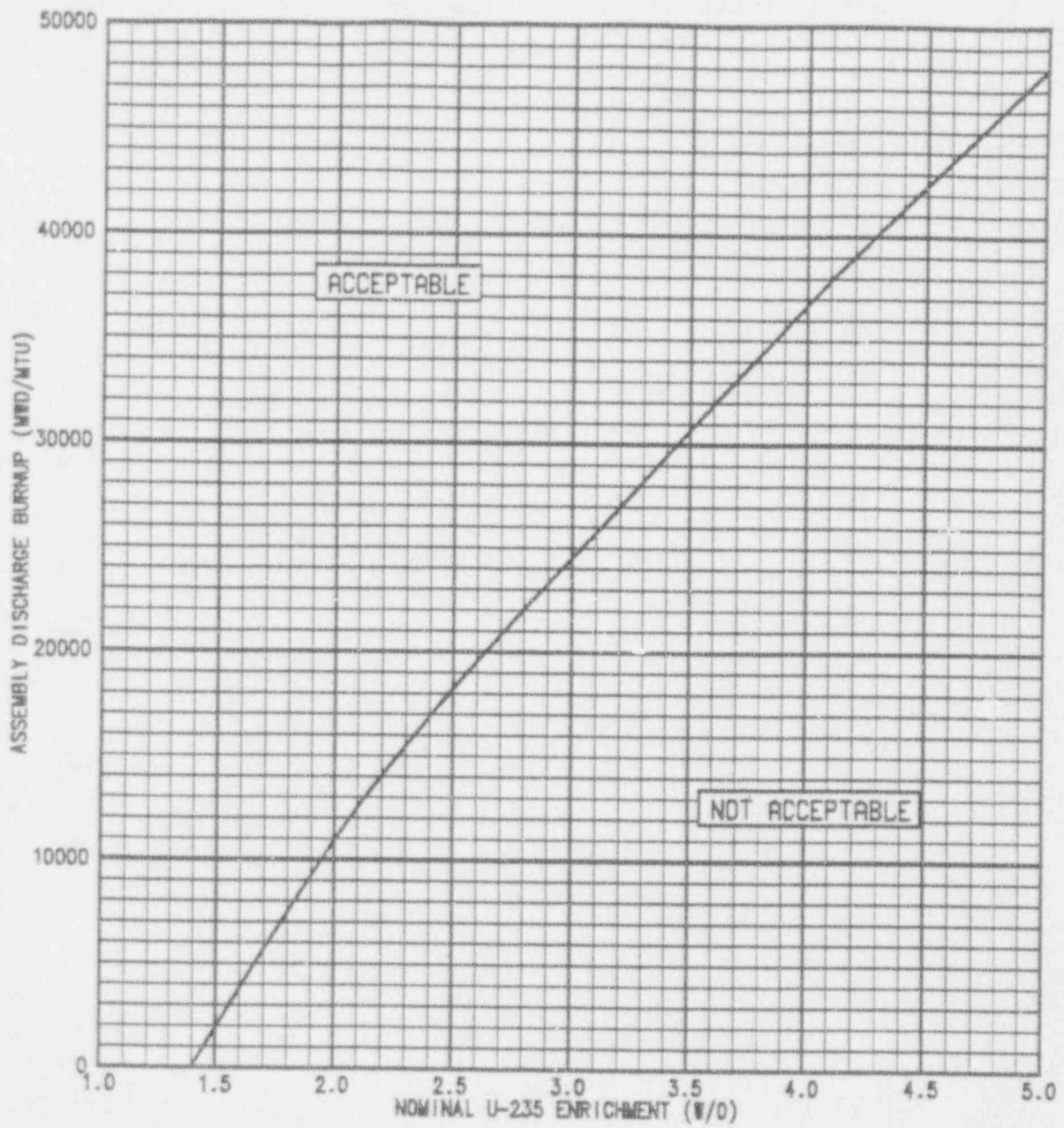
Figure 12   Region 3 Minimum Burnup Requirements
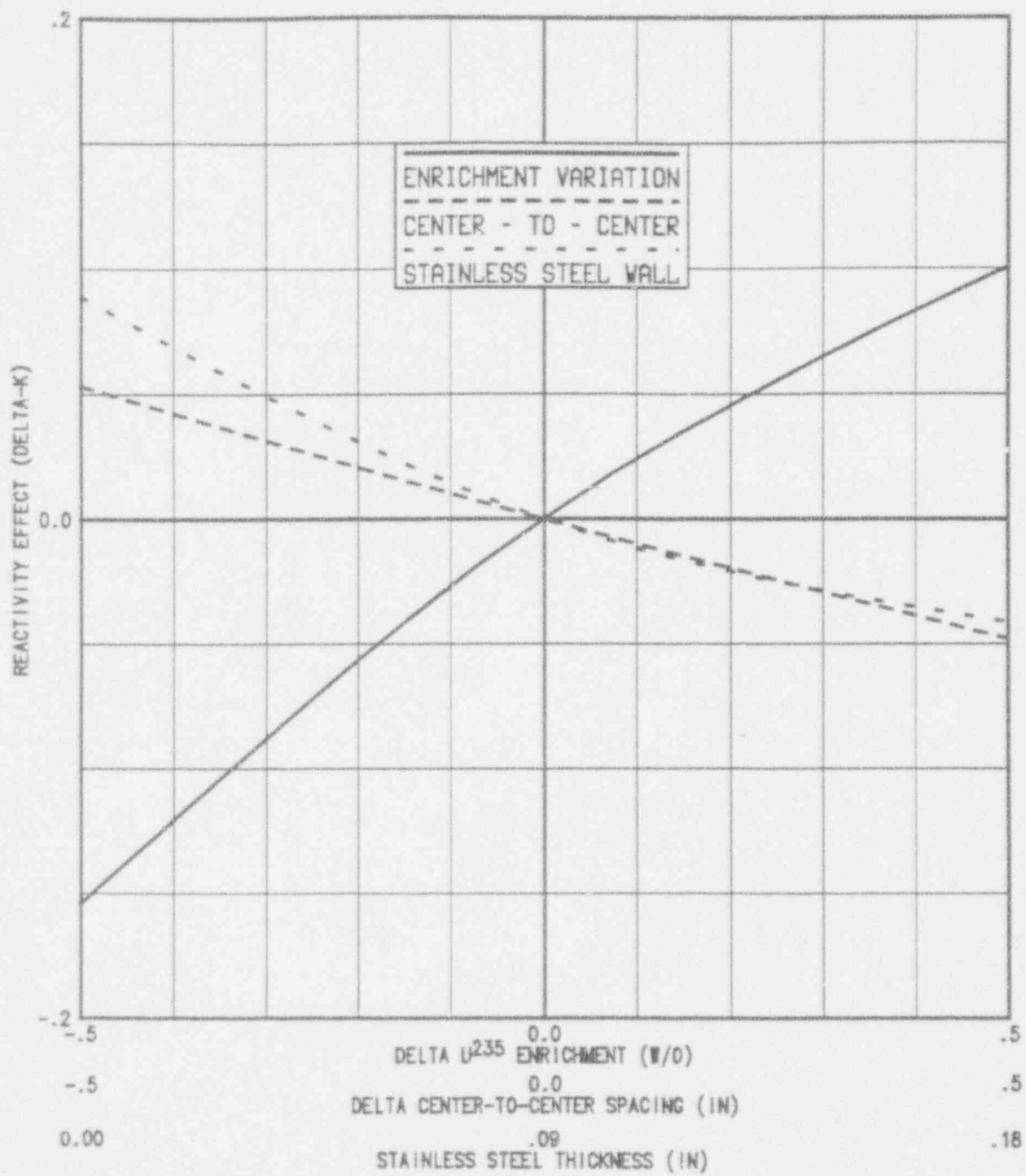
Figure 13   Region 3 Reactivity Sensitivities
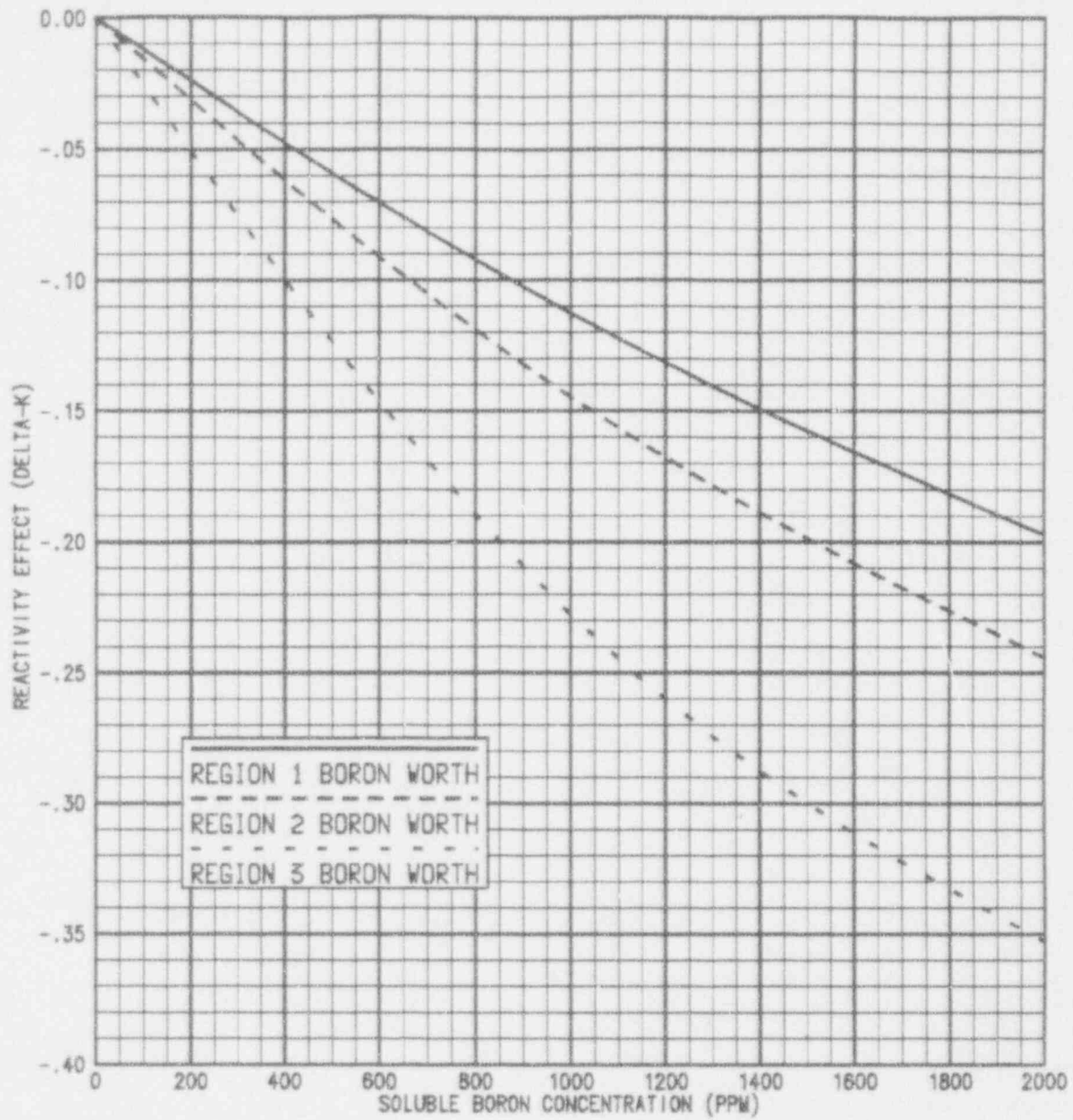
Figure 14   Spent Fuel Rack Soluble Boron Worth
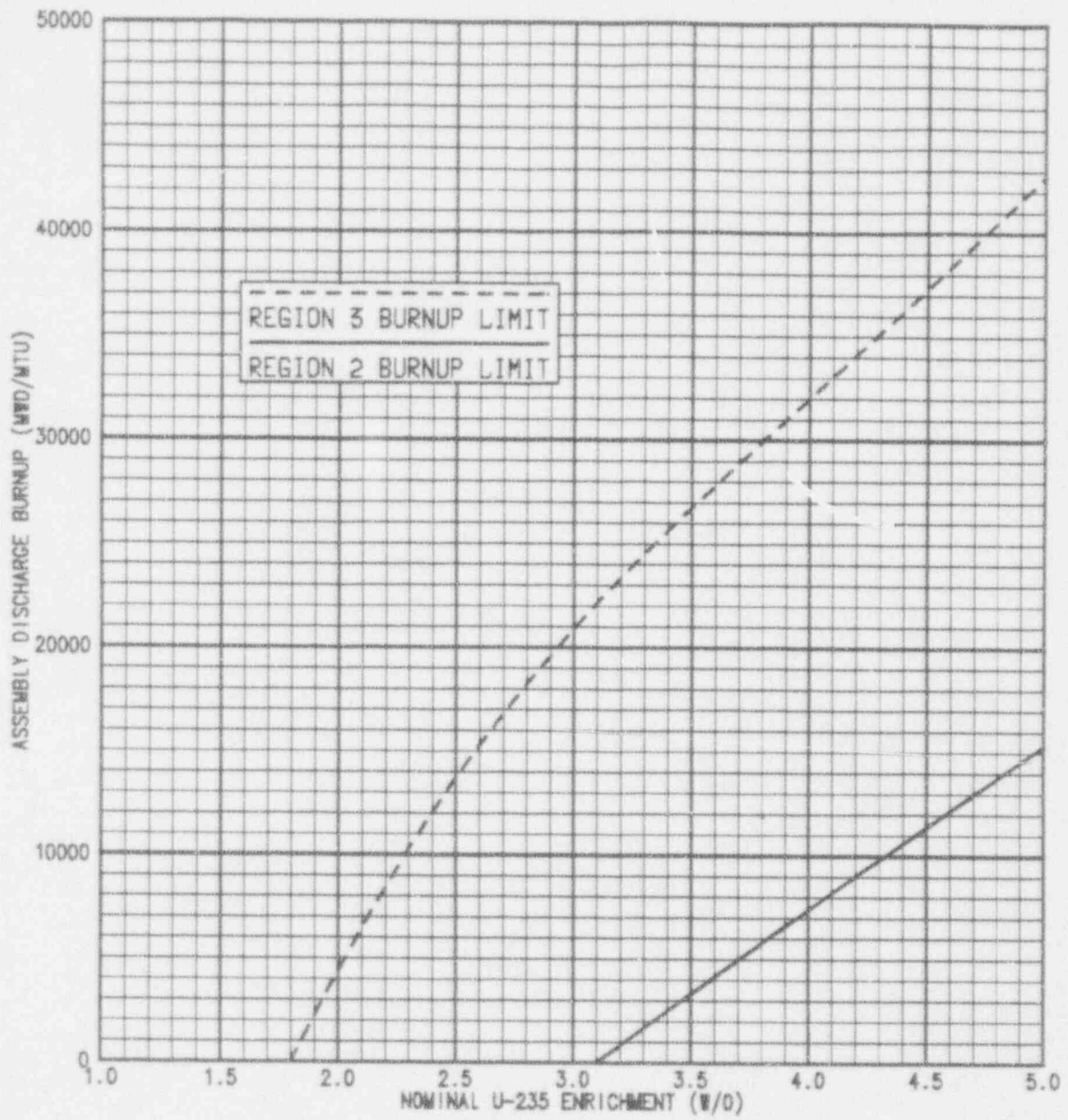
Figure 15   Regions 2 & 3 Minimum Burnup Requirements With 300 PPM
            Boron

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5.0 CRITICALITY ANALYSIS OF FRESH FUEL RACKS

This section describes the analytical techniques and models employed to perform the criticality analysis for storage of fresh fuel in the V. C. Summer fresh fuel racks.

Since the fresh fuel racks are maintained in a dry condition, the criticality analysis will show that the rack K_{eff} is less than 0.95 for the full density and low density optimum moderation conditions. The low density optimum moderation scenario is an accident situation in which no credit can be taken for soluble boron. The criticality method and cross-section library are the same as those discussed in Section 2 of this report.

The following assumptions were used to develop the nominal case KENO model for the storage of fresh fuel in the fresh fuel racks under full density and low density optimum moderation conditions:

1. The fuel assembly contains the highest enrichment authorized, is at its most reactive point in life, and no credit is taken for any burnable poison in the fuel rods.

2. All fuel rods contain uranium dioxide at an enrichment of 5.0 w/o U^{235} over the infinite length of each rod.

3. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the buildup of fission product poison material.

4. No credit is taken for any spacer grids or spacer sleeves.

Calculations for these racks have shown that the W 17x17 OFA fuel assembly yields a larger K_{eff} than does the W 17x17 Standard fuel assembly when both fuel assemblies have the same U^{235} enrichment in full density water. Thus, only the W 17x17 OFA fuel assembly was analyzed (See Table 2 for fuel parameters) in full density water.

5.1 FULL DENSITY MODERATION ANALYSIS

In the nominal case KENO model for the full density moderation analysis, the moderator is pure water at a temperature of 68°F. A conservative value of 1.0 gm/cm³ is used for the density of water. The fuel array is infinite in lateral and axial extent which precludes any neutron leakage from the array.

The KENO calculation for the nominal case resulted in a K_{eff} of 0.9235 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0082.

The maximum K_{eff} under normal conditions arises from consideration of mechanical and material thickness tolerances resulting from the manufacturing process in addition to asymmetric positioning of fuel assemblies within the storage cells. Studies of asymmetric positioning of fuel assemblies within the storage cells has shown that symmetrically placed fuel assemblies yield conservative results in rack K_{eff}. The manufacturing tolerances are stacked in such a manner to minimize the assembly center-to-center spacing and the total volume of steel thereby causing an increase in reactivity. The sheet metal tolerances are considered along with construction tolerances related to the cell I.D. and cell center-to-center spacing. For the fresh fuel storage racks, the assembly center-to-center spacing is reduced from a nominal value of 21" to a minimum of 20.94". Thus, the most conservative, or "worst case", KENO model of the fresh fuel storage racks contains a minimum water gap of 11.72" with symmetrically placed fuel assemblies.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the V. C. Summer fresh fuel storage racks:

$$K_{eff} = K_{worst} + B_{method} + \sqrt{[(ks)^2_{worst} + (ks)^2_{method}]}$$

where:

K_{worst}
= worst case KENO K_{eff} that includes material tolerances, and mechanical tolerances which can result in spacings between assemblies less than nominal

B_{method}
= method bias determined from benchmark critical comparisons

kS_{worst} = 95/95 uncertainty in the worst case KENO K_{eff}

kS_{method} = 95/95 uncertainty in the method bias

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

$K_{eff} = 0.9235 + 0.0083 + \sqrt{[(0.0082)^2 + (0.0018)^2]} = 0.9402$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability confidence level, the acceptance criteria for criticality is met.

5.2 LOW DENSITY OPTIMUM MODERATION ANALYSIS

In the low density optimum moderation analysis, the fuel array is infinite in only the axial extent which precludes any neutron leakage from the top or bottom of the array.

Calculations have shown that the W 17x17 STD fuel assembly yields a larger K_{eff} than does the W 17x17 OFA fuel assembly when both assemblies have the same U^{235} enrichment at low water densities. Thus, the W 17x17 STD assembly was used in the optimum moderation analysis.

Analysis of the V. C. Summer racks has shown that the maximum rack K_{eff} under low density moderation conditions occurs at 0.04 gm/cm³ water density. The KENO calculation of the V. C. Summer fresh racks at 0.04 gm/cm³ water density resulted in a peak K_{eff} of 0.8959 with a 95 percent probability and 95 percent confidence level uncertainty of ±0.0079. Figure 19 shows the fresh fuel rack reactivity as a function of the water density.

The minimum cell center-to-center spacing, rack module spacing and material tolerances have been included in the base case model and result in a storage cell separation distance of 11.86" and a rack module separation distance of 20.94 inches. Studies of asymmetric positioning of fuel assemblies within the storage cells has shown that symmetrically placed fuel assemblies yield conservative results in rack K_{eff}.

Based on the analysis described above, the following equation is used to develop the maximum K_{eff} for the V. C. Summer fresh fuel storage racks under low density optimum moderation conditions:

$K_{eff} = K_{base} + B_{method} + \sqrt{[(ks)^2_{base} + (ks)^2_{method}]}$

where:

K_{base}
= base case KENO K_{eff} that includes nominal mechanical and material dimension

B_{method}
= method bias determined from benchmark critical comparisons

kS_{base}
= 95/95 uncertainty in the base case KENO K_{eff}

kS_{method}
= 95/95 uncertainty in the method bias

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

$$K_{eff} = 0.8959 + 0.0083 + \sqrt{[(0.0079)^2 + (0.0018)^2]} = 0.9123$$

Since K_{eff} is less than 0.95 including uncertainties at a 95/95 probability/confidence level, the acceptance criteria for criticality is met.

6.0 ACCEPTANCE CRITERION FOR CRITICALITY

The neutron multiplication factor in spent fuel pool and fresh fuel vault shall be less than or equal to 0.95, including all uncertainties, under all conditions.

The analytical methods employed herein conform with ANSI N18.2-1973, "Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants," Section 5.7, Fuel Handling System; ANSI 57.2-1983, "Design Objectives for LWR Spent Fuel Storage Facilities at Nuclear Power Stations," Section 6.4.2; ANSI N16.9-1975, "Validation of Calculational Methods for Nuclear Criticality Safety," NRC Standard Review Plan, Section 9.1.2, "Spent Fuel Storage"; and the NRC guidance, "NRC Position for Review and Acceptance of Spent Fuel Storage and Handling Applications," ANSI 57.3-1983, "Design Requirements for New Fuel Storage Facilities at Light Water Reactor Plants."

Table 2. Fuel Parameters Employed in Criticality Analysis

Parameter	W 17x17 OFA	W 17x17 STANDARD
Number of Fuel Rods per Assembly	264	264
Rod Zirc-4 Clad O.D. (inch)	0.360	0.374
Clad Thickness (inch)	0.0225	0.0225
Fuel Pellet O.D. (inch)	0.3088	0.3225
Fuel Pellet Density (% of Theoretical)	96	96
Fuel Pellet Dishing Factor	0.0	0.0
Rod Pitch (inch)	0.496	0.496
Number of Zirc-4 Guide Tubes	24	24
Guide Tube O.D. (inch)	0.474	0.484[1]
Guide Tube Thickness (inch)	0.016	0.018[1]
Number of Instrument Tubes	1	1
Instrument Tube O.D. (inch)	0.474	0.484[1]
Instrument Tube Thickness (inch)	0.016	0.018[1]

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[1] Revised design data shows the Tube O.D. and thickness to be 0.482 and 0.016 inches respectively. These changes will have no significant effect on the results and conclusions of this analysis.
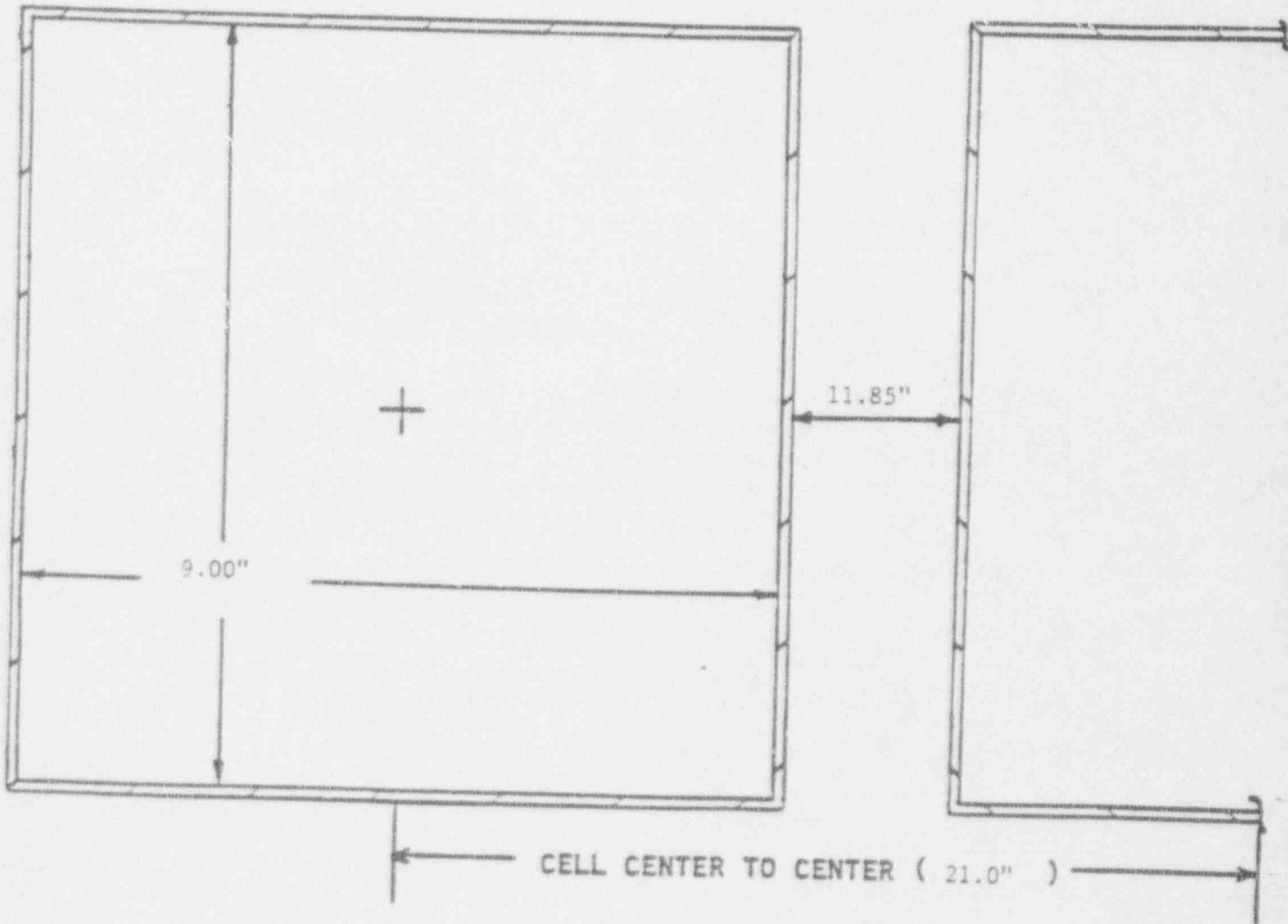
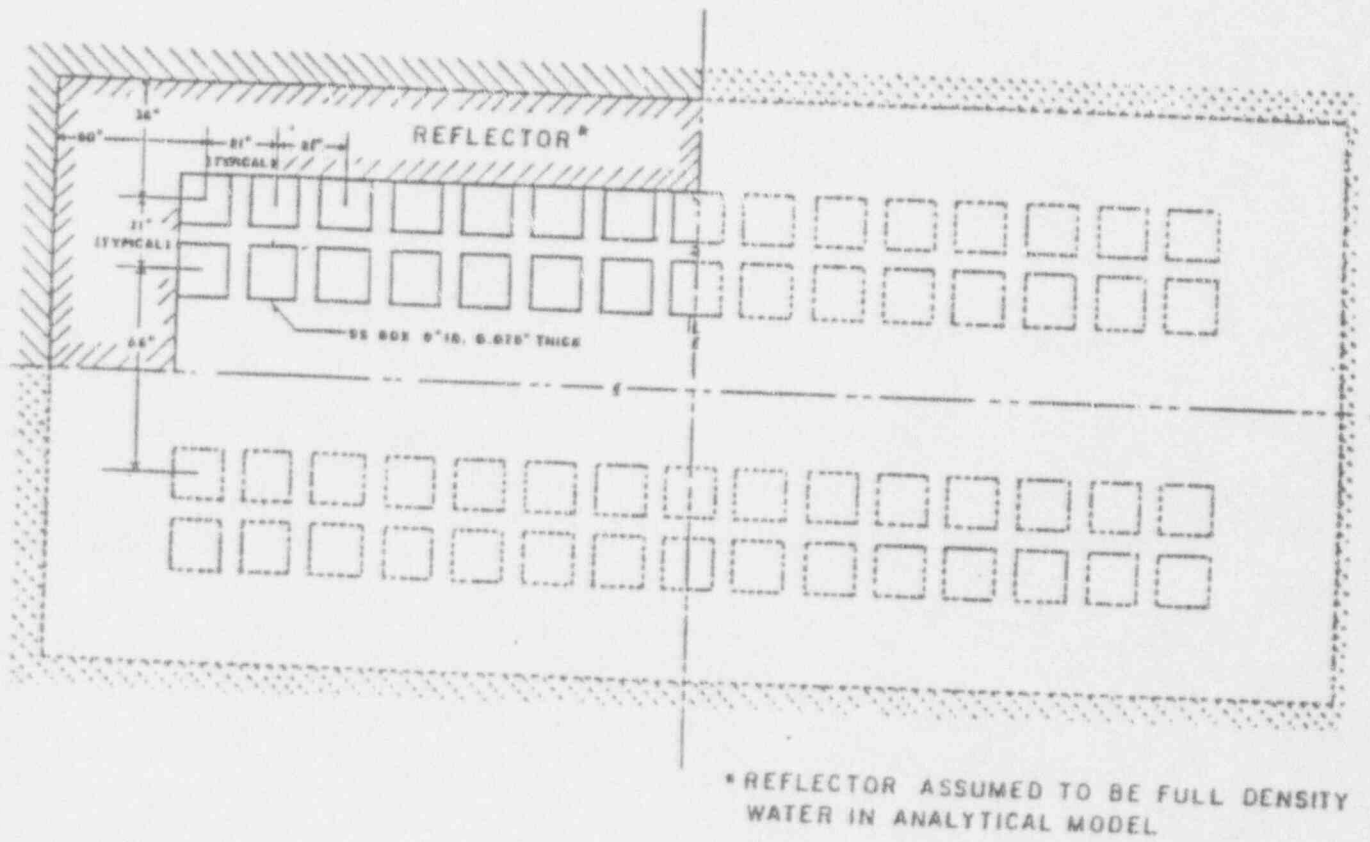Figure 6. SCE&G Fresh Fuel Storage Cell Nominal Dimensions

* REFLECTOR ASSUMED TO BE FULL DENSITY
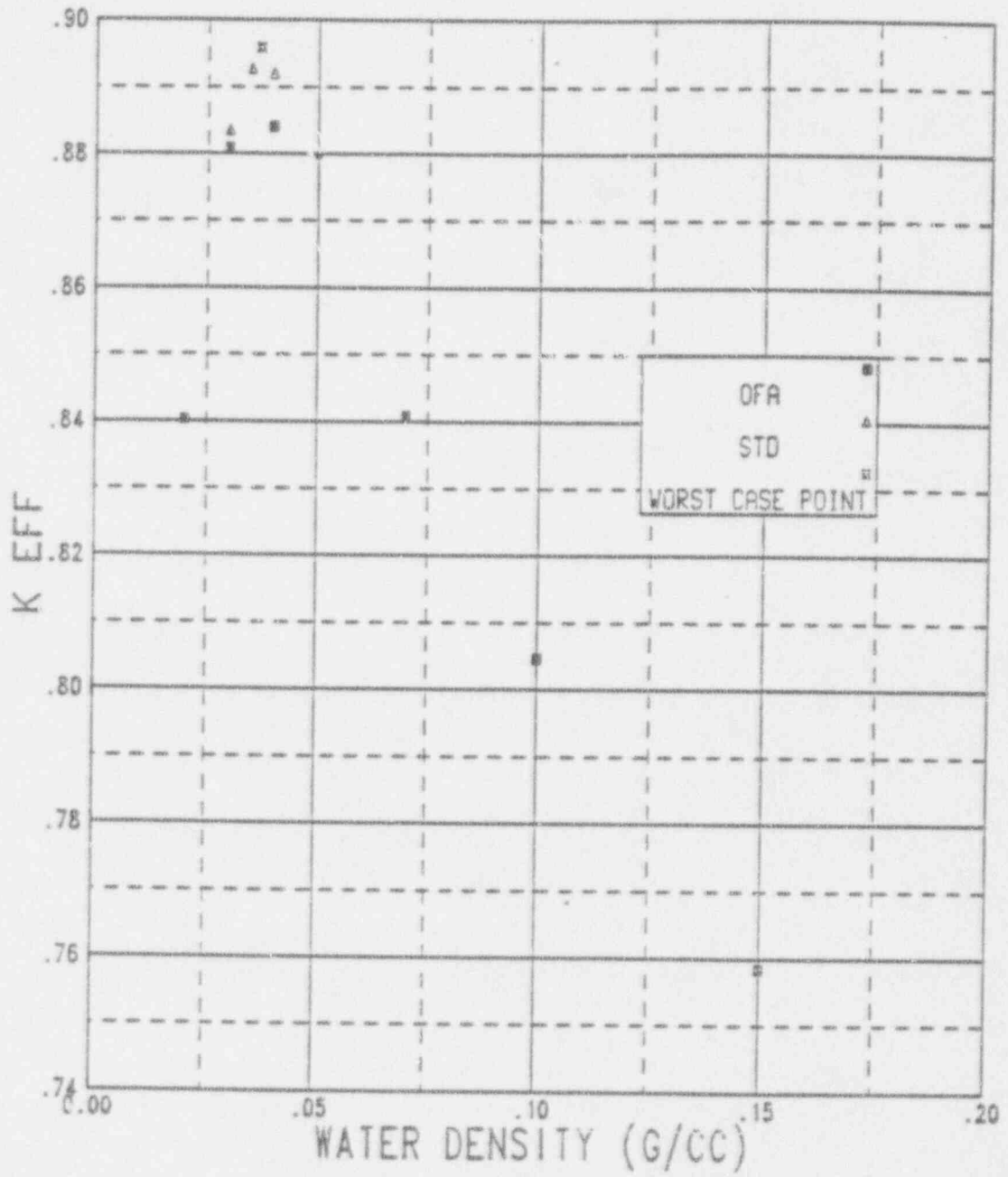WATER IN ANALYTICAL MODEL

Figure 7. SCE&G Fresh Fuel Rack Layout

Figure 19. Sensitivity of K_{eff} to Water Density in the SCE&G Fresh Fuel Storage Racks

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93CG*-G-0041
April 30, 1993

CU-27202

Mr. B. L. Johnson, Supervisor
Core Engineering
South Carolina Electric and Gas Company
Mail Code 563
V. C. Summer Nuclear Station
P. O. Box 88
Jenkinsville, SC 29065

Dear Mr. Johnson:

SOUTH CAROLINA ELECTRIC AND GAS COMPANY
VIRGIL C. SUMMER NUCLEAR STATION
FINAL CRITICALITY ANALYSIS REPORT

Enclosed is the final report, entitled "V. C. Summer Spent Fuel Rack Criticality Analysis Considering Boraflex Shrinkage and Gaps." The report shows that Westinghouse 17x17 fuel assemblies with nominal enrichments up to 5.0 w/o can be safely stored in all three regions of the V. C. Summer Spent Fuel Storage Racks. Credit is taken for burnup and IFBAs. The criticality report also includes analysis which takes credit for 300 ppm of soluble boron in the spent fuel pool.
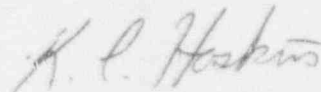
Also attached is the "Procedure to Calculate the Infinite Multiplication Factor for the V. C. Summer Region 1 Spent Fuel Racks." This attachment describes how to use PHOENIX-P to calculate an equivalent fuel assembly reactivity for IFBA credit in the V. C. Summer Region 1 Spent Fuel Racks.

The attached report has been verified. SCE&G comments from the draft review have also been incorporated.

Per SCE&G specifications, ten bound and one unbound copy have been provided.

1501v

If you should require further assistance, please call either Bill Newmeyer at 412/374-6534 or me at 412/374-2373.

Sincerely,

Kevin C. Hoskins
Project Engineer
Domestic Sales & Customer Projects

cc: M. N. Browne
      L. Cartin
      B. Christiansen
      W. Haltiwanger
      B. Jolley W

1501v

Procedure to Calculate the Infinite Multiplication Factor
for the V. C. Summer Region 1 Spent Fuel Storage Racks

In addition to the supplied IFBA credit curve for storing fuel assemblies with nominal U^{235} enrichments greater than 4.0 w/o in the V. C. Summer Region 1 spent fuel racks, an alternate method can be used to establish the criticality criteria for storage of IFBA fuel in the spent fuel storage racks. This method uses the fuel assembly infinite multiplication factor, k_∞, to establish a reference reactivity. The reference reactivity point i˙ compared to the fuel assembly peak reactivity to determine its acceptability for storage in the fuel rack. The established fuel assembly reactivity, k_∞, as determined for the V. C. Summer Region 1 spent fuel racks is 1.460. This method is useful when the fuel assembly type being considered for storage does not quite satisfy the IFBA credit curve. The procedure to calculate the infinite multiplication factor for the V. C. Summer Region 1 spent fuel rack is discussed below.

The fuel assembly k_∞ calculation is performed using the Westinghouse licensed core design code PHOENIX-P. The following assumptions are used to develop the infinite multiplication factor model:
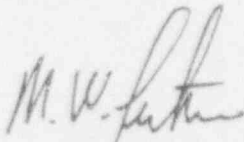
1. The fuel assembly is modeled at its most reactivity point in life.

2. The fuel pellets are modeled assuming nominal value for theoretical density and dishing fraction.

3. No credit is taken for any natural enrichment axial blankets.

4. No credit is taken for any U^{234} or U^{236} in the fuel, nor is any credit taken for the build up of fission product poison material.

5. The moderator is pure water (no boron) at a temperature of 68°F with a density of 1.0 gm/cm^3.

6. Burnable absorber loading are as-built or nominal less a 5% manufacturing tolerance.

7. Burnable absorber locations are modeled exactly.

8. Part-length burnable absorbers are modeled with a reduced B^{10} loading based on the ratio of the absorber length to the fuel rod length. For example, the B^{10} loading for a 108 inch IFBA rod would be reduced by 25% (108 inches / 144 inches).
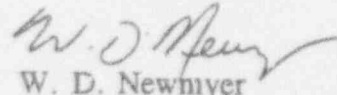
Based on standard core design methodology, ALPHA can be used to run a Hot Full Power Unit Assembly as shown in Figure 1. The results should then be restarted at Cold Zero Power conditions as shown in Figure 2. These example decks were used to develop the infinite multiplication factor, k_∞, of 1.460 which is the limit for acceptable storage in the Region 1 racks at 4.0 w/o U^{235}.

The example input decks can be modified to determine the reactivity of fuel assembly types used at V. C. Summer. If the result is less than the k_∞ limit of 1.460, the fuel assembly type is acceptable for storage in the Region 1 racks.

W. D. Newmyer
Criticality Product Line Leader
Date: 4-29-93

Verified:

M. W. Fecteau
Core Design A
Date: 4/29/93

Figure 1
Sample HFP Input Deck

```
(ALPHA Loader)
/
TITLE=SCE&G PHNX UA 17OFA 4.00 W/O HFP CONDITIONS
/
CALC(31)= 01 / UNIT(31)= 1 / FILEID(31)= 17OFA40H /
/
/
PUNCH= FALSE / CORE=3LOOP / CATEGORY=2 / 3-LOOP 17X17 PLANT
/
POWER   = 2775.0 / FROM WCAP-12564 CY6 NDR
THZP    =  557.0 /
TIN     =  554.8 /
LOADING = 66411 / 157*0.423 OFA LOADING
/
ENRICHMENT(1)= 4.0 / TYPEFUEL(1)= 2 / 17OFA FUEL ASSEMBLY
/
FRACDENS(1)= 0.950 / UTOPICS(2,1)= 1.0E-20, 1.0E-20 /
/
DISH(1)= 1.2110 / GASPRES(1)= 275.0 / IFBADENS(1)= 0 /
/
ASSEMGEOM(1,1)= 16,1,1,1,6*212,217 / 17OFA FUEL ASSEMBLY
/
ASSEMBU(1,1)= **0 / PPM=**0 /
/
/  ** OFF-NOMINAL RESTART INPUTS **
/
READFILE(31,1) 17OFA40H / READUNIT(31,1) 1 / READSTEP(1,31) 1 /
/
RPRESSURE 14.7 / RRELPOW 0 / TCZP 68.0 /
/
STOP
```

Figure 2
Sample CZP Input Deck for Final k_∞ Calculation

```
(ALPHA Loader)
/
TITLE=SCE&G PHNX UA 17OFA 4.00 W/O CZP CONDITIONS
/
CALC(31)= 03 / UNIT(31)= 1 / FILEID(31)= 17OFA40C /
/
/
PUNCH= FALSE / CORE=3LOOP / CATEGORY=2 / 3-LOOP 17X17 PLANT
/
POWER   = 2775.0 /  FROM WCAP-12564 CY6 NDR
THZP   =  557.0 /
TIN   =  554.8 /
LOADING =  66411 / 157*0.423 OFA LOADING
/
ENRICHMENT(1)= 4.0 / TYPEFUEL(1)= 2 / 17OFA FUEL ASSEMBLY
/
FRACDENS(1)= 0.950 / UTOPICS(2,1)= 1.0E-20, 1.0E-20 /
/
DISH(1)= 1.2110 / GASPRES(1)= 275.0 / IFBADENS(1)= 0 /
/
ASSEMGEOM(1,1)= 16,1,1,1,6*212,217 / 17OFA FUEL ASSEMBLY
/
ASSEMBU(1,1)= **0 / PPM=**0 /
/
/   ** OFF-NOMINAL RESTART INPUTS **
/
READFILE(31,1)= 17OFA40H / READUNIT(31,1)= 1 / READSTEP(1,31)= 1 /
/
RPRESSURE= 14.7 / RRELPOW= 0 / TCZP= 68.0 /
/
STOP
```