Byron and Braidwood Spent Fuel Rack Criticality Analysis Considering Boraflex Gaps and Shrinkage

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W.D. Newmyer
H.R. Lam
J.W. Miller
M.J. Hone

Verified: S. Srinilta

S. Srinilta
Core Design B

Approved: for C. R. Savage, Manager
Core Design B

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1.0 Introduction

This report presents the results of a criticality analysis of the Commonwealth Edison Byron and Braidwood spent fuel storage racks with consideration of Boraflex shrinkage and gaps.

The spent fuel storage rack designs considered herein are existing arrays of fuel racks, previously qualified for storage of various 17x17 fuel assembly types with maximum enrichments up to 4.25 w/o U^{235}.

In this analysis, each of the two unique storage racks in the Byron and Braidwood spent fuel pools will be reanalyzed with consideration of Boraflex shrinkage and gap development. To provide for future fuel management flexibility, storage limits will be developed to allow storage of Westinghouse 17x17 OFA fuel with nominal 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:

Spent Fuel Racks Region 1	Storage of 17x17 OFA fuel assemblies with nominal enrichments up to 4.2 w/o U^{235} utilizing all available storage cells. Fresh and burned fuel assemblies with higher initial nominal enrichments up to 5.0 w/o U^{235} can also be stored in these racks 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.
Spent Fuel Racks Region 2	Storage of Westinghouse 17x17 OFA assemblies utilizing all available storage cells. The Westinghouse 17x17 OFA fuel assemblies must have an initial enrichment no greater than 1.60 w/o U^{235} (nominal) or satisfy a minimum burnup requirement.

The Byron and Braidwood spent fuel rack analyses are based on maintaining $K_{eff} \leq 0.95$ for storage of 17x17 OFA fuel assemblies under full water density conditions.

1.1 Design Description

The Byron and Braidwood spent fuel storage rack layout is depicted in Figure 1 on page 30. The spent fuel rack storage cells for Region 1 and Region 2 are shown in Figure 2 on page 31 and Figure 3 on page 32, respectively, with nominal dimensions provided on each figure.

The fuel parameters relevant to this analysis are given in Table 1 on page 20. With the simplifying assumptions employed in this analysis (no grids, sleeves, axial blankets, etc.), the various types of Westinghouse 17x17 OFA fuel (V5, V+, and P+) are beneficial in terms of extending burnup capability and improving fuel reliability, but do not contribute to any

meaningful increase in the basic assembly reactivity. Therefore, future fuel assembly upgrades do not require a criticality analysis if the fuel parameters specified in Table 1 continue to remain bounding.

1.2 Design Criteria

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

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[1].

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[2,3] system of codes for cross-section generation and KENO Va[4] for reactivity determination.

The 227 energy group cross-section library that is the common starting point for all cross-sections used for the benchmarks of KENO Va and the KENO Va storage rack calculations is generated from ENDF/B-V[2] data. The NITAWL[3] 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[3] program which is a one-dimensional S_n transport theory code. These multigroup cross-section sets are then used as input to KENO Va[4] which is a three dimensional Monte Carlo theory program designed for reactivity calculations.

KENO Va Monte Carlo calculations are always performed with sufficient neutron histories to assure convergence. A typical KENO Va Monte Carlo calculation involves more than 60,000 neutron histories which is significantly more than the default of 30,000. To assure adequate convergence, the KENO Va edits which show Average K_{eff} per Generation Run and Average K_{eff} by Generation Skipped are examined. These edits provide a visual inspection on the overall convergence of the KENO Va Monte Carlo results.

A set of 44 critical experiments[5,6,7,8,9] 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 (B_4C, 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 (Plexiglass and air). Comparison with these experiments demonstrates the wide range of applicability of the method. Table 2 on page 21 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 0.9930. Comparison with the average measured experimental K_{eff} of 1.0007 results in a method bias of 0.0077. The standard deviation of the bias value is 0.00136 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 0.0030 ΔK. This KENO Va bias and uncertainty are consistent with the previous Westinghouse bias and uncertainty calculated for KENO IV[10].

Material and construction tolerance reactivity effects and reactivity sensitivities are determined using the transport theory computer code, PHOENIX[11]. PHOENIX is a depletable, two-dimensional, multigroup, discrete ordinates, transport theory code which utilizes a 42 energy group nuclear data library.

The agreement between reactivities computed with PHOENIX and the results of 81 critical benchmark experiments is summarized in Table 3 on page 22. Key parameters describing each of the 81 experiments are given in Table 4 on page 23. These reactivity comparisons again show good agreement between experiment and PHOENIX calculations.

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[12] 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 Byron and Braidwood spent fuel racks. The data points on the reactivity equivalence curve are generated with the transport theory computer code, PHOENIX.

A study was done to examine fuel reactivity as a function of time following reactor shutdown. Fission product decay was accounted for using CINDER[13]. CINDER is a point-depletion computer code used to determine fission product activities. The fission products were permitted to decay for 30 years after shutdown. The fuel reactivity was found to reach a maximum at approximately 100 hours after shutdown. 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 shutdown. Therefore, the most reactive time for a fuel assembly after shutdown of 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 reactor shutdown. 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 5 on page 25. The measurements were made on fuel discharged from Yankee Core 5[14]. The data in Table 5 on page 25 shows that the agreement between PHOENIX predictions and measured isotopic compositions is good.

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 Byron and Braidwood 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 other storage rack facilities, 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 both the Region 1 and Region 2 spent fuel rack criticality evaluations performed for this report.

Previous generic studies of Boraflex shrinkage and reactivity effects have been performed[15] for storage rack geometries which resemble the Byron and Braidwood spent fuel racks. The results of these studies[1] (and experience gained in performing similar studies for other rack geometries) indicate that:

- When absorber panel shrinkage occurs evenly and uniformly (equal pullback 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 10.08 inches given the initial Byron and Braidwood Region 1 Boraflex panel length of 139.5 inches and 5.76 inches given the initial Byron and Braidwood Region 2 Boraflex panel length of 144 inches. For this level of uniform top and bottom exposure, generic study data indicates that reactivity will increase by about 0.01 ΔK for Region 1 and will not increase for Region 2.
- 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 Region 1 racks and by 0.02 ΔK in the Region 2 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 Byron and Braidwood, the data indicates that reactivity will increase by more than 0.06 ΔK if all shrinkage is modeled as a single, large (5.58 inch in Region 1 and 5.76 inch in Region 2) gap at the centerline.

These generic study results indicate that Boraflex shrinkage and gap formation will result in

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1. Note: The generic data in Reference 14 does not include the effect of Boral inserts.

extremely large reactivity impacts for the conservative scenarios of single-end exposure and mid-plane gap development. Accommodating this level of impact in the Byron and Braidwood spent fuel 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 and future development of shrinkage and gaps, the following assumptions will be employed in the criticality evaluations performed for each of the Byron and Braidwood 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 (5.58 inches in Region 1 and 5.76 inches in Region 2) 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 or top end shrinkage.
4. Gaps will be distributed randomly with respect to axial position for the absorber panels which are modeled with gaps.
5. 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 nonuniform shrinkage (random gaps).
   - 50% of the panels experience nonuniform shrinkage (random gaps) and the remaining 50% of panels experience uniform shrinkage (pullback) from the bottom-end.
   - 50% of the panels experience nonuniform shrinkage (random gaps) and the remaining 50% of panels experience uniform shrinkage (pullback) from the top-end.
   - 100% of the panels experience uniform shrinkage (pullback) from the bottom-end.
   - 100% of the panels experience uniform shrinkage (pullback) from the top-end.
6. A criticality model which simulates 16 storage cells and 64 individual absorber panels for Region 1 and 16 storage cells and 32 individual absorber panels for Region 2 will be employed to provide sufficient problem size and flexibility for considering gaps and shrinkage on a random basis.
7. 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 upper bound values for shrinkage and gaps recommended by EPRI.

3.0 Criticality Analysis of Region 1 Spent Fuel Racks

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the Byron and Braidwood Region 1 spent fuel storage racks.

Section 3.1 describes the reactivity calculations performed for Region 1 with the nominal enrichment up to 4.20 w/o U^{235}. Section 3.2 describes the analysis which allows for storage of assemblies with nominal enrichments above 4.20 w/o U^{235} and up to 5.00 w/o U^{235} by taking credit for Integral Fuel Burnable Absorbers (IFBAs). Section 3.3 presents the results of calculations performed to show the reactivity sensitivity of variations in enrichment, center-to-center spacing, and Boraflex loading.

3.1 Reactivity Calculations

To show that storage of burned and fresh 17x17 OFA fuel assemblies in the Region 1 spent fuel racks 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. The nominal temperature range of 50°F to 140°F is considered in the analysis. 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 storage of fuel assemblies in the Byron and Braidwood Region 1 spent fuel rack:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 28 for fuel parameters).
2. All fuel assemblies contain uranium dioxide at a nominal enrichment of 4.20 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 or reduced 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 buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. The moderator is pure water (no boron) at a temperature of 68°F. A limiting value of 1.0 gm/cm^3 is used for the density of water to conservatively bound the range of normal (50°F to 140°F) spent fuel pool water temperatures.
9. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
10. All available storage cells are loaded with fuel assemblies.
11. Nominal Boraflex poison plate dimensions for width, thickness and length are assumed.

12. Boral inserts are modeled at the worst case thickness of 0.079 inches.

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% gap and 100% shrinkage. Assignment of which panels have gaps or shrinkage, and the axial location of the gap is based on random selection.

With the above assumptions, the KENO calculation for the nominal case results in a K_{eff} of 0.9232 with a 95 percent probability/95 percent confidence level uncertainty of ±0.0024 ΔK. This K_{eff} is the nominal reactivity assuming no Boraflex gaps or shrinkage.

KENO calculation for the worst case of Boraflex gaps and shrinkage resulted in no increase in the K_{eff}. This is due to the presence of Boral inserts which are present next to the areas where Boraflex gaps and shrinkage are modeled. The K_{eff} for the nominal case without Boraflex gaps and shrinkage will therefore be used as the reference reactivity for the Region 1 storage configuration.

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 0.0077 ΔK.

B^{10} Self Shielding: To correct for the modeling assumption that individual B^{10} atoms are homogeneously distributed within the absorber mateial (versus clustered about each B_4C particle), a bias of 0.0011 ΔK is applied.

Water Temperature: To account for the effect of the normal range of spent fuel pool water temperatures (50°F to 140°F) on water cross section properties, a reactivity bias of 0.0011 ΔK is applied. The reactivity effect of spent fuel pool water temperature on water density was considered in assumption 8 above.

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/construction dimensions, PHOENIX perturbation calculations are performed. For the Byron and Braidwood Region 1 spent fuel rack configuration, UO_2 material tolerances are considered along with construction tolerances related to the cell I.D., cell pitch, stainless steel thickness, and Boraflex poison panels. Uncertainties associated with calculation and methodology accuracy are also considered in the statistical summation of uncertainty components.

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

U^{235} Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o U^{235} about the nominal 4.20 w/o U^{235} reference enrichment was evaluated with PHOENIX and resulted in a reactivity increase of 0.0022 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 0.0027 ΔK.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 2.0% (about the nominal 1.211% 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 0.0001 ΔK.

Storage Cell Pitch : The ±0.05 inch tolerance about the nominal 10.32 inch reference cell pitch in the north/south direction was evaluated with PHOENIX and resulted in a reactivity increase of 0.0007 ΔK. The ±0.05 inch tolerance about the nominal 10.42 inch reference cell pitch in the east/west direction was evaluated with PHOENIX and resulted in a reactivity increase of 0.0008 ΔK.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.06 inch reference stainless steel wall thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0003 ΔK.

Boraflex Absorber Width: The ±0.0625 inch tolerance about the nominal 7.75 inch Boraflex panel width was evaluated with PHOENIX and resulted in a reactivity increase of 0.0002 ΔK.

Boraflex Absorber Thickness: The ±0.007 inch tolerance about the nominal 0.075 inch Boraflex panel thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0003 ΔK.

Boraflex B^{10} Loading: The ±0.0017 gm/cm^2 tolerance about the nominal 0.0238 gm/cm^2 Boraflex B^{10} loading was evaluated with PHOENIX and resulted in a reactivity increase of 0.0014 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 ±0.0024 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 0.0030 ΔK.

The maximum K_{eff} for the Byron and Braidwood alternating rows storage configuration is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the KENO reference reactivity. The summation is shown in Table 6 on page 26 and results in a maximum K_{eff} of 0.9389.

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 storage of 17x17 OFA fuel assemblies with nominal enrichment up to 4.2 w/o U^{235} in the Byron and Braidwood Region 1 spent fuel racks.

3.2 IFBA Credit Reactivity Equivalencing

Storage of fuel assemblies with nominal enrichments greater than 4.20 w/o U^{235} in the 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)[12]. 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 racks.

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 Region 1 spent fuel racks. 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 20 for fuel parameters).
2. The fuel assembly is modeled at its most reactive point in life.
3. The fuel pellets are modeled assuming nominal values for theoretical density and dishing fraction.
4. No credit is taken for any natural enrichment or reduced enrichment axial blankets.
5. 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.
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.
8. The IFBA B^{10} loading is reduced by 5% 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. The array is infinite in lateral (x and y) and axial (vertical) extent. This precludes any neutron leakage from the array.

Figure 4 on page 33 shows the constant K_{eff} contour generated for the Region 1 spent fuel racks. Note the endpoint at 0 IFBA rods where the nominal enrichment is 4.20 w/o and at 64(1X) IFBA rods where the nominal enrichment is 5.00 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 5.00 w/o U^{235} with each containing 64(1.0X) IFBA rods is equivalent to the reactivity of

the rack when filled with fuel assemblies enriched to a nominal 4.20 w/o and containing no IFBAs. The data in Figure 4 on page 33 is also provided on Table 7 on page 27 for both 1.0X and 2.0X IFBA rods.

It is important to recognize that the curve in Figure 4 on page 33 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 4 on page 33 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 4 on page 33 also include a conservatism of approximately 10% on the total number of IFBA rods at the 5.00 w/o end (i.e., about 6 extra IFBA rods for a 5.00 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 5.00 w/o fuel assemblies allows a reduction in the IFBA rod requirement from 64 IFBA rods per assembly to 32 IFBA rods per assembly (64 divided by the ratio 2.0X/1.0X).

3.2.2 Infinite Multiplication Factor

The infinite multiplication factor, K_∞, is used as a reference criticality reactivity point, and offers an alternative method for determining the acceptability of fuel assembly storage in the Region 1 spent fuel racks. The reference K_∞ is determined for a nominal fresh 4.20 w/o fuel assembly.

The fuel assembly K_∞ calculations are performed using the Westinghouse licensed core design code PHOENIX-P[11]. 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 20 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 a nominal enrichment of 4.20 w/o U^{235} over the entire length of each rod.
3. The fuel array model is based on a unit assembly configuration (infinite in the lateral and axial extent) in Byron and Braidwood 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 the Byron and Braidwood core geometry resulted in a reference K_∞ of 1.470. This includes a 1% ΔK reactivity bias to conservatively account for calculational uncertainties. This bias is consistent with the standard conservatism included in the Byron and Braidwood core design refueling shutdown margin calculations.

For IFBA credit, all 17x17 fuel assemblies placed in the Region 1 spent fuel racks must comply with the enrichment-IFBA requirements of Figure 4 on page 33 or have a reference K_∞ less than or equal to 1.470. 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 and Soluble Boron Worth

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC[1], 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 0.50 inch delta about the nominal case center-to-center spacing.
3. Boraflex B^{10} loading, with a 0.01 gm/cm^2 delta about the nominal case Boraflex B^{10} loading.

Results of the sensitivity analysis are shown in Figure 5 on page 34.

PHOENIX calculations were also performed to evaluate the reactivity benefits of soluble boron for the Region 1 spent fuel storage configuration. Results of these calculations are provided in Figure 6 on page 35. As the curve shows, the presence of soluble boron in the Byron and Braidwood spent fuel pool provides substantial reactivity margin.

4.0 Criticality Analysis of Region 2 Spent Fuel Racks

This section describes the analytical techniques and models employed to perform the criticality analysis and reactivity equivalencing evaluations for the Byron and Braidwood Region 2 spent fuel storage racks.

Section 4.1 describes the reactivity calculations performed for Region 2 with Westinghouse 17x17 OFA assemblies at nominal enrichments up to 1.60 w/o U^{235}. Section 4.2 describes the analysis which allows for storage of Westinghouse 17x17 OFA above 1.60 w/o and up to 5.0 w/o U^{235} with minimum burnup requirements. Section 4.3 presents the results of calculations performed to show the reactivity sensitivity of variations in enrichment, center-to-center spacing, and Boraflex loading.

4.1 Reactivity Calculations

To show that storage of burned and fresh Westinghouse 17x17 OFA fuel assemblies in the Region 2 spent fuel racks 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. The nominal temperature range of 50°F to 140°F is considered in the analysis. 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 storage of fuel assemblies in the Byron and Braidwood Region 2 spent fuel rack:

1. The fuel assembly parameters relevant to the criticality analysis are based on the Westinghouse 17x17 OFA design (see Table 1 on page 20 for fuel parameters).
2. All fuel assemblies contain uranium dioxide at a nominal enrichment of 1.60 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 or reduced 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 buildup of fission product poison material.
6. No credit is taken for any spacer grids or spacer sleeves.
7. No credit is taken for any burnable absorber in the fuel rods.
8. The moderator is pure water (no boron) at a temperature of 68°F. A limiting value of 1.0 gm/cm^3 is used for the density of water to conservatively bound the range of normal (50°F to 140°F) spent fuel pool water temperatures.
9. The array is infinite in lateral (x and y) extent and finite in axial (vertical) extent.
10. All available storage cells are loaded with fuel assemblies.
11. Nominal Boraflex poison plate dimensions for width, thickness and length are assumed.

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% gap and 100% shrinkage. Assignment of which panels have gaps or shrinkage, and the axial location of the gap is based on random selection.

With the above assumptions, the KENO calculation for the nominal case results in a K_{eff} of 0.9113 with a 95 percent probability/95 percent confidence level uncertainty of $\pm$ 0.0018 ΔK. This K_{eff} is the nominal reactivity assuming no Boraflex gaps or shrinkage.

Three gap and shrinkage cases were considered for the worst case of Boraflex gaps and shrinkage. The results are shown below with 95/95 uncertainty:

- 100% of the panels experience uniform shrinkage (pullback) from the bottom end assuming the Boraflex panel starts 6.0625" from the bottom of the rack.
  KENO $K_{eff} = 0.9371 \pm 0.0018\ \Delta K$
- 50% of the panels experience nonuniform shrinkage (random gaps) and the remaining 50% of the panels experience uniform shrinkage (pullback) from the bottom end assuming the Boraflex panel starts 6.0625" from the bottom of the rack.
  KENO $K_{eff} = 0.9206 \pm 0.0018\ \Delta K$
- 100% of the panels experience uniform shrinkage (pullback) from the bottom end assuming the Boraflex panel starts 5.0625" from the bottom of the rack.
  KENO $K_{eff} = 0.9244 \pm 0.0018\ \Delta K$

The KENO results show the highest K_{eff} for the case assuming the Boraflex panels start 6.0625" from the bottom of the rack. The KENO result for the case assuming the Boraflex panels start 5.0625" from the bottom of the racks shows a more favorable K_{eff}. Since uniform shrinkage (pullback) for the bottom end of every Boraflex panel is an overly conservative estimate of the occurance of Boraflex gaps and shrinkage, it is more realistic and still conservative to use the 50% nonuniform shrinkage and 50% uniform shrinkage K_{eff} as the worst case of realistic Boraflex gaps and shrinkage. This K_{eff} will be used as the reference reactivity for the Region 2 storage configuration.

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 0.0077 ΔK.

B^{10} Self Shielding: To correct for the modeling assumption that individual B^{10} atoms are homogeneously distributed within the absorber material (versus clustered about each B_4C particle), a bias of 0.0026 ΔK is applied.

Water Temperature: To account for the effect of the normal range of spent fuel pool water temperatures (50°F to 140°F) on water cross section properties, a reactivity bias of 0.0020 ΔK is applied. The reactivity effect of spent fuel pool water temperature on water density was considered in the above assumption.

To evaluate the reactivity effects of possible variations in material characteristics and mechanical/

construction dimensions, PHOENIX perturbation calculations are performed. For the Byron and Braidwood Region 2 spent fuel rack configuration, UO_2 material tolerances are considered along with construction tolerances related to the cell I.D., cell pitch, stainless steel thickness, and Boraflex poison panels. Uncertainties associated with calculation and methodology accuracy are also considered in the statistical summation of uncertainty components.

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

U^{235} Enrichment: The standard DOE enrichment tolerance of ±0.05 w/o U^{235} about the nominal 1.60 w/o U^{235} reference enrichment was evaluated with PHOENIX and resulted in a reactivity increase of 0.0104 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 0.0037 ΔK.

Fuel Pellet Dishing: A variation in fuel pellet dishing fraction from 0.0% to 2.0% (about the nominal 1.211% reference value) was evaluated with PHOENIX and resulted in a reactivity increase of 0.0022 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 0.0012 ΔK.

Storage Cell Pitch : The +0.021/-0.059 inch tolerance about the nominal 9.011 inch reference cell pitch was evaluated with PHOENIX and resulted in a reactivity increase of 0.0008 ΔK.

Stainless Steel Wall Thickness: The ±0.005 inch tolerance about the nominal 0.06 inch reference stainless steel wall thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0004 ΔK.

Boraflex Absorber Width: The ±0.0625 inch tolerance about the nominal 7.25 inch Boraflex panel width was evaluated with PHOENIX and resulted in a reactivity increase of 0.0010 ΔK.

Boraflex Absorber Thickness: The ±0.007 inch tolerance about the nominal 0.041 inch Boraflex panel thickness was evaluated with PHOENIX and resulted in a reactivity increase of 0.0002 ΔK.

Boraflex B^{10} Loading: The ±0.0009 gm/cm^2 tolerance about the nominal 0.0130 gm/cm^2 Boraflex B^{10} loading was evaluated with PHOENIX and resulted in a reactivity increase of 0.0028 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 ±0.0018 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 0.0030 ΔK.

The maximum K_{eff} for the Byron and Braidwood Region 2 spent fuel storage configuration is developed by adding the calculational and methodology biases and the statistical sum of independent uncertainties to the KENO reference reactivity. The summation is shown in Table 8 on page 28 and results in a maximum K_{eff} of 0.9449.

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 storage of Westinghouse 17x17 OFA fuel assemblies with nominal enrichments up to 1.60 w/o U^{235} in the Byron and Braidwood Region 2 spent fuel racks.

4.2 Burnup Credit Reactivity Equivalencing

Storage of burned fuel assemblies in the Byron and Braidwood Region 2 spent fuel racks 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 or the addition of IFBA fuel rods. 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 7 on page 36 shows the constant K_{eff} contour generated for the Byron and Braidwood 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 Westinghouse 17x17 OFA fresh fuel (zero burnup) at 1.60 w/o U^{235}.

Note in Figure 7 on page 36, the endpoints are 0 MWD/MTU where the Westinghouse 17x17 OFA enrichment is 1.60 w/o, and 45089 MWD/MTU where the Westinghouse 17x17 OFA enrichment is 5.00 w/o. The interpretation of the endpoint data is as follows: the reactivity of the spent fuel rack containing Westinghouse 17x17 OFA 5.00 w/o fuel at 45089 MWD/MTU is equivalent to the reactivity of the rack containing Westinghouse 17x17 OFA 1.60 w/o fresh fuel. The burnup credit curve shown in Figure 7 on page 36 includes a reactivity uncertainty of 0.0150 ΔK, consistent with the minimum burnup requirement of 45089 MWD/MTU for Westinghouse 17x17 OFA at 5.00 w/o.

It is important to recognize that the curve in Figure 7 on page 36 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 7 on page 36 is also provided in Table 9 on page 29. Use of linear interpolation between the tabulated values is acceptable since the curve shown in Figure 7 on page 36 is linear in between the tabulated points.

The effect of axial burnup distribution on assembly reactivity has been considered in the development of the Byron and Braidwood 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[16]. The previous evaluations show that axial burnup effects can cause assembly reactivity to increase at burnup-enrichment combinations which are well beyond those calculated for the Byron and Braidwood Region 2 burnup credit limit. Therefore, additional accounting of axial burnup distribution effects in the Byron and Braidwood Region 2 burnup credit limit is not necessary.

4.3 Sensitivity Analysis and Soluble Boron Worth

To show the dependence of K_{eff} on fuel and storage cells parameters as requested by the NRC[1], 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 +0.50/-0.0425 inch delta about the nominal case center-to-center spacing.
3. Boraflex B^{10} loading, with a 0.01 gm/cm^2 delta about the nominal case Boraflex B^{10} loading.

Results of the sensitivity analysis are shown in Figure 8 on page 37.

PHOENIX calculations were also performed to evaluate the reactivity benefits of soluble boron for the Region 2 spent fuel storage configuration. Results of these calculations are provided in Figure 6 on page 35. As the curve shows, the presence of soluble boron in the Byron and Braidwood Region 2 spent fuel pool provides substantial reactivity margin.

5.0 Discussion of Postulated Accidents

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

Fuel assembly drop on top of rack	The rack structure pertinent for criticality is not excessively deformed and the dropped assembly which comes to rest horizontally on top of the rack has sufficient water separating it from the active fuel height of stored assemblies to preclude neutronic interaction.
Fuel assembly drop between rack modules	Design of the spent fuel racks is such that it precludes the insertion of a fuel assembly between rack modules.
Loss of cooling systems	Reactivity decreases since loss of cooling causes an increase in temperature, which causes a decrease in water density, which results in decreased reactivity.

However, two accident can be postulated which would increase reactivity beyond the analyzed condition. One such postulated accident would be a fuel assembly misload into a position for which the restrictions on location, enrichment, or burnup are not satisfied. To very conservatively estimate the reactivity impacts of such an occurrence in the spent fuel racks, the impact of loading a fresh assembly at 4.2 w/o U^{235} in the middle of a 5x5 array of Region 2 spent fuel rack cells with fresh assemblies at 1.60 w/o U^{235} fuel assemblies was determined. The reactivity increase associated with this misloading is less than 0.0438 ΔK.

A second accident which could result in increased reactivity would be a "cooldown" event during which the pool temperature would drop below 50°F. Calculations show that if the Region 1 spent fuel pool water temperature was to decrease from 50°F to 32°F, reactivity could increase by about 0.0011 ΔK, and if the Region 2 spent fuel pool water temperature was to decrease from 50°F to 32°F, reactivity could increase by 0.0020 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 Byron and Braidwood spent fuel pool has been calculated with PHOENIX and is shown in Figure 6 on page 35. 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 0.0438 ΔK reactivity increase from the most limiting accident in the spent fuel racks, it is estimated that 300 ppm of soluble boron is required.

Therefore should a postulated accident occur which causes a reactivity increase in the Byron and Braidwood spent fuel racks, K_{eff} will be maintained less than or equal to 0.95 due to the presence of at least 300 ppm of soluble boron in the spent fuel pool water.

6.0 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 Byron and Braidwood Fresh Fuel Storage Racks for the storage of Westinghouse 17x17 OFA fuel assemblies and for the Byron and Braidwood Spent Fuel Storage Racks for the storage of 17x17 fuel assemblies with the following configurations and enrichment limits:

Spent Fuel Racks Region 1	Storage of 17x17 OFA fuel assemblies with nominal enrichments up to 4.2 w/o U^{235} utilizing all available storage cells. Fresh and burned fuel assemblies with higher initial enrichments up to 5.0 w/o U^{235} can also be stored in these racks 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.
Spent Fuel Racks Region 2	Storage of Westinghouse 17x17 OFA assemblies utilizing all available storage cells. The Westinghouse 17x17 OFA fuel assemblies must have an initial enrichment no greater than 1.60 w/o U^{235} (nominal) or satisfy a minimum burnup requirement.

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 OFA
Number of Fuel Rods per Assembly	264
Rod Zirc-4 Clad O.D. (inch)	0.3600
Clad Thickness (inch)	0.0225
Fuel Pellet O.D.(inch)	0.3088
Fuel Pellet Density (% of Theoretical)	95
Fuel Pellet Dishing Factor (%)	1.211
Rod Pitch (inch)	0.496
Number of Zirc-4 Guide Tubes	24
Guide Tube O.D. (inch)	0.474
Guide Tube Thickness (inch)	0.016
Number of Instrument Tubes	1
Instrument Tube O.D. (inch)	0.474
Instrument Tube Thickness (inch)	0.016

Table 2. Benchmark Critical Experiments

Critical Number	General Description	Enrichment U^{235} (w/o)	Reflector	Separating Material	Soluble Boron (ppm)	Measured K_{eff}	KENO Reactivity (K_{eff} +/- One Sigma)
1	UO_2 Rod Lattice	2.46	water	water	0	1.0002	0.99347 +/- 0.00234
2	UO_2 Rod Lattice	2.46	water	water	1037	1.0001	0.99361 +/- 0.00193
3	UO_2 Rod Lattice	2.46	water	water	764	1.0000	0.99459 +/- 0.00194
4	UO_2 Rod Lattice	2.46	water	B_4C pins	0	0.9999	0.98766 +/- 0.00217
5	UO_2 Rod Lattice	2.46	water	B_4C pins	0	1.0000	0.98838 +/- 0.00221
6	UO_2 Rod Lattice	2.46	water	B_4C pins	0	1.0097	1.00132 +/- 0.00221
7	UO_2 Rod Lattice	2.46	water	B_4C pins	0	0.9998	0.99570 +/- 0.00225
8	UO_2 Rod Lattice	2.46	water	B_4C pins	0	1.0083	0.99905 +/- 0.00210
9	UO_2 Rod Lattice	2.46	water	water	0	1.0030	0.99660 +/- 0.00299
10	UO_2 Rod Lattice	2.46	water	water	143	1.0001	0.99707 +/- 0.00199
11	UO_2 Rod Lattice	2.46	water	stainless steel	514	1.0000	0.99862 +/- 0.00203
12	UO_2 Rod Lattice	2.46	water	stainless steel	217	1.0000	0.99411 +/- 0.00207
13	UO_2 Rod Lattice	2.46	water	borated aluminum	15	1.0000	0.99229 +/- 0.00218
14	UO_2 Rod Lattice	2.46	water	borated aluminum	92	1.0001	0.98847 +/- 0.00208
15	UO_2 Rod Lattice	2.46	water	borated aluminum	395	0.9998	0.98424 +/- 0.00205
16	UO_2 Rod Lattice	2.46	water	borated aluminum	121	1.0001	0.98468 +/- 0.00209
17	UO_2 Rod Lattice	2.46	water	borated aluminum	487	1.0000	0.99521 +/- 0.00195
18	UO_2 Rod Lattice	2.46	water	borated aluminum	197	1.0002	0.99203 +/- 0.00211
19	UO_2 Rod Lattice	2.46	water	borated aluminum	634	1.0002	0.98924 +/- 0.00201
20	UO_2 Rod Lattice	2.46	water	borated aluminum	320	1.0003	0.99461 +/- 0.00197
21	UO_2 Rod Lattice	2.46	water	borated aluminum	72	0.9997	0.98700 +/- 0.00220
22	UO_2 Rod Lattice	2.35	water	borated aluminum	0	1.0000	0.99347 +/- 0.00128
23	UO_2 Rod Lattice	2.35	water	stainless steel	0	1.0000	0.99566 +/- 0.00116
24	UO_2 Rod Lattice	2.35	water	water	0	1.0000	0.99785 +/- 0.00239
25	UO_2 Rod Lattice	2.35	water	stainless steel	0	1.0000	0.98964 +/- 0.00240
26	UO_2 Rod Lattice	2.35	water	borated aluminum	0	1.0000	0.98841 +/- 0.00234
27	UO_2 Rod Lattice	2.35	water	B_4C	0	1.0000	0.99015 +/- 0.00231
28	UO_2 Rod Lattice	4.31	water	stainless steel	0	1.0000	0.99063 +/- 0.00247
29	UO_2 Rod Lattice	4.31	water	water	0	1.0000	0.98986 +/- 0.00228
30	UO_2 Rod Lattice	4.31	water	stainless steel	0	1.0000	1.00011 +/- 0.00248
31	UO_2 Rod Lattice	4.31	water	borated aluminum	0	1.0000	1.00070 +/- 0.00254
32	UO_2 Rod Lattice	4.31	water	borated aluminum	0	1.0000	1.00088 +/- 0.00253
33	U-metal Cylinders	93.2	bare	air	0	1.0000	0.98997 +/- 0.00257
34	U-metal Cylinders	93.2	bare	air	0	1.0000	0.99815 +/- 0.00242
35	U-metal Cylinders	93.2	bare	air	0	1.0000	0.99250 +/- 0.00230
36	U-metal Cylinders	93.2	bare	air	0	1.0000	0.99288 +/- 0.00247
37	U-metal Cylinders	93.2	bare	air	0	1.0000	0.99869 +/- 0.00235
38	U-metal Cylinders	93.2	bare	air	0	1.0000	0.99796 +/- 0.00236
39	U-metal Cylinders	93.2	bare	plexiglass	0	1.0000	0.99799 +/- 0.00261
40	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.00061 +/- 0.00265
41	U-metal Cylinders	93.2	bare	plexiglass	0	1.0000	0.99961 +/- 0.00243
42	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.01054 +/- 0.00272
43	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.00471 +/- 0.00246
44	U-metal Cylinders	93.2	paraffin	plexiglass	0	1.0000	1.00375 +/- 0.00274

Table 3. Benchmark Critical Experiments PHOENIX Comparison

Description of Experiments	Number of Experiments	PHOENIX K_{eff} Using Experiment Buckling
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 4. Data for U Metal and UO_2 Critical Experiments (Part 1 of 2)

Case Number	Cell Type	A/O U^{235}	H_2O/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	B594	.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	B594	.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	2.6162	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 4. Data for U Metal and UO_2 Critical Experiments (Part 2 of 2)

Case Number	Cell Type	A/O U^{235}	H_2O/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	1.6916	.07112	2.6162	0.0
44	Hexa	1.307	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
45	Hexa	1.307	4.02	18.90	1.5240	Aluminum	1.6916	.07112	3.3249	0.0
46	Hexa	1.160	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
47	Hexa	1.160	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0
48	Hexa	1.160	2.02	18.90	1.5240	Aluminum	1.6916	.07112	2.6162	0.0
49	Hexa	1.160	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
50	Hexa	1.160	4.02	18.90	1.5240	Aluminum	1.6916	.07112	3.3249	0.0
51	Hexa	1.040	1.01	18.90	1.5240	Aluminum	1.6916	.07112	2.1742	0.0
52	Hexa	1.040	1.51	18.90	1.5240	Aluminum	1.6916	.07112	2.4054	0.0
53	Hexa	1.040	2.02	18.90	1.5240	Aluminum	1.6916	.07112	2.6162	0.0
54	Hexa	1.040	3.01	18.90	1.5240	Aluminum	1.6916	.07112	2.9896	0.0
55	Hexa	1.040	4.02	18.90	1.5240	Aluminum	1.6916	.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	.07620	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	1.6916	.07112	2.6160	0.0
77	Hexa	1.310	3.01	18.88	1.5240	Aluminum	1.6916	.07112	2.9900	0.0
78	Hexa	1.159	2.02	18.88	1.5240	Aluminum	1.6916	.07112	2.6160	0.0
79	Hexa	1.159	3.01	18.88	1.5240	Aluminum	1.6916	.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 5. Comparison of PHOENIX Isotopics Predictions to Yankee Core 5 Measurements

Quantity (Atom Ratio)	% Difference
U^{235}/U	-0.67
U^{236}/U	-0.28
U^{238}/U	-0.03
Pu^{239}/U	+3.27
Pu^{240}/U	+3.63
Pu^{241}/U	-7.01
Pu^{242}/U	-0.20
Pu^{239}/U^{238}	+3.24
Mass(Pu/U)	+1.41
FISS-Pu/TOT-Pu	-0.02

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

	ΔK	K_{eff}
Nominal KENO Reference Reactivity:		**0.9232**
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	+0.0077	
B^{10} Particle Self-Shielding Bias	+0.0011	
Pool Temperature Bias (50°F - 140°F)	+0.0011	
TOTAL Bias	+0.0099	
Best-Estimate Nominal K_{eff}:		**0.9331**
Tolerances & Uncertainties:		
UO_2 Enrichment Tolerance	+0.0022	
UO_2 Density Tolerance	+0.0028	
Fuel Pellet Dishing Variation	+0.0016	
Cell Inner Diameter	+0.0001	
Cell Pitch North/South	+0.0007	
Cell Pitch East/West	+0.0008	
Stainless Steel Thickness	+0.0003	
Borafiex Thickness	+0.0003	
Boraflex Width	+0.0002	
B^{10} Loading	+0.0014	
Calculational Uncertainty (95/95)	+0.0024	
Methodology Bias Uncertainty (95/95)	+0.0030	
TOTAL Uncertainty (statistical)	+0.0057	
Final K_{eff} Including Uncertainties & Tolerances:		**0.9389**

Table 7. Byron and Braidwood Region 1 Spent Fuel Rack IFBA Requirement

Enrichment (w/o)	1.0X (1.50 mg./in) IFBA Rods In Assembly	2.0X (3.00 mg./in) IFBA Rods In Assembly
4.20	0	0
4.40	16	8
4.60	32	16
4.80	48	24
5.00	64	32

Table 8. Byron and Braidwood Region 2 Spent Fuel Rack K_{eff} Summary

	ΔK	K_{eff}
Nominal KENO Reference Reactivity:		**0.9206**
Calculational & Methodology Biases:		
Methodology (Benchmark) Bias	+0.0077	
B^{10} Particle Self-Shielding Bias	+0.0026	
Pool Temperature Bias (50°F - 140°F)	+0.0020	
TOTAL Bias	+0.0123	
Best-Estimate Nominal K_{eff}:		**0.9329**
Tolerances & Uncertainties:		
UO_2 Enrichment Tolerance	+0.0104	
UO_2 Density Tolerance	+0.0037	
Fuel Pellet Dishing Variation	+0.0022	
Cell Inner Diameter	+0.0012	
Cell Pitch	+0.0008	
Stainless Steel Thickness	+0.0004	
Boraflex Thickness	+0.0002	
Boraflex Width	+0.0010	
B^{10} Loading	+0.0028	
Calculational Uncertainty (95/95)	+0.0018	
Methodology Bias Uncertainty (95/95)	+0.0030	
TOTAL Uncertainty (statistical)	+0.0120	
Final K_{eff} Including Uncertainties & Tolerances:		**0.9449**

Table 9. Byron and Braidwood Region 2 Spent Fuel Rack Minimum Burnup Requirement

Nominal Enrichment (w/o)	Burnup (MWD/MTU)
1.60	0
1.80	4500
2.00	8316
2.20	11500
2.40	14300
2.60	16890
2.80	19500
3.00	22080
3.20	24400
3.40	27000
3.60	29300
3.80	31700
4.00	34026
4.20	36300
4.40	38500
4.60	40800
4.80	43000
5.00	45089

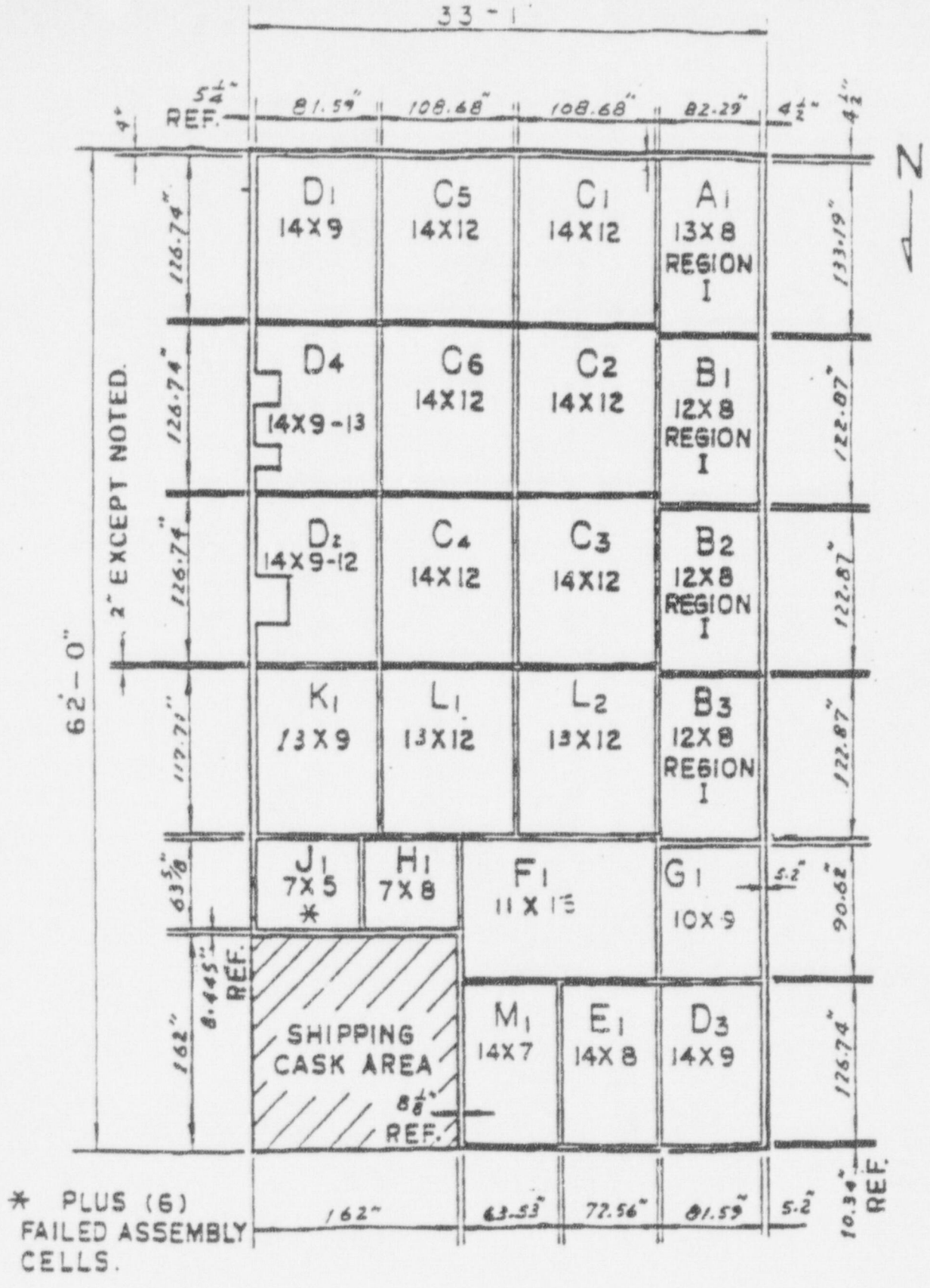

Figure 1. Byron and Braidwood Spent Fuel Pool Layout

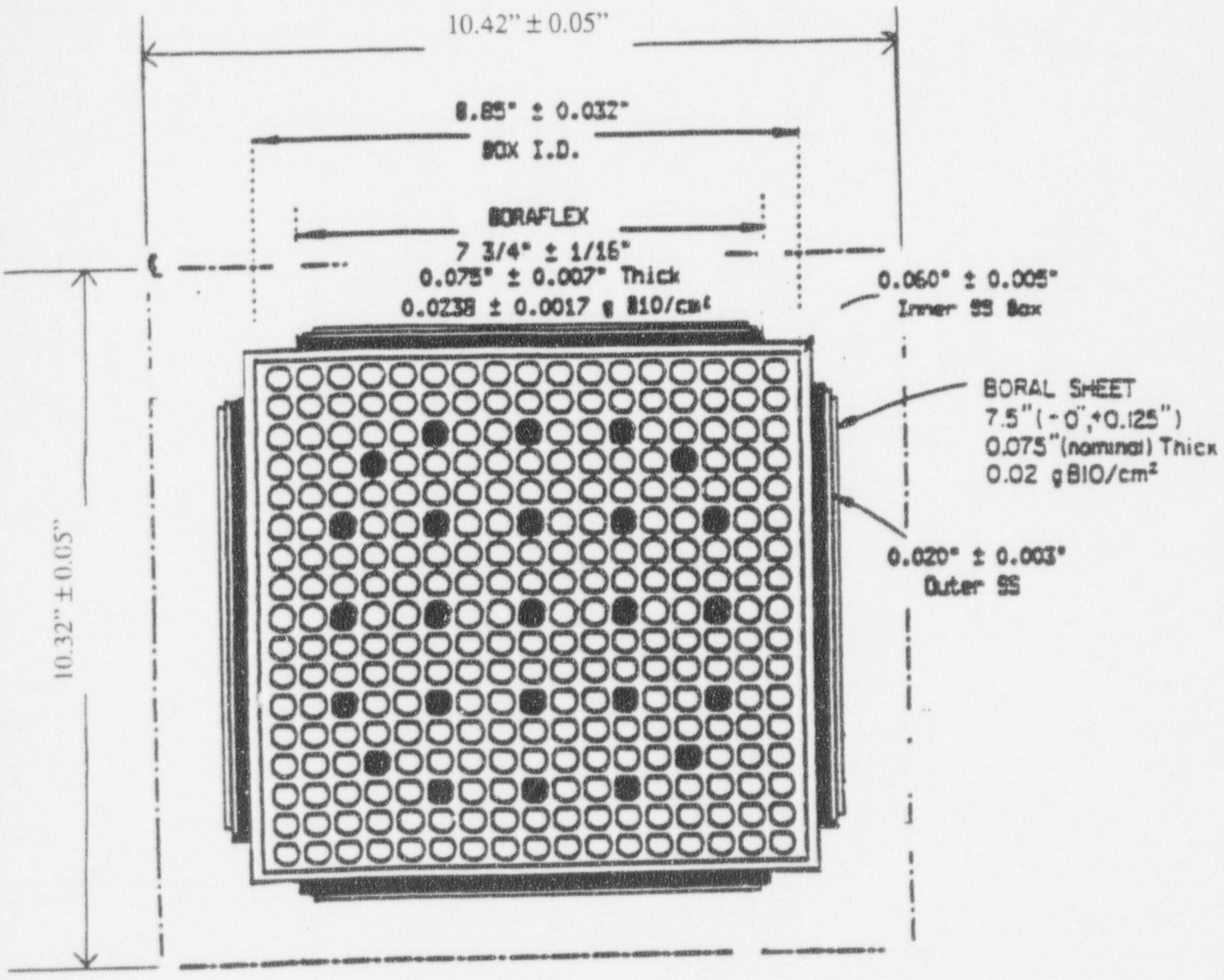

Figure 2. Byron and Braidwood Region 1 Spent Fuel Rack Storage Cell

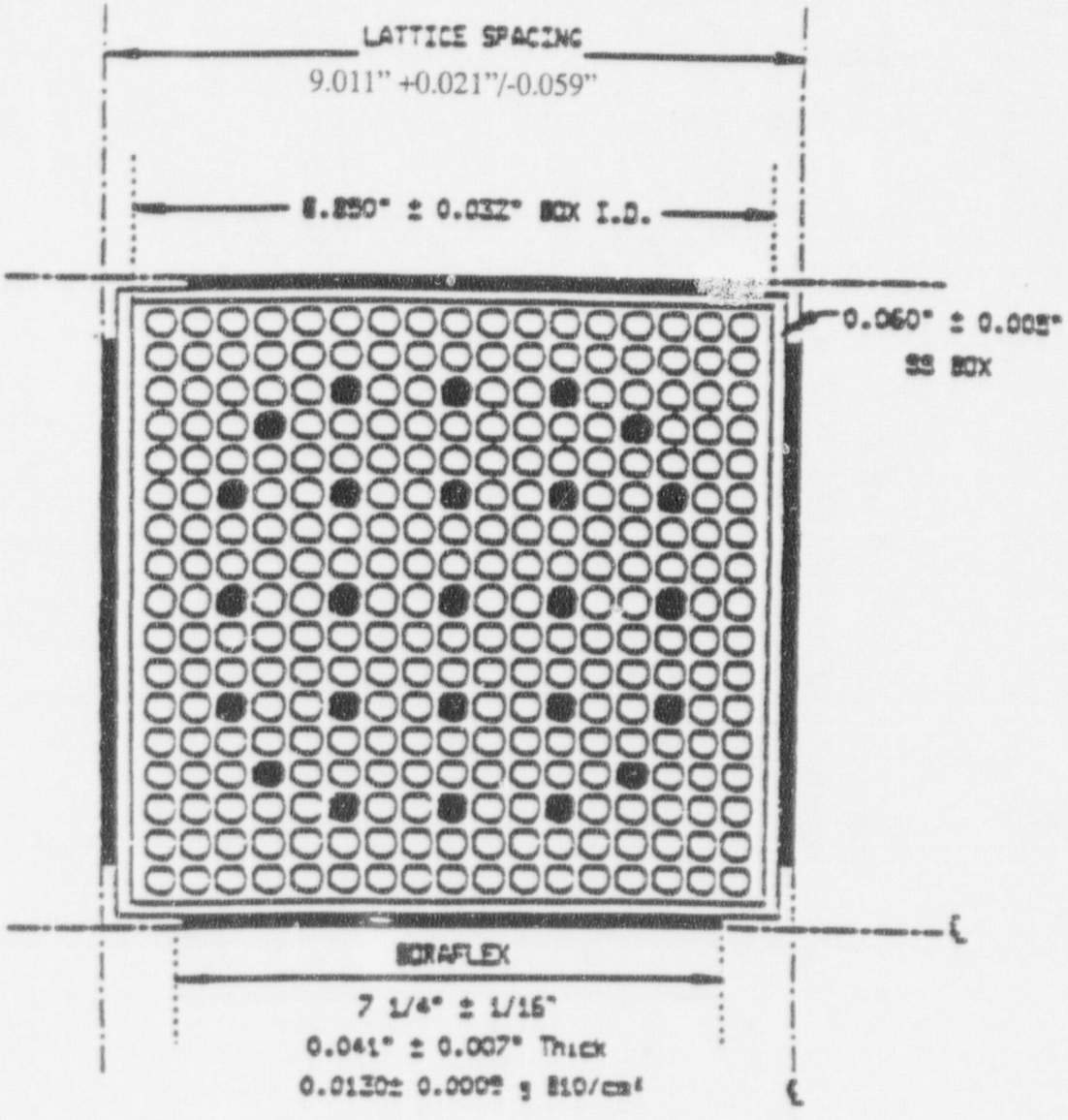

Figure 3. Byron and Braidwood Region 2 Spent Fuel Rack Storage Cell

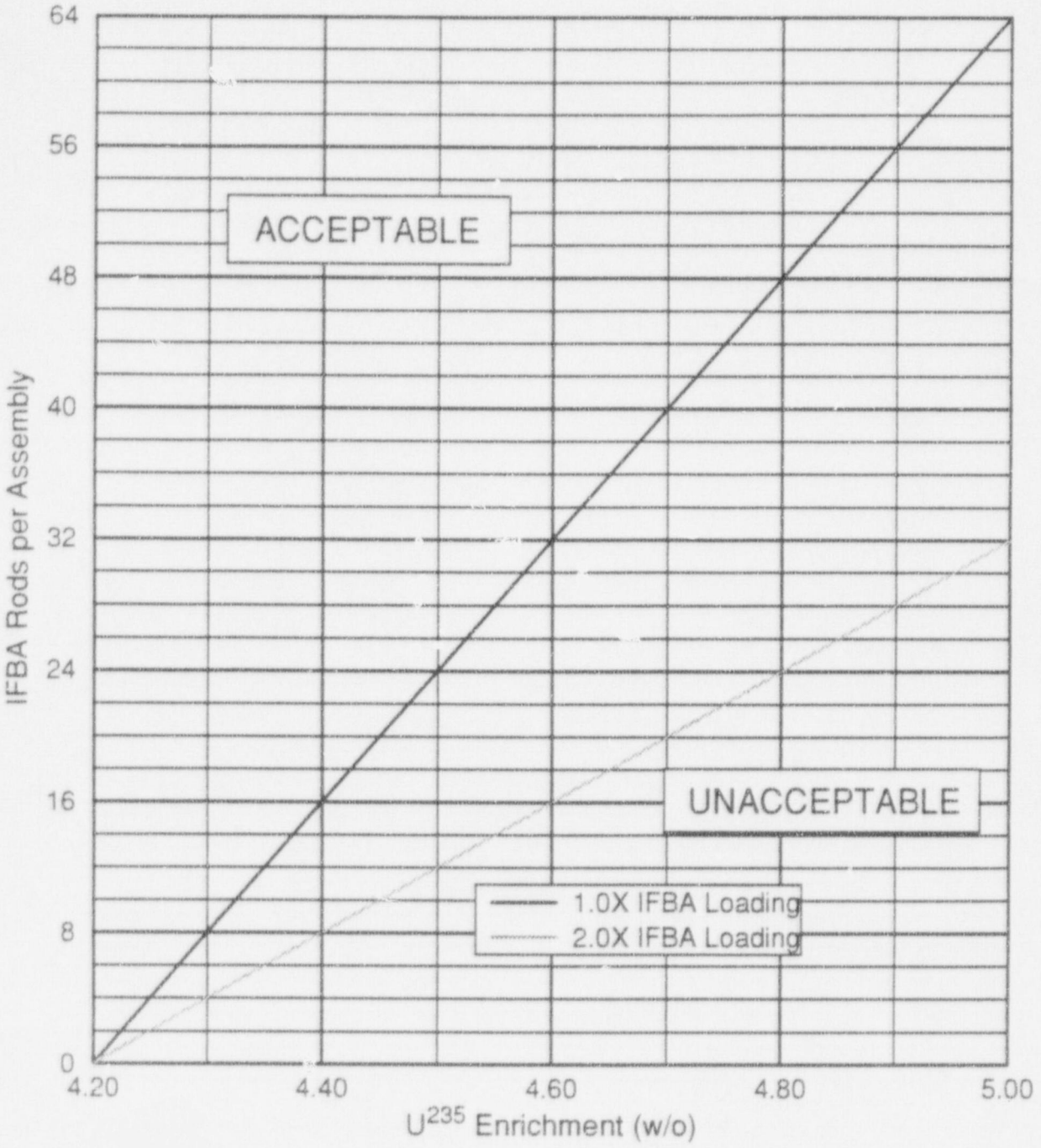

Figure 4. Byron and Braidwood Region 1 Spent Fuel Rack IFBA Requirement

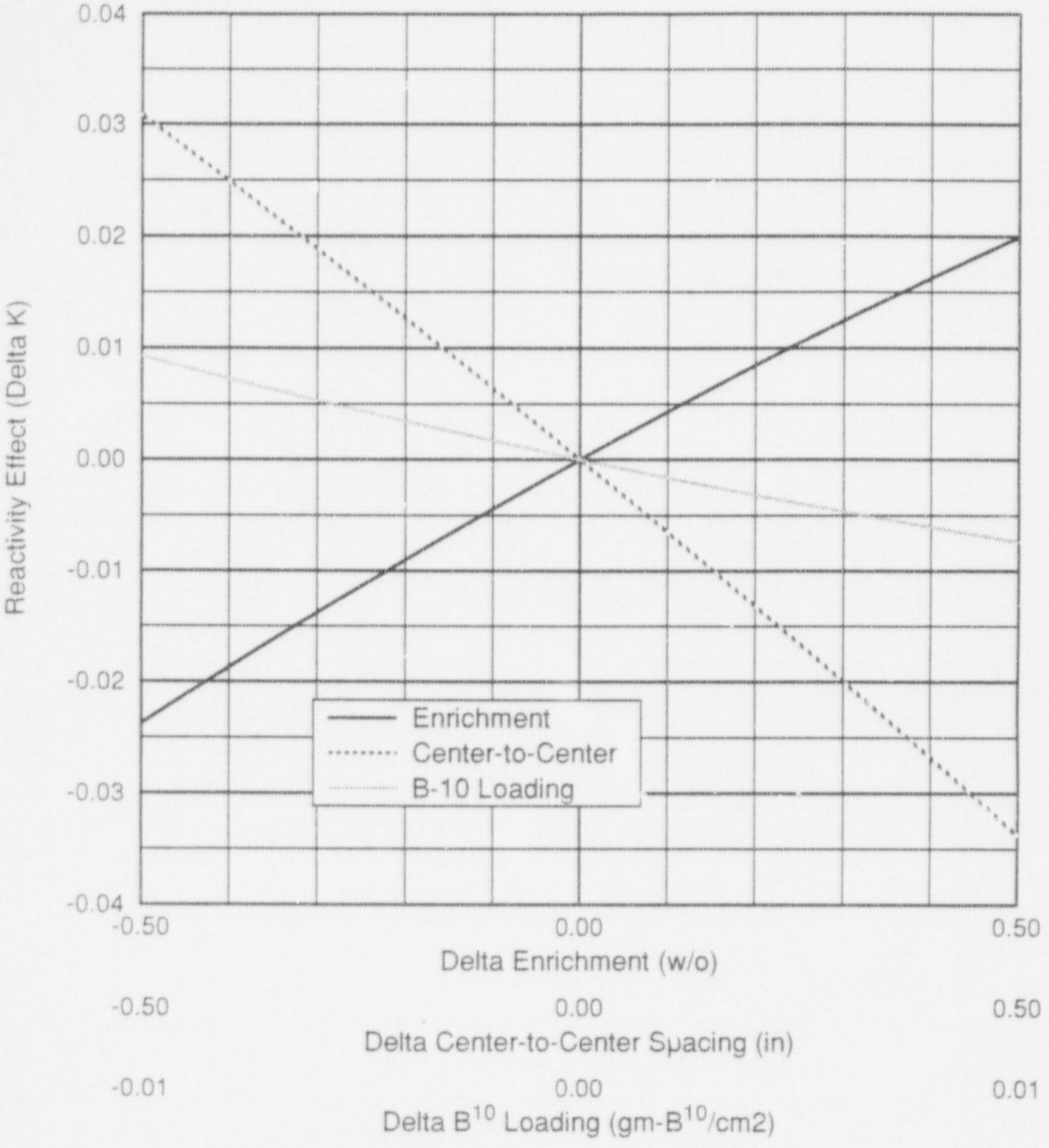

Figure 5. Byron and Braidwood Region 1 Spent Fuel Rack Reactivity Sensitivity

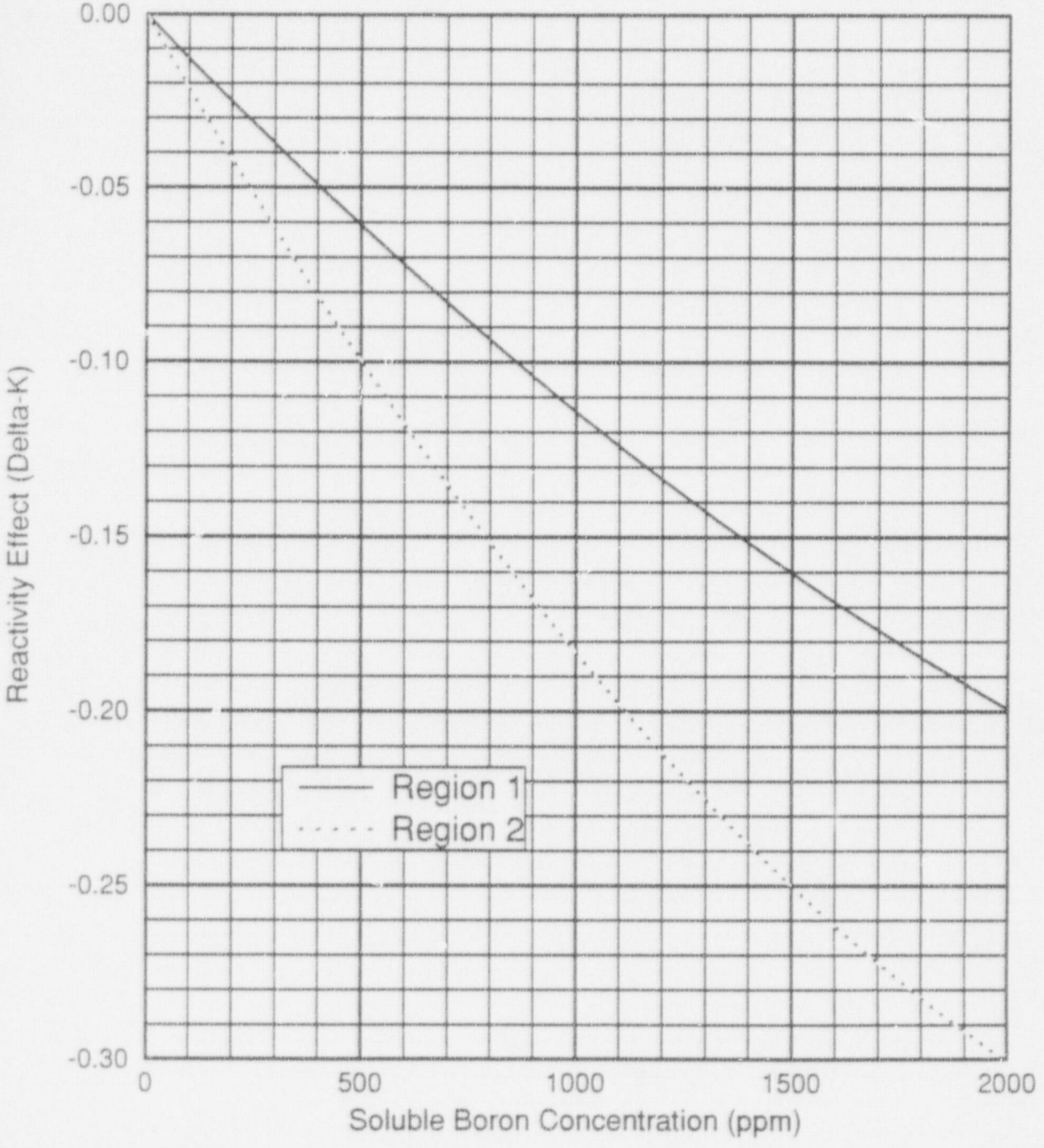

Figure 6. Byron and Braidwood Region 1 and 2 Spent Fuel Rack Soluble Boron Worth

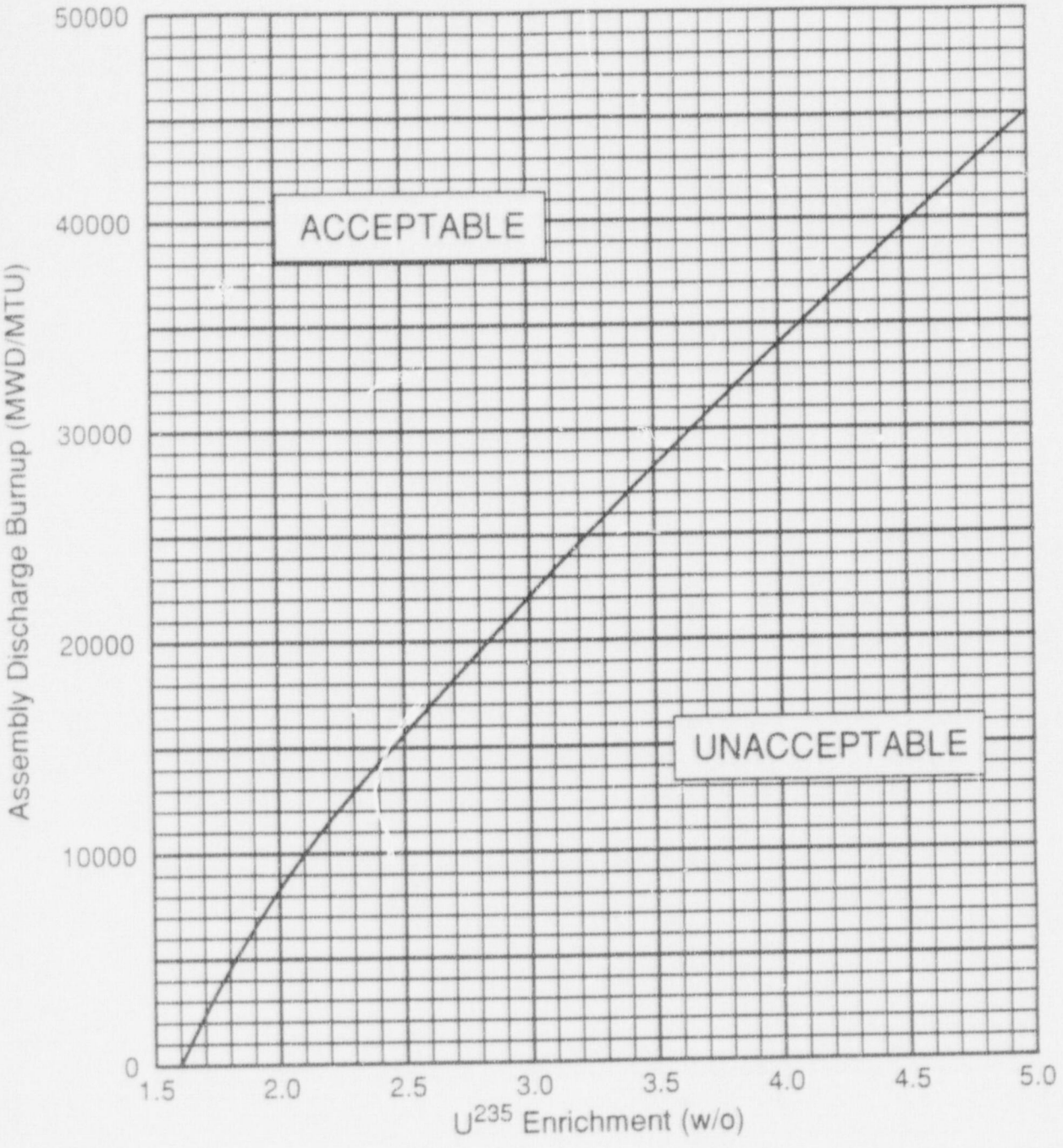

Figure 7. Byron and Braidwood Region 2 Spent Fuel Rack Burnup Credit

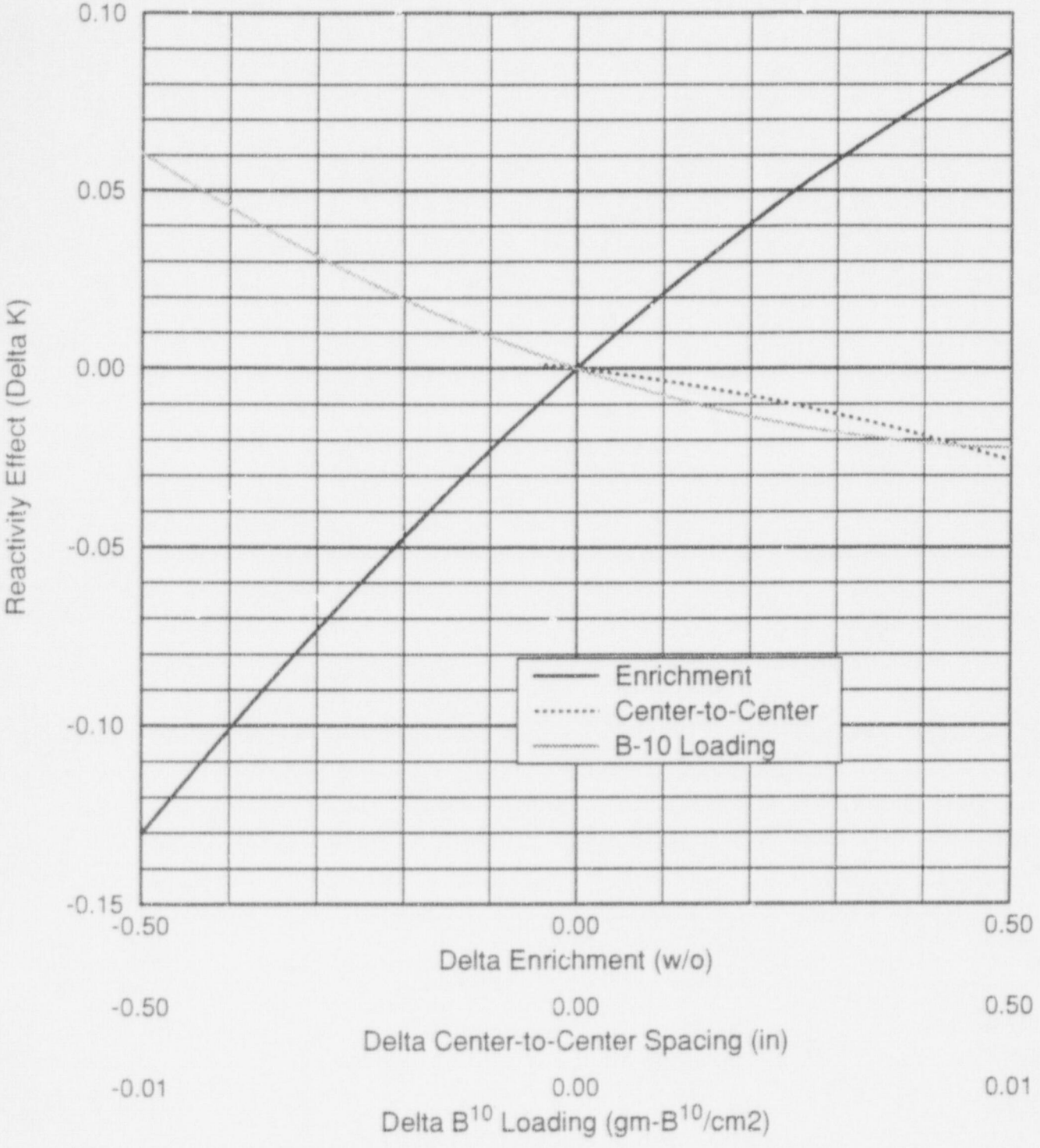

Figure 8. Byron and Braidwood Region 2 Spent Fuel Rack Reactivity Sensitivity

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