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QA Record

EVALUATION OF THE EFFECT OF THE USE OF TRITIUM PRODUCING BURNABLE ABSORBER RODS (TPBARS) ON FUEL STORAGE REQUIREMENTS

FOR

SEQUOYAH (TVA)

APPROVED
This approval does not relieve the Contractor from any part of his responsibility for the correctness of design, details and dimensions.
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SUMMARY OF REVISIONS

Revision 01: This revision of the report incorporates TVA comments transmitted to Holtec International via TVA Letter 30M422 from Mr. D. Lafever (TVA) to Dr. K. K. Niyogi (Holtec International).

Revision 02: This document is revised to incorporate client comments transmitted to Holtec International by TVA via Letter 30M439 dated May 28, 2002. There are no changes to the conclusions of the report.

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1.0 INTRODUCTION AND SUMMARY

1.1 Objectives and General Description

The objective of the criticality safety analysis documented in this report is to evaluate the safe storage configuration of fresh and spent fuel assemblies in the Sequoyah Nuclear Plant spent fuel storage racks. This new analysis is performed with fuel assemblies depleted containing tritium producing burnable absorber rods (TPBARs), which are removed at the time the fuel assemblies are placed in storage. Previous analysis performed by Holtec International [8] determined the safe storage patterns for spent fuel depleted with burnable absorber rods, such as Burnable Poison Rod Assemblies (BPRAs), Wet Annular Burnable Absorber (WABA) rods, Integral Fuel Burnable Absorber (IFBA) rods, and gadolinia rods. Credit is taken for soluble boron in pool water, fuel burnup, cooling times and gadolinia rods in the assemblies, where appropriate. Soluble boron in pool water is also used to protect against a mis-loaded assembly accident, where necessary. The analysis uses the MCNP4a/4b Monte Carlo code 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 geometries to define the enrichment-burnup-cooling time combinations for spent fuel configurations that assure a safe storage of fresh and spent fuel in the pool.

The following storage patterns, depicted in Figure 1-1, were investigated in this analysis:

Region 1a — Checkerboard storage of fresh and spent fuel assemblies (1 fresh and 3 spent fuel assemblies in a 2x2 array). The fresh fuel assembly is assumed to contain no gadolinia rods.

Region 1b — Checkerboard storage of fresh and spent fuel assemblies (1 fresh and 3 spent fuel assemblies in a 2x2 array). The fresh fuel assembly is assumed to contain four (4) or eight (8) 2 wt% Gadolinia rods with a 4.95 wt% U carrier enrichment.

Region 2 — Storage of spent fuel face adjacent to each other with no other restriction except burnup.

Region 3 Checkerboard storage of 2 fresh fuel assemblies and 2 empty cells in a 2x2 array. The fresh fuel assemblies are assumed to contain no gadolinia rods.

Postulated accident conditions, where a fresh fuel assembly without gadolinia rods, is inadvertently placed into a cell intended to remain empty, contain spent fuel, or fresh fuel with gadolinia rods, have also been evaluated.

1.2 Summary of Results

Region 1a

The maximum k_{eff} values for the checkerboard storage of 1 fresh and 3 spent fuel assemblies (in a 2x2 array) were determined. The effect of cooling time of spent fuel on the calculated reactivity was also included in the analysis. For each cooling time, minimum burnup values were determined that assure the maximum k_{eff}, including all reactivity effects of the calculational and manufacturing uncertainties, remains less than 1.0 under the assumed condition of the loss of all soluble boron in pool water. Table 6.6 summarizes the result at 0 cooling time for spent fuel. The curves in Figure 1-3 shows the minimum acceptable burnup for fuel of various cooling times for the spent fuel assemblies in the pool. All points on the curves have the same maximum reactivity.

Region 1b

The effects on the calculated k_{eff} of the gadolinia present in some of the fresh fuel rods for the checkerboard storage of 1 fresh and 3 spent fuel assemblies were also investigated in this analysis. The fresh fuel assemblies were assumed to contain either 4 or 8 gadolinia bearing fuel rods. It was assumed that these rods had 2.0 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 assemblies containing gadolinia and spent fuel assemblies in the spent fuel pool. For each cooling time, minimum burnup values were determined that assure the maximum k_{eff}, including all reactivity effects of the calculational and manufacturing uncertainties, remains less than 1.0 under the assumed condition of the loss of all soluble boron in pool water. Table 6.7 summarizes the results for this storage pattern at zero cooling time. Figure 1-4 shows the minimum acceptable burnup for fuel of various cooling times in the spent fuel pool. All points on the curves have the same maximum reactivity.

Region 2

The maximum k-effective values for storage of spent fuel face adjacent to each other were determined assuming an infinite radial array of storage cells with a finite axial length, water reflected. For each spent fuel cooling time, minimum burnup values were determined that assure the maximum k_{eff}, 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. Table 6.8 summarizes the results of these analyses at zero cooling time. Figure 1-5 shows the minimum acceptable burnup for fuel of various cooling time in the spent fuel 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, for the storage of spent fuel in the patterns analyzed and described above (Region 1a, 1b and 2) is 500 PPM.

Region 3

Analyses performed and reported in Reference [8] determined that the checkerboard storage of fresh fuel assemblies and empty cells alternately in the pool meets the regulatory requirements for k_{eff}, without any credit for soluble boron in the pool. Analyses were also performed in Reference [8] 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 material bearing components. These analyses also 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. These analysis remain valid for storage configurations, which include fuel assemblies that have been depleted with

TPBARs.

Accident Conditions

Accident conditions, where a fresh fuel assembly without any gadolinia rods is misplaced into the location of a spent fuel or empty cell, have also been evaluated. Previous analysis [8], established that the misplaced fuel accident scenario with the most serious consequences was the accidental placement of a fresh fuel assembly, containing no gadolinia, into an empty cell in the Region 3 configuration. This accident scenario involves only fresh fuel of 4.95% enrichment. Evaluation of this postulated accident condition demonstrated 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. This limiting soluble boron requirement remains valid and will bound all other postulated fuel misloading accidents. 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 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.

General Guidelines on Fuel Storage Patterns and Interface Requirements

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

- The arrangement in Region 1a or 1b sub-arrays must not allow a configuration with fresh assemblies adjacent to each other.
- For the interface with Region 1a or 1b storage cells, fresh fuel in Region 1a or 1b should not be stored adjacent to spent fuel assemblies in the Region 2 storage cells.
- For the interface between Region 1a or 1b 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 1a, 1b or Region 2 cell in any arrangement.

- The previous analysis [8] had evaluated the maximum k_{eff} for various configurations based on the fuel assemblies, which had contained IFBAs, WABAs, BPRAs, or Gadolinia during core operation. The present analysis evaluated the maximum k_{eff} for storage of fuel, which had contained TPBARs during core operation. The design criteria are the same for both fuel types and the maximum reactivities are closely comparable. To achieve the (nearly) same maximum reactivities of the various arrays, a higher burnup is required of fuel, which had used TPBARs than fuel used in Reference 8. Consequently, there are no additional restrictions on the interfaces between Regions with fuel using TPBARs and Regions using fuel from Reference 8. The normal restrictions for the Regions and fuel types apply.

In summary, results of the analyses confirm that the spent fuel storage racks can safely accommodate fuel, that contained TPBARs, 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 burnup limits, cooling time and loading patterns for the spent fuel as defined in Figures 1-1 to 1-5. The required burnup for safe storage of spent fuel in the pool, for the different acceptable storage configurations described above, at various cooling time are given in Appendix C.

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 V5H 17x17 fuel assemblies, which were determined to be more reactive than the Framatome ANP Mark BW-17 or Alliance fuel assemblies.
- No credit is taken for the presence of the Uranium-236 isotope in the fuel for this analysis.
- Minor structural materials were neglected; i.e., spacer grids were conservatively assumed to be replaced by water.
- 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 analysis.
- The reactivity effect of Boral cutouts, present in the rack Boral panels, was addressed.
- No axial blankets were assumed to be present in the fuel rods. The entire active fuel length was assumed to have the same enrichment.
- When Burnable Poison Rod Assemblies (BPRAs) are analyzed, 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.
- Boron-10 was used to simulate the Li-6 in the TPBAR's, since CASMO-4 does not include Li-6 in the cross-section library. To accomplish this, the number density of B-10 was adjusted to give the same absorption cross section as the Li-6 by KENO-5a calculations. This is a conservative assumption, since B-10 (Li-6) was not depleted.
- The reactivity effect of depleting fuel assemblies with TPBARs was calculated assuming the maximum number of TPBAR rods and the maximum Li-6 loading in these rods. The

depletion with TPBAR rods was assumed to occur throughout the life of the fuel assembly (TPBARs were not removed during the depletion).

- It is assumed that the TPBAR's are removed at the time the spent fuel is placed in storage.

- The density of the fuel was assumed to be 96% of the nominal theoretical density, with a tolerance of ± 2%.

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 from 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 FCF Alliance fuel. Table 4.1 provides the design details for the fuel assemblies. Any burnable poison, which may be in the fresh fuel assemblies such as gadolinia rods, would reduce reactivity. The gadolinia loading and the gadolinia rod patterns in the fuel assemblies were specified by TVA [9]. The presence of four (4) and eight (8) gadolinia rods in the fresh fuel assemblies were considered. The gadolinia rods were assumed to be full length. Design specifications for the TPBARs are obtained from Reference 9.

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 4.1. Each storage cell is composed of single Boral absorber panels positioned between two 8.75 inch I.D., 0.060 inches 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 inches and an as-built B-10 areal density of 0.03388 g/cm^2 (0.03218 g B-10 cm^2 minimum).

4.3 Operating Parameters

The core operating parameters for performing the depletion calculations were obtained from Reference 1. The principal core operating parameters, used in this study, are summarized in the table below.

Core Operating Parameters	Value
Fuel Temperature (°F)	1370
Moderator Temperature (°F)	592
Average Soluble Boron in Moderator (ppm)	700

5.0 METHODOLOGY

The primary criticality analyses were performed with the three-dimensional MCNP4a and MCNP4b Monte Carlo code [4]. Benchmark calculations, presented in Appendix A, indicate a bias of 0.0009±0.0011 (95%/95%) [3]. CASMO4, a two-dimensional deterministic code [5] 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 results of the MCNP4a/MCNP4b calculations for a comparable 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 was explicitly described in the calculational model. The fuel cladding material was zirconium. The large water gaps between rack modules were not modeled.

Monte Carlo (KENO5a and MCNP4a / MCNP4b) 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 3 million neutron histories was accumulated in each calculation. A comparable number of neutron histories were accumulated in the MCNP calculations. Three-dimensional MCNP calculations were necessary to describe the geometry of the checkerboard cases. However, MCNP cannot perform depletion calculations. Depletion calculations were performed with CASMO4 with explicit description of the fission product nuclide concentration. To compensate for those few fission product nuclides that cannot be described in MCNP, an equivalent boron-10 in the fuel was determined which produced the same reactivity in MCNP as the CASMO4 result. This methodology incorporates approximately 40 of the most important fission products, accounting for all but about 1% in k. The remaining ~1 % in k is included by the equivalent B-10 concentration in the fuel.

Burnable poison rod assemblies (BPRA's) are often used to augment reactivity control and are removed usually after the first cycle. In the core operation, the BPRA rods displace water and result in a slightly greater production of plutonium. Because of this, removal of the BPRA rods results in an increase in reactivity slightly above that which would occur in the absence of the BPRA. Calculation of the reactivity increase were made assuming all of the control rod thimbles (24 rods) contained TPBAR's. These calculations showed that the TPBAR's resulted in a higher k-eff and therefore bounds cases where BPRA's may be present.

The boral panels in the Sequoyah spent fuel racks contain cutouts along the edge of the panels through which the steel sheath is spot-welded. These cutouts may be readily modeled in the KENO5a calculations used in Reference 8, but are much more complicated in MCNP. Therefore, the reactivity effect of these cutouts were determined by differential KENO5a calculations and treated as a bias.

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 Alliance fuel, described in Table 4.1. The calculations showed that the Westinghouse 17x17 fuel exhibits higher reactivity.

Burnup, GWD/MTU	k_{inf} (W 17X17 V5H)	k_{inf} (FCF Alliance)
0	1.1879	1.1867
10	1.1083	1.1072
15	1.0764	1.0752
20	1.0470	1.0459
25	1.0197	1.0187
30	0.9938	0.9928
35	0.9689	0.9680
40	0.9452	0.9444
45	0.9224	0.9217
50	0.9008	0.9002
60	0.8611	0.8607

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. 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 *Mechanical Tolerances*

CASMO4 calculations were made to determine the uncertainties in reactivity associated with mechanical tolerances. The mechanical tolerances to be evaluated have been assumed to be the same as that reported in the earlier analysis [8]. The reactivity effects of each independent tolerance were combined statistically.

6.2.1.1 *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 6.4.

6.2.1.2 *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 6.4.

6.2.1.3 *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 6.4.

6.2.2 *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 6.2.

The reactivity uncertainties associated with the tolerance in fuel enrichment are shown in Table 6.3.

6.2.3 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. This uncertainty is tabulated in Tables 6.6 – 6.8.

6.2.4 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. Previous calculations have confirmed that the eccentric positioning of fuel assemblies at the position of closest approach yields a reduction in reactivity (Ref. 8), confirming that the normal centered position is the most reactive. This is due to the fact that the increased neutron coupling between the four assemblies is counter-acted by the larger water gap on the other side of the fuel.

6.2.5 Tolerance in Gadolinia Loading

For rods containing gadolinia burnable poison, the initial concentration was assumed to be 2% by weight of Gd_2O_3. The tolerance in gadolinia loading was assumed to be $\pm$5% of the nominal design value. The calculations assumed 95% of the design basis in order to assure conservative calculations.

6.2.6 TPBAR Model

CASMO4 cannot model Li-6 (as used in the TPBARs), therefore, an equivalent boron concentration was used to simulate the absorption in Li-6. Since this approximation could introduce some uncertainty, a sensitivity analysis was performed with KENO5a by increasing the boron concentration in the simulated TPBARs by 25%. Results of this analysis showed that the effect on the residual reactivity was small and the reactivity allowance Δk is shown in Tables 6.6 to 6.8.

The following listing compares the reactivity of an assembly (CASMO-4 calculations for the reference case and for ± 25% of the equivalent Li-6 loading in the TPBARs). Also shown in the listing below is a calculation using ORIGEN-S to estimate the Li-6 depletion at several fuel burnups and inserting the reduced Li-6 concentration into the CASMO calculation at the corresponding burnups. Although the ORIGEN-S calculation is only approximate, the results indicate that the reference calculation is conservative. The TPBAR target rods would most likely in the assembly for the duration of its lifetime. However, they could potentially be replaced periodically. The reference calculation (no Li-6 depletion) therefore bounds any management program of the TPBARs, and incorporates an allowance for up to 25% higher Li-6 loading than is currently contemplated.

Burnup, MWD/KgU	k_{inf}			
	75% Li-6	Reference Li-6	125% Li-6	Li-6 Depletion
0	1.1879	1.1879	1.1879	1.1879
20	1.0461	1.0470	1.0477	1.0464
40	0.9428	0.9452	0.9469	0.9390
50	0.8976	0.9008	0.9031	0.8893
60	0.8570	0.8611	0.8641	0.8421

6.2.7 Boral Cutout Model

The Boral panels in the Sequoyah spent fuel racks were manufactured with 12 rectangular cutouts (1.875" by 1.25") at intervals along both sides of the poison panels, through which the steel backing plate was spot-welded to the cell box. KENO5a calculations for 10 different fuel types and array configurations were performed to determine the effect of these cutouts. The reactivity effect of these cutouts is small, averaging 0.0026Δk, and is treated as an additive penalty in Tables 6.6, 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 6.1. 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. Three different fuel misloading accident scenarios were considered in this study:

a) For a checkerboard pattern of storage of fresh and spent fuel (1 fresh fuel assembly in 4), a fresh fuel assembly containing no gadolinia rods was postulated to be misplaced face adjacent to another fresh fuel assembly in the location of a spent fuel.

b) For the storage of spent fuel of a certain burnup, face adjacent to each other, a fresh fuel assembly containing no gadolinia rods was postulated to be misplaced in the location of a spent fuel assembly.

c) For the checkerboard pattern of the storage of fresh fuel assemblies and empty cells filled with water, a fresh fuel assembly *containing no* gadolinia rods is postulated to be misplaced in the location of an empty cell face adjacent to another fresh fuel assembly, *containing no* gadolinia rod. This is the most serious and controlling credible accident condition.

Since a fuel misloading scenario would be considered an accident, evaluations 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 or a cell intended to remain empty could potentially exceed the regulatory limit on k_{eff}. Calculations indicate that credit for 700 ppm soluble boron would maintain the maximum reactivity below the regulatory limit for all the scenarios described above. The accidental mis-loading of a fresh fuel assembly outside and adjacent to the rack is bounded by the evaluation of a fresh assembly misloaded internally to the rack.

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 would result in a slightly lower reactivity than that calculated for the uniform 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.

In the calculations reported here, the actual fission product concentrations in the spent fuel were used. The active fuel region was divided into 10 axial zones and the burnup equivalent actinide and fission product concentrations determined for each zone. The axial enrichment distribution used is based on a generic study by Turner [7] and has been previously used for such analysis of spent fuel pool racks [8]. Thus, the calculations inherently include the effect of the axial distribution in burnup.

6.5 Criticality Analyses Results

Region 1a

The results for the analysis of the storage of fresh fuel in a Region 1a checkerboard pattern with spent fuel are summarized in Table 6.6. This storage pattern is depicted in Figure 1-1. In this analysis no credit was taken for the presence of gadolinia 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 Sequoyah spent fuel pool, as long as the spent fuel has reached a burnup of 56.91 MWD/KgU with no credit for cooling time. Figure 1-3 summarizes the burnup requirements at different cooling times for the spent fuel.

Region 1b

The results of the analysis of the storage of fresh fuel, containing gadolinia, in a checkerboard pattern with spent fuel (Region 1b) is shown in Table 6-7. In this analysis the fresh fuel assembly was assumed to contain 4 or 8 rods with gadolinia. The results show that this configuration of fuel storage meets the regulatory criteria and can be safely stored in the Sequoyah spent fuel pool, with no credit for cooling time, as long as the spent fuel has reached a burnup of 53.73 MWD/KgU when stored with fresh fuel containing 4 gadolinia rods and a burnup of 50 MWD/KgU when stored with fresh fuel containing 8 gadolinia rods. Figure 1-4 summarizes the burnup requirements at different cooling times for the spent fuel assemblies with gadolinia in the fresh fuel.

Region 2

A summary of the results of the criticality safety analysis for the storage of spent fuel (initial enrichment of 4.95±0.05 wt%) face adjacent to each other in the spent fuel pool racks is given in Table 6.8. 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 33.062 MWD/kg-U burnup meets the regulatory requirements, with no credit for cooling time. Figure 1-5 summarizes the burnup requirements for other spent fuel cooling time for the storage of spent fuel face adjacent to each other.

Region 3

Analyses were also performed to investigate the checkerboard pattern storage (Figure 1-1) of fresh fuel assemblies and empty cells, filled with water, in the spent fuel pool. The calculations were performed under the assumption that the fresh fuel assemblies contained no gadolinia 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.

Interface Requirements Between Regions

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. The results of these calculations are described in section 1.2.

7.0 OTHER BURNABLE POISON ROD INSERTS IN THE FUEL ASSEMBLIES

The fuel assemblies used at the Sequoyah may contain poison rods other than the TPBARs such as BPRAs. Analyses show that the fuel assemblies containing TPBARs are more reactive than those containing BPRAs at the burnups of interest. These results are summarized in Table 6.9.

8.0 CONCLUSIONS

Previous analysis [8] had evaluated the maximum k_{eff} for various configurations based on fuel assemblies, which had contained IFBAs, WABAs, BPRAs, or Gadolinia during core operation. The present analysis evaluated the maximum k_{eff} for the same configurations based on fuel, which had contained TPBARs during core operation. The design criteria, used in both Reference [8] and the present analysis, are the same and the maximum reactivities are closely comparable. To achieve the (nearly) same maximum reactivities of the various arrays, a higher burnup is required of fuel, which had used TPBARs than of fuel used in Reference [8]. Consequently, there are no additional restrictions on the interfaces between Regions with fuel using TPBARs and Regions using fuel from Reference 8. The normal restrictions for the Regions and fuel types apply. Results are documented in the tables and figures provided. In order to determine the allowable storage locations for fuel assemblies, each assembly will continue to be characterized by reactivity (cooling time-burnup combinations) prior to insertion into the spent fuel storage racks. The empirical fits provided in Appendix B give a very close approximation, within acceptable bounds, to the calculated values. Specific conclusions on the storage of spent fuel, which had contained TPBARs, are given below.

- Fuel assemblies in a checkerboard pattern (1 fresh 4.95±0.05 wt% U-235 assembly out of 4 assemblies) may be stored in the spent fuel racks provided they meet the burnup and cooling time criteria as depicted in Figure 1-3 (Region 1a).
- 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 as shown in Figure 1-4 (Region 1b).
- Fuel assemblies with spent fuel having the burnup, and cooling time criteria as depicted in Figure 1-5 may be safely accommodated in the storage racks, with no other constraints (Region 2).
- The storage of fresh fuel alternately with water-filled cells (2 fresh 4.95±0.05 wt% U-235 assemblies in a 2x2 array: Region 3) results in a calculated k_{eff} less than 0.95 without any credit for soluble boron.
- A water cell will always be less reactive than an irradiated fuel assembly. Conservatively, 75% of water may be safely displaced by non-fissile materials in Regions 1, 2 and 3.
- 700 ppm of soluble boron in the spent fuel pool provides margins to criticality sufficient to mitigate the effects of the most serious accident condition+.

+ The boron dilution accident analysis (Holtec Report 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.

9.0 REFERENCES

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6. 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.

7. S. E. Turner, "Uncertainty Analysis – Burnup Distributions," Presented at the 1988 DOE/SANDIA Technical Meeting on Fuel Burnup Credit

8. Holtec Report No. HI-992349, Revision 1

9. TVA Letter 30M400 to Holtec International, dated January 8, 2001

Table 4.1 Design Basis Fuel Assembly Specifications

FUEL ROD DATA	W 17X17	ALLIANCE
Cladding Outside diameter, in.	0.374	0.374
Cladding inside diameter, in.	0.329	0.329
Cladding material	Zr-4	M5
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	0.3225
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	0.490
Guide/Inst. tubes I.D., in.	0.442	0.451

Table 6.1 Reactivity Effects of Temperature and Void for Westinghouse 17x17 V5H 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	1.1389	-0.0252
10	1.1102	1.1083	-0.0019	1.1008	-0.0075	1.0854	-0.0229	1.0606	-0.0248
20	1.0487	1.0470	-0.0017	1.0399	-0.0071	1.0252	-0.0218	1.0006	-0.0246
30	0.9953	0.9938	-0.0015	0.9872	-0.0066	0.9735	-0.0203	0.9492	-0.0243
40	0.9465	0.9452	-0.0013	0.9392	-0.0060	0.9267	-0.0185	0.9030	-0.0237
50	0.9018	0.9008	-0.0010	0.8955	-0.0053	0.8842	-0.0166	0.8611	-0.0231
60	0.8619	0.8611	-0.0008	0.8565	-0.0046	0.8463	-0.0148	0.8239	-0.0224

\+ difference with results @ 4 °C

* difference with results @ 20 °C

** difference with results at 120 °C

Table 6.2 Reactivity Effects of Fuel Density Tolerance for Westinghouse 17x17 V5H Fuel in TVA Sequoyah Nuclear Plant Spent Fuel Racks.

BURNUP, MWD/KGU	REFERENCE	DENSITY TOLERANCE	
	k_{inf}	k_{inf}	Δk
0	1.1879	1.1893	0.0014
10	1.1083	1.1093	0.0010
20	1.0470	1.0480	0.0010
30	0.9938	0.9950	0.0012
40	0.9452	0.9467	0.0015
50	0.9008	0.9027	0.0019
60	0.8611	0.8635	0.0024

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	ENRICHMENT TOLERANCE	
	k_{inf}	k_{inf}	Δk
0	1.1879	1.1900	0.0021
10	1.1083	1.1106	0.0023
20	1.0470	1.0493	0.0023
30	0.9938	0.9961	0.0023
40	0.9452	0.9475	0.0023
50	0.9008	0.9030	0.0022
60	0.8611	0.8631	0.002

Table 6.4 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		STATISTICAL SUM
	k_{inf}	k_{inf}	Δk	k_{inf}	Δk	k_{inf}	Δk	k_{inf}	Δk	Δk
0	1.1879	1.1891	0.0012	1.1880	0.0001	1.1889	0.0010	1.1907	0.0028	0.0032
10	1.1083	1.1095	0.0012	1.1084	0.0001	1.1092	0.0009	1.1109	0.0026	0.0030
20	1.0470	1.0481	0.0011	1.0471	0.0001	1.0478	0.0008	1.0494	0.0024	0.0028
30	0.9938	0.9948	0.0010	0.9938	0.0000	0.9945	0.0007	0.9960	0.0022	0.0025
40	0.9452	0.9462	0.0010	0.9452	0.0000	0.9459	0.0007	0.9473	0.0021	0.0024
50	0.9008	0.9018	0.0010	0.9009	0.0001	0.9015	0.0007	0.9028	0.0020	0.0023
60	0.8611	0.8620	0.0009	0.8612	0.0001	0.8618	0.0007	0.8630	0.0019	0.0022

Table 6.5 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 6.6 Summary of the Criticality Safety Analyses for Checkerboard Storage of Fresh and Spent Fuel Assemblies (Region 1a), 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	56.91 MWD/kg-U*
Reference k_{eff} (MCNP)	0.9783
Correction for Boral Cutouts	0.0026
Allowance for Li^6 Loading	0.0028
MCNP Bias	0.0009
MCNP Bias Uncertainty	± 0.0011
MCNP Statistics (95/95) Uncertainty	±0.0007
Mechanical Tolerance Uncertainty	± 0.0023
Fuel Density Tolerance	± 0.0022
Enrichment Tolerance Uncertainty	± 0.0022
Depletion Uncertainty	± 0.0095
Temperature Effect to 4 °C Uncertainty	± 0.0010
Fuel Eccentricity Uncertainty	Negative
Statistical Combination of Uncertainties	± 0.0104
Maximum k_{eff}	0.9950
Regulatory Limiting k_{eff}	1.0000

* Other cooling time-burnup combinations shown in Figure 1-3 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 (Region 1b), 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	53.73 MWD/kg-U*	50 MWD/kg-U*
Reference k_{eff} (MCNP)	0.9774	0.9798
Allowance for Li^6 Loading	0.0026	0.0023
MCNP Bias	0.0009	0.0009
Correction For Boral Cutouts	0.0026	0.0026
MCNP Bias Uncertainty	± 0.0011	± 0.0011
MCNP Statistics (95/95) Uncertainty	± 0.0007	± 0.0007
Mechanical Tolerance Uncertainty	± 0.0023	± 0.0023
Fuel Density Tolerance	±0.0022	± 0.0019
Enrichment Tolerance Uncertainty	± 0.0022	± 0.0022
Depletion Uncertainty	±0.0114	± 0.0093
Temperature Effect to 4 °C Uncertainty	±0.0010	± 0.0010
Fuel Eccentricity Uncertainty	Negative	Negative
Statistical Combination of Uncertainties	±0.0121	± 0.0101
Maximum k_{eff}	0.9956	0.9957
Regulatory Limiting k_{eff}	1.0000	1.0000

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

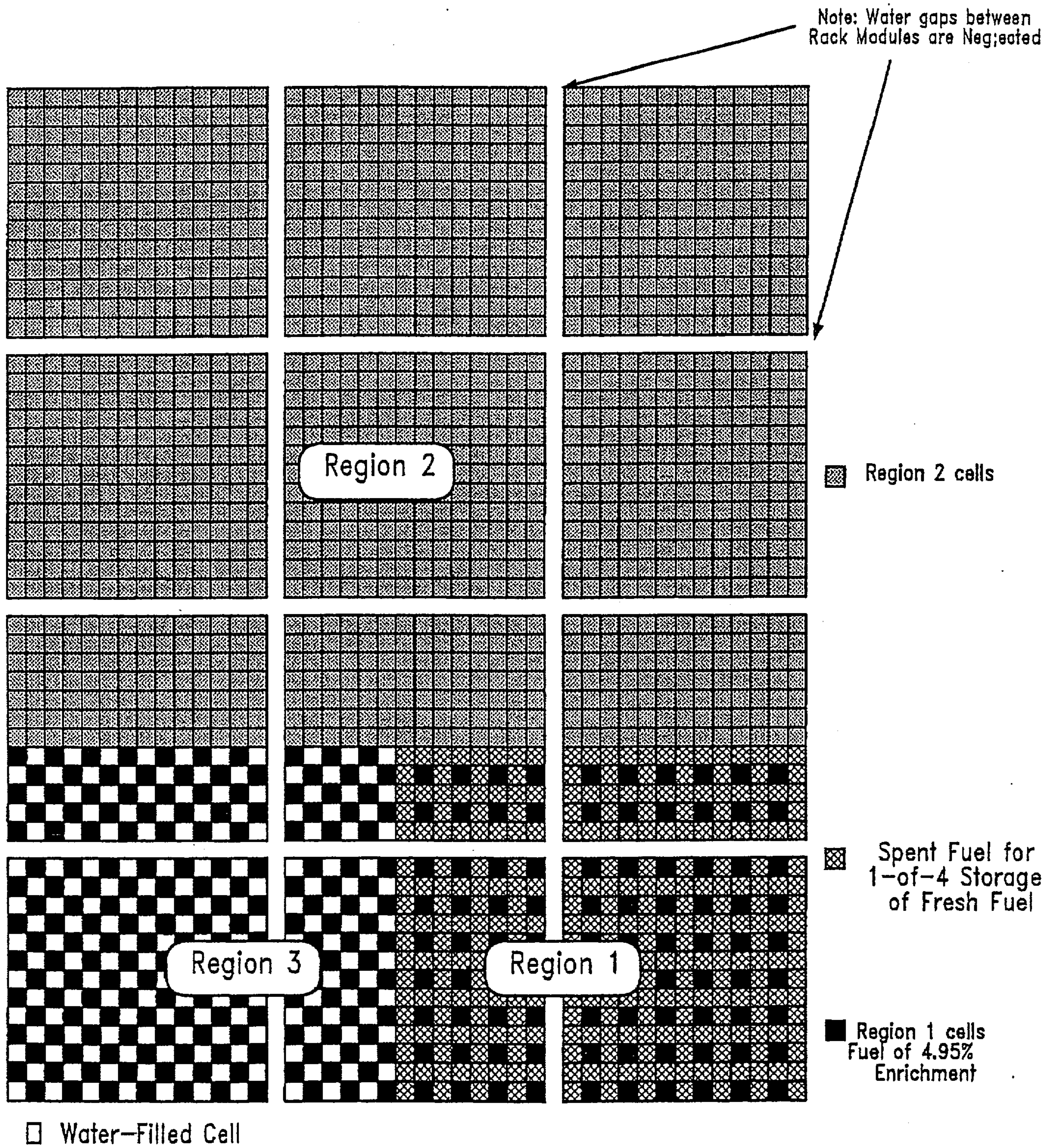
Table 6.8 Summary of the Criticality Safety Analyses for the Face Adjacent Storage of Spent Fuel in the Racks (Region 2).

STORAGE ARRANGEMENT	Region 2: Face Adjacent Spent Fuel Storage
Design Basis Burnup at 4.95±0.05 % wt. ^{235}U	33.062 MWD/kg-U*
Reference k_{eff} (MCNP)	0.9743
Correction for Boral cutouts	0.0026
MCNP Bias	0.0009
Allowance for Li^6 Loading	0.0013
MCNP Bias Uncertainty	± 0.0011
MCNP Statistics (95/95) Uncertainty	± 0.0007
Mechanical Tolerance Uncertainty	± 0.0025
Fuel Density Tolerance	± 0.0013
Enrichment Tolerance Uncertainty	± 0.0023
Depletion Uncertainty	± 0.0105
Temperature Effect to 4 °C Uncertainty	± 0.0014
Fuel Eccentricity Uncertainty	Negative
Statistical Combination of Uncertainties	± 0.0113
Maximum k_{eff}	0.9904
Regulatory Limiting k_{eff}	1.0000

* Other cooling time-burnup combinations shown in Figure 1-5 have the same maximum reactivity.

Table 6.9 Comparison of the reactivity of fuel assemblies with different burnable poison rods.

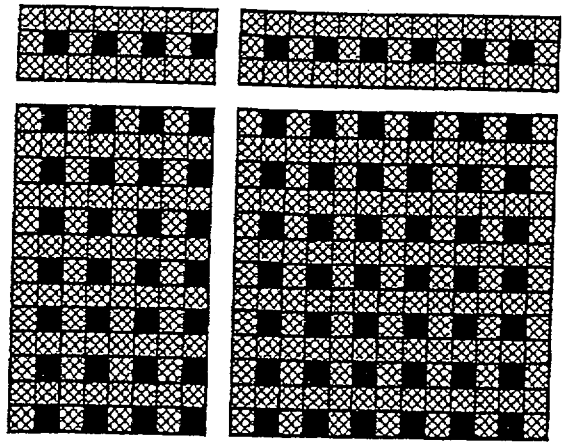
Burnup,GWD/MTU	W-V5H with TPBAR	W-V5H with BPRA
	k_{inf}	k_{inf}
0	1.1879	1.1879
10	1.1083	1.1074
20	1.0470	1.0420
30	0.9938	0.9817
40	0.9452	0.9200
50	0.9008	0.8605
60	0.8611	0.8050



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 in Section 1.2 of the text.

FIG 1-1 ACCEPTABLE SPENT FUEL POOL LOADING PATTERN – Example

(Spent Fuel Initially Contained TPBAR's)



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

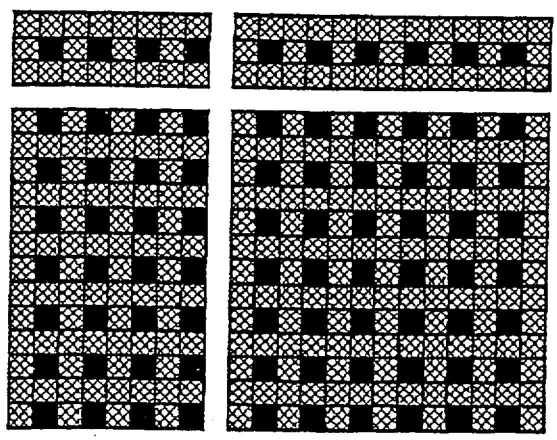


Fig. 1-2 Acceptable Spent Fuel Pool Loading Patterns for Checkerboard Storage of Fresh and Spent Fuel Assemblies - Example

(Spent Fuel Initially Contained TPBAR's)

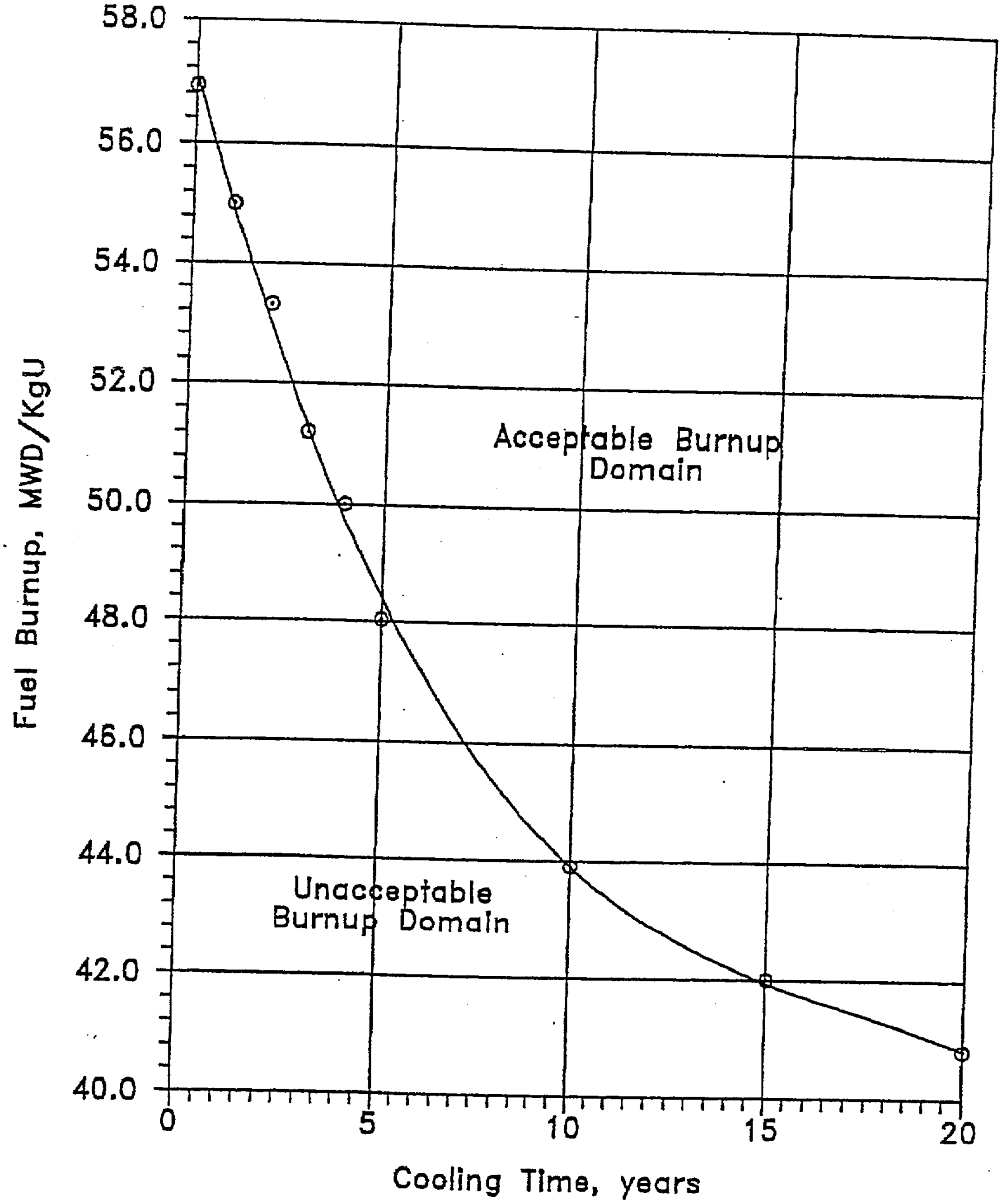


Fig. 1–3 Limiting Burnup Requirements in Region 1A, Checker-board Array of 1 Fresh and 3 Spent Fuel Assemblies

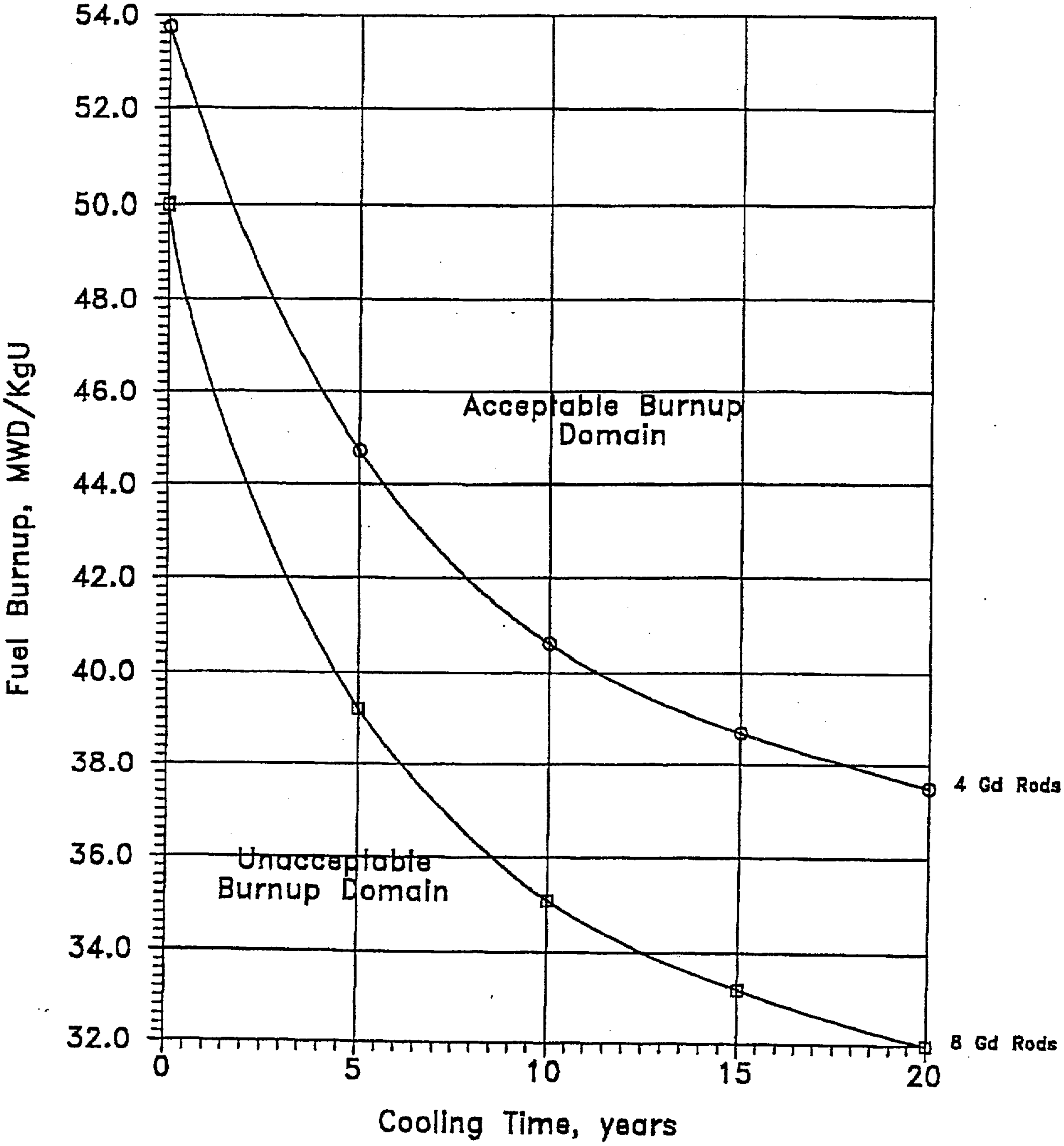


Fig. 1–4 Limiting Burnup Requirements in Region 1B, Checkerboard Array of 1 Fresh (with Gadolinia) and 3 Spent Fuel Assemblies

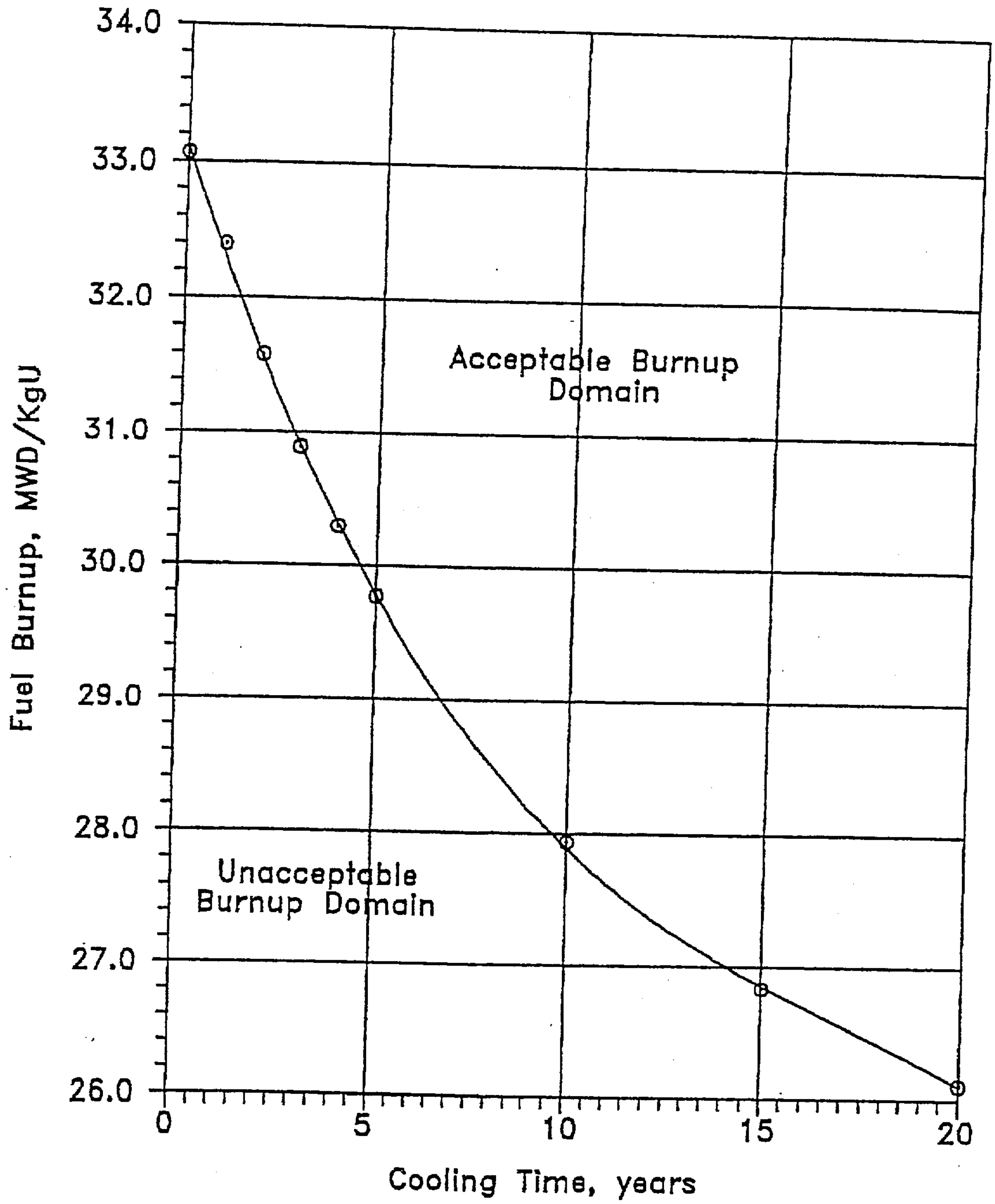


Fig. 1—5 Limiting Burnup Requirements In Region 2, Face Adjacent Storage of Spent Fuel Assemblies

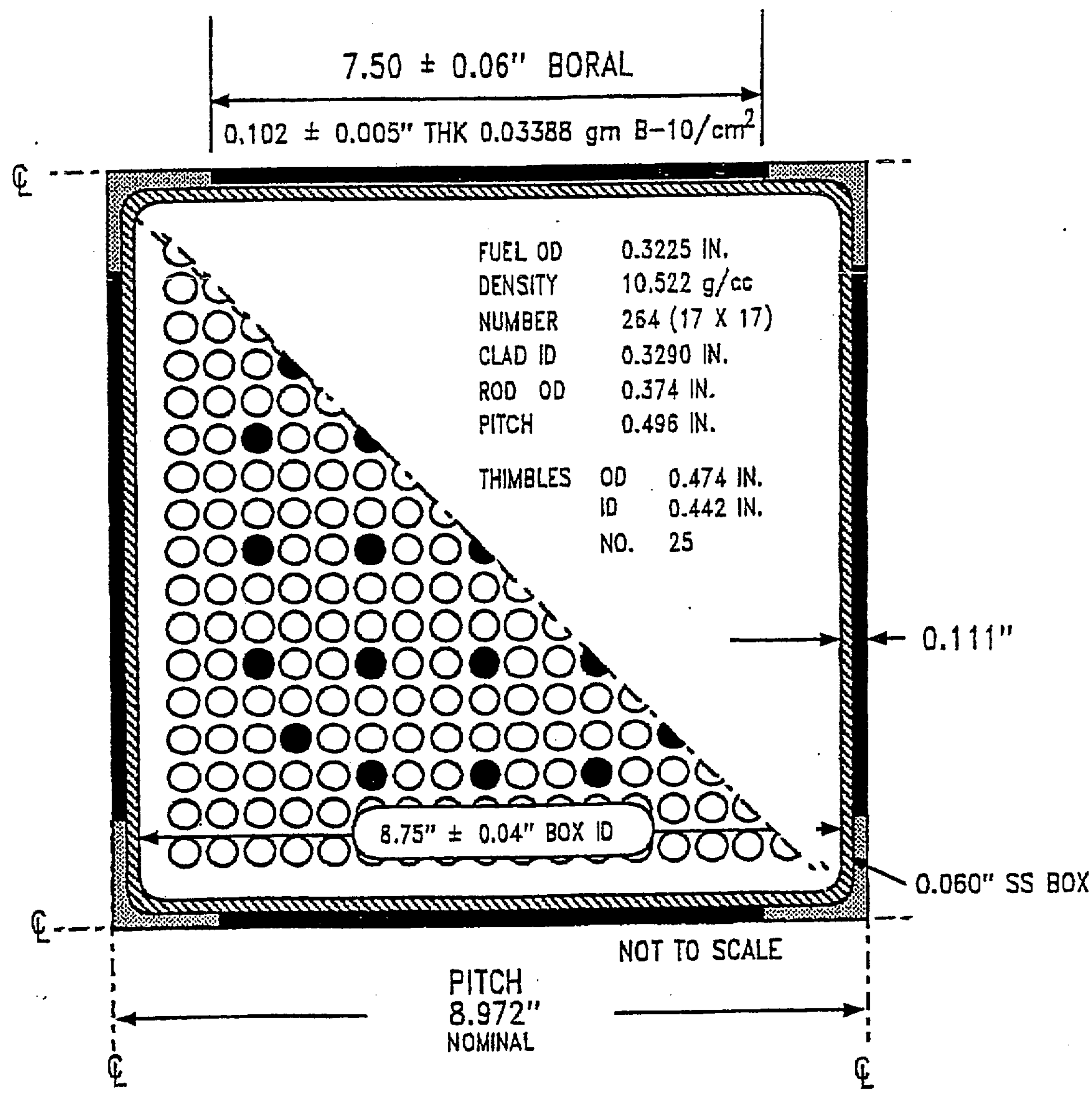


FIG. 4-1 FUEL STORAGE CELL CROSS SECTION

APPENDIX A: Benchmark Calculations

(Total of 26 Pages Including This Page)

Note: This appendix was taken from a different report. Hence, the next page is labeled "Appendix 4A, Page 1".

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).

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

† 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).

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Table 4A.1

Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF [†] (eV) MCNP4a	EALF [†] (eV) 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} MCNP4a	Calculated k_{eff} KENO5a	EALF † (eV) MCNP4a	EALF † (eV) 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} MCNP4a	Calculated k_{eff} KENO5a	EALF [†] (eV) MCNP4a	EALF [†] (eV) 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} MCNP4a	Calculated k_{eff} KENO5a	EALF[†] (eV) MCNP4a	EALF[†] (eV) 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} MCNP4a	Calculated k_{eff} KENO5a	EALF† (eV) MCNP4a	EALF† (eV) 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 ($>3\sigma$) 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.

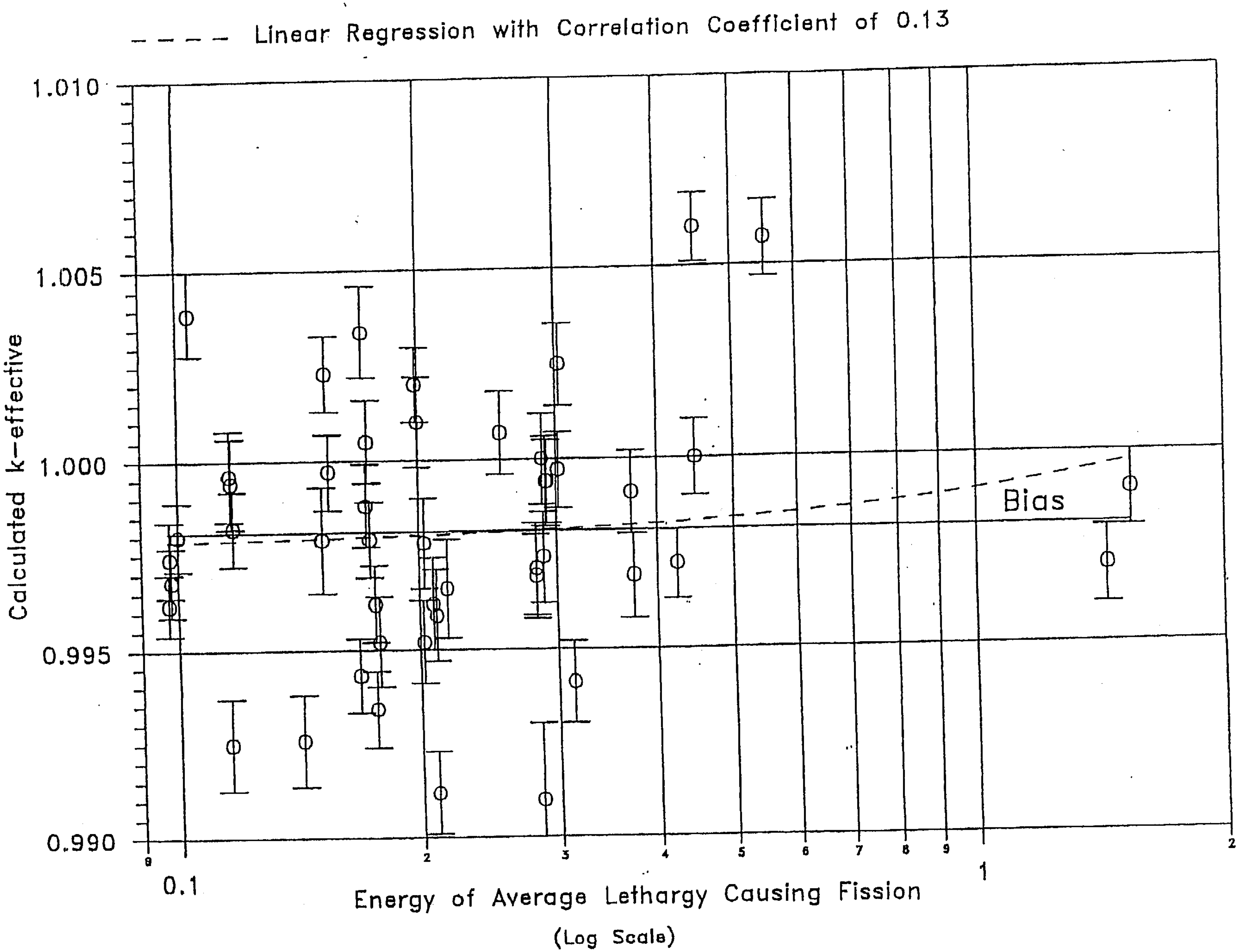

FIGURE 4A.1 MCNP CALCULATED k-eff VALUES for VARIOUS VALUES OF THE SPECTRAL INDEX

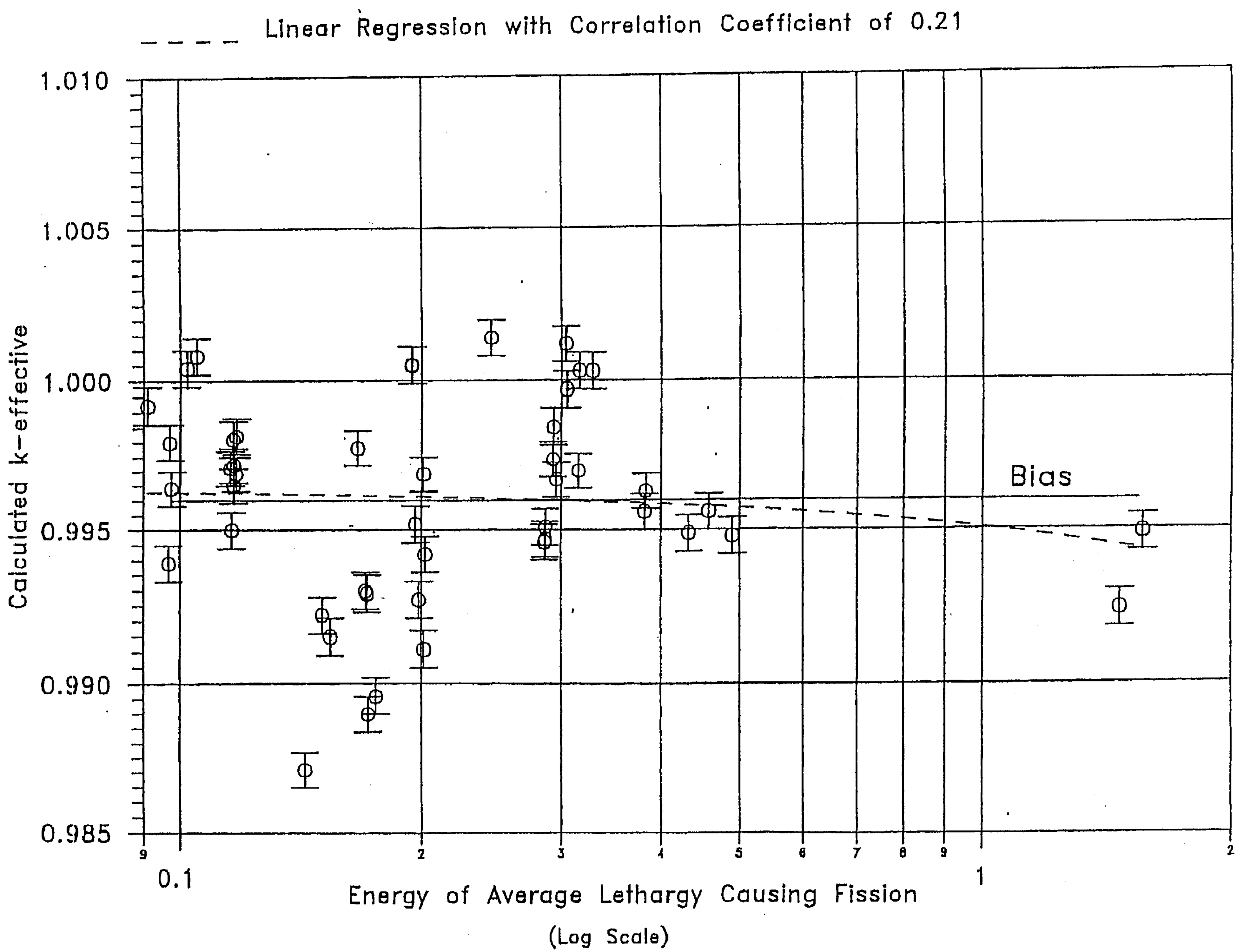

FIGURE 4A.2 KENO5a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

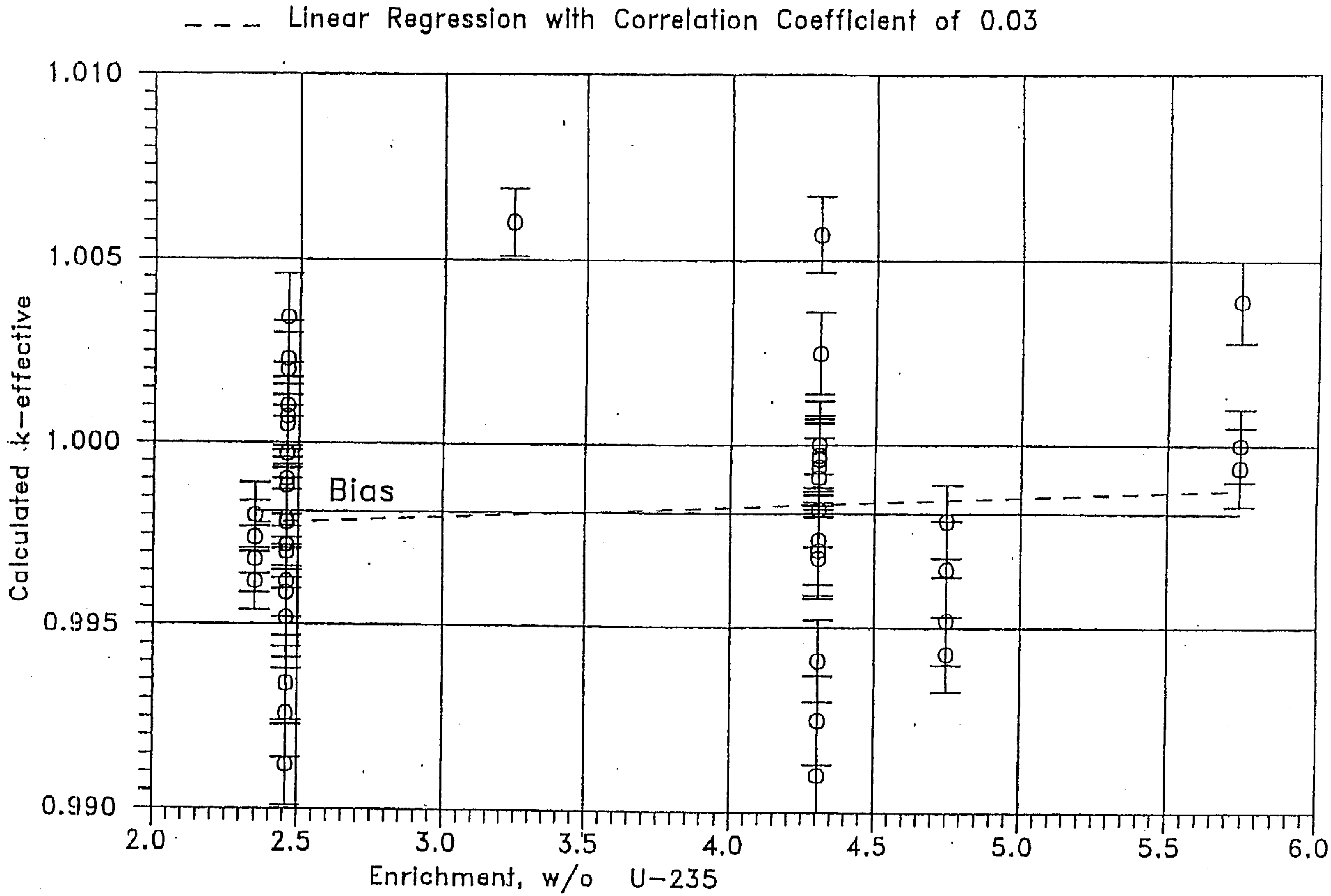

FIGURE 4A.3 MCNP CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

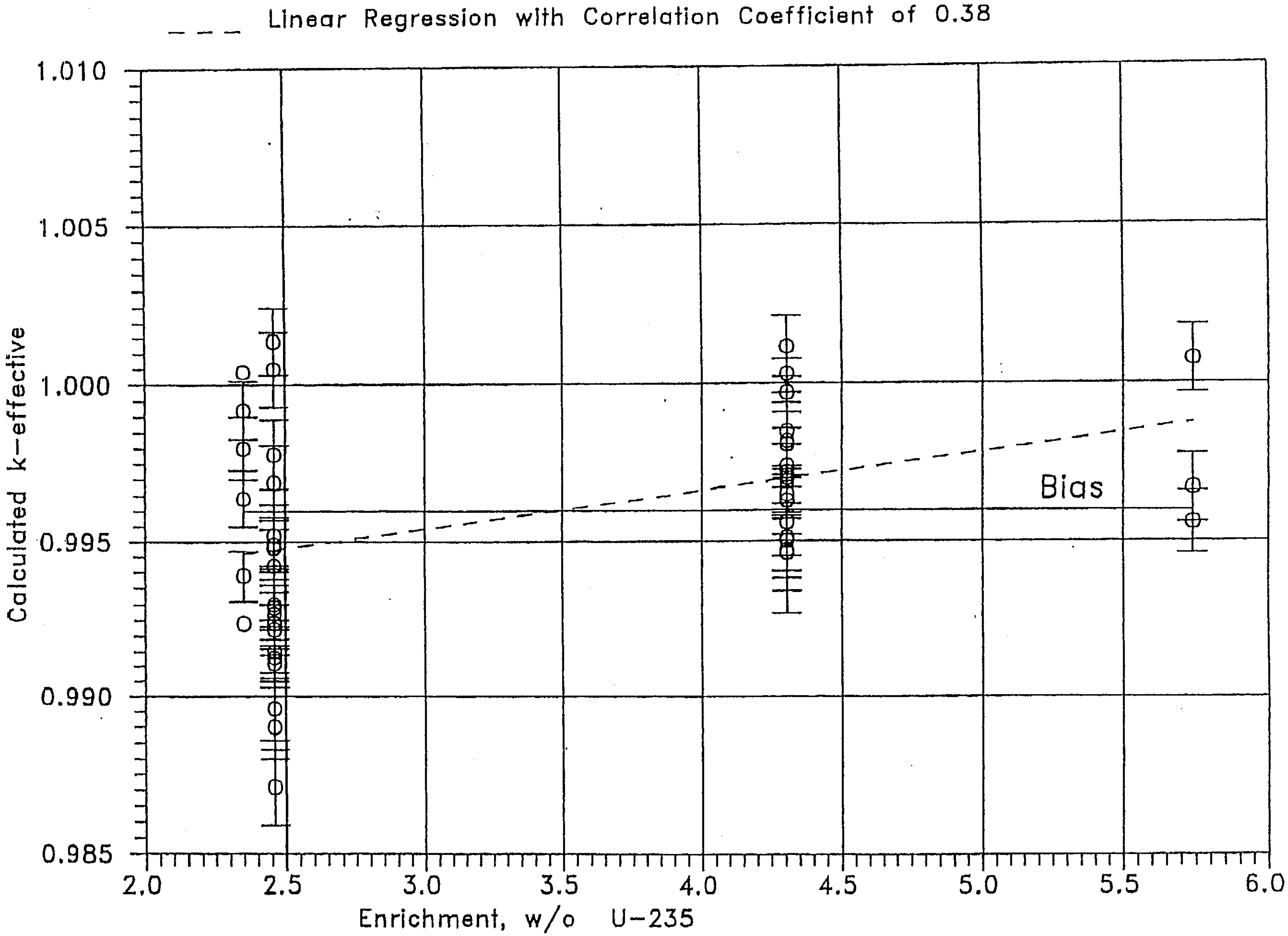

FIGURE 4A.4. KENO CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

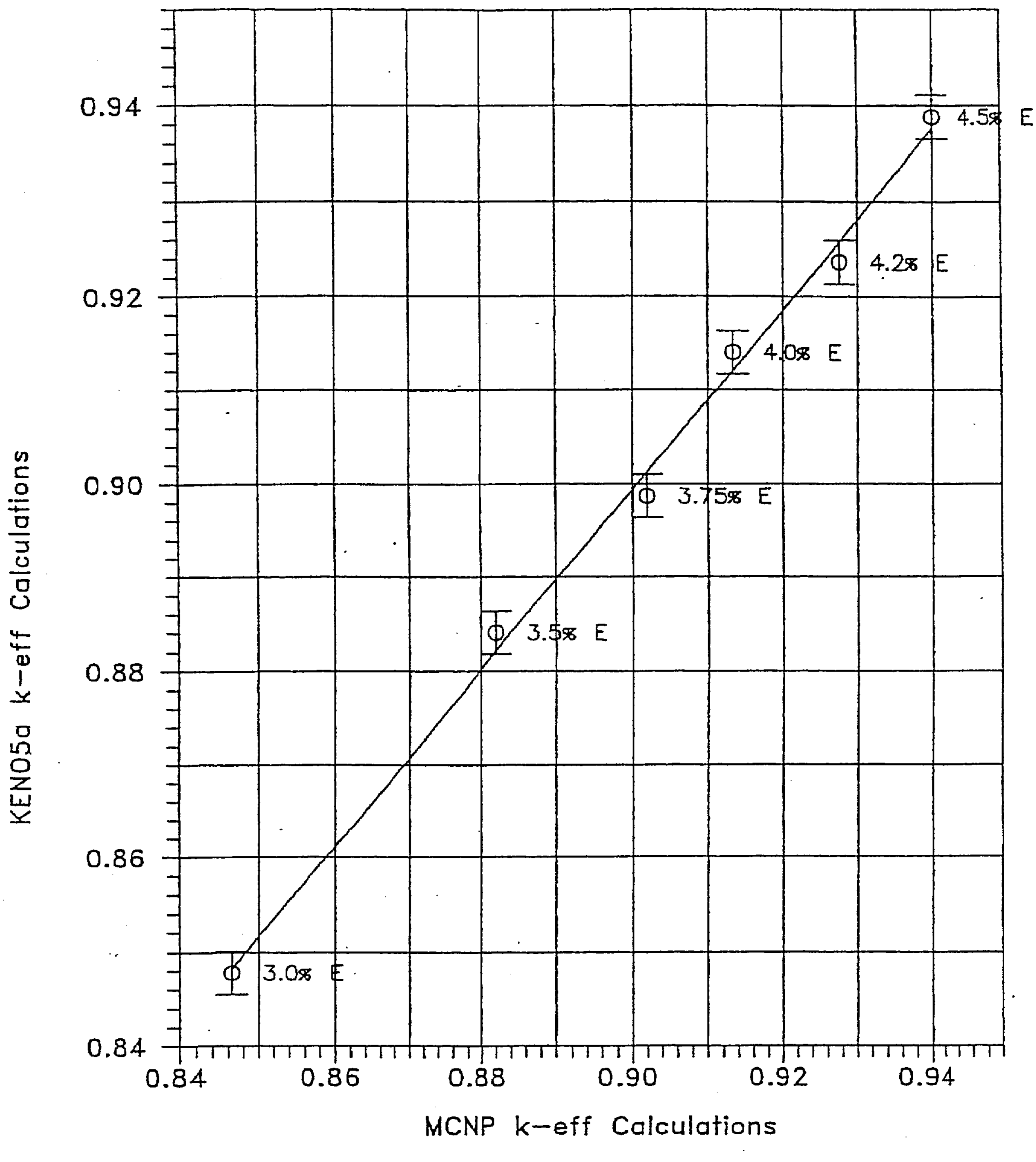

FIGURE 4A.5 COMPARISON OF MCNP AND KENO5A CALCULATIONS FOR VARIOUS FUEL ENRICHMENTS

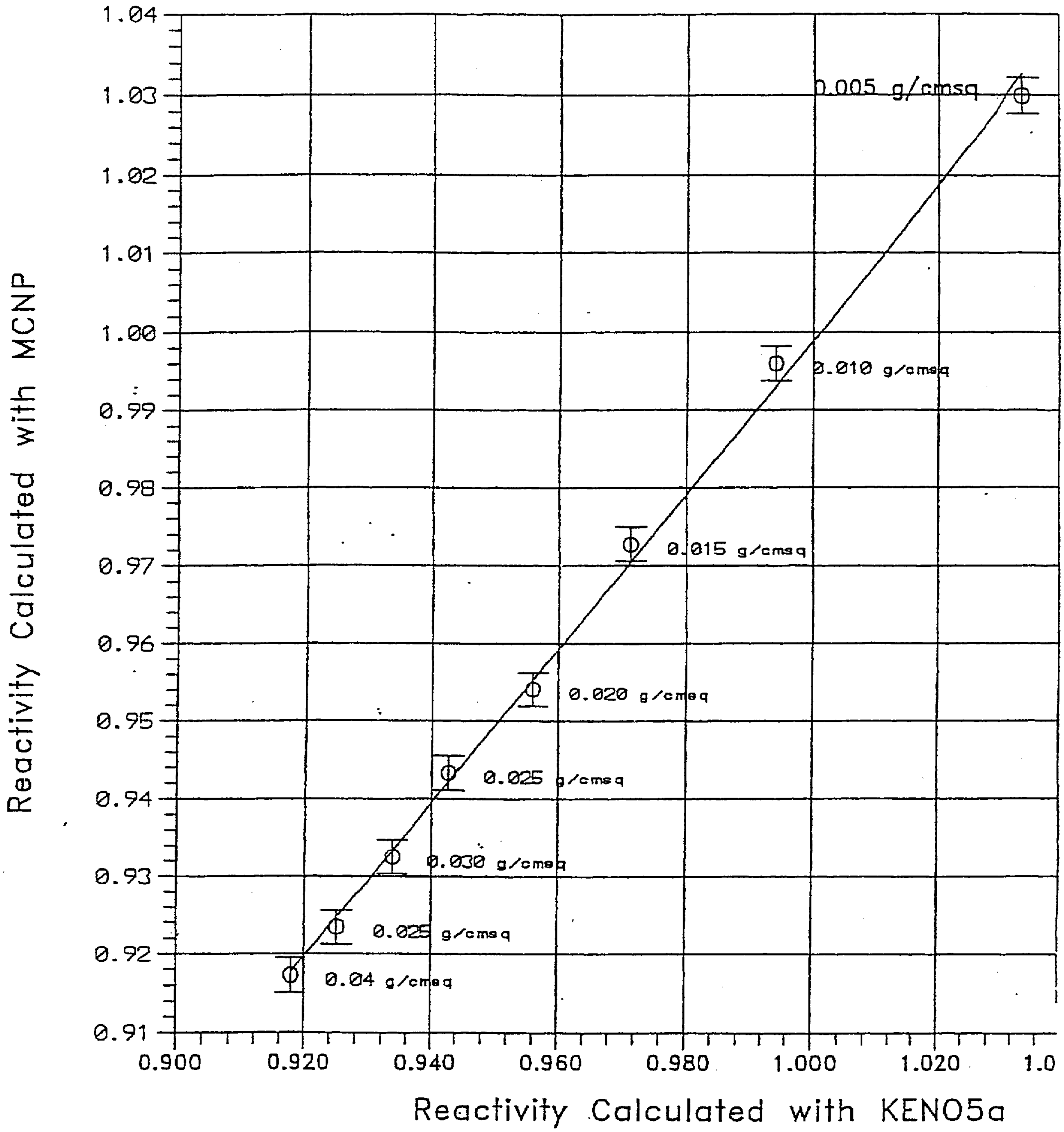

FIGURE 4A.6 COMPARISON OF MCNP AND KENO5a CALCULATIONS FOR VARIOUS BORON-10 AREAL DENSITIES

APPENDIX B: List of Input Files

The list of computer files consists of those computer code input files that were used in the analysis and a brief description of each of the input files. This information provides details on the method of analysis and if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, analysis and licensing of a similar product. This list is, therefore, deemed proprietary and is not presented in this in this non-proprietary version of HI-2012629.

APPENDIX C: Relationships Between Limiting Burnup and Cooling Time

Limiting Burnup For Checkerboard of Fresh and Spent Fuel (Region 1A: 1 Fresh Assembly and 3 Spent Fuel Assemblies in a 2x2 arrangement)

$$Bu\ (limit) = 57.118 - 2.13277 * CT + 0.0772537 * CT^2 + 0.00127446 * CT^3 - 0.0000915855 * CT^4$$

Gadolinia Credit: Limiting Burnup for Checkerboard Storage of Fresh and Spent Fuel (Region 1B: 1 Fresh Assembly and 3 Spent Fuel Assemblies in a 2x2 arrangement)

4 gadolinia rods

$$Bu\ (limit) = 53.73 - 2.5265 * CT + 0.172283 * CT^2 - 0.00585995 * CT^3 + 0.0000766655 * CT^4$$

8 gadolinia rods

$$Bu\ (limit) = 50.00 - 3.26817 * CT + 0.276117 * CT^2 - 0.0117934 * CT^3 + 0.000195334 * CT^4$$

Face Adjacent Storage of Spent Fuel (Region 2)

$$Bu\ (limit) = 33.1095 - 0.845146 * CT + 0.0399888 * CT^2 - 0.000762846 * CT^3$$

Note:
1. If more than 8 Gadolinia rods per assembly use the 8 rod correlation.
2. BU = Fuel Burnup, MWD/Kg-U ; CT = Cooling Time of Spent Fuel Assemblies, Years
3. These empirical fits give a very close approximations, within acceptable bounds, to the data presented in Tables B-2 to B-4, which present the calculated values.

Table C-1.
k-infinite values for 4.95% Enriched Fuel

BURNUP, MWD/KG-U	0 YEAR COOL	1 YEAR COOL	2 YEARS COOL	3 YEARS COOL	4 YEARS COOL	5 YEAR SCOOL	10 YEARS COOL	15 YEARS COOL	20 YEARS COOL
0	1.1879	1.1879	1.1879	1.1879	1.1879	1.1879	1.1879	1.1879	1.1879
10	1.1083	1.1079	1.1075	1.1071	1.1067	1.1063	1.1047	1.1035	1.1027
20	1.0470	1.0459	1.0440	1.0423	1.0407	1.0391	1.0327	1.0281	1.0248
30	0.9938	0.9909	0.9871	0.9836	0.9803	0.9773	0.9649	0.9561	0.9498
40	0.9452	0.9402	0.9342	0.9287	0.9236	0.9190	0.9004	0.8875	0.8783
50	0.9008	0.8935	0.8854	0.8780	0.8712	0.8650	0.8408	0.8242	0.8124
60	0.8611	0.8517	0.8417	0.8326	0.8244	0.8169	0.7879	0.7683	0.7544

Table C-2 Limiting Burnup Required for the Storage of Spent Fuel in the Region 2 Pattern

Cooling Time (years)	Burnup, MWD/KgU
0	33.062
1	32.389
2	31.582
3	30.890
4	30.289
5	29.771
10	27.938
15	26.830
20	26.105

Table C-3 Limiting Burnup Required for the Storage of Spent Fuel in the Region 1A Pattern

Cooling Time (years)	Burnup, MWD/KgU
0	56.91
1	55.00
2	53.29
3	51.20
4	50.00
5	48.03
10	43.91
15	42.01
20	40.81

Table C-4 Limiting Burnup Required for the Storage of Spent Fuel in the Region 1B Pattern

Cooling Time (years)	Burnup, MWD/KgU	
	4 Gadolinia Rods	8 Gadolinia Rods
0	53.73	50.00
5	44.72	39.21
10	40.60	35.09
15	38.7	33.19
20	37.5	31.99

APPENDIX D: LIST OF HOLTEC'S QA APPROVED COMPUTER CODES LIST

The list of Holtec's QA approved computer codes consists of all the codes that have been developed or verified by Holtec International for its use in nuclear safety-related applications. This information, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, analysis and licensing of a similar product. This list is, therefore, deemed proprietary and is not presented in this non-proprietary version of HI-2012629.

ENCLOSURE 2

TENNESSEE VALLEY AUTHORITY
SEQUOYAH NUCLEAR PLANT (SQN)
UNITS 1 AND 2
DOCKET NOS. 327 AND 328

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION (RAI)
TECHNICAL SPECIFICATION (TS) CHANGE 00-06

WESTINGHOUSE ELECTRIC CORPORATION AFFIDAVIT AND
APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Mr. Samuel J. Collins

Direct tel: (412) 374-5282
Direct fax: (412) 374-4011
e-mail: Sepp1ha@westinghouse.com

Our ref: CAW-02-1537

July 12, 2002

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: "Response to NRC letter dated June 6, 2002, 'Sequoyah Nuclear Plant Units 1 and 2 – Request for Additional Information on Technical Specification Change No. 00-06, Tritium Production Cores" (Proprietary)

Dear Mr. Collins:

The proprietary information for which withholding is being requested in the above-referenced report is further identified in Affidavit CAW-02-1537 signed by the owner of the proprietary information, Westinghouse Electric Company LLC. The affidavit, which accompanies this letter, sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR Section 2.790 of the Commission's regulations.

Accordingly, this letter authorizes the utilization of the accompanying Affidavit by the Tennessee Valley Authority.

Correspondence with respect to the proprietary aspects of the application for withholding or the Westinghouse affidavit should reference this letter, CAW-02-1537 and should be addressed to the undersigned.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

Enclosures

Cc: G. Shukla/NRR

CAW-02-1537

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared H. A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC ("Westinghouse"), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

H. A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 15th day
of July, 2002

Notary Public

Notarial Seal
Kay E. Gongaware, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Feb. 7, 2005
Member, Pennsylvania Association of Notaries

KAY E. GONGAWARE COMMONWEALTH OF PENNSYLVANIA NOTARY PUBLIC

(1) I am Manager, Regulatory and Licensing Engineering, in Nuclear Services, Westinghouse Electric Company LLC ("Westinghouse"), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Electric Company LLC.

(2) I am making this Affidavit in conformance with the provisions of 10CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Electric Company LLC in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in the Response to NRC letter dated June 6, 2002, "Sequoyah Nuclear Plant Units 1 and 2 - Request for Additional Information on Technical Specification Change No. 00-06, Tritium Production Cores", being transmitted by the Tennessee Valley Authority letter and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk, Attention Mr. Samuel J. Collins. The proprietary information as submitted for use by Westinghouse Electric Company LLC for Sequoyah Units 1 and 2 is expected to be applicable for other licensees in confirming post-LOCA long term core cooling capabilities.

This information is part of that which will enable Westinghouse to:

(a) Provide responses to NRC questions on post-LOCA Hot Leg Switchover time for Sequoyah Units 1 and 2.

(b) Provide a quantitative technical justification for the adequacy of the post-LOCA Hot Leg Switchover time.

(c) Assist the Tennessee Valley Authority in obtaining a license amendment for the Tritium Production Core.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of establishing post-LOCA Hot Leg Switchover times.

(b) Westinghouse can sell support and defense of the methodology for establishing post-LOCA Hot Leg Switchover times.

(c) The information requested to be withheld reveals the distinguishing aspects of a methodology which was developed by Westinghouse.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar calculations and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

PROPRIETARY INFORMATION NOTICE

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) contained within parentheses located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

COPYRIGHT NOTICE

ENCLOSURE 3

TENNESSEE VALLEY AUTHORITY
SEQUOYAH NUCLEAR PLANT (SQN)
UNITS 1 AND 2
DOCKET NOS. 327 AND 328

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION (RAI)
TECHNICAL SPECIFICATION (TS) CHANGE 00-06

HOLTEC INTERNATIONAL AFFIDAVIT AND
APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION

AFFIDAVIT PURSUANT TO 10CFR2.790

I, Kalyan K. Niyogi, being duly sworn, depose and state as follows:

(1) I am Director of Consulting Division of Holtec International and have reviewed the information described in paragraph (2) which is sought to be withheld, and am authorized to apply for its withholding.

(2) The information sought to be withheld is included in the following Holtec International Calculation Report:

- Holtec Report No. HI-2012629, "Evaluation Of The Effect Of The Use Of TPBARS On Fuel Storage Requirements", Revision 2.

This information is considered proprietary to Holtec International.

(3) In making this application for withholding of proprietary information of which it is the owner, Holtec International relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4) and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10CFR Part 9.17(a)(4), 2.790(a)(4), and 2.790(b)(1) for "trade secrets and commercial or financial information obtained from a person and privileged or confidential" (Exemption 4). The material for which exemption from disclosure is here sought is all "confidential commercial information", and some portions also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

(4) Some examples of categories of information which fit into the definition of proprietary information are:

a. Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by Holtec's competitors without license from Holtec International constitutes a competitive economic advantage over other companies;

b. Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.

c. Information which reveals cost or price information, production, capacities, budget levels, or commercial strategies of Holtec International, its customers, or its suppliers;

d. Information which reveals aspects of past, present, or future Holtec International customer-funded development plans and programs of potential commercial value to Holtec International;

e. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs 4.a, 4.b, 4.d, and 4.e, above.

(5) The information sought to be withheld is being submitted to the NRC in confidence. The information (including that compiled from many sources) is of a sort customarily held in confidence by Holtec International, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by Holtec International. No public disclosure has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to the NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the

value and sensitivity of the information in relation to industry knowledge. Access to such documents within Holtec International is limited on a "need to know" basis.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist or other equivalent authority, by the manager of the cognizant marketing function (or his designee), and by the Legal Operation, for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside Holtec International are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information classified as proprietary was developed and compiled by Holtec International at a significant cost to Holtec International. This information is classified as proprietary because it contains detailed descriptions of analytical approaches and methodologies not available elsewhere. This information would provide other parties, including competitors, with information from Holtec International's technical database and the results of evaluations performed by Holtec International. Release of this information would improve a competitor's position without the competitor having to expend similar resources for the

development of the database. A substantial effort has been expended by Holtec International to develop this information.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to Holtec International's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of Holtec International's comprehensive spent fuel storage technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology, and includes development of the expertise to determine and apply the appropriate evaluation process.

The research, development, engineering, and analytical costs comprise a substantial investment of time and money by Holtec International.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology is difficult to quantify, but it clearly is substantial.

Holtec International's competitive advantage will be lost if its competitors are able to use the results of the Holtec International experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to Holtec International would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive Holtec International of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing these very valuable analytical tools.

AFFIDAVIT PURSUANT TO 10CFR2.790

STATE OF NEW JERSEY)
) ss:
COUNTY OF BURLINGTON)

Dr. K. K. Niyogi, being duly sworn, deposes and says:

That he has read the foregoing affidavit and the matters stated therein are true and correct to the best of his knowledge, information, and belief.

Executed at Marlton, New Jersey, this 7th day of December, 2001.

K. K. Niyogi
Holtec International

Subscribed and sworn before me this 7th day of December, 2001.

MARIA C. PEPE
NOTARY PUBLIC OF NEW JERSEY
My Commission Expires April 25, 2005