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Holtec International
555 Lincoln Drive West
Marlton, New Jersey 08053

Attention: Mr. K. K. Niyogi

Gentlemen:

SEQUOYAH NUCLEAR PLANT UNITS 1 AND 2 - SPENT FUEL POOL CRITICALITY ANALYSIS WITH BORON CREDIT - CONTRACT 99NNQ-254781 - LETTER NO. 30M384

DOCUMENT SUBMITTAL - SPENT FUEL CRITICALITY ANALYSIS WITH BORON CREDIT - N2N-056

We acknowledge receipt of the document listed below submitted by your letter dated March 21, 2000, and return herewith one copy marked (A), "Approved".

Document No.	Revision	Title
HI-992349	01	Spent Fuel Criticality Analysis with Boron Credit Summary Report, Units 1 and 2

We also acknowledge receipt of your letters dated April 5, 2000, and April 11, 2000, which submitted amended versions of pages 4, 8, 14, 38, 39, 42, 43 and 44 for the subject report. These pages were submitted to address TVA review comments on the final version of the subject report which were discussed with Holtec in telephone conversations held between April 3 and 10, 2000. We have inserted the amended pages into the base report submitted by your March 21 letter such that the TVA approved version of the report contains all the amended pages.

We note that the above document was revised to address the TVA comments on the previous revision of the spent fuel pool criticality analysis summary report which were documented by TVA Letter 30M379.

The spent fuel pool criticality analysis summary report will be submitted to NRC for review as part of the technical basis for the formal Sequoyah license amendment request (Sequoyah Technical Specification Change No. TVA-SQN-TS-99-17) which will modify the present spent fuel pool fuel storage requirements to be consistent with the revised spent fuel pool criticality calculations documented in the report. The revised spent fuel pool criticality calculations take partial credit for dissolved boron in the spent fuel pool water in accordance with 10CFR50.68 requirements.

QA Record B88 000421 801

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CRITICALITY SAFETY ANALYSES OF SEQUOYAH SPENT FUEL RACKS WITH ALTERNATIVE ARRANGEMENTS

FOR

TENNESSEE VALLEY AUTHORITY

APPROVED
This approval does not relieve the Contractor from any part of his responsibility for the correctness of design, details and dimensions.
Letter No. 30M384
Date: April 20, 2000
TENNESSEE VALLEY AUTHORITY
SQEP (N) BY M. J. Barzynski

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Summary of Revisions
Holtec Report No. HI-992349

Revision1: Revision 1 of the report is issued to incorporate the client comments on revision 0 of the report. (Letter No. 30M379 from W.M. Justice, TVA to K.K. Niyogi, Holtec International).

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1.0 INTRODUCTION AND SUMMARY

The purpose of this evaluation of the storage racks is to document the criticality safety of the racks in the spent fuel pool of the Sequoyah Nuclear Plant of Tennessee Valley Authority. Credit was taken for soluble boron in pool water, integral fuel burnable absorber rods and gadolinia, fuel burnup, and spent fuel cooling time, where appropriate. The analysis uses the KENO5a Monte Carlo code with the 238-group cross-section library developed by the Oak Ridge National Laboratory as the primary code for the calculations. CASMO4 was used for calculation of fuel depletion effects and manufacturing tolerances. As permitted in the USNRC guidelines, parametric evaluations were performed for each of the manufacturing tolerances and the associated reactivity uncertainties were combined statistically. All calculations were made for an explicit modeling of the fuel and storage cell to define the enrichment-burnup-cooling time combinations for spent fuel configurations that assure a safe storage of spent fuel in the pool. Specifically, the following analyses were performed.

The maximum k-effective values for storage of spent fuel face adjacent to each other (Region 2), as shown in Figure 1-5, were determined with the KENO5a code, assuming an infinite radial array of storage cells with a finite axial length, water reflected. For each initial enrichment and spent fuel cooling time, minimum burnup values were determined that assure the maximum k-effective, including calculational and manufacturing uncertainties, remains less than 1.0 for this storage configuration under the assumed condition of the loss of all soluble boron. Figure 1-1 and Figure 1-6 summarize the results of these analyses, showing the minimum acceptable burnup for fuel of various initial enrichments along with the cooling time of the spent fuel in the pool. These calculations are also valid for the future cask pit rack, which has received regulatory approval but has not been installed yet. All points on the curves have the same maximum reactivity. Figure 1-1a shows the minimum acceptable burnup for fuel of various initial enrichments along

with the burnup of the spent fuel currently in storage as a function of initial enrichment (the data points), for the Region 2 racks. This figure shows that almost all the spent fuel currently in storage can be safely stored in this configuration. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, for the face adjacent storage of spent fuel in the pool was determined to be 300 PPM.

The maximum k-effective values for the checkerboard storage of fresh and spent fuel (Region 1; 1 fresh fuel assembly in 4 fuel assembly groups), as shown in Figure 1-5 and Figure 1-5a, were also determined. In the base case, no credits were taken for the presence of integral fuel burnable absorbers (IFBA) or gadolinia rods in the fresh fuel. The effect of cooling time of spent fuel on the calculated reactivity was also investigated. For each initial enrichment, minimum burnup values were determined that assure the maximum k_{eff}, including all calculational and manufacturing uncertainties, remains less than 1.0 under the assumed condition of the loss of all soluble boron. The curves in Figure 1-2 and Figure 1-7 summarize the results of the analyses, showing the minimum acceptable burnup for fuel of various initial enrichments along with the required cooling times for the spent fuel assemblies in the pool. All points on the curves have the same maximum reactivity. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm.

The effect of gadolinia present in some of the fresh fuel rods on the calculated k_{eff} for the Region 1 checkerboard storage of fresh and spent fuel, as shown in Figure 1-5 and Figure 1-5a, was also investigated in this analysis. The results are shown in Figure 1-3. Four (4) and eight (8) gadolinia rod patterns were investigated. It was assumed that these rods had 2 wt% gadolinia with 4.95±0.05 wt% carrier uranium enrichment. The results establish the requirements for safe storage of a checkerboard pattern of fresh fuel containing

gadolinia and spent fuel (Figure 1-5 and Figure 1-5a) in the spent fuel pool. For these gadolinia cases, no credit is taken for the cooling time of the spent fuel in the pool. The minimum acceptable burnup for fuel of various initial enrichments, for varying numbers of gadolinia rods in the fresh fuel assemblies, required for safe storage is shown in Figure 1-3. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm.

The effect of IFBA rods on the calculated k_{eff} for the Region 1 checkerboard storage of fresh and spent fuel, as shown in Figure 1-5 and Figure 1-5a, was also investigated in these analyses. In this case, no credit is taken for the cooling time of the spent fuel in the pool. The results are shown in Figure 1-4. The results indicate that a checkerboard pattern of fresh fuel with 1.5X IFBA[+] and spent fuel (Figure 1-5 and Figure 1-5a) can be safely stored in the spent fuel pool. The minimum acceptable burnup for fuel of various initial enrichments, as a function of the number of IFBA rods in the fresh fuel assemblies, required for this storage pattern is shown in Figure 1-4. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm.

Evaluation of postulated accident conditions demonstrate that 700 ppm of soluble boron in the spent fuel pool provides margins to criticality sufficient to mitigate the effects of the most serious fuel handling or misloading accident, assuring that the maximum reactivity remains below the regulatory limit of 0.95. Recent USNRC Guidelines allow partial credit for soluble boron, and this would be more than adequate to protect against the most serious fuel handling accident. In this analysis, partial credit was taken for

+ Westinghouse standard notation referring to the thickness of the zirconium diboride coating on the fuel rods

soluble boron in the spent fuel pool to ensure that the calculated k_{eff} for the storage racks, including all calculational biases and uncertainties, remained below the regulatory limit of 0.95 for both normal and accident cases. The SQN spent fuel storage pool normally contains 2000 ppm soluble boron, which is more than adequate to assure the continued criticality safety of the storage pool. With 2000 ppm boron, even the incredible condition of completely filling the pool with fresh fuel of the maximum reactivity would not result in criticality.

Analyses were performed to determine that the storage of fresh fuel assemblies and empty cells alternately in the pool (2 fresh fuel assemblies in 4 as shown in Figure 1-5) meets the regulatory requirements for k_{eff}, without any credit for soluble boron in the pool (Region 3). Analyses were also performed to determine the limiting amount of water which could be displaced in order to checkerboard non-fissile bearing components (such as a boral coupon tree, thimble plug etc.) with fresh fuel. It was conservatively determined 75% of water can be safely displaced in empty cells by non-fissile bearing components. These analyses confirm that non-fuel bearing assembly components (i.e. thimble plugs, rod cluster control assemblies (RCCAs) etc.) may be stored in the fuel assemblies without affecting the storage requirements for the assemblies.

The following restrictions apply for the storage patterns of fuel assemblies in the pool:

- The arrangement in Region 1 sub-arrays must not allow a configuration with fresh assemblies adjacent to each other.
- For the interface with Region 1 storage cells, fresh fuel in Region 1 should not be stored adjacent to spent fuel assemblies in the Region 2 storage cells.
- For the interface between Region 1 and Region 3 storage region, fresh fuel assemblies should not be stored adjacent to each other.
- An empty cell is less reactive than any cell containing fuel and therefore may be used as a Region 1 or Region 2 cell in any arrangement.

In summary, results of the analyses confirm that the spent fuel storage racks can safely accommodate fuel with initial enrichments up to 4.95 ±0.05 %, with assurance that under normal and accident conditions the maximum reactivity, including calculational and

manufacturing uncertainties and credit taken for soluble boron, will be less than 0.95, with 95% probability at the 95% confidence level, provided the fuel conforms to the enrichment, burnup limits, cooling time and loading patterns for the spent fuel as defined in Figures 1-1 to 1-7. The relationships between the initial enrichment, burnup and cooling time for the different acceptable storage configurations, as described above and depicted in Figures 1-1 to 1-4, 1-6 and 1-7, are given in Appendix B.

2.0 ANALYSIS CRITERIA AND ASSUMPTIONS

To assure the true reactivity will always be less than the calculated reactivity, the following conservative analysis criteria or assumptions were used.

- Criticality safety analyses are based upon an infinite radial array of cells; i.e., no credit is taken for radial neutron leakage, except for evaluating accident conditions where neutron leakage is inherent.

- The analyses assumed Westinghouse 17x17 fuel assemblies, which were determined to be more reactive than the FCF Mark BW-17 fuel assemblies.

- No credit is taken for the presence of the Uranium-236 isotope in the fuel for this analysis.

- All calculations were performed at a temperature of 20 °C. Effect of the temperature down to 4 °C is treated as an additional uncertainty in the calculations.

- As built composition was used for the Boral panels and the uncertainty associated with the minimum B-10 loading was addressed in the calculations.

- No axial blankets were assumed to be present in the fuel rods. The entire active fuel length was assumed to have the same enrichment.

- The reactivity penalty resulting from the removal of a Burnable Poison Rod Assembly (BPRA), present during operation, was calculated assuming the maximum number of burnable poison rods and the maximum boron loading in these rods. Removal of the BPRA rods was assumed to occur at a fuel depletion of 30,000 MWD/MTU. This penalty is then imposed on the calculated k_{eff} from the analyses, and is bounding with respect to gadolinia and IFBA rodded fuel assemblies.

- The density of the fuel was assumed to be 96% of the nominal theoretical density.

3.0 ACCEPTANCE CRITERIA

The primary acceptance criterion is that, under storage of fuel under the assumption of the loss of all the boron in the pool, the maximum k_{eff} shall be less than 1.0, including calculation uncertainties and effects of mechanical tolerances. Moreover, for normal storage of fuel, the maximum k_{eff} shall be less than 0.95, including calculation uncertainties and effects of mechanical tolerances, with partial credit for soluble boron in the pool water. For the accident scenarios, when credit is taken for the soluble boron in pool water, the maximum k_{eff} shall be less than 0.95, including calculation uncertainties and effects of mechanical tolerances. Applicable codes, standards, and regulations, or pertinent sections thereof, include the following:

- General Design Criterion 62, Prevention of Criticality in Fuel Storage and Handling.
- Code of Federal Regulation 10CFR50.68, Criticality Accident Requirements
- USNRC Standard Review Plan, NUREG-0800, Section 9.1.2, Spent Fuel Storage.

- USNRC letter of April 14, 1978, to all Power Reactor Licensees - OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications, including modification letter dated January 18, 1979.
- USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2 (proposed), December, 1981.
- ANSI-8.17-1984, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors.
- L. Kopp, "Guidance On The Regulatory Requirements For Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants", USNRC Internal Memorandum L. Kopp to Timothy Collins, August 19, 1998.

4.0 DESIGN AND INPUT DATA

4.1 Fuel Assembly Design Specifications

Two different fuel assembly designs were considered in the analyses; the Westinghouse 17x17 and the Framatome Mark BW-17 fuel. Table 4.1 provides the design details for the fuel assemblies. Any burnable poison, which may be in the fuel assemblies such as IFBA or gadolinia rods or a burnable poison rod assembly (BPRA), would reduce reactivity. The presence of four (4) and eight (8) gadolinia rods in the fresh fuel assemblies were considered. The presence of sixteen (16), thirty two (32), forty eight (48) and sixty four (64) IFBA rods in the fresh fuel assemblies were considered in this analysis. Figures 4-1 and 4-2 illustrate the fuel rod array used in the analyses for gadolinia and IFBA rod locations patterns. In each case, the gadolinia or IFBA rods were full length.

4.2 High Density Fuel Storage Cells

The spent fuel storage cell used for the criticality analyses of the Sequoyah spent fuel storage cells is shown in Figure 4.3. Each storage cell is composed of single Boral absorber panels positioned between two 8.75 inch I.D., 0.060 inch thick stainless steel boxes. Peripheral cells use a 0.060" stainless steel sheathing on the outside supporting the Boral panel. The fuel assemblies are normally located in the center of each storage cell on a nominal lattice spacing of 8.97±0.04 inches. The Boral absorber has a thickness of 0.102±0.005 inch and an as-built B-10 areal density of 0.03388 g/cm^2 (0.03218 g B-10 cm^2 minimum).

5.0 METHODOLOGY

The primary criticality analyses were performed with the three-dimensional NITAWL-KENO5a Monte Carlo code package [1]. NITAWL was used with the 238-group SCALE-4.3 cross-section library and the Nordheim integral treatment for U-238 resonance shielding effects. Benchmark calculations, presented in Appendix A, indicate a bias of 0.0030 ± 0.0012 (95%/95%) [2]. Verification calculations for selected cases were made with the MCNP code[(4)] (bias of 0.0009 ± 0.0011, as shown in Appendix A). CASMO4, a two-dimensional deterministic code [4] using transmission probabilities, was used to evaluate the small (differential) reactivity effects of manufacturing tolerances. Validity of the CASMO4 code was established by comparison with KENO5a and MCNP calculations for a comparable rack case.

In the geometric model used in the calculations, each fuel rod and each fuel assembly were explicitly described. Reflecting boundary conditions effectively defined an infinite radial array of storage cells. In the axial direction, a 30-cm water reflector was used to conservatively describe axial neutron leakage. Each stainless steel box and water within

the box were also explicitly described in the calculational model. The fuel cladding material was zirconium. Large water gaps between rack modules were not modeled.

Monte Carlo (KENO5a and MCNP) calculations inherently include a statistical uncertainty due to the random nature of neutron tracking. To minimize the statistical uncertainty of the KENO5a calculated reactivities, a minimum of 4 million neutron histories were accumulated in each calculation. A comparable number of neutron histories were accumulated in the MCNP verification calculations.

6.0 ANALYSIS RESULTS

6.1 Bounding Fuel Assembly

Calculations were performed, using CASMO4, to evaluate the reactivity of both the Westinghouse 17x17 and the Framatome Mark-BW17 fuel, described in Table 4.1. These showed that the Westinghouse 17x17 fuel exhibits higher reactivity.

Burnup, GWD/MTU	**k_{inf} (W 17X17)**	**k_{inf} (Framatome BW-17)**
0	1.1879	1.1861
10	1.1046	1.1030
15	1.0687	1.0672
20	1.0346	1.0332
25	1.0018	1.0003
30	0.9697	0.9681
35	0.9380	0.9363
40	0.9067	0.9048
45	0.8758	0.8738
50	0.8456	0.8434

6.2 Evaluation of Uncertainties

Calculations were made to determine the uncertainties in reactivity associated with manufacturing tolerances. Tolerances that would increase reactivity were calculated;

negative values are expected to be of equal magnitude but opposite in sign over the small tolerance variations. Results of these calculations are shown in Table 6.1. The reactivity effects were separately evaluated in a sensitivity study for each independent tolerance and the results were combined statistically. Tolerances considered include the following :

6.2.1 *Tolerance in Lattice Pitch or Box I.D.*

The nominal cell pitch is 8.972 inches. The nominal box ID is 8.75 inches with a tolerance of ± 0.04 inches. The reactivity uncertainty associated with this tolerance is given in Table 6.1.

6.2.2 *Tolerance in the Box Wall Thickness*

The nominal tolerance in steel thickness is 10% of box wall thickness. The nominal box wall thickness is 0.060 inches with a tolerance of ± 0.006 inches. The reactivity uncertainties associated with this tolerance are given in Table 6.1.

6.2.3 *Tolerances in Fuel Enrichment and Density*

For estimating the reactivity uncertainties associated with tolerances in fuel enrichment and density, conservative tolerances of ± 0.05% in enrichment and ± 0.200 g/cc in UO_2 density were assumed. The reactivity uncertainty associated with the fuel density tolerance is summarized in Table 6.1. The reactivity uncertainties associated with the tolerance in fuel enrichment are shown in Table 6.3.

6.2.4 *Uncertainty in Depletion Calculations*

The uncertainty in depletion calculations was taken as 5% of the reactivity decrement

from beginning-of-life to the burnup of concern.

6.2.5 Uncertainty in B-10 Loading Density in Boral Panels and Boral Panel Width

The Boral panels have a nominal width of 7.50 in with a tolerance of ±0.06 in. The panels are 0.102±0.005 in thick. The as built Boral loading density of 0.03388 gm B-10 / cm^2 was used in these analyses. The minimum B-10 loading in these panels was 0.03218 gm B-10/cm^2. The uncertainties associated with the minimum B-10 loading and Boral panel widths were calculated and are tabulated in Table 6.1.

6.2.6 Eccentric Locations of Fuel Assemblies

The fuel assemblies are nominally stored in the center of the storage cells. Eccentric positioning of fuel assemblies in the cells normally results in a reduction in reactivity for poisoned racks. Calculations have been made confirming the eccentric positioning of four fuel assemblies at the position of closest approach yields a reduction in reactivity, confirming that the normal centered position is the most reactive. The increased neutronic coupling between the four assemblies is off-set by the increased water spacing on the opposite side of the fuel.

6.2.7 Tolerance in Gadolinia and IFBA Loading

For rods containing gadolinia burnable poison, the initial concentration was assumed to be 2% by weight of Gd_2O_3. In the case of IFBA rods, the nominal Zirconium Diboride was assumed to be 2.36 mg B10/inch (commonly called 1.5X). The tolerance in gadolinia and IFBA (Zirconium Diboride) loading was assumed to be ±5% of the nominal design value. Results of KENO5a calculations provided the reactivity uncertainties associated with these tolerances, as shown in Tables 6.7 and 6.8.

6.3 Abnormal and Accident Conditions

6.3.1 *Temperature and Void Effects*

Temperature effects were also evaluated in the temperature range from 4 °C to 120 °C and the results are listed in Table 6.2. These results show that the temperature coefficient of reactivity is negative and that at 4 °C (maximum spent fuel pool water density) highest reactivity is predicted. The calculations for the reactivities under different storage conditions were performed at a water temperature of 20 °C. The reactivity increment between 4 °C and 20 °C is taken into account as additional uncertainty in the analyses. The void coefficient of reactivity (boiling conditions) was found to be negative.

6.3.2 *Misloaded Fuel Assembly Accident*

The potential effects of abnormal and accident conditions were also considered in this study. Five different fuel misloading accident scenarios were considered in this study:

a) For storage of spent fuel of a certain burnup, face adjacent to each other as shown in Figure 1-5 (Region 2), a fresh fuel assembly containing no gadolinia or IFBA was postulated to be misplaced in the location of a spent fuel assembly.

b) For a checkerboard pattern of storage of fresh and spent fuel assemblies (1 fresh fuel assembly in 4), Region 1 as shown in Figure 1-5 and Figure 1-5a, a fresh fuel assembly containing no gadolinia or IFBA was postulated to be misplaced in the location of a spent fuel face adjacent to another fresh fuel assembly containing no gadolinia or IFBA.

c) For a checkerboard pattern of storage of fresh and spent fuel assemblies (1 fresh fuel

assembly in 4), Region 1 as shown in Figure 1-5 and Figure 1-5a, with credit for the presence of gadolinia or IFBA rods in fresh fuel assemblies, a fresh fuel assembly (containing gadolinia or IFBA rods) was postulated to be misplaced in the location of a spent fuel assembly face adjacent to another fresh fuel assembly.

d) For a checkerboard pattern of storage of fresh and spent fuel (Region 1: 1 fresh fuel assembly, containing gadolinia or IFBA rods, in 4 fuel assemblies), as shown in Figure 1-5 and Figure 1-5a, a fresh fuel assembly (*containing no* gadolinia or IFBA rods) was postulated to be misplaced in the location of a spent fuel assembly.

e) For the checkerboard pattern storage of fresh fuel assemblies and empty cells filled with water (Region 3), as shown in Figure 1-5 and Figure 1-5a, a fresh fuel assembly (*containing no* gadolinia or IFBA rods) is postulated to be misplaced in the location of an empty cell face adjacent to another fresh fuel assembly (*containing no* gadolinia or IFBA rods).

Since a fuel misloading scenario would be considered an accident, calculations were performed to determine the soluble boron concentration required to prevent criticality in the pool under such scenarios (i.e. the calculated k_{eff} maintained less than 0.95). The misloading of a fresh Westinghouse 17x17 fuel assembly of 4.95±0.05 % enrichment into a cell intended for spent fuel could potentially exceed the regulatory limit on k_{eff}. For this condition, calculations indicate that credit for 700 ppm soluble boron would maintain the maximum reactivity below the regulatory k_{eff} limit of 0.95 for all the scenarios described above. The spent fuel pool water normally contains 2000 ppm soluble boron, which is more than adequate to assure the continued criticality safety of the storage pool. Calculation with 2000 ppm soluble boron, assuming the incredible condition of the racks being completely filled with fresh fuel (infinite array), confirmed that the pool remains subcritical. Accidents that might occur in the cask pit rack are bounded by the accident

evaluations described above. In particular, a fuel mis-placement outside and adjacent to the cask pit rack is bounded by the analysis for fuel misplacement within the racks.

6.4 Reactivity Effect of Axial Burnup Distribution

Initially, fuel loaded into the reactor will burn with a slightly skewed cosine power distribution. As burnup progresses, the burnup distribution will tend to flatten, becoming more highly burned in the central regions than in the upper and lower ends. At high burnup, the more reactive fuel near the ends of the fuel assembly (less than average burnup) occurs in regions of lower reactivity worth due to neutron leakage. Consequently, it would be expected that over most of the burnup history, distributed burnup fuel assemblies would exhibit a slightly lower reactivity than that calculated for the average burnup. As burnup progresses, the distribution, to some extent, tends to be self-regulating as controlled by the axial power distribution, precluding the existence of large regions of significantly reduced burnup.

Calculations were performed, based on the equivalent enrichments for the spent fuel, to obtain the axial enrichment distribution. The active fuel region was divided into 10 axial zones and the equivalent enrichment for each zone was obtained. The methodology used for obtaining the axial enrichment distribution is based on a generic study by Turner [6] and has been previously used for such analysis of spent fuel pool racks [7].

In order to determine the reactivity effect of the axial burnup distribution for these assemblies, three KENO5a calculations were performed for each burnup considered (Face Adjacent Storage of 30 MWD/kg-U Burnup Fuel, Checkerboard of 1 Fresh with Spent Fuel of 45 and 50 MWD/kg-U Burnup). The first run used a distributed axial burnup distribution represented by 10 axial zones (using equivalent enrichments). The second run used an average burnup distribution over the entire axial length. The k_{eff}

values from these runs were compared to determine the reactivity effect at the analyzed burnups.

The results of comparing the k_{eff} from the calculation using the axial burnup distribution and the calculation using an assembly-average uniform burnup show that using the axial burnup distribution profile, as opposed to an uniform burnup, results in a slightly lower k_{eff}. This decrease in reactivity is neglected in this study.

The absence of a positive reactivity effect is expected because:

(1) The burnup requirement for the face adjacent storage of spent fuel is low for a positive reactivity effect, consistent with previous calculations (Reference 6).

(2) For the checkerboard arrangements, the fresh fuel dominates the reactivity. The axial flux distribution is nearly cosine for fresh fuel which flux-weights the central region of the low-reactivity spent fuel and results in an overall negative reactivity effect of the axial distribution in burnup.

6.5 Criticality Analyses Results

A summary of the results of the criticality safety analysis for the storage of spent fuel (initial enrichment of 4.95±0.05 %) face adjacent to each other (Region 2) in the spent fuel pool racks is given in Table 6.5. The table also contains the calculational biases and the uncertainties. The results indicate that face adjacent storage of the spent fuel with a burnup of 30.27 MWD/kg-U burnup meets the regulatory requirements, with no credit for cooling time. The effect of cooling time of spent fuel on the acceptability of such a pattern is also shown in Figure 1-1. These calculations are also valid for the cask-pit region rack. Figure 1-1 summarizes the burnup requirements for other initial enrichments for the storage of spent fuel face adjacent to each other. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and

calculational tolerances, for this storage pattern for spent fuel in the pool was determined to be 300 PPM. For the accident scenario of the placement of a fresh fuel assembly, containing no gadolinia or IFBA, in the intended location of a spent fuel assembly, it would require about 600 ppm of soluble boron to maintain k_{eff} in the rack below the regulatory requirement of 0.95.

The results for the analysis of the storage of fresh fuel in a Region 1 checkerboard pattern with spent fuel (spent fuel with approximately 46 MWD/kg-U Burnup, 1 fresh assembly out of 4 assemblies) are summarized in Table 6.6. This storage pattern is depicted in Figure 1-5 and Figure 1-5a. In this analysis no credit was taken for the presence of gadolinia or IFBA in the fresh fuel assemblies. The results show that this configuration of fuel storage meets the regulatory criteria and can be safely stored in the spent fuel pool of TVA Sequoyah Plant. Figure 1-2 summarizes the burnup requirements for other initial enrichments for the same checkerboard pattern storage. The effect of cooling time of spent fuel on the acceptability of such a checkerboard pattern of storage of fresh fuel and spent fuel (Region 1 in Figure 1-5 and Figure 1-5a) is also depicted in Figure 1-2. Significant reduction in the required burnup of the spent fuel can be obtained when the cooling time is taken into consideration, principally at higher initial enrichments. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm. For the postulated scenario of the misplacement of a fresh fuel assembly, containing no gadolinia or IFBA, in the place of a spent fuel assembly, face adjacent to another fresh fuel assembly containing no gadolinia or IFBA, it is conservatively calculated that this would require 600 ppm of soluble boron to maintain k_{eff} in the rack below the regulatory requirement of 0.95.

The results of the analysis of the storage of fresh fuel, containing gadolinia, in a checkerboard pattern with spent fuel (Region 1: 1 fresh fuel assembly out of 4

assemblies), as depicted in Figure 1-5 and Figure 1-5a, is shown in Table 6-7. No credit was taken for the cooling time of the spent fuel. The results show that this configuration of fuel storage meets the regulatory criteria and can be safely stored in the spent fuel pool of TVA Sequoyah Plant. Figure 1-3 summarizes the burnup requirements for other initial enrichments for the same checkerboard pattern storage (Figure 1-5 and Figure 1-5a) for both four (4) rod and eight (8) rod gadolinia pattern in the fresh fuel. It can be concluded that the presence of gadolinia in the fresh fuel reduces the required burnup for the safe storage of fresh and spent fuel in a checkerboard pattern. The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm. For the postulated scenario of the misplacement of a fresh fuel assembly, the following cases were considered:

- Misplacement of a fresh fuel assembly, containing gadolinia, in the place of a spent fuel assembly face adjacent to another fresh fuel assembly containing gadolinia.
- Misplacement of a fresh fuel assembly, containing no gadolinia or IFBA rods, in the place of a spent fuel assembly face adjacent to another fresh fuel assembly containing gadolinia.

It is conservatively calculated that these configurations would require 600 PPM and 700 PPM, respectively, of soluble boron to maintain k_∞ in the rack below the regulatory requirement of 0.95.

The results for the analysis of the storage of fresh fuel, containing IFBA rods, in a checkerboard pattern with spent fuel (Region 1: 1 fresh assembly out of 4 assemblies) is shown in Table 6.8. This storage pattern is also depicted in Figure 1-5 and Figure 1-5a. It was assumed that the fresh fuel assembly contains 16, 32, 48 or 64 rods with 1.5X IFBA. The results show that this configuration of fuel storage meets the regulatory criteria and

can be safely stored in the spent fuel pool of TVA Sequoyah Nuclear Plant. Figure 1-4 summarizes the burnup requirements for other initial enrichments for a same checkerboard pattern storage, for different numbers of IFBA rods in the fuel assembly. It can be concluded that the presence of IFBA rods in the fresh fuel assemblies reduces the required burnup for the safe storage of fresh and spent fuel in a checkerboard pattern (Figure 1-5 and Figure 1-5a). The minimum soluble boron concentration required to maintain k_{eff} below 0.95, including all manufacturing and calculational tolerances, under this pattern of storage of fuel in the pool was determined to be 300 ppm. For the postulated scenario of the misplacement of a fresh fuel assembly, the following cases were considered:

- Misplacement of a fresh fuel assembly, containing IFBA rods, in the place of a spent fuel assembly face adjacent to another fresh fuel assembly containing 16 1.5X IFBA rods.
- Misplacement of a fresh fuel assembly, containing no gadolinia or IFBA rods, in the place of a spent fuel assembly face adjacent to another fresh fuel assembly containing 16 1.5X IFBA rods.

It is conservatively calculated that these configurations would require 600 PPM and 700 PPM, respectively, of soluble boron to maintain k_∞ in the rack below the regulatory requirement of 0.95.

Analyses were also performed to investigate the checkerboard pattern storage (Figure 1-5) of fresh fuel assemblies and empty cells, filled with water, in the spent fuel pool of the Sequoyah Nuclear Plant (Region 3). The calculations were performed under the assumption that the fresh fuel assemblies contained no gadolinia or IFBA rods. It was determined that the storage of fresh fuel assemblies and empty cells alternately (2 fresh in 4) in the pool meets the regulatory requirements. The calculated k_{eff} was below the regulatory limit of 0.95, including all calculational biases and manufacturing tolerances,

without any credit for soluble boron. For the postulated accident scenario of the misplacement of a fresh fuel assembly, containing no IFBA or gadolinia rods, in the place of a water filled cell, face adjacent to another fresh fuel assembly (containing no gadolinia or IFBA rods), it was conservatively calculated that this would require 700 PPM of soluble boron to maintain k_{eff} in the rack below the regulatory requirement of 0.95.

Since the results show that a number of storage patterns are acceptable for safely storing fresh and spent fuel assemblies in the pool, analyses were performed to study the effect of storing fuel in these patterns next to each other. Calculations for the interface between three different regions (Face adjacent storage of spent fuel assemblies, 1 fresh fuel assembly in 4 fuel assemblies checkerboard with spent fuel and checkerboard of fresh fuel assemblies and empty cells) show that there is no adverse effect on criticality except for the interface between Region 2 storage of spent fuel and Region 1 checkerboard storage of fresh and spent fuel. For this configuration the fresh fuel in the checkerboard pattern should not be stored next to the Region 2 spent fuel.

In order to determine the allowable storage locations for fuel assemblies, each assembly will continue to be characterized by reactivity (i.e., initial enrichment–burnup combination) prior to insertion in the spent fuel storage rack.

6.6 Code Comparison Calculations- CASMO4, KENO5a and MCNP

An independent method of analyses (MCNP) was used to verify the reference KENO5a calculations. In addition, these calculations also serve to verify the CASMO4 code, since CASMO4 is a two-dimensional code and cannot be directly validated against critical experiments. The USNRC guidelines, however, endorse CASMO4 and KENO5a as acceptable methods of criticality analysis. Results of these code comparison calculations are listed in Table 6.9, corrected for bias. These results are considered to be in good

agreement, confirming the basic KENO5a and CASMO4 calculations.

7.0 CONCLUSIONS

- Fuel assemblies having the burnup, initial enrichment and cooling time criteria as depicted in Figure 1-1 may be safely accommodated in the storage racks, with no other constraints (Region 2).
- Fuel assemblies in a checkerboard pattern (1 fresh 4.95±0.05 wt% U-235 assembly out of 4 assemblies as shown in Figure 1-5 and Figure 1-5a) may be stored in the spent fuel racks provided they meet the burnup, initial enrichment and cooling time criteria as depicted in Figure 1-2 (Region 1).
- The effect of gadolinia present in the fresh fuel provides additional reduction in the burnup requirements for the checkerboard pattern storage of fresh and spent fuel (Figure 1-5 and Figure 1-5a) as shown in Figure 1-3 (Region 1).
- The effect of IFBA present in the fresh fuel also provides reduction in the burnup requirements for the checkerboard pattern storage of fresh and spent fuel (Figure 1-5 and Figure 1-5a) as shown in Figure 1-4 (Region 1).
- The storage of fresh fuel alternately with water-filled cells (2 fresh 4.95±0.05 wt% U-235 assemblies out of 4 cells) results in a calculated k_{eff} less than 0.95 without any credit for soluble boron.
- Conservatively, 75% of water may be safely displaced by non-fissile materials in the postulated checkerboard pattern of storage of fresh fuel assemblies and empty cells (Figure 1-5) filled with water (Region 3).
- 700 PPM of soluble boron in the spent fuel provides margins to criticality sufficient to mitigate the effects of the most serious accident condition[+].

+ The boron dilution accident analysis (HI-992302) was based on a conservative assumption of the final required soluble boron concentration (800 ppm). Final detailed calculations show that the minimum soluble boron concentration, to guard against the most severe postulated accident, is 700 ppm. The 700 ppm required, therefore, represents a safety limit on the soluble boron concentration in the pool whereas 800 ppm represents an operational limit.

8.0 REFERENCES

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Table 4.1 Design Basis Fuel Assembly Specifications

FUEL ROD DATA	W 17X17	F MARK-BW17*
Outside diameter, in.	0.374	0.374
Cladding inside diameter, in.	0.3290	0.326
Cladding material	Zr-4	Zr-4
Active Fuel Length, in	144	144
Stack density, gms UO_2/cc	10.52±0.20	10.52±0.20
Pellet diameter, in.	0.3225	0.3195
Maximum enrichment, wt. % U-235	4.95 ±0.05 %	4.95 ±0.05 %
Fuel rod array	17x17	17 x 17
Number of fuel rods	264	264
Fuel rod pitch, in.	0.496	0.496
Number of guide tubes/Inst. Tubes	25	25
Guide/Inst. tubes O.D., in.	0.474	0.482
Guide/Inst. tubes I.D., in.	0.442	0.450

* One advanced Framatome fuel assembly comparable in reactivity to the Westinghouse 17x17 fuel assembly may be in the process of being developed.

Table 6.1 Reactivity Effects of Manufacturing Tolerances for Westinghouse 17x17 Fuel in TVA Sequoyah Nuclear Plant Spent Fuel Racks.

BURNUP, MWD/KG	REFERENCE	MIN. PITCH		MAX. BOX WALL		MIN. BORAL WIDTH		MIN. B-10 LOADING DENSITY		FUEL DENSITY		STATISTICAL SUM*
	k_{inf}	k_{inf}	Δk	k_{inf}	Δk	k_{inf}	Δk	k_{inf}	Δk	k_{inf}	Δk	
0	1.1879	1.1891	0.0012	1.1883	0.0004	1.1889	0.0010	1.1907	0.0028	1.1893	0.0014	0.0040
20	1.0346	1.0355	0.0009	1.0348	0.0002	1.0354	0.0008	1.0370	0.0024	1.0358	0.0012	0.0035
30	0.9697	0.9705	0.0008	0.9701	0.0004	0.9705	0.0008	0.9719	0.0022	0.9714	0.0017	0.0035
40	0.9067	0.9073	0.0006	0.9070	0.0003	0.9075	0.0008	0.9088	0.0021	0.9090	0.0023	0.0037
50	0.8457	0.8461	0.0004	0.8459	0.0002	0.8463	0.0006	0.8476	0.0019	0.8488	0.0031	0.0039

* Statistical Sum Includes the Δk correction from 20 °C to 4 °C. Statistical sum was calculated from program outputs with 5 significant digits.

Table 6.2 Reactivity Effects of Temperature and Void for Westinghouse 17x17 Fuel in TVA Sequoyah Nuclear Plant Spent Fuel Racks.

BURNUP, MWD/KGU	T = 4 °C	T = 20 °C		T = 60 °C		T = 120 °C		T = 120 °C + VOID	
	k_{inf}	k_{inf}	Δk^{+}	k_{inf}	Δk^{*}	k_{inf}	Δk^{*}	k_{inf}	Δk^{*}
0	1.1897	1.1879	-0.0018	1.1802	-0.0077	1.1641	-0.0238	1.1092	-0.0787
10	1.1065	1.1046	-0.0019	1.0970	-0.0076	1.0815	-0.0231	1.0276	-0.0770
20	1.0363	1.0346	-0.0017	1.0274	-0.0072	1.0126	-0.0220	0.9596	-0.0750
30	0.9713	0.9697	-0.0016	0.9631	-0.0066	0.9495	-0.0202	0.8979	-0.0718
40	0.9080	0.9067	-0.0013	0.9009	-0.0058	0.8887	-0.0180	0.8393	-0.0674
50	0.8467	0.8457	-0.0010	0.8407	-0.0050	0.8303	-0.0154	0.7836	-0.0621

+ difference with results @ 4 °C
* difference with results @ 20 °C

Table 6.3 Reactivity Effects of Fuel Enrichment Tolerance for Westinghouse 17x17 Fuel in TVA Sequoyah Nuclear Plant Spent Fuel Racks.

BURNUP, MWD/KGU	REFERENCE REACTIVITY	REACTIVITY AT ENRICHMENT TOLERANCE	
	k_{inf}	k_{inf}	Δk
0	1.1879	1.1900	0.0021
10	1.1046	1.1070	0.0024
20	1.0346	1.0373	0.0027
30	0.9697	0.9726	0.0029
40	0.9067	0.9098	0.0031
50	0.8457	0.8489	0.0032

Table 6.4 Reactivity Effects of Abnormal And Accident Conditions

ACCIDENT/ABNORMAL CONDITIONS	REACTIVITY EFFECT
Temperature increase	Negative
Void (Boiling)	Negative
Misplacement of a fresh fuel assembly	Worst case requires minimum 700 PPM soluble boron

Table 6.5 Summary of the Criticality Safety Analyses for the Face Adjacent Storage of Spent Fuel in Region 2 Racks.

STORAGE ARRANGEMENT	Face Adjacent Spent Fuel Storage (See Figure 1-5)
Design Basis Burnup at 4.95±0.05 % wt. ^{235}U	30.27 MWD/kg-U*
K_{eff}(KENO5a)	0.9667
Keno5a Bias	+ 0.0030
Maximum Penalty for BPRA's	± 0.0105
KENO5a Bias Uncertainty	± 0.0012
KENO Statistics (95/95) Uncertainty	± 0.0006
B-10 Loading Uncertainty	± 0.0022
Boral Width Uncertainty	± 0.0008
Lattice Spacing Uncertainty	± 0.0008
Box Wall Thickness Uncertainty	± 0.0004
Fuel Density Tolerance	± 0.0017
Enrichment Tolerance Uncertainty	± 0.0032
Depletion Uncertainty	± 0.0111
Temperature Effect to 4 °C Uncertainty	± 0.0016
Statistical Combination of Uncertainties	± 0.0121
Fuel Eccentricity Uncertainty	Negative
Axial Burnup Distribution Penalty	Negative
Maximum k_{eff}	0.9923
Regulatory Limiting k_{eff}	1.0000

* Other enrichment-burnup combinations shown in Figure 1-1 have the same maximum reactivity.

Table 6.6 Summary of the Criticality Safety Analyses for Checkerboard Storage of Fresh and Spent Fuel Assemblies (1 Fresh in 4), with No Cooling Time for the Spent Fuel.

STORAGE ARRANGEMENT	Checkerboard of 1 Fresh and 3 Spent Fuel Assemblies, 0 Cooling Time
Design Basis Burnup at 4.95±0.05 % wt. ^{235}U	46.04 MWD/kg-U*
Reference k_{eff} (KENO5a)	0.9798
Keno5a Bias	+ 0.0030
Maximum Penalty for BPRA's	+ 0.0052
KENO5a Bias Uncertainty	± 0.0012
KENO Statistics (95/95) Uncertainty	± 0.0006
B-10 Loading Uncertainty	± 0.0021
Boral Width Uncertainty	± 0.0008
Lattice Spacing Uncertainty	± 0.0006
Box Wall Thickness Uncertainty	± 0.0003
Fuel Density Tolerance	± 0.0023
Enrichment Tolerance Uncertainty	± 0.0032
Depletion Uncertainty	± 0.0081
Temperature Effect to 4 °C Uncertainty	± 0.0013
Statistical Combination of Uncertainties	± 0.0095
Fuel Eccentricity Uncertainty	Negative
Axial Burnup Distribution Penalty	Negative
Maximum k_{eff}	0.9975
Regulatory Limiting k_{eff}	1.0000

* Other enrichment-burnup combinations shown in Figure 1-2 have the same maximum reactivity.

Table 6.7 Summary of the Criticality Safety Analyses for Checkerboard Storage of Fresh Fuel Assemblies Containing Gadolinia Rods and Spent Fuel Assemblies (1 fresh of 4), with No Cooling Time for the Spent Fuel.

STORAGE ARRANGEMENT	Checkerboard of 1 Fresh (with Gadolinia Rods) and 3 Spent Fuel Assemblies	
Number of Gadolinia Rods in the Fuel Assembly	4 Gadolinia Rods	8 Gadolinia Rods
Design Basis Burnup at 4.95±0.05 % wt ^{235}U	44.21 MWD/kg-U*	39.31 MWD/kg-U*
Reference k_{eff} (KENO5a)	0.9802	0.9802
Keno5a Bias	+ 0.0030	+ 0.0030
Maximum Penalty for BPRA's	+0.0052	+0.0052
KENO5a Bias Uncertainty	± 0.0012	± 0.0012
KENO Statistics (95/95) Uncertainty	± 0.0006	± 0.0006
B-10 Loading Uncertainty	± 0.0021	± 0.0021
Boral Width Uncertainty	± 0.0008	± 0.0008
Lattice Spacing Uncertainty	± 0.0006	± 0.0006
Box Wall Thickness Uncertainty	± 0.0003	± 0.0003
Fuel Density Tolerance	± 0.0023	± 0.0023
Enrichment Tolerance Uncertainty	± 0.0032	± 0.0032
Depletion Uncertainty	± 0.0066	± 0.0067
Tolerance in Gd Loading	± 0.0002	± 0.0005
Temperature Effect to 4 °C Uncertainty	± 0.0013	± 0.0013
Statistical Combination of Uncertainties	± 0.0083	± 0.0083
Fuel Eccentricity Uncertainty	Negative	Negative
Axial Burnup Distribution Penalty	Negative	Negative
Maximum k_{eff}	0.9967	0.9967
Regulatory Limiting k_{eff}	1.0000	1.0000

* Other enrichment-burnup combinations shown in Figure 1-3 have the same maximum reactivity.

Table 6.8 Summary of the Criticality Safety Analyses for Checkerboard Storage of Fresh Fuel (with IFBA Rods) and Spent Fuel (1 Fresh in 4), with No Cooling Time for the Spent Fuel.

STORAGE ARRANGEMENT	Checkerboard of 1 Fresh Fuel Assembly Containing IFBA Rods & 3 Spent Fuel Assemblies			
Number of IFBA Rods in the Fuel Assembly	16 Rods	32 Rods	48 Rods	64 Rods
Design Basis Burnup at 4.95±0.05 % wt. ^{235}U	42.95*	39.83*	37.08*	35.43*
Reference k_{eff} (KENO5a)	0.9806	0.9792	0.9803	0.9803
Keno5a Bias	+0.0030	0.0030	0.0030	0.0030
Maximum Penalty for BPRA's	+0.0052	0.0052	0.0052	0.0052
KENO5a Bias Uncertainty	±0.0012	±0.0012	±0.0012	±0.0012
KENO Statistics (95/95) Uncertainty	±0.0006	±0.0006	±0.0006	±0.0006
B-10 Loading Uncertainty	±0.0021	±0.0021	±0.0021	±0.0021
Boral Width Uncertainty	±0.0008	±0.0008	±0.0008	±0.0008
Lattice Spacing Uncertainty	±0.0006	±0.0006	±0.0006	±0.0006
Box Wall Thickness Uncertainty	±0.0003	±0.0003	±0.0003	±0.0003
Fuel Density Tolerance	±0.0023	±0.0023	±0.0023	±0.0023
Enrichment Tolerance Uncertainty	±0.0032	±0.0032	±0.0032	±0.0032
Depletion Uncertainty	±0.0073	±0.0068	±0.0064	±0.0061
Tolerance in IFBA Loading	±0.0000	±0.0011	±0.0004	±0.0017
Temperature Effect to 4 °C Uncertainty	±0.0013	±0.0013	±0.0013	±0.0013
Statistical Combination of Uncertainties	±0.0088	±0.0085	±0.0081	±0.0080
Fuel Eccentricity Uncertainty	Negative	Negative	Negative	Negative
Axial Burnup Distribution Penalty	Negative	Negative	Negative	Negative
Maximum k_{eff}	0.9976	0.9959	0.9966	0.9965
Regulatory Limiting k_{eff}	1.0000	1.0000	1.0000	1.0000

* Other enrichment-burnup combinations shown in Figure 1-4 have the same maximum reactivity.

Table 6.9 Comparison of Calculations by Different Codes.

CASE	CASMO-4	KENO5a*	MCNP*
1) 4.95% E @30 MWD/Kg-U, Infinite Axial Length	0.9697	0.9723± 0.00012	0.9734±0.0013
2) Face Adjacent Storage of 30 MWD/kg-U Burnup Fuel, Finite Axial Length	-	0.9730± 0.00012	0.9713±0.00013
3) Checkerboard in Rack, 1 Fresh and Three 47.94 GWD/MTU Burnup Fuel, E=1.456%**	-	0.9767± 0.00012	0.9750±0.00013
4) Checkerboard in Rack, Fresh and Empty Cell	-	0.8251±0.00012	0.8226±0.00013
5) Checkerboard in Rack, Fresh Fuel Assembly with 8 Gadolinia Rods and 50 GWD/MTU Burnup Fuel (E=1.219%**), 1 Fresh in 4	-	0.9447 ± .00012	0.9415 ± 0.00013

* Calculational bias have been added to the results. These cases do not reflect the final converged solution, but are provided for code comparison purposes only. The uncertainty shown includes the uncertainty in bias at the 95% probability level with a 95% confidence factor.

** Reactivity equivalent enrichments from CASMO4 runs, at these indicated burnups.

Table 6.10 Effect of Eccentric Location of Fuel Assemblies in the Spent Fuel Racks

Storage Configuration	k_{eff} for Centered Position	k_{eff} for Eccentric Position
Region 2 Storage	0.9700±0.0003	0.9668±0.0003
1 Fresh and 3 Spent Fuel Checkerboard	0.9674±0.0003	0.9653±0.0003

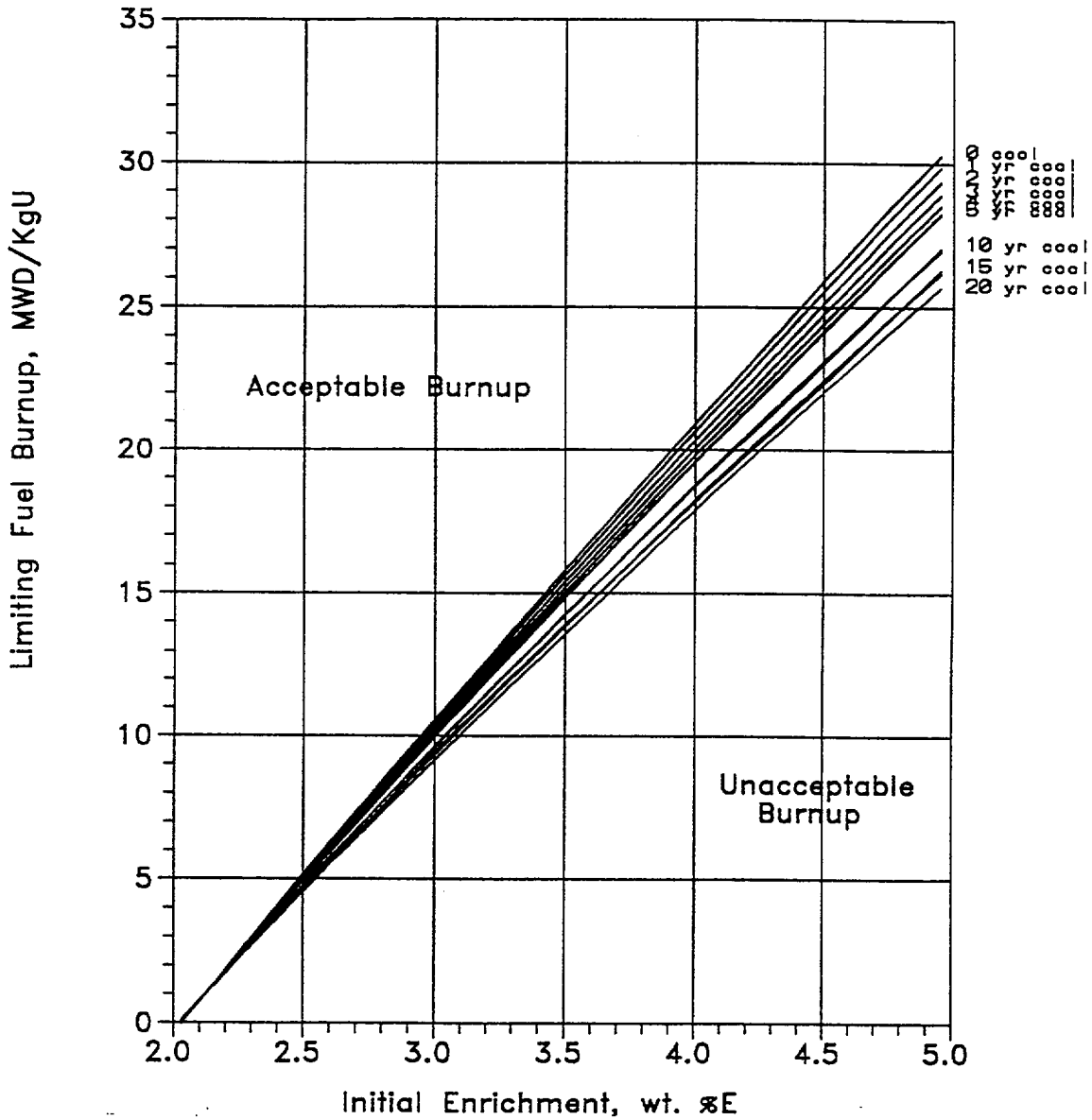


Figure 1-1 Minimum Burnup Requirements for Face Adjacent Storage of Spent Fuel in the TVA Sequoyah Nuclear Plant Storage Racks

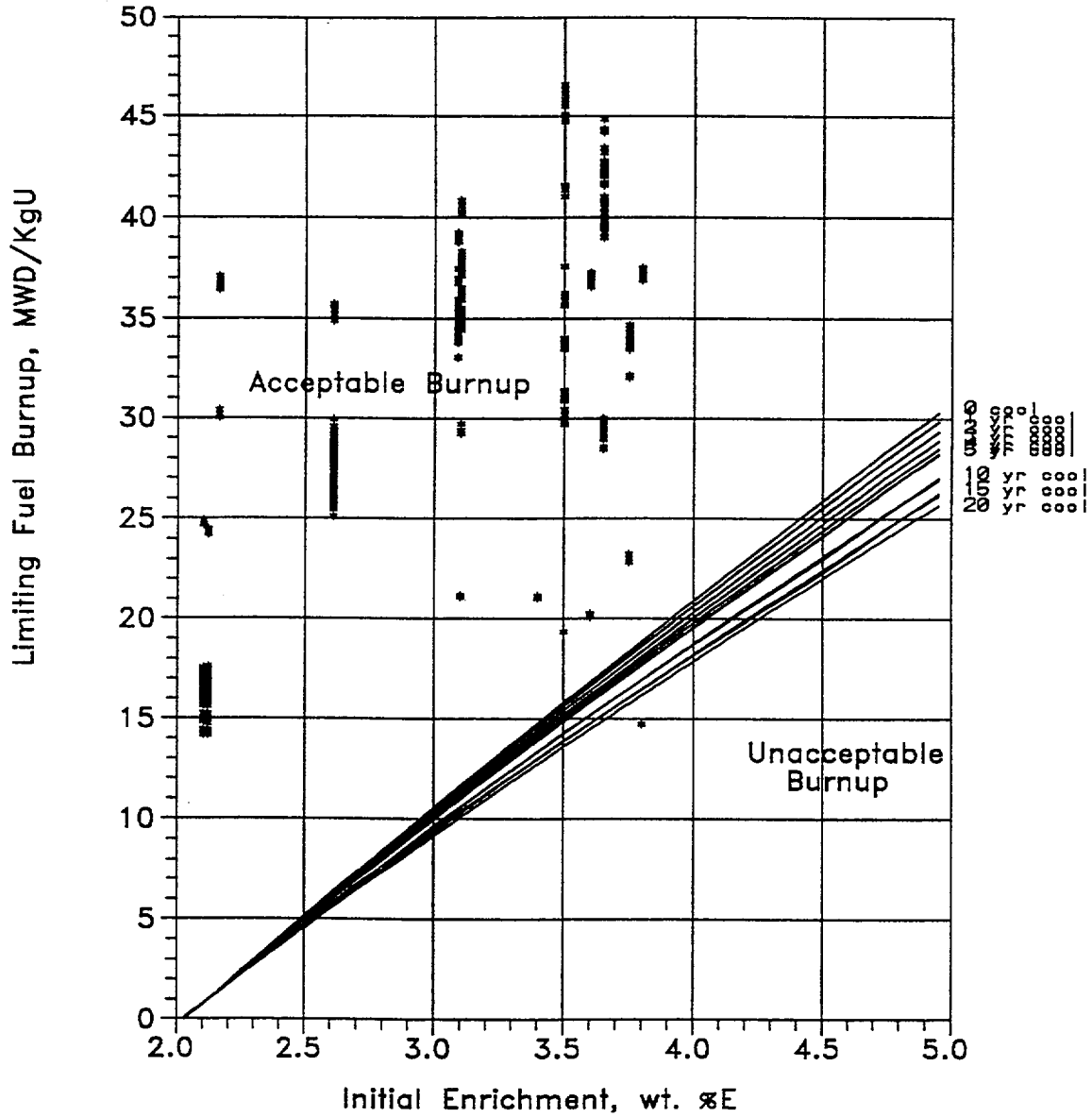


Figure 1-1a Minimum Burnup Requirements for Face Adjacent Storage of Spent Fuel in the TVA Sequoyah Nuclear Plant Storage Racks with Burnup-Enrichment Combinations for Spent Fuel Currently in Storage, with No Cooling Time for the Spent Fuel

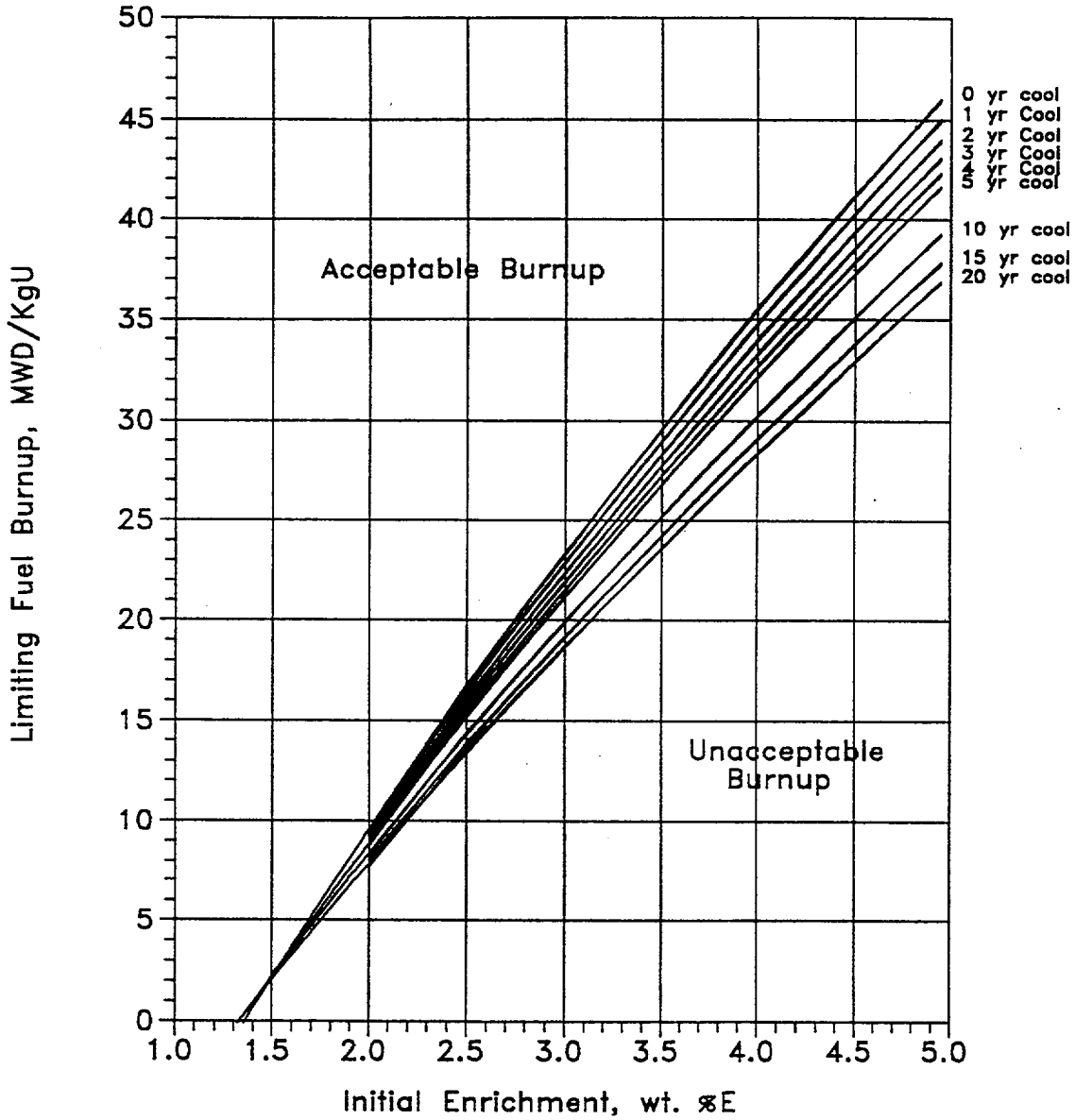


Figure 1-2 Effect of Cooling Time on the Minimum Burnup Requirements for Checkerboard (1 Fresh of 4) Storage of Spent Fuel and Fresh Fuel in the TVA Sequoyah Nuclear Plant Storage Racks

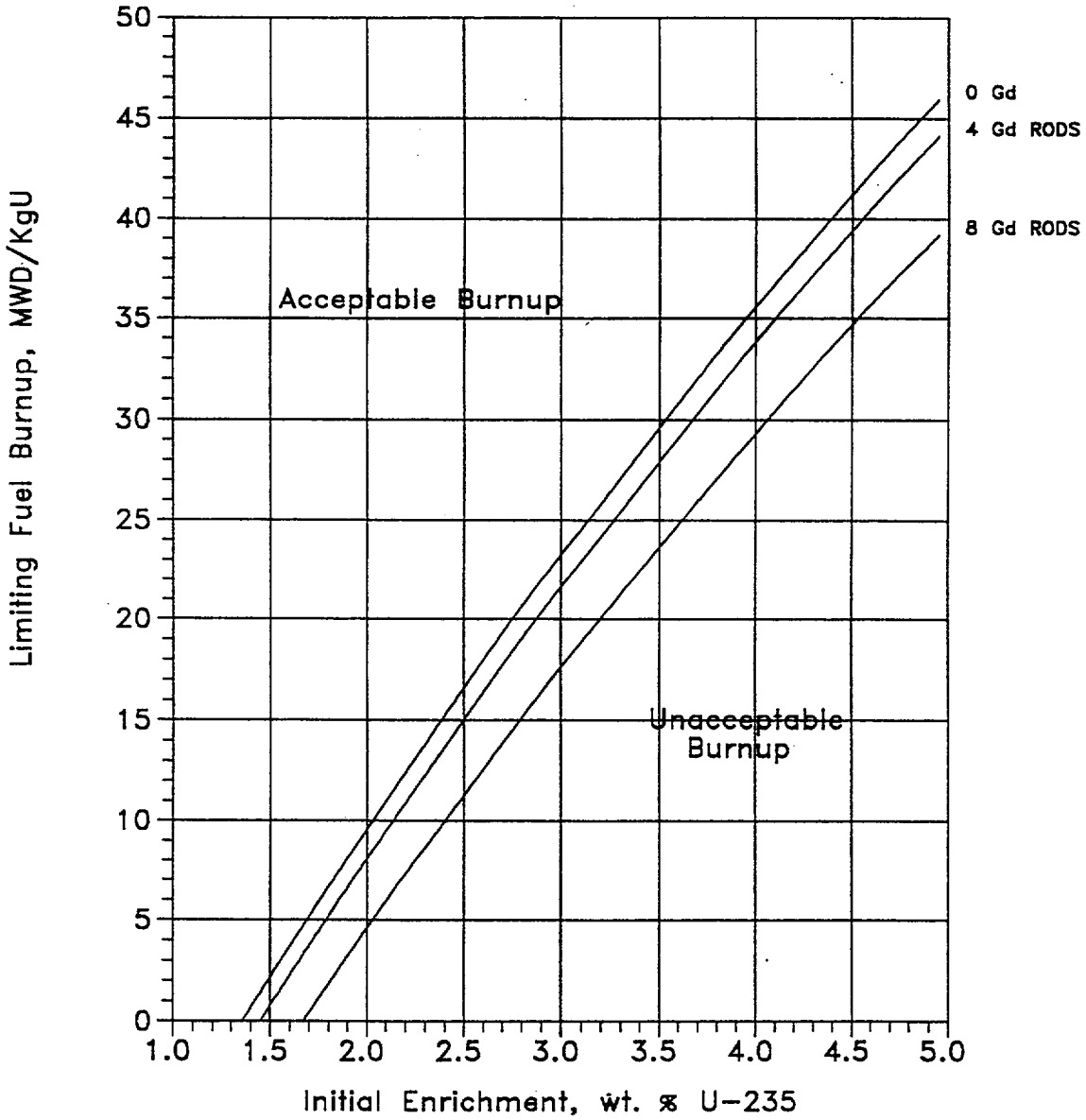


Figure 1-3 Effect of Gadolinia in Fresh Fuel on the Minimum Burnup Requirements for Spent Fuel for Checkerboard Pattern Storage of Fresh Fuel and Spent Fuel Assemblies (1 Fresh in 4) in the TVA Sequoyah Nuclear Plant Storage Racks

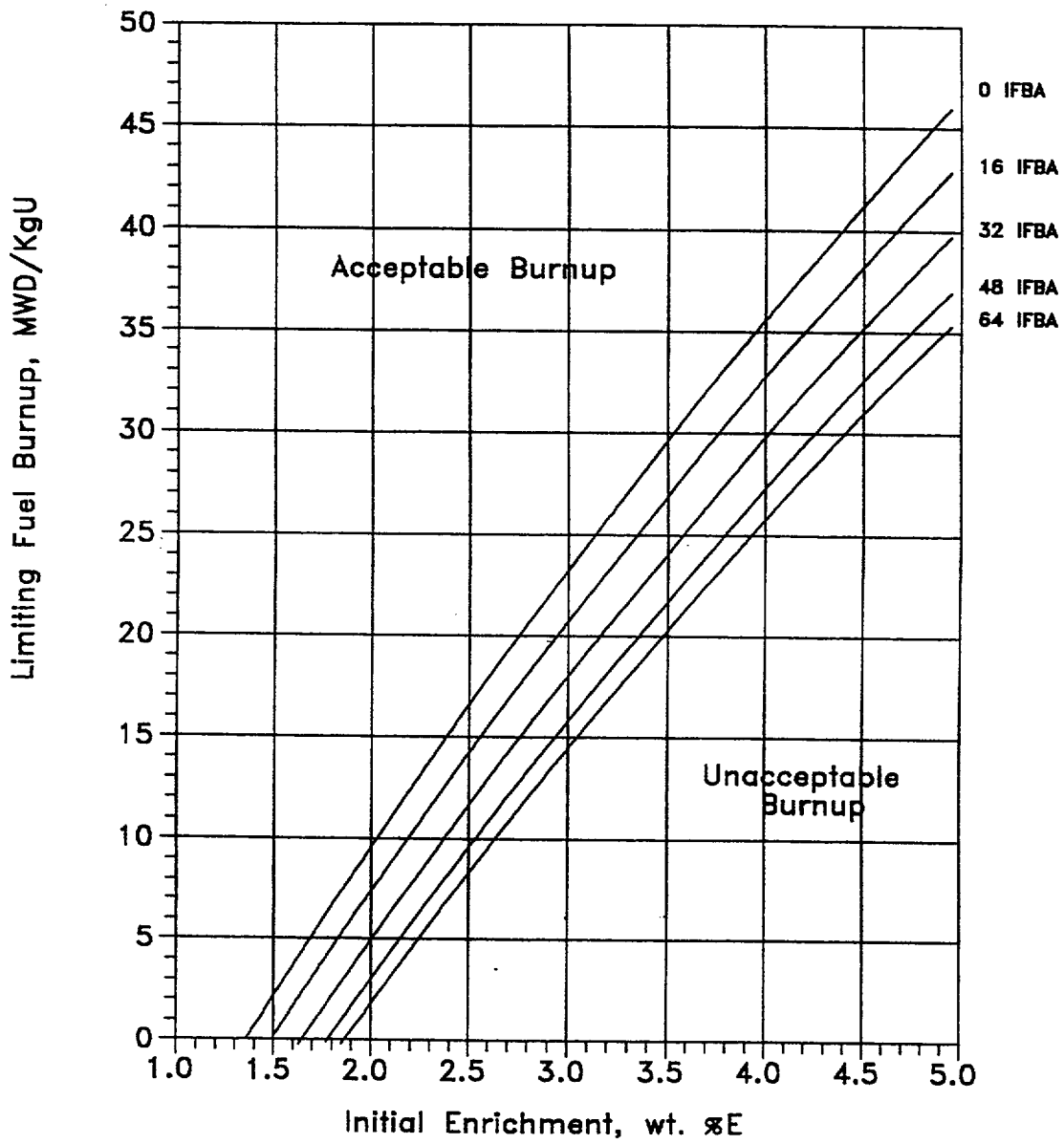
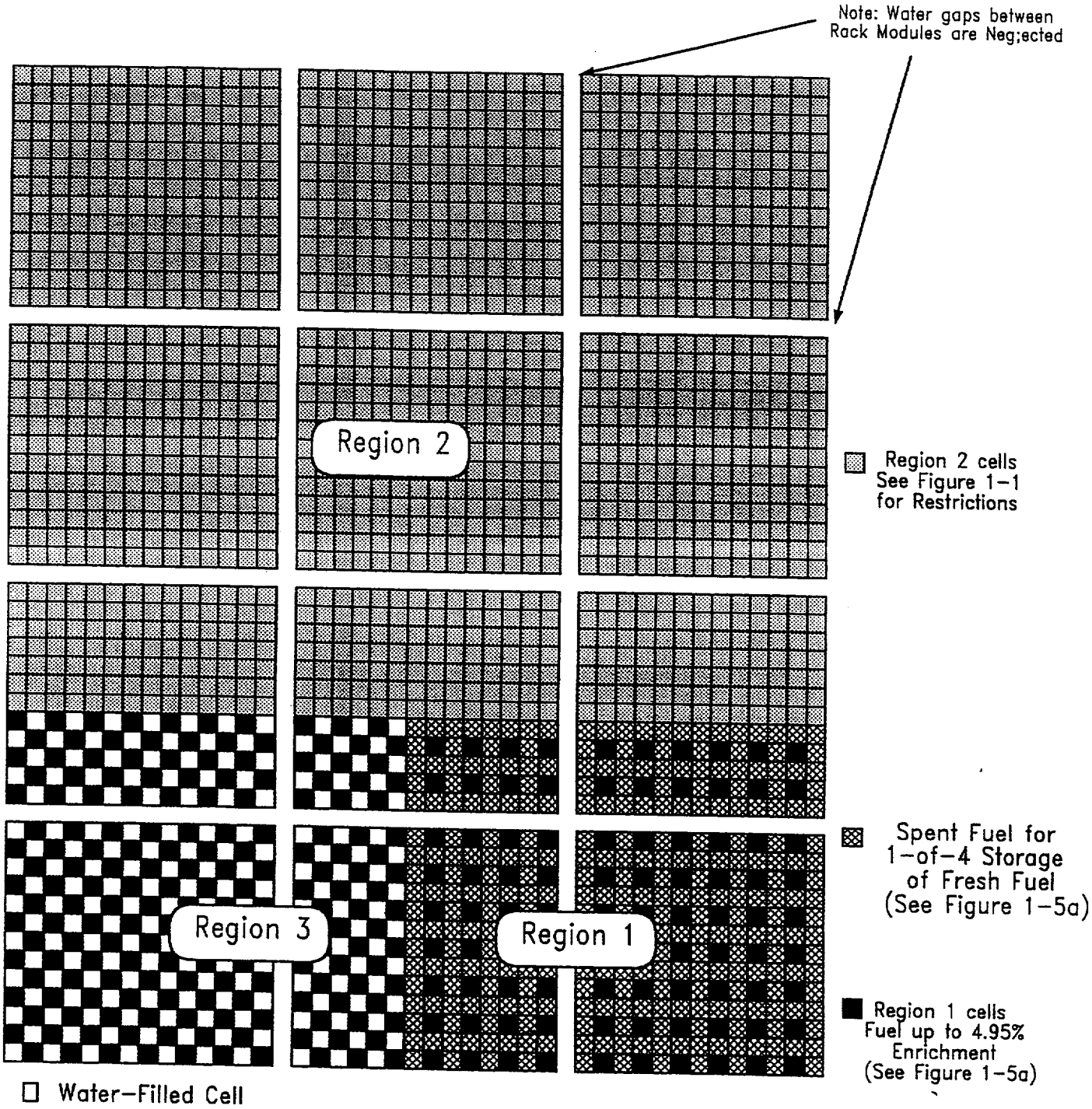
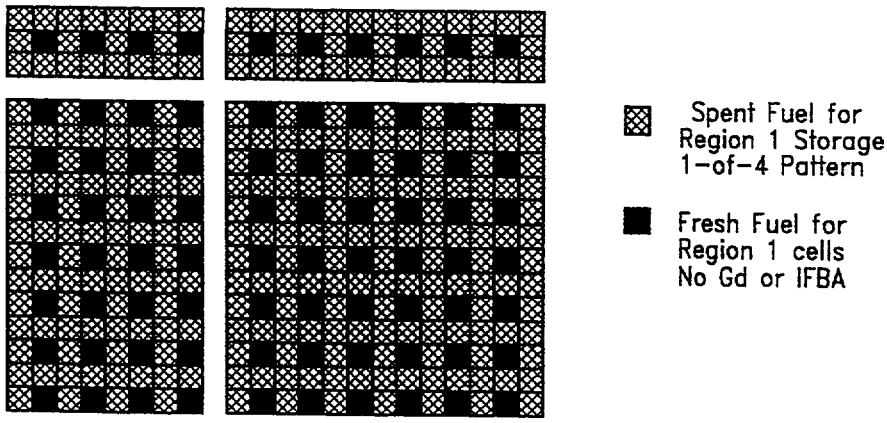


Figure 1-4 Effect of IFBA in Fresh Fuel on the Minimum Burnup Requirements for Spent Fuel for Checkerboard Pattern Storage of Fresh Fuel and Spent Fuel Assemblies (1 Fresh in 4) in the TVA Sequoyah Nuclear Plant Storage Racks



Note: The edges of the sketch above are not necessarily the edges of the pool. The Regions may appear anywhere in the pool and in any orientation, subject to the restrictions on Page 4 of the text.

Figure 1-5 Acceptable Spent Fuel Pool Loading Pattern - Example



NOTE: WHEN CREDIT IS TAKEN FOR GADOLINIA OR IFBA RODS IN FRESH ASSEMBLIES THE SPENT FUEL ASSEMBLIES NEED NOT HAVE CONTAINED GADOLINIA OR IFBA RODS..

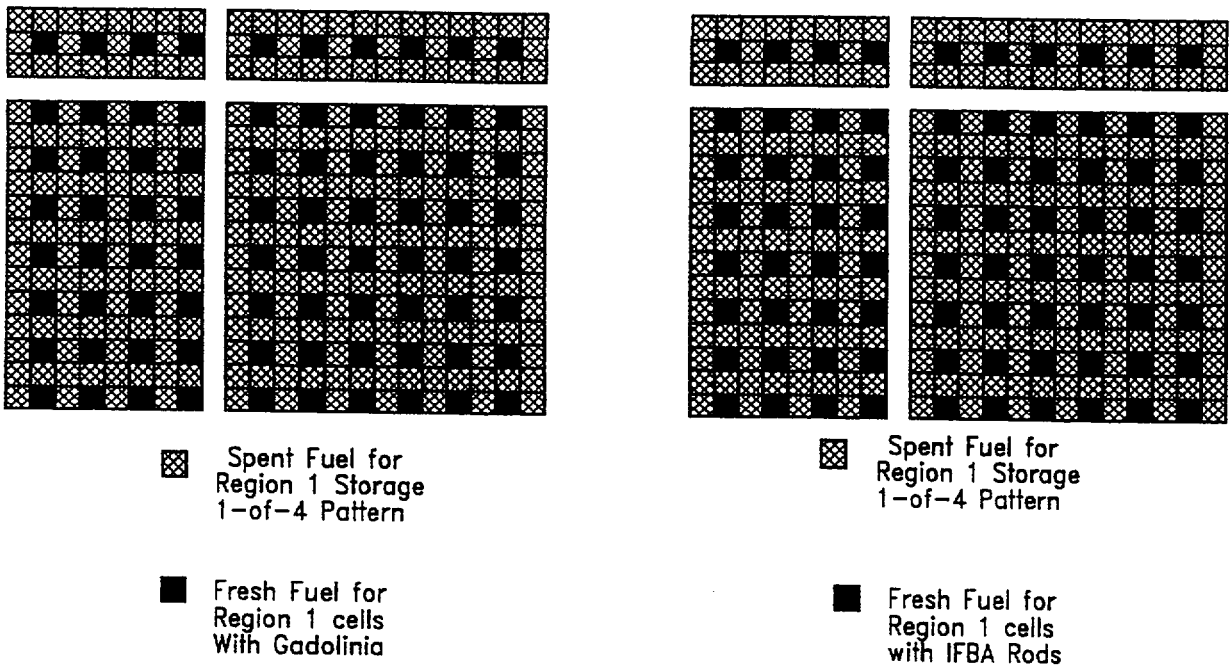


Figure 1-5a Acceptable Spent Fuel Pool Loading Patterns for Checkerboard Storage of Fresh and Spent Fuel Assemblies - Example

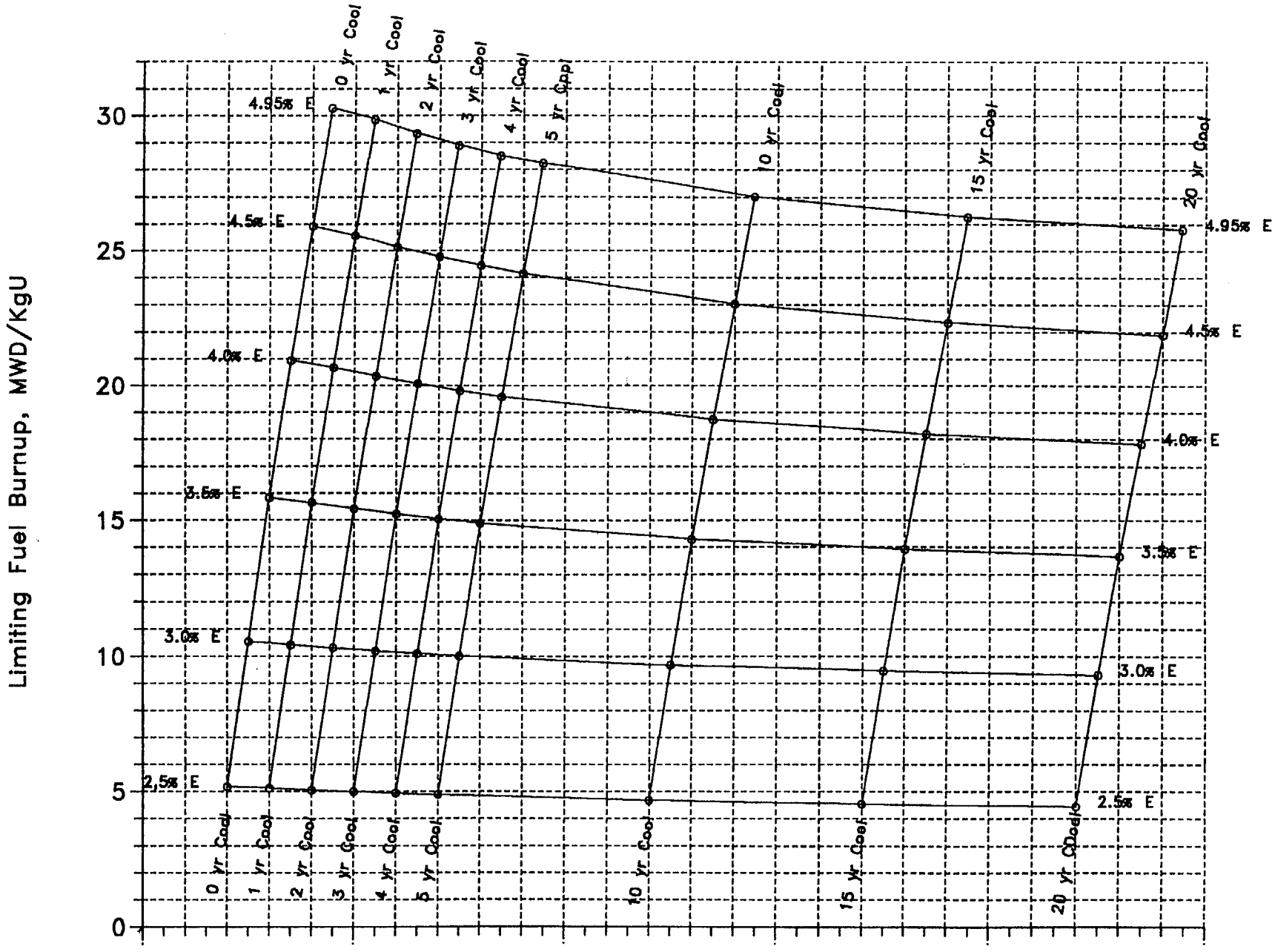


Figure 1-6 Surface Plot for the Face Adjacent Storage of Spent Fuel in Region 2 Racks

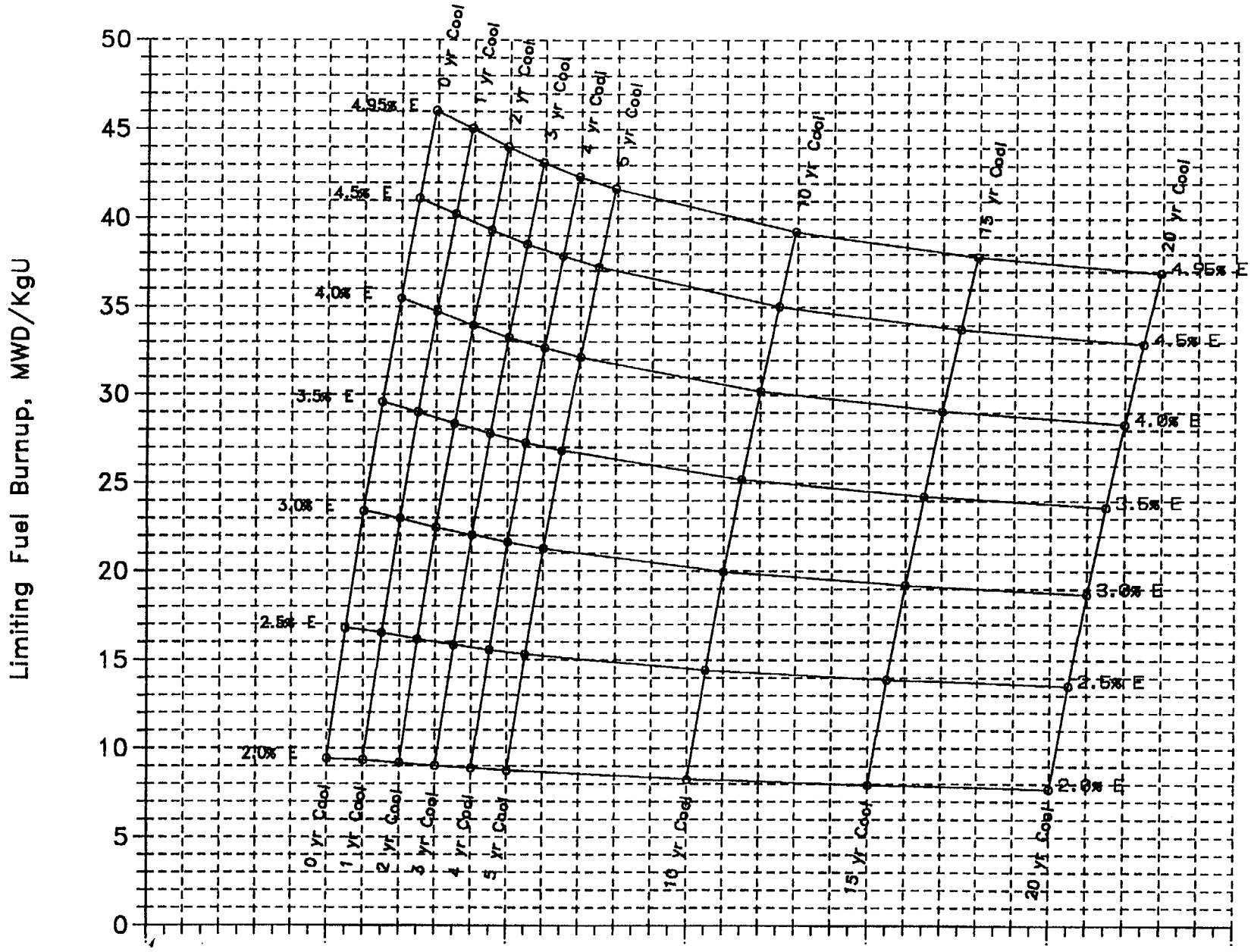


Figure 1-7 Surface Plot for Checkerboard (1 Fresh in 4) Storage of Fresh Fuel Assemblies (No Gadolinia or IFBA) and Spent Fuel Assemblies in Region 1 Racks

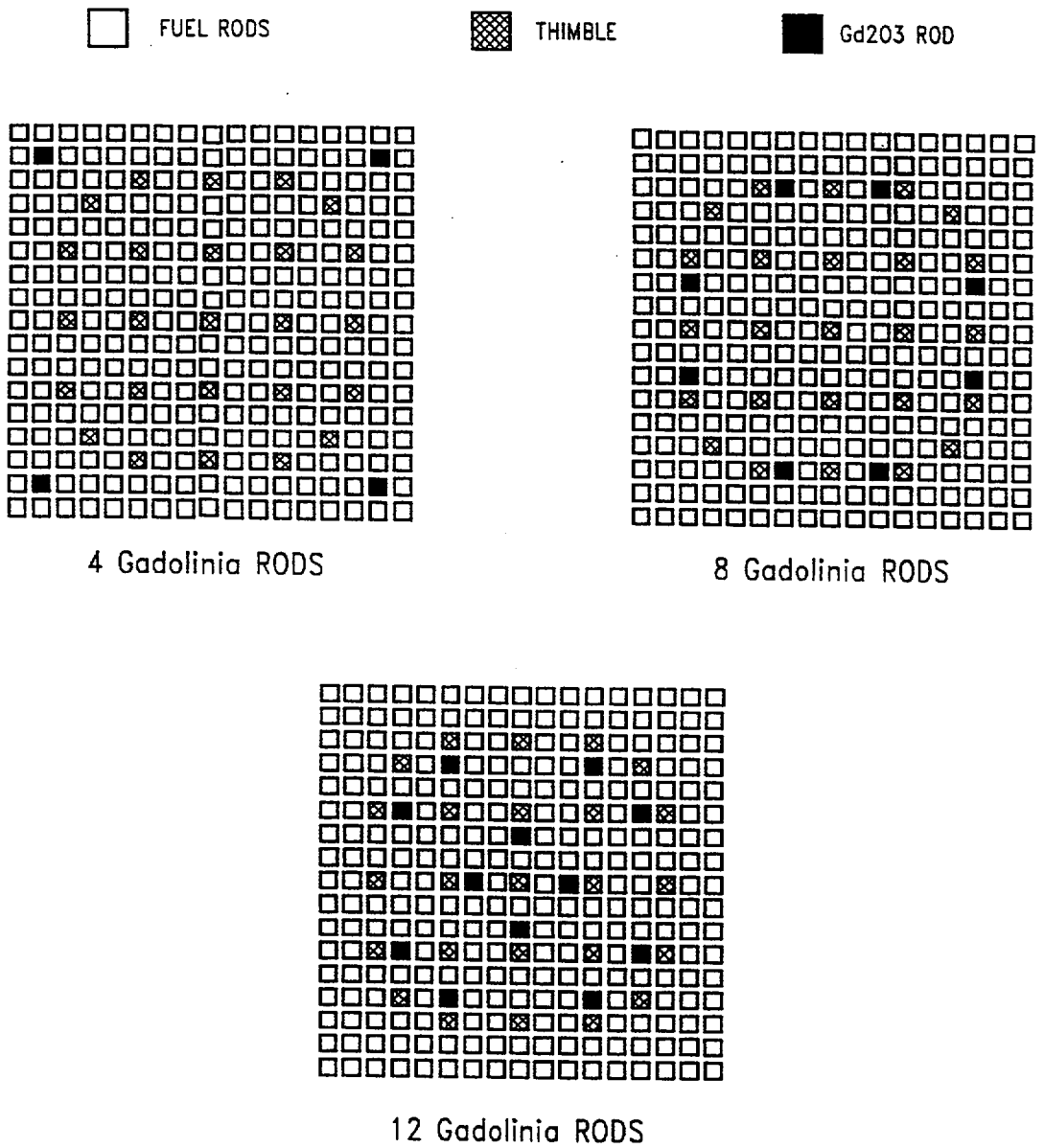


Fig. 4-1 Layout of Gadolinia Rods Used in the Calculations

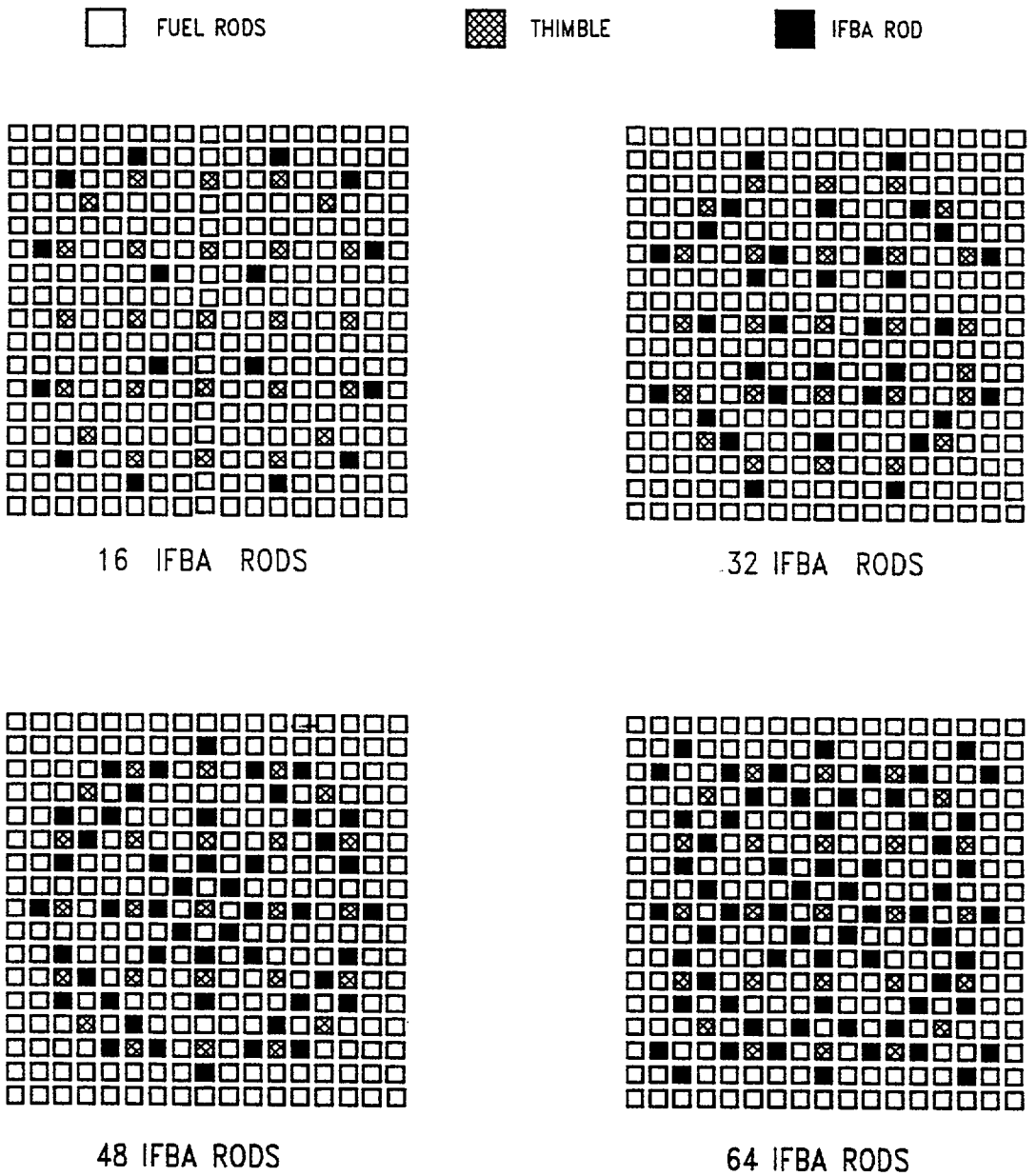


Figure 4-2 Layout of IFBA Rods Used in the Calculations

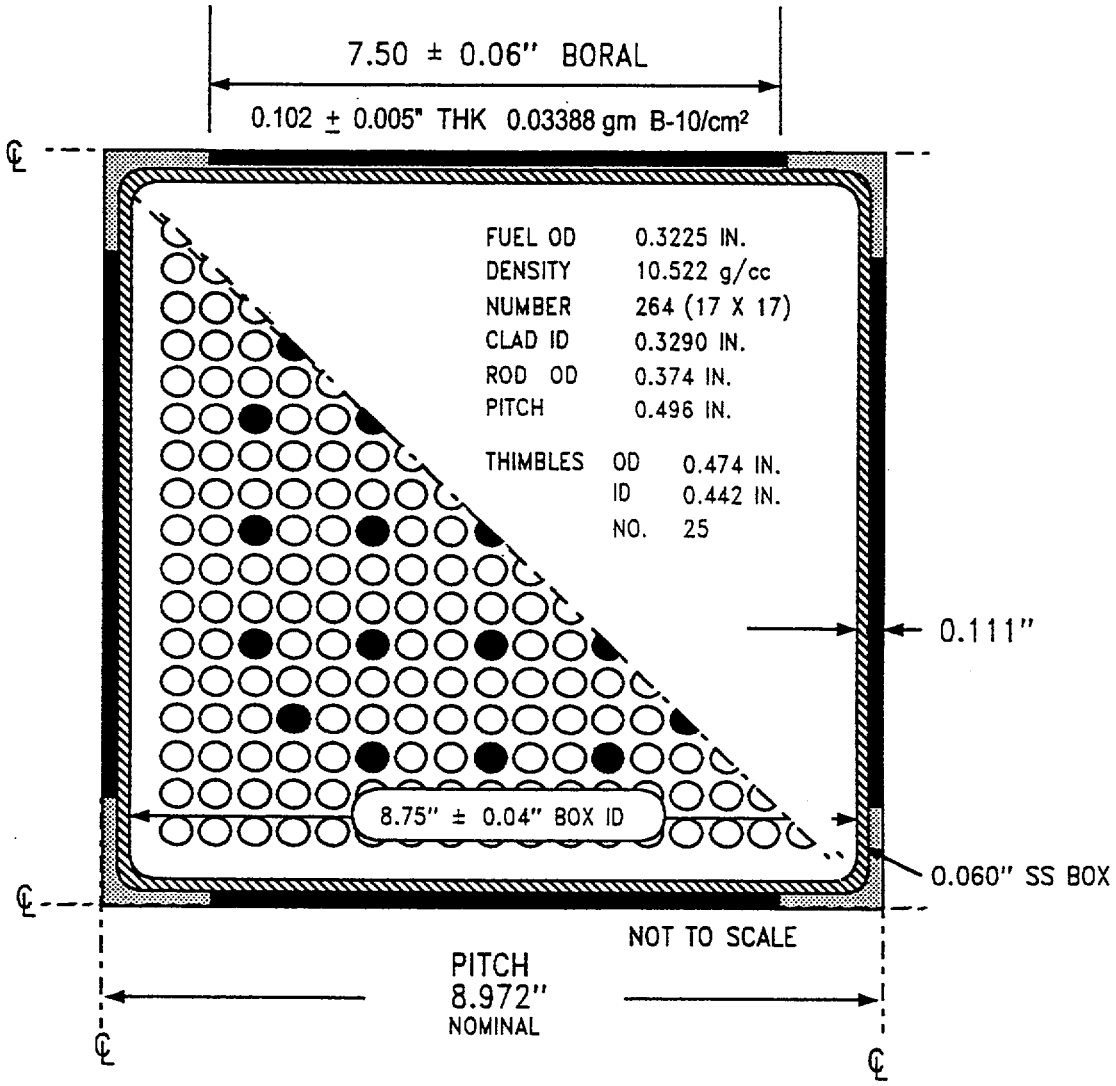


FIG. 4-3 FUEL STORAGE CELL CROSS SECTION

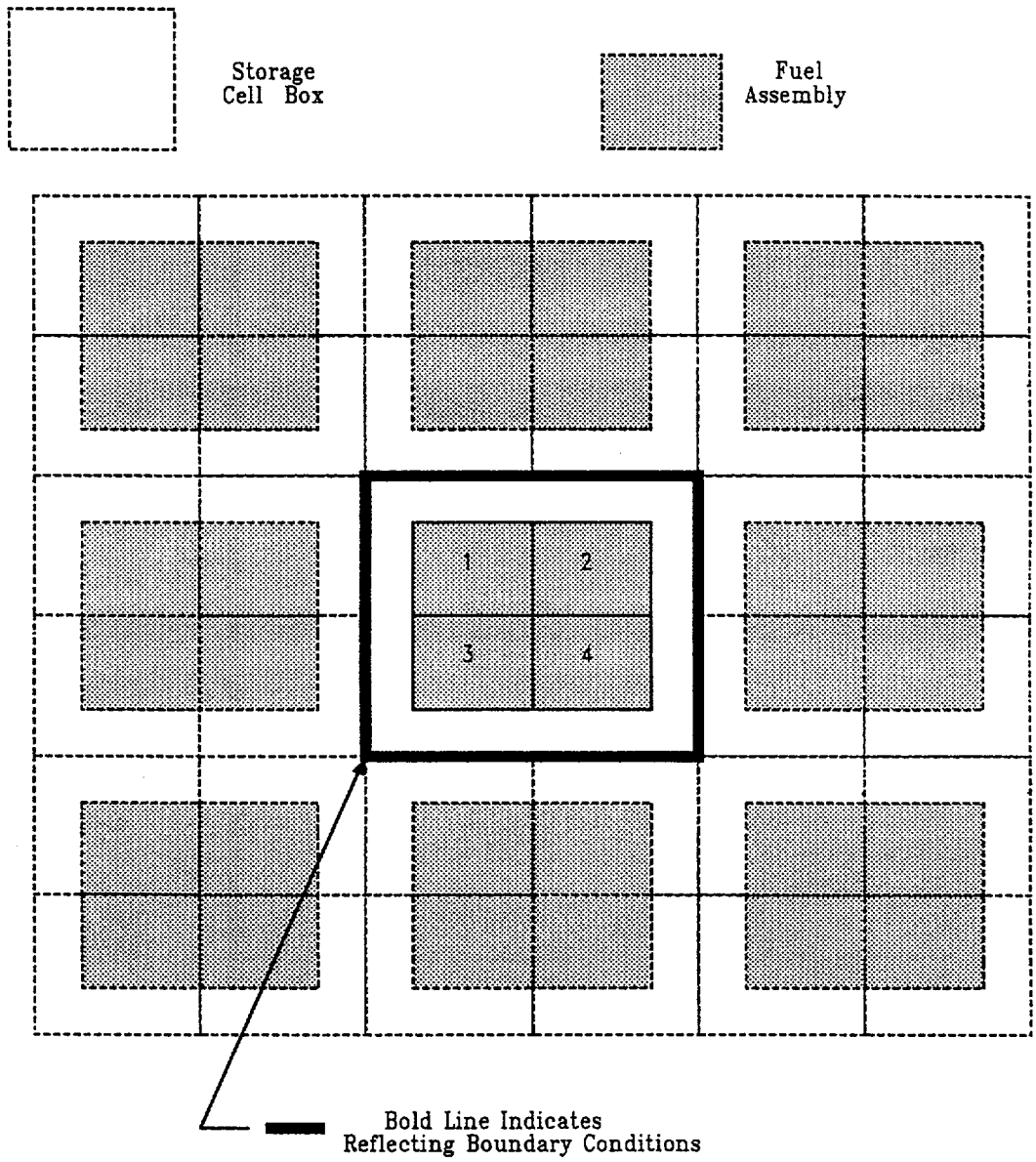


Figure 6-1 Pictorial Description of Calculational Model for Eccentrically Positioned Fuel Assemblies

(Four Assemblies at Closest Approach)

Appendix A: Benchmark Calculations

(Total of 26 Pages Including This Page)

APPENDIX 4A: BENCHMARK CALCULATIONS

4A.1 INTRODUCTION AND SUMMARY

Benchmark calculations have been made on selected critical experiments, chosen, in so far as possible, to bound the range of variables in the rack designs. Two independent methods of analysis were used, differing in cross section libraries and in the treatment of the cross sections. MCNP4a [4A.1] is a continuous energy Monte Carlo code and KENO5a [4A.2] uses group-dependent cross sections. For the KENO5a analyses reported here, the 238-group library was chosen, processed through the NITAWL-II [4A.2] program to create a working library and to account for resonance self-shielding in uranium-238 (Nordheim integral treatment). The 238 group library was chosen to avoid or minimize the errors† (trends) that have been reported (e.g., [4A.3 through 4A.5]) for calculations with collapsed cross section sets.

In rack designs, the three most significant parameters affecting criticality are (1) the fuel enrichment, (2) the ^{10}B loading in the neutron absorber, and (3) the lattice spacing (or water-gap thickness if a flux-trap design is used). Other parameters, within the normal range of rack and fuel designs, have a smaller effect, but are also included in the analyses.

Table 4A.1 summarizes results of the benchmark calculations for all cases selected and analyzed, as referenced in the table. The effect of the major variables are discussed in subsequent sections below. It is important to note that there is obviously considerable overlap in parameters since it is not possible to vary a single parameter and maintain criticality; some other parameter or parameters must be concurrently varied to maintain criticality.

One possible way of representing the data is through a spectrum index that incorporates all of the variations in parameters. KENO5a computes and prints the "energy of the average lethargy causing fission" (EALF). In MCNP4a, by utilizing the tally option with the identical 238-group energy structure as in KENO5a, the number of fissions in each group may be collected and the EALF determined (post-processing).

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† Small but observable trends (errors) have been reported for calculations with the 27-group and 44-group collapsed libraries. These errors are probably due to the use of a single collapsing spectrum when the spectrum should be different for the various cases analyzed, as evidenced by the spectrum indices.

Figures 4A.1 and 4A.2 show the calculated k_{eff} for the benchmark critical experiments as a function of the EALF for MCNP4a and KENO5a, respectively (UO_2 fuel only). The scatter in the data (even for comparatively minor variation in critical parameters) represents experimental error† in performing the critical experiments within each laboratory, as well as between the various testing laboratories. The B&W critical experiments show a larger experimental error than the PNL criticals. This would be expected since the B&W criticals encompass a greater range of critical parameters than the PNL criticals.

Linear regression analysis of the data in Figures 4A.1 and 4A.2 show that there are no trends, as evidenced by very low values of the correlation coefficient (0.13 for MCNP4a and 0.21 for KENO5a). The total bias (systematic error, or mean of the deviation from a k_{eff} of exactly 1.000) for the two methods of analysis are shown in the table below.

Calculational Bias of MCNP4a and KENO5a	
MCNP4a	0.0009±0.0011
KENO5a	0.0030±0.0012

The bias and standard error of the bias were derived directly from the calculated k_{eff} values in Table 4A.1 using the following equations††, with the standard error multiplied by the one-sided K-factor for 95% probability at the 95% confidence level from NBS Handbook 91 [4A.18] (for the number of cases analyzed, the K-factor is ~2.05 or slightly more than 2).

$$\bar{k} = \frac{1}{n} \sum_{i}^{n} k_i \qquad (4A.1)$$

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† A classical example of experimental error is the corrected enrichment in the PNL experiments, first as an addendum to the initial report and, secondly, by revised values in subsequent reports for the same fuel rods.

†† These equations may be found in any standard text on statistics, for example, reference [4A.6] (or the MCNP4a manual) and is the same methodology used in MCNP4a and in KENO5a.

$$\sigma_{\bar{k}}^2 = \frac{\sum_{i=1}^{n} k_i^2 - (\sum_{i=1}^{n} k_i)^2 / n}{n\ (n-1)} \tag{4A.2}$$

$$Bias = (1 - \bar{k}) \pm K\ \sigma_{\bar{k}} \tag{4A.3}$$

where k_i are the calculated reactivities of n critical experiments; $\sigma_{\bar{k}}$ is the unbiased estimator of the standard deviation of the mean (also called the standard error of the bias (mean)); K is the one-sided multiplier for 95% probability at the 95% confidence level (NBS Handbook 91 [4A.18]).

Formula 4.A.3 is based on the methodology of the National Bureau of Standards (now NIST) and is used to calculate the values presented on page 4.A-2. The first portion of the equation, (1- $\bar{k}$), is the actual bias which is added to the MCNP4a and KENO5a results. The second term, $K\sigma_{\bar{k}}$, is the uncertainty or standard error associated with the bias. The K values used were obtained from the National Bureau of Standards Handbook 91 and are for one-sided statistical tolerance limits for 95% probability at the 95% confidence level. The actual K values for the 56 critical experiments evaluated with MCNP4a and the 53 critical experiments evaluated with KENO5a are 2.04 and 2.05, respectively.

The bias values are used to evaluate the maximum k_{eff} values for the rack designs. KENO5a has a slightly larger systematic error than MCNP4a, but both result in greater precision than published data [4A.3 through 4A.5] would indicate for collapsed cross section sets in KENO5a (SCALE) calculations.

4A.2 Effect of Enrichment

The benchmark critical experiments include those with enrichments ranging from 2.46 w/o to 5.74 w/o and therefore span the enrichment range for rack designs. Figures 4A.3 and 4A.4 show the calculated k_{eff} values (Table 4A.1) as a function of the fuel enrichment reported for the critical experiments. Linear regression analyses for these data confirms that there are no trends, as indicated by low values of the correlation coefficients (0.03 for MCNP4a and 0.38 for KENO5a). Thus, there are no corrections to the bias for the various enrichments.

As further confirmation of the absence of any trends with enrichment, a typical configuration was calculated with both MCNP4a and KENO5a for various enrichments. The cross-comparison of calculations with codes of comparable sophistication is suggested in Reg. Guide 3.41. Results of this comparison, shown in Table 4A.2 and Figure 4A.5, confirm no significant difference in the calculated values of k_{eff} for the two independent codes as evidenced by the 45° slope of the curve. Since it is very unlikely that two independent methods of analysis would be subject to the same error, this comparison is considered confirmation of the absence of an enrichment effect (trend) in the bias.

4A.3 Effect of ^{10}B Loading

Several laboratories have performed critical experiments with a variety of thin absorber panels similar to the Boral panels in the rack designs. Of these critical experiments, those performed by B&W are the most representative of the rack designs. PNL has also made some measurements with absorber plates, but, with one exception (a flux-trap experiment), the reactivity worth of the absorbers in the PNL tests is very low and any significant errors that might exist in the treatment of strong thin absorbers could not be revealed.

Table 4A.3 lists the subset of experiments using thin neutron absorbers (from Table 4A.1) and shows the reactivity worth (Δk) of the absorber.†

No trends with reactivity worth of the absorber are evident, although based on the calculations shown in Table 4A.3, some of the B&W critical experiments seem to have unusually large experimental errors. B&W made an effort to report some of their experimental errors. Other laboratories did not evaluate their experimental errors.

To further confirm the absence of a significant trend with ^{10}B concentration in the absorber, a cross-comparison was made with MCNP4a and KENO5a (as suggested in Reg. Guide 3.41). Results are shown in Figure 4A.6 and Table 4A.4 for a typical geometry. These data substantiate the absence of any error (trend) in either of the two codes for the conditions analyzed (data points fall on a 45° line, within an expected 95% probability limit).

† The reactivity worth of the absorber panels was determined by repeating the calculation with the absorber analytically removed and calculating the incremental (Δk) change in reactivity due to the absorber.

4A.4 Miscellaneous and Minor Parameters

4A.4.1 Reflector Material and Spacings

PNL has performed a number of critical experiments with thick steel and lead reflectors.† Analysis of these critical experiments are listed in Table 4A.5 (subset of data in Table 4A.1). There appears to be a small tendency toward overprediction of k_{eff} at the lower spacing, although there are an insufficient number of data points in each series to allow a quantitative determination of any trends. The tendency toward overprediction at close spacing means that the rack calculations may be slightly more conservative than otherwise.

4A.4.2 Fuel Pellet Diameter and Lattice Pitch

The critical experiments selected for analysis cover a range of fuel pellet diameters from 0.311 to 0.444 inches, and lattice spacings from 0.476 to 1.00 inches. In the rack designs, the fuel pellet diameters range from 0.303 to 0.3805 inches O.D. (0.496 to 0.580 inch lattice spacing) for PWR fuel and from 0.3224 to 0.494 inches O.D. (0.488 to 0.740 inch lattice spacing) for BWR fuel. Thus, the critical experiments analyzed provide a reasonable representation of power reactor fuel. Based on the data in Table 4A.1, there does not appear to be any observable trend with either fuel pellet diameter or lattice pitch, at least over the range of the critical experiments applicable to rack designs.

4A.4.3 Soluble Boron Concentration Effects

Various soluble boron concentrations were used in the B&W series of critical experiments and in one PNL experiment, with boron concentrations ranging up to 2550 ppm. Results of MCNP4a (and one KENO5a) calculations are shown in Table 4A.6. Analyses of the very high boron concentration experiments (>1300 ppm) show a tendency to slightly overpredict reactivity for the three experiments exceeding 1300 ppm. In turn, this would suggest that the evaluation of the racks with higher soluble boron concentrations could be slightly conservative.

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† Parallel experiments with a depleted uranium reflector were also performed but not included in the present analysis since they are not pertinent to the Holtec rack design.

4A.5 MOX Fuel

The number of critical experiments with PuO_2 bearing fuel (MOX) is more limited than for UO_2 fuel. However, a number of MOX critical experiments have been analyzed and the results are shown in Table 4A.7. Results of these analyses are generally above a k_{eff} of 1.00, indicating that when Pu is present, both MCNP4a and KENO5a overpredict the reactivity. This may indicate that calculation for MOX fuel will be expected to be conservative, especially with MCNP4a. It may be noted that for the larger lattice spacings, the KENO5a calculated reactivities are below 1.00, suggesting that a small trend may exist with KENO5a. It is also possible that the overprediction in k_{eff} for both codes may be due to a small inadequacy in the determination of the Pu-241 decay and Am-241 growth. This possibility is supported by the consistency in calculated k_{eff} over a wide range of the spectral index (energy of the average lethargy causing fission).

4A.6 References

[4A.1] J.F. Briesmeister, Ed., "MCNP4a - A General Monte Carlo N-Particle Transport Code, Version 4A; Los Alamos National Laboratory, LA-12625-M (1993).

[4A.2] SCALE 4.3, "A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation", NUREG-0200 (ORNL-NUREG-CSD-2/U2/R5, Revision 5, Oak Ridge National Laboratory, September 1995.

[4A.3] M.D. DeHart and S.M. Bowman, "Validation of the SCALE Broad Structure 44-G Group ENDF/B-Y Cross-Section Library for Use in Criticality Safety Analyses", NUREG/CR-6102 (ORNL/TM-12460) Oak Ridge National Laboratory, September 1994.

[4A.4] W.C. Jordan et al., "Validation of KENOV.a", CSD/TM-238, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, December 1986.

[4A.5] O.W. Hermann et al., "Validation of the Scale System for PWR Spent Fuel Isotopic Composition Analysis", ORNL-TM-12667, Oak Ridge National Laboratory, undated.

[4A.6] R.J. Larsen and M.L. Marx, An Introduction to Mathematical Statistics and its Applications, Prentice-Hall, 1986.

[4A.7] M.N. Baldwin et al., Critical Experiments Supporting Close Proximity Water Storage of Power Reactor Fuel, BAW-1484-7, Babcock and Wilcox Company, July 1979.

[4A.8] G.S. Hoovier et al., Critical Experiments Supporting Underwater Storage of Tightly Packed Configurations of Spent Fuel Pins, BAW-1645-4, Babcock & Wilcox Company, November 1991.

[4A.9] L.W. Newman et al., Urania Gadolinia: Nuclear Model Development and Critical Experiment Benchmark, BAW-1810, Babcock and Wilcox Company, April 1984.

[4A.10] J.C. Manaranche et al., "Dissolution and Storage Experimental Program with 4.75 w/o Enriched Uranium-Oxide Rods," Trans. Am. Nucl. Soc. 33: 362-364 (1979).

[4A.11] S.R. Bierman and E.D. Clayton, Criticality Experiments with Subcritical Clusters of 2.35 w/o and 4.31 w/o ^{235}U Enriched UO_2 Rods in Water with Steel Reflecting Walls, PNL-3602, Battelle Pacific Northwest Laboratory, April 1981.

[4A.12] S.R. Bierman et al., Criticality Experiments with Subcritical Clusters of 2.35 w/o and 4.31 w/o ^{235}U Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls, PNL-3926, Battelle Pacific Northwest Laboratory, December, 1981.

[4A.13] S.R. Bierman et al., Critical Separation Between Subcritical Clusters of 4.31 w/o ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons, PNL-2615, Battelle Pacific Northwest Laboratory, October 1977.

[4A.14] S.R. Bierman, Criticality Experiments with Neutron Flux Traps Containing Voids, PNL-7167, Battelle Pacific Northwest Laboratory, April 1990.

[4A.15] B.M. Durst et al., Critical Experiments with 4.31 wt % ^{235}U Enriched UO_2 Rods in Highly Borated Water Lattices, PNL-4267, Battelle Pacific Northwest Laboratory, August 1982.

[4A.16] S.R. Bierman, Criticality Experiments with Fast Test Reactor Fuel Pins in Organic Moderator, PNL-5803, Battelle Pacific Northwest Laboratory, December 1981.

[4A.17] E.G. Taylor et al., Saxton Plutonium Program Critical Experiments for the Saxton Partial Plutonium Core, WCAP-3385-54, Westinghouse Electric Corp., Atomic Power Division, December 1965.

[4A.18] M.G. Natrella, Experimental Statistics, National Bureau of Standards, Handbook 91, August 1963.

Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff}		EALF † (eV)	
				MCNP4a	KENO5a	MCNP4a	KENO5a
1	B&W-1484 (4A.7)	Core I	2.46	0.9964 ± 0.0010	0.9898± 0.0006	0.1759	0.1753
2	B&W-1484 (4A.7)	Core II	2.46	1.0008 ± 0.0011	1.0015 ± 0.0005	0.2553	0.2446
3	B&W-1484 (4A.7)	Core III	2.46	1.0010 ± 0.0012	1.0005 ± 0.0005	0.1999	0.1939
4	B&W-1484 (4A.7)	Core IX	2.46	0.9956 ± 0.0012	0.9901 ± 0.0006	0.1422	0.1426
5	B&W-1484 (4A.7)	Core X	2.46	0.9980 ± 0.0014	0.9922 ± 0.0006	0.1513	0.1499
6	B&W-1484 (4A.7)	Core XI	2.46	0.9978 ± 0.0012	1.0005 ± 0.0005	0.2031	0.1947
7	B&W-1484 (4A.7)	Core XII	2.46	0.9988 ± 0.0011	0.9978 ± 0.0006	0.1718	0.1662
8	B&W-1484 (4A.7)	Core XIII	2.46	1.0020 ± 0.0010	0.9952 ± 0.0006	0.1988	0.1965
9	B&W-1484 (4A.7)	Core XIV	2.46	0.9953 ± 0.0011	0.9928 ± 0.0006	0.2022	0.1986
10	B&W-1484 (4A.7)	Core XV ††	2.46	0.9910 ± 0.0011	0.9909 ± 0.0006	0.2092	0.2014
11	B&W-1484 (4A.7)	Core XVI ††	2.46	0.9935 ± 0.0010	0.9889 ± 0.0006	0.1757	0.1713
12	B&W-1484 (4A.7)	Core XVII	2.46	0.9962 ± 0.0012	0.9942 ± 0.0005	0.2083	0.2021
13	B&W-1484 (4A.7)	Core XVIII	2.46	1.0036 ± 0.0012	0.9931 ± 0.0006	0.1705	0.1708

Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff}		EALF † (eV)	
				MCNP4a	KENO5a	MCNP4a	KENO5a
14	B&W-1484 (4A.7)	Core XIX	2.46	0.9961 ± 0.0012	0.9971 ± 0.0005	0.2103	0.2011
15	B&W-1484 (4A.7)	Core XX	2.46	1.0008 ± 0.0011	0.9932 ± 0.0006	0.1724	0.1701
16	B&W-1484 (4A.7)	Core XXI	2.46	0.9994 ± 0.0010	0.9918 ± 0.0006	0.1544	0.1536
17	B&W-1645 (4A.8)	S-type Fuel, w/886 ppm B	2.46	0.9970 ± 0.0010	0.9924 ± 0.0006	1.4475	1.4680
18	B&W-1645 (4A.8)	S-type Fuel, w/746 ppm B	2.46	0.9990 ± 0.0010	0.9913 ± 0.0006	1.5463	1.5660
19	B&W-1645 (4A.8)	SO-type Fuel, w/1156 ppm B	2.46	0.9972 ± 0.0009	0.9949 ± 0.0005	0.4241	0.4331
20	B&W-1810 (4A.9)	Case 1 1337 ppm B	2.46	1.0023 ± 0.0010	NC	0.1531	NC
21	B&W-1810 (4A.9)	Case 12 1899 ppm B	2.46/4.02	1.0060 ± 0.0009	NC	0.4493	NC
22	French (4A.10)	Water Moderator 0 gap	4.75	0.9966 ± 0.0013	NC	0.2172	NC
23	French (4A.10)	Water Moderator 2.5 cm gap	4.75	0.9952 ± 0.0012	NC	0.1778	NC
24	French (4A.10)	Water Moderator 5 cm gap	4.75	0.9943 ± 0.0010	NC	0.1677	NC
25	French (4A.10)	Water Moderator 10 cm gap	4.75	0.9979 ± 0.0010	NC	0.1736	NC
26	PNL-3602 (4A.11)	Steel Reflector, 0 separation	2.35	NC	1.0004 ± 0.0006	NC	0.1018

Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff}		EALF † (eV)	
				MCNP4a	KENO5a	MCNP4a	KENO5a
27	PNL-3602 (4A.11)	Steel Reflector, 1.321 cm sepn.	2.35	0.9980 ± 0.0009	0.9992 ± 0.0006	0.1000	0.0909
28	PNL-3602 (4A.11)	Steel Reflector, 2.616 cm sepn	2.35	0.9968 ± 0.0009	0.9964 ± 0.0006	0.0981	0.0975
29	PNL-3602 (4A.11)	Steel Reflector, 3.912 cm sepn.	2.35	0.9974 ± 0.0010	0.9980 ± 0.0006	0.0976	0.0970
30	PNL-3602 (4A.11)	Steel Reflector, infinite sepn.	2.35	0.9962 ± 0.0008	0.9939 ± 0.0006	0.0973	0.0968
31	PNL-3602 (4A.11)	Steel Reflector, 0 cm sepn.	4.306	NC	1.0003 ± 0.0007	NC	0.3282
32	PNL-3602 (4A.11)	Steel Reflector, 1.321 cm sepn.	4.306	0.9997 ± 0.0010	1.0012 ± 0.0007	0.3016	0.3039
33	PNL-3602 (4A.11)	Steel Reflector, 2.616 cm sepn.	4.306	0.9994 ± 0.0012	0.9974 ± 0.0007	0.2911	0.2927
34	PNL-3602 (4A.11)	Steel Reflector, 5.405 cm sepn.	4.306	0.9969 ± 0.0011	0.9951 ± 0.0007	0.2828	0.2860
35	PNL-3602 (4A.11)	Steel Reflector, Infinite sepn. ††	4.306	0.9910 ± 0.0020	0.9947 ± 0.0007	0.2851	0.2864
36	PNL-3602 (4A.11)	Steel Reflector, with Boral Sheets	4.306	0.9941 ± 0.0011	0.9970 ± 0.0007	0.3135	0.3150
37	PNL-3926 (4A.12)	Lead Reflector, 0 cm sepn.	4.306	NC	1.0003 ± 0.0007	NC	0.3159
38	PNL-3926 (4A.12)	Lead Reflector, 0.55 cm sepn.	4.306	1.0025 ± 0.0011	0.9997 ± 0.0007	0.3030	0.3044
39	PNL-3926 (4A.12)	Lead Reflector, 1.956 cm sepn.	4.306	1.0000 ± 0.0012	0.9985 ± 0.0007	0.2883	0.2930

Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff}		EALF † (eV)	
				MCNP4a	KENO5a	MCNP4a	KENO5a
40	PNL-3926 (4A.12)	Lead Reflector, 5.405 cm sepn.	4.306	0.9971 ± 0.0012	0.9946 ± 0.0007	0.2831	0.2854
41	PNL-2615 (4A.13)	Experiment 004/032 - no absorber	4.306	0.9925 ± 0.0012	0.9950 ± 0.0007	0.1155	0.1159
42	PNL-2615 (4A.13)	Experiment 030 - Zr plates	4.306	NC	0.9971 ± 0.0007	NC	0.1154
43	PNL-2615 (4A.13)	Experiment 013 - Steel plates	4.306	NC	0.9965 ± 0.0007	NC	0.1164
44	PNL-2615 (4A.13)	Experiment 014 - Steel plates	4.306	NC	0.9972 ± 0.0007	NC	0.1164
45	PNL-2615 (4A.13)	Exp. 009 1.05% Boron-Steel plates	4.306	0.9982 ± 0.0010	0.9981 ± 0.0007	0.1172	0.1162
46	PNL-2615 (4A.13)	Exp. 012 1.62% Boron-Steel plates	4.306	0.9996 ± 0.0012	0.9982 ± 0.0007	0.1161	0.1173
47	PNL-2615 (4A.13)	Exp. 031 - Boral plates	4.306	0.9994 ± 0.0012	0.9969 ± 0.0007	0.1165	0.1171
48	PNL-7167 (4A.14)	Experiment 214R - with flux trap	4.306	0.9991 ± 0.0011	0.9956 ± 0.0007	0.3722	0.3812
49	PNL-7167 (4A.14)	Experiment 214V3 - with flux trap	4.306	0.9969 ± 0.0011	0.9963 ± 0.0007	0.3742	0.3826
50	PNL-4267 (4A.15)	Case 173 - 0 ppm B	4.306	0.9974 ± 0.0012	NC	0.2893	NC
51	PNL-4267 (4A.15)	Case 177 - 2550 ppm B	4.306	1.0057 ± 0.0010	NC	0.5509	NC
52	PNL-5803 (4A.16)	MOX Fuel - Type 3.2 Exp. 21	20% Pu	1.0041 ± 0.0011	1.0046 ± 0.0006	0.9171	0.8868

Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff}		EALF † (eV)	
				MCNP4a	KENO5a	MCNP4a	KENO5a
53	PNL-5803 (4A.16)	MOX Fuel - Type 3.2 Exp. 43	20% Pu	1.0058 ± 0.0012	1.0036 ± 0.0006	0.2968	0.2944
54	PNL-5803 (4A.16)	MOX Fuel - Type 3.2 Exp. 13	20% Pu	1.0083 ± 0.0011	0.9989 ± 0.0006	0.1665	0.1706
55	PNL-5803 (4A.16)	MOX Fuel - Type 3.2 Exp. 32	20% Pu	1.0079 ± 0.0011	0.9966 ± 0.0006	0.1139	0.1165
56	WCAP-3385 (4A.17)	Saxton Case 52 PuO2 0.52" pitch	6.6% Pu	0.9996 ± 0.0011	1.0005 ± 0.0006	0.8665	0.8417
57	WCAP-3385 (4A.17)	Saxton Case 52 U 0.52" pitch	5.74	1.0000 ± 0.0010	0.9956 ± 0.0007	0.4476	0.4580
58	WCAP-3385 (4A.17)	Saxton Case 56 PuO2 0.56" pitch	6.6% Pu	1.0036 ± 0.0011	1.0047 ± 0.0006	0.5289	0.5197
59	WCAP-3385 (4A.17)	Saxton Case 56 borated PuO2	6.6% Pu	1.0008 ± 0.0010	NC	0.6389	NC
60	WCAP-3385 (4A.17)	Saxton Case 56 U 0.56" pitch	5.74	0.9994 ± 0.0011	0.9967 ± 0.0007	0.2923	0.2954
61	WCAP-3385 (4A.17)	Saxton Case 79 PuO2 0.79" pitch	6.6% Pu	1.0063 ± 0.0011	1.0133 ± 0.0006	0.1520	0.1555
62	WCAP-3385 (4A.17)	Saxton Case 79 U 0.79" pitch	5.74	1.0039 ± 0.0011	1.0008 ± 0.0006	0.1036	0.1047

Notes: NC stands for not calculated.

† EALF is the energy of the average lethargy causing fission.

†† These experimental results appear to be statistical outliers (>3σ) suggesting the possibility of unusually large experimental error. Although they could justifiably be excluded, for conservatism, they were retained in determining the calculational basis.

Table 4A.2

COMPARISON OF MCNP4a AND KENO5a CALCULATED REACTIVITIES† FOR VARIOUS ENRICHMENTS

Enrichment	Calculated $k_{eff} \pm 1\sigma$	
	MCNP4a	KENO5a
3.0	0.8465 ± 0.0011	0.8478 ± 0.0004
3.5	0.8820 ± 0.0011	0.8841 ± 0.0004
3.75	0.9019 ± 0.0011	0.8987 ± 0.0004
4.0	0.9132 ± 0.0010	0.9140 ± 0.0004
4.2	0.9276 ± 0.0011	0.9237 ± 0.0004
4.5	0.9400 ± 0.0011	0.9388 ± 0.0004

† Based on the GE 8x8R fuel assembly.

Table 4A.3

MCNP4a CALCULATED REACTIVITIES FOR CRITICAL EXPERIMENTS WITH NEUTRON ABSORBERS

Ref.	Experiment		Δk Worth of Absorber	MCNP4a Calculated k_{eff}	EALF † (eV)
4A.13	PNL-2615	Boral Sheet	0.0139	0.9994±0.0012	0.1165
4A.7	B&W-1484	Core XX	0.0165	1.0008±0.0011	0.1724
4A.13	PNL-2615	1.62% Boron-steel	0.0165	0.9996±0.0012	0.1161
4A.7	B&W-1484	Core XIX	0.0202	0.9961±0.0012	0.2103
4A.7	B&W-1484	Core XXI	0.0243	0.9994±0.0010	0.1544
4A.7	B&W-1484	Core XVII	0.0519	0.9962±0.0012	0.2083
4A.11	PNL-3602	Boral Sheet	0.0708	0.9941±0.0011	0.3135
4A.7	B&W-1484	Core XV	0.0786	0.9910±0.0011	0.2092
4A.7	B&W-1484	Core XVI	0.0845	0.9935±0.0010	0.1757
4A.7	B&W-1484	Core XIV	0.1575	0.9953±0.0011	0.2022
4A.7	B&W-1484	Core XIII	0.1738	1.0020±0.0011	0.1988
4A.14	PNL-7167	Expt 214R flux trap	0.1931	0.9991±0.0011	0.3722

†EALF is the energy of the average lethargy causing fission.

Table 4A.4

COMPARISON OF MCNP4a AND KENO5a
CALCULATED REACTIVITIES† FOR VARIOUS ^{10}B LOADINGS

^{10}B, g/cm^2	Calculated $k_{eff} \pm 1\sigma$	
	MCNP4a	KENO5a
0.005	1.0381 ± 0.0012	1.0340 ± 0.0004
0.010	0.9960 ± 0.0010	0.9941 ± 0.0004
0.015	0.9727 ± 0.0009	0.9713 ± 0.0004
0.020	0.9541 ± 0.0012	0.9560 ± 0.0004
0.025	0.9433 ± 0.0011	0.9428 ± 0.0004
0.03	0.9325 ± 0.0011	0.9338 ± 0.0004
0.035	0.9234 ± 0.0011	0.9251 ± 0.0004
0.04	0.9173 ± 0.0011	0.9179 ± 0.0004

† Based on a 4.5% enriched GE 8x8R fuel assembly.

Table 4A.5

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH THICK LEAD AND STEEL REFLECTORS†

Ref.	Case	E, wt%	Separation, cm	MCNP4a k_{eff}	KENO5a k_{eff}
4A.11	Steel Reflector	2.35	1.321	0.9980±0.0009	0.9992±0.0006
		2.35	2.616	0.9968±0.0009	0.9964±0.0006
		2.35	3.912	0.9974±0.0010	0.9980±0.0006
		2.35	∞	0.9962±0.0008	0.9939±0.0006
4A.11	Steel Reflector	4.306	1.321	0.9997±0.0010	1.0012±0.0007
		4.306	2.616	0.9994±0.0012	0.9974±0.0007
		4.306	3.405	0.9969±0.0011	0.9951±0.0007
		4.306	∞	0.9910±0.0020	0.9947±0.0007
4A.12	Lead Reflector	4.306	0.55	1.0025±0.0011	0.9997±0.0007
		4.306	1.956	1.0000±0.0012	0.9985±0.0007
		4.306	5.405	0.9971±0.0012	0.9946±0.0007

† Arranged in order of increasing reflector-fuel spacing.

Table 4A.6

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH VARIOUS SOLUBLE BORON CONCENTRATIONS

Reference	Experiment	Boron Concentration, ppm	Calculated k_{eff}	
			MCNP4a	KENO5a
4A.15	PNL-4267	0	0.9974 ± 0.0012	-
4A.8	B&W-1645	886	0.9970 ± 0.0010	0.9924 ± 0.0006
4A.9	B&W-1810	1337	1.0023 ± 0.0010	-
4A.9	B&W-1810	1899	1.0060 ± 0.0009	-
4A.15	PNL-4267	2550	1.0057 ± 0.0010	-

Table 4A.7

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH MOX FUEL

Reference	Case†	MCNP4a		KENO5a	
		k_{eff}	EALF††	k_{eff}	EALF††
PNL-5803 [4A.16]	MOX Fuel - Exp. No. 21	1.0041±0.0011	0.9171	1.0046±0.0006	0.8868
	MOX Fuel - Exp. No. 43	1.0058±0.0012	0.2968	1.0036±0.0006	0.2944
	MOX Fuel - Exp. No. 13	1.0083±0.0011	0.1665	0.9989±0.0006	0.1706
	MOX Fuel - Exp. No. 32	1.0079±0.0011	0.1139	0.9966±0.0006	0.1165
WCAP-3385-54 [4A.17]	Saxton @ 0.52" pitch	0.9996±0.0011	0.8665	1.0005±0.0006	0.8417
	Saxton @ 0.56" pitch	1.0036±0.0011	0.5289	1.0047±0.0006	0.5197
	Saxton @ 0.56" pitch borated	1.0008±0.0010	0.6389	NC	NC
	Saxton @ 0.79" pitch	1.0063±0.0011	0.1520	1.0133±0.0006	0.1555

Note: NC stands for not calculated

† Arranged in order of increasing lattice spacing.

†† EALF is the energy of the average lethargy causing fission.

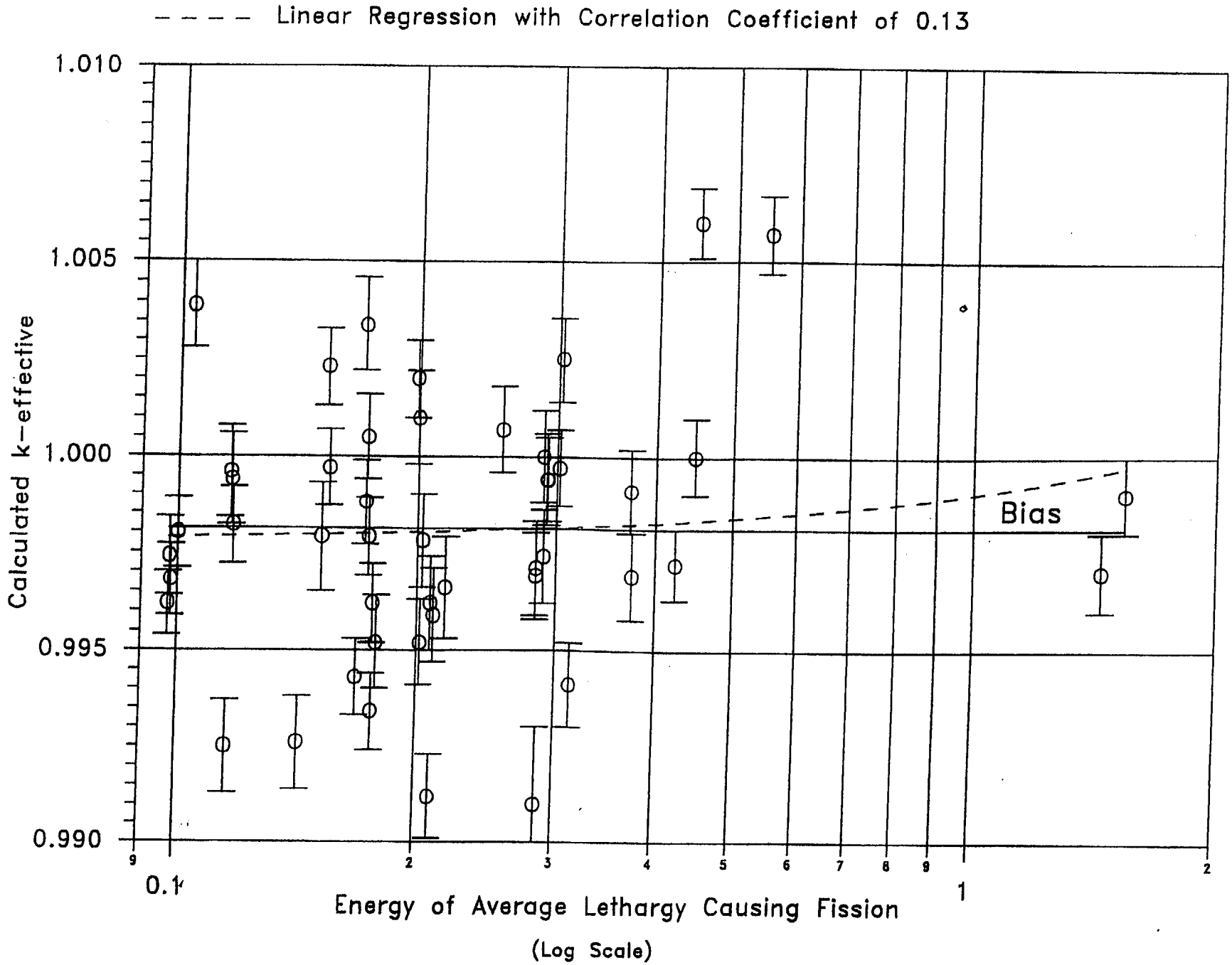

FIGURE 4A.1 MCNP CALCULATED k-eff VALUES for VARIOUS VALUES OF THE SPECTRAL INDEX

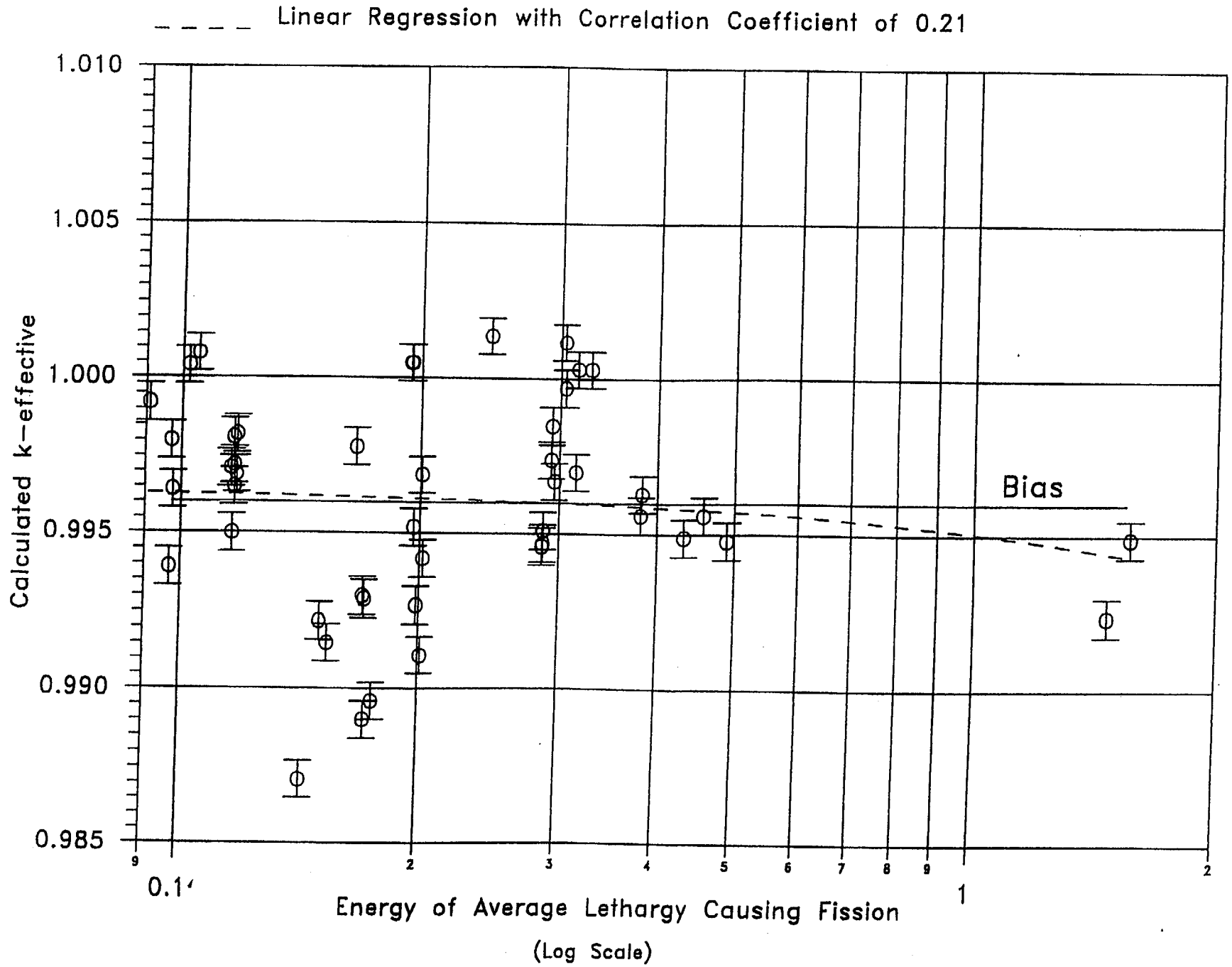

FIGURE 4A.2 KENO5a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

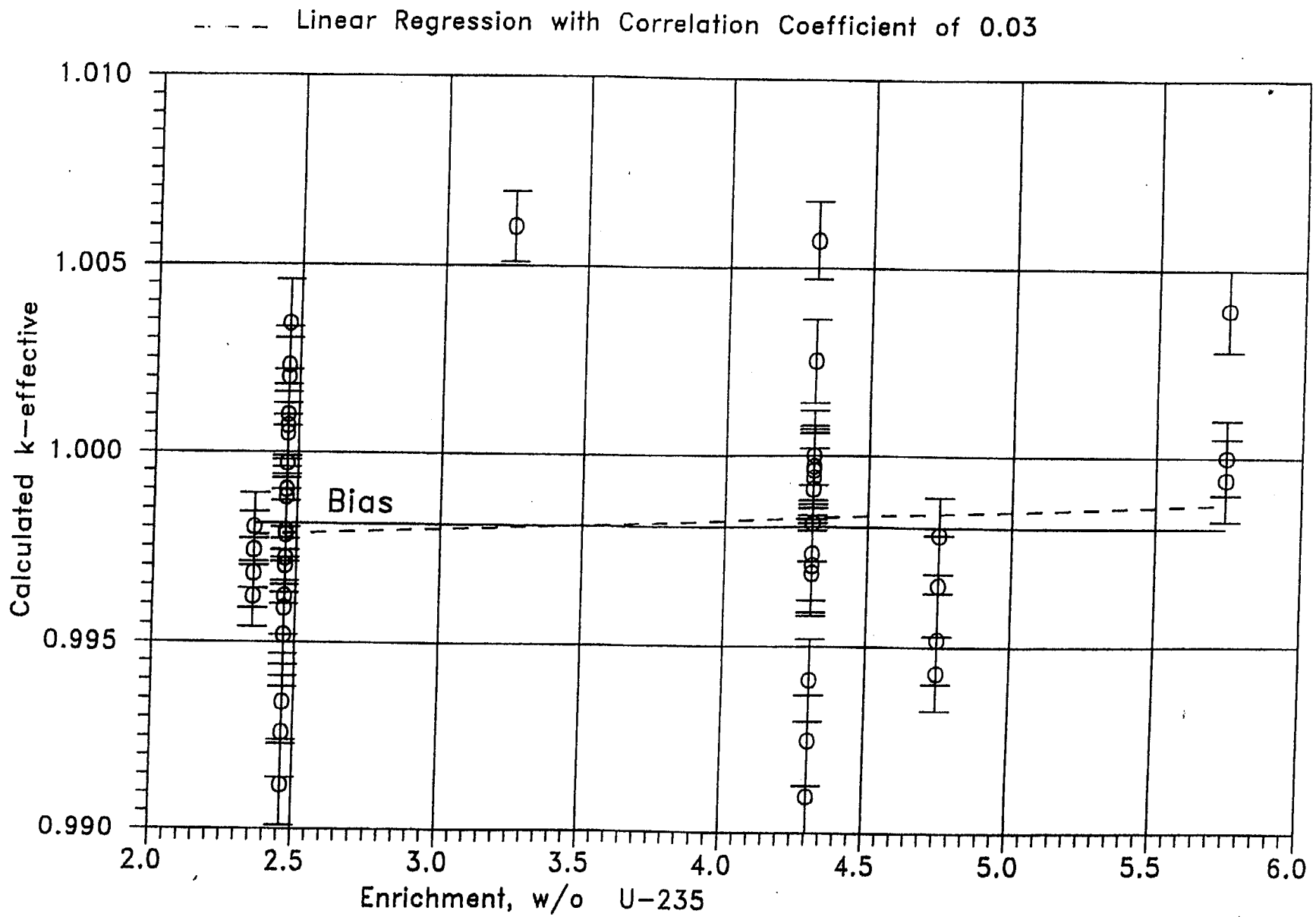

FIGURE 4A.3 MCNP CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

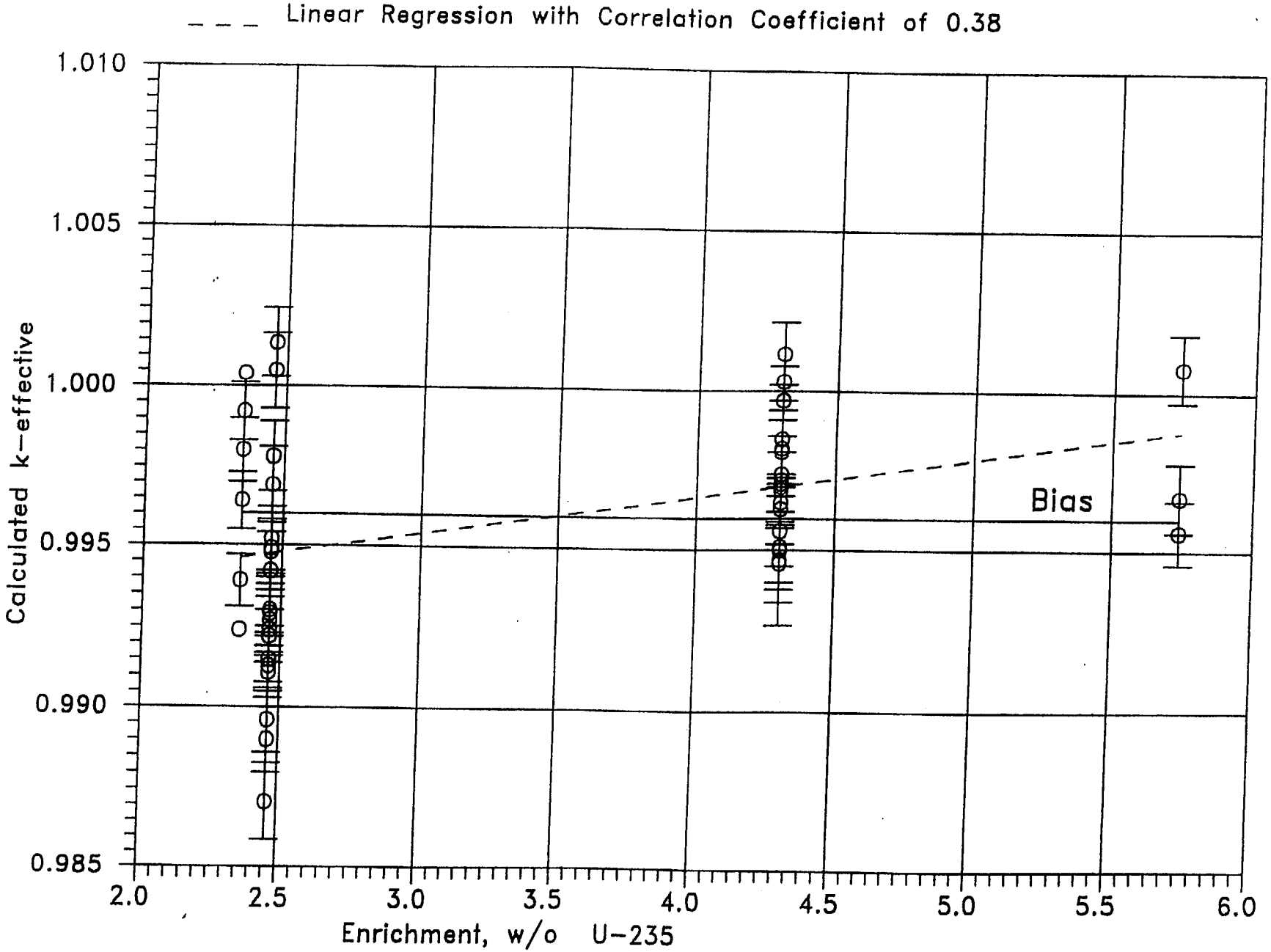

FIGURE 4A.4 KENO CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

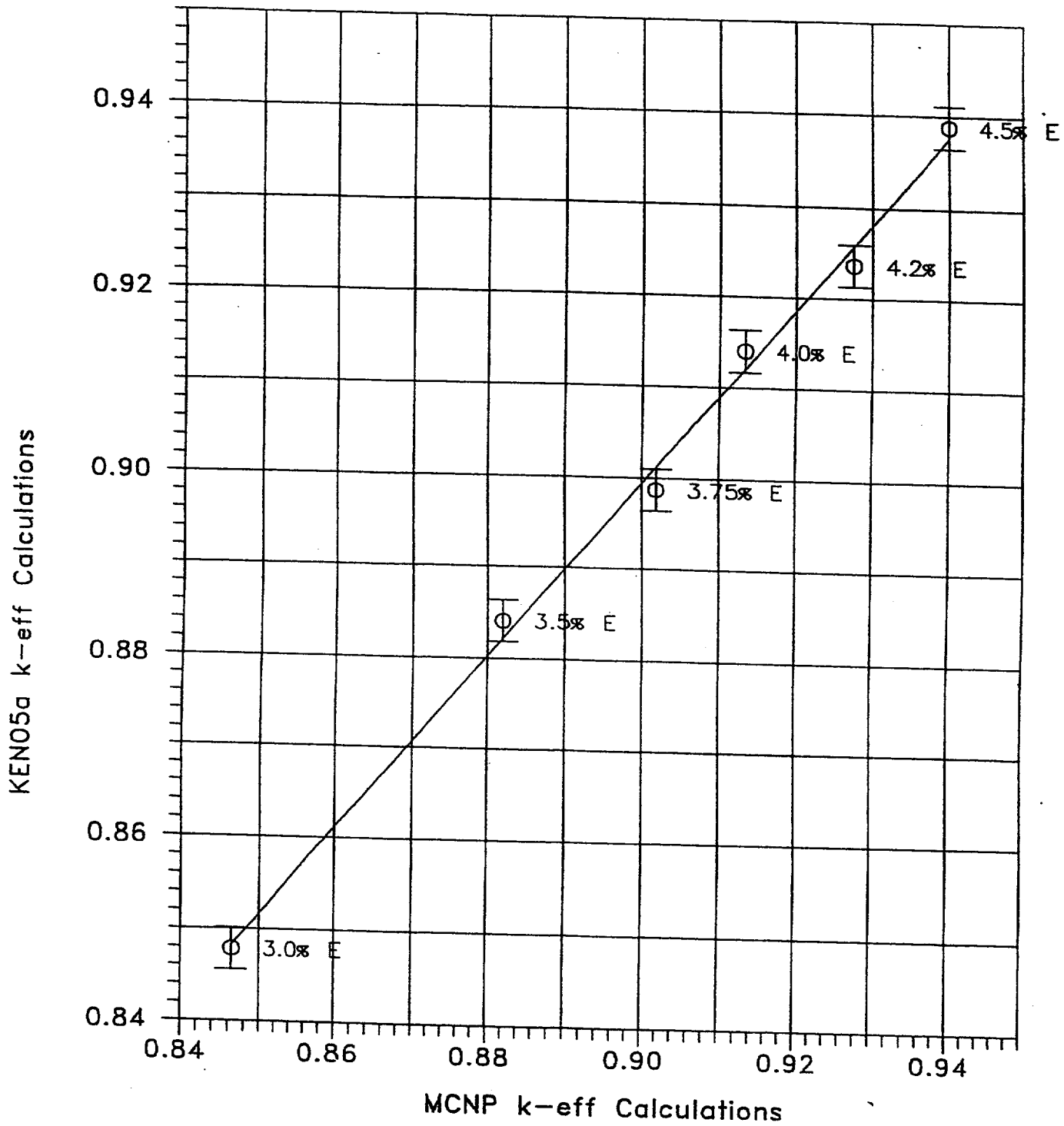

FIGURE 4A.5 COMPARISON OF MCNP AND KENO5A CALCULATIONS FOR VARIOUS FUEL ENRICHMENTS

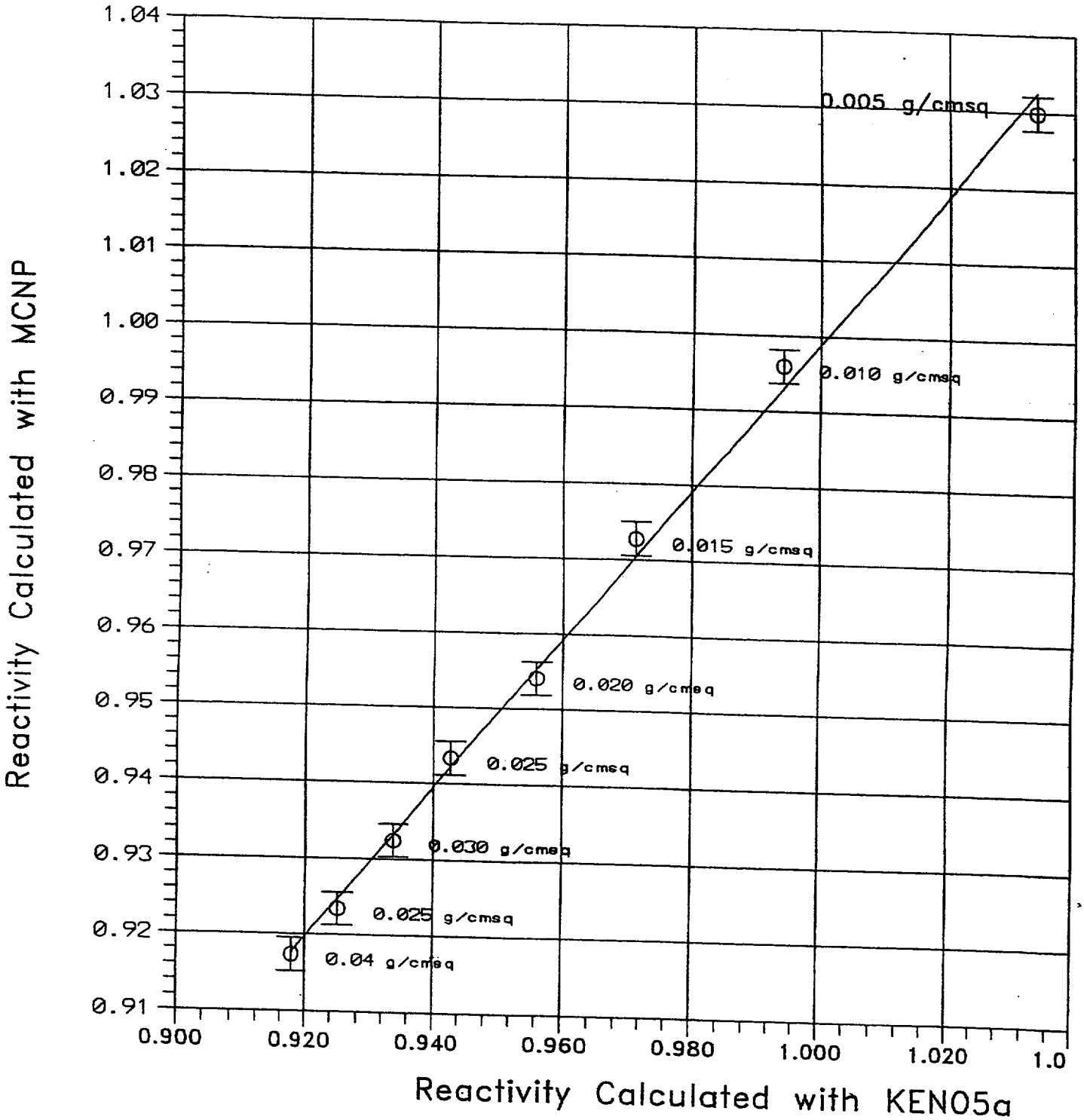

FIGURE 4A.6 COMPARISON OF MCNP AND KENO5a CALCULATIONS FOR VARIOUS BORON-10 AREAL DENSITIES

APPENDIX B: Relationships Between Limiting Burnup, Cooling Time And Fuel Enrichment

(Total of 4 Pages Including This Page)

Face Adjacent Storage of Spent Fuel (Region 2)

Zero Cooling Time

$$Bu\ (limit) = -\ 23.8702 + 12.3026 \times E - 0.275672 \times E^2$$

1 Year Cooling Time

$$Bu\ (limit) = -\ 23.6854 + 12.2384 \times E - 0.287498 \times E^2$$

2 Years Cooling Time

$$Bu\ (limit) = -\ 23.499 + 12.1873 \times E - 0.305988 \times E^2$$

3 Years Cooling Time

$$Bu\ (limit) = -\ 23.3124 + 12.1249 \times E - 0.319566 \times E^2$$

4 Years Cooling Time

$$Bu\ (limit) = -\ 23.1589 + 12.0748 \times E - 0.332212 \times E^2$$

5 Years Cooling Time

$$Bu\ (limit) = -\ 22.6375 + 11.7906 \times E - 0.307623 \times E^2$$

10 Years Cooling Time

$$Bu\ (limit) = -\ 21.7256 + 11.3660 \times E - 0.31029 \times E^2$$

15 Years Cooling Time

$$Bu\ (limit) = -\ 21.1160 + 11.0663 \times E - 0.306231 \times E^2$$

20 Years Cooling Time

$$Bu\ (limit) = -\ 20.6055 + 10.7906 \times E - 0.29291 \times E^2$$

Limiting Burnup For Checkerboard of Fresh and Spent Fuel (1 Fresh Assembly in 4)

For Zero Year Cooling Time

$$Bu\ (limit) = -28.1868 + 23.0765 \times E - 2.46264 \times E^2 + 0.167868 \times E^3$$

For One Year Cooling Time

$$Bu\ (limit) = -27.3317 + 22.5087 \times E - 2.40586 \times E^2 + 0.164207 \times E^3$$

For Two Years Cooling Time

$$Bu\ (limit) = -26.4693 + 21.8404 \times E - 2.31873 \times E^2 + 0.158218 \times E^3$$

For Three Years Cooling Time

$$Bu\ (limit) = -25.7404 + 21.2659 \times E - 2.24287 \times E^2 + 0.153018 \times E^3$$

For Four Years Cooling Time

$$Bu\ (limit) = -25.1367 + 20.7910 \times E - 2.18484 \times E^2 + 0.1499363 \times E^3$$

For Five Years Cooling Time

$$Bu\ (limit) = -24.5981 + 20.3568 \times E - 2.12719 \times E^2 + 0.145431 \times E^3$$

For Ten Years Cooling Time

$$Bu\ (limit) = -23.2050 + 19.2969 \times E - 2.06993 \times E^2 + 0.145875 \times E^3$$

For Fifteen Years Cooling Time

$$Bu\ (limit) = -22.6098 + 18.8544 \times E - 2.08617 \times E^2 + 0.150473 \times E^3$$

For Twenty Years Cooling Time

$$Bu\ (limit) = -22.3017 + 18.622 \times E - 2.11206 \times E^2 + 0.15467 \times E^3$$

Gadolinia Credit: Limiting Burnup for Checkerboard of Fresh and Spent Fuel (1 Fresh Assembly in 4)

Zero Year Cooling Time, 0 Gadolinia Rods

$$Bu\ (limit) = -28.1868 + 23.0765 \times E - 2.46264 \times E^2 + 0.167868 \times E^3$$

Zero Year Cooling Time, 4 Gadolinia Rods

$$Bu\ (limit) = -28.4012 + 22.0062 \times E - 2.19268 \times E^2 + 0.143601 \times E^3$$

Zero Year Cooling Time, 8 Gadolinia Rods

$$Bu\ (limit) = -31.4262 + 22.0768 \times E - 2.38845 \times E^2 + 0.164888 \times E^3$$

Note: If more than 8 Gadolinia rods per assembly, use the 8 rod correlation.

IFBA Credit: Limiting Burnup for Checkerboard of Fresh and Spent Fuel (1 Fresh Assembly in 4)

Zero Year Cooling Time, 0 IFBA Rods

$$Bu\ (limit) = -28.1868 + 23.0765 \times E - 2.46264 \times E^2 + 0.167868 \times E^3$$

Zero Year Cooling Time, 16 IFBA Rods

$$Bu\ (limit) = -28.5048 + 21.6411 \times E - 2.15262 \times E^2 + 0.140904 \times E^3$$

Zero Year Cooling Time, 32 IFBA Rods

$$Bu\ (limit) = -31.0949 + 22.0435 \times E - 2.36088 \times E^2 + 0.162229 \times E^3$$

Zero Year Cooling Time, 48 IFBA Rods

$$Bu\ (limit) = -33.1342 + 22.3999 \times E - 2.55367 \times E^2 + 0.18082 \times E^3$$

Zero Year Cooling Time, 64 IFBA Rods

$$Bu\ (limit) = -36.0468 + 24.1492 \times E - 3.11807 \times E^2 + 0.233987 \times E^3$$

Note: If more than 64 IFBA rods per assembly, use the correlation for 64 IFBA rods.