Attachment 2

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Part 50 Criticality Analysis of the MPC-32 for ANO Unit 2 – Non- Proprietary

HOLTEC
INTERNATIONAL

Holtec Center, 555 Lincoln Drive West, Marlton, NJ 08053
Telephone (856) 797- 0900
Fax (856) 797 - 0909

Part 50 Criticality Analysis of The MPC-32 for ANO Unit 2

FOR

ANO

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Table of Contents

1. Introduction

1.1 Statement of Purpose

This report documents the criticality safety evaluation for the storage of CE 16 x 16 spent nuclear fuel assemblies in a Holtec MPC-32 basket in the ANO spent fuel pool without taking credit for soluble boron under normal operating conditions. The scope of the analysis is limited to fuel assemblies with an initial nominal enrichment of no more than 4.95 wt% ^{235}U.

The objective of this analysis is to determine the minimum burnup requirements for initial fuel enrichments necessary to meet the requirements of 10CFR50.68. Since the analysis will not take any credit for soluble boron under normal conditions, it is necessary to demonstrate that k_{eff} is less than 0.95 with the MPC flooded with fresh water. The maximum calculated reactivities include a margin for uncertainty in reactivity calculations, including manufacturing tolerances, and are calculated with a 95% probability at a 95% confidence level [1].

Reactivity effects of accident conditions have also been evaluated to assure that under all credible conditions, the reactivity will not exceed the regulatory limit of 0.95, considering the presence of an acceptable soluble boron level.

1.2 About This Document

This work product has been labeled a safety-significant document in Holtec's QA System. In order to gain acceptance as a safety-significant document in the company's quality assurance system, this document is required to undergo a prescribed review and concurrence process that requires the preparer and reviewer(s) of the document to answer a long list of questions crafted to ensure that the document has been purged of all errors of any material significance. A record of the review and verification activities is maintained in electronic form within the company's network to enable future retrieval and recapitulation of the programmatic acceptance process leading to the acceptance and release of this document under the company's QA system. Among the numerous requirements that a document of this genre must fulfill to muster approval within the company's QA program are:

- The preparer(s) and reviewer(s) are technically qualified to perform their activities per the applicable Holtec Quality Procedure (HQP).
- The input information utilized in the work effort must be drawn from referencable sources. Any assumed input data is so identified.
- All significant assumptions, as applicable, are stated.

- The analysis methodology is consistent with the physics of the problem.
- Any computer code and its specific versions that may be used in this work have been formally admitted for use within the company's QA system.
- The format and content of the document is in accordance with the applicable Holtec quality procedure.
- The material content of this document is understandable to a reader with the requisite academic training and experience in the underlying technical disciplines.

Once a safety significant document produced under the company's QA System completes its review and certification cycle, it should be free of any materially significant error and should not require a revision unless its scope of treatment needs to be altered. Except for regulatory interface documents (i.e., those that are submitted to the NRC in support of a license amendment and request), revisions to Holtec safety-significant documents to amend grammar, to improve diction, or to add trivial calculations are made only if such editorial changes are warranted to prevent erroneous conclusions from being inferred by the reader. In other words, the focus in the preparation of this document is to ensure accuracy of the technical content rather than the cosmetics of presentation.

In accordance with the foregoing, this Calculation Package has been prepared pursuant to the provisions of Holtec Quality Procedures HQP 3.0 and 3.2, which require that all analyses utilized in support of the design of a safety-related or important-to-safety structure, component, or system be fully documented such that the analyses can be reproduced at any time in the future by a specialist trained in the discipline(s) involved. HQP 3.2 sets down a rigid format structure for the content and organization of Calculation Packages that are intended to create a document which is complete in terms of the exhaustiveness of content. Calculation Packages, however, may lack the narrational smoothness of a Technical Report, and are not intended to serve as a Technical Report.

Because of its function as a repository of all analyses performed on the subject of its scope, this document is typically revised only if an error is discovered in the computations or the equipment design is modified. Additional analyses in the future may be added as numbered supplements to this Package. Each time a supplement is added or the existing material is revised, the revision status of this Package is advanced to the next number and the Table of Contents is amended. They are shared with a client only under strict controls on their use and dissemination.

This Calculation Package will be saved as a Permanent Record under the company's QA System.

2. Methodology

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3. Acceptance Criteria

The objective of this analysis is to ensure that the effective neutron multiplication factor (k_{eff}) is less than or equal to 0.95 with the MPC-32 basket fully loaded with fuel of the highest permissible reactivity. For normal conditions, the MPC-32 basket is analyzed as flooded with fresh water, and for accident conditions, credit for soluble boron is

permitted. The maximum calculated reactivities include a margin for uncertainty in reactivity calculations, manufacturing tolerances, and temperature effects, and are calculated with a 95% probability at a 95% confidence level [1].

Applicable codes, standards, and regulations or pertinent sections thereof, include the following:

- *Code of Federal Regulations*, Title 10, Part 50, Appendix A, General Design Criterion 62, "Prevention of Criticality in Fuel Storage and Handling."
- USNRC Standard Review Plan, NUREG-0800, Section 9.1.2, Spent Fuel Storage, Rev. 3 - July 1981.
- 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.
- L. Kopp, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," NRC Memorandum from L. Kopp to T. Collins, August 19, 1998.
- USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2 (proposed), December 1981.
- ANSI ANS-8.17-1984, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors.
- Code of Federal Regulation 10CFR50.68, Criticality Accident Requirements (for soluble boron)

4. Assumptions

The following assumptions were employed in the analysis:

1) All depletion calculations are performed with 3 years of cooling time credited, which bounds the minimum cooling time allowable for spent fuel storage in the MPC-32.

2) Neutron absorption in minor structural members is neglected, i.e., spacer grids are replaced by water.

3) {

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4) {

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5) { }

6) The MPC-32 and HI-STAR or HI-TRAC is located in the cask pit area, which is assumed to be neutronically isolated from the rest of the spent fuel pool because the loaded fuel will be at least 12 inches from fuel stored in the adjacent racks. Therefore interfaces need not be considered.

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10) {

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Additional assumptions regarding the computer models are provided in Section 5.4 of this report.

5. Input Data

5.1 Fuel Assembly and Operational Data

The core operating temperatures (fuel and moderator), average soluble boron level, and power density in the depletion calculations use the same values as the depletion calculation (CASMO) inputs used in [10].

The fuel assembly dimensions and axial burnup profile are taken from [9] with the appropriate assumptions in Section 4 applied.

5.2 MPC-32 Basket Data

The MPC-32 basket geometry model is based on [11] with the appropriate assumptions from Section 4 applied and the geometric modeling approach described in Section 5.3 below. Material composition of the stainless steel material is taken from [8]. The modeled composition of the MPC-32 basket poison material is described in assumption 7 in Section 4 of this report.

5.3 Geometric Description of the 3-D MCNP Model

The criticality calculation adequately represents an MPC-32 loaded into either a HI-TRAC or HI-STAR overpack, however, the system is not modeled exactly. {

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1) { }

2) {

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3) { }

4) {

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5) { }

6) { }

7) {
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6. Computer Codes

The following computer codes were used during this analysis.

- MCNP4a [2] is a three-dimensional continuous energy Monte Carlo code developed at Los Alamos National Laboratory. This code offers the capability of performing full three-dimensional calculations for the loaded MPC. MCNP4a was run on the PCs at Holtec.

- CASMO-4, Version 2.05.03 [3-5] is a two-dimensional multigroup transport theory code developed by Studsvik of Sweden. CASMO-4 performs cell criticality calculations and burnup. CASMO-4 has the capability of analytically restarting burned fuel assemblies in an infinite representation of the MPC-32 configuration. This code was used to determine the isotopic composition of the fuel, the reactivity effects of tolerances and fuel depletion, and was used in various studies. The CASMO-4 code was run on a PC at Holtec.

7. Analysis

This section describes the calculations that were used to determine the acceptable storage criteria for the MPC-32. In addition, this section discusses the possible abnormal and accident conditions.

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

Generic analytic results of the axial burnup effect for assemblies without axial blankets have been provided by Turner [7] based upon calculated and measured axial burnup distributions. These analyses confirm the minor and generally negative reactivity effect of the axially distributed burnup, becoming positive at burnups greater than about 30 GWD/MTU. The trends observed in [7] suggest the possibility of a small positive reactivity effect above 30 GWD/MTU increasing to slightly over 1% Δk at 40 GWD/MTU. {

}

Pool water temperature effects on reactivity have been calculated with CASMO-4 and the results are presented in Table 1. The results show that the spent fuel pool temperature coefficient of reactivity is negative, i.e. a lower temperature results in a higher reactivity. {

}

The MCNP code bias effect determined in Appendix A is also applied directly in each of the final k_{eff} calculations as a bias.

The maximum allowable value for the calculated k_{eff} at each enrichment/burnup combination is summarized in Table 7 and is determined by the following:

Max k_{eff} = Regulatory Limit – biases – statistically combined uncertainties

Where the regulatory limit = 0.95 for all cases.

7.1 Uncertainties

The uncertainties described in the subsections below are statistically combined via square root of the sum of the squares. The statistical combination of uncertainties plus the temperature and code biases are added to the MCNP calculated k_{eff} at each burnup/enrichment combination to determine the maximum k_{eff}. The minimum required burnup at each enrichment interval that meets the acceptance criteria is then used to generate the burnup vs enrichment relationship.

7.11 Fuel Assembly

ANO Unit 2 only uses a CE 16 x 16 assembly, which is explicitly modeled in this analysis. {

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7.12 MPC Manufacturing Tolerances

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7.13 Fuel Enrichment Tolerance

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7.14 Uncertainty in Depletion Calculations

Since critical experiment data with spent fuel is not available for determining the uncertainty in burnup-dependent reactivity calculations, an allowance for uncertainty in reactivity was assigned based upon other considerations. Assuming the uncertainty in depletion calculations is less than 5% of the total reactivity decrement, a burnup dependent uncertainty in reactivity for burnup calculations may be assigned. {

}

7.15 Eccentric Fuel Assembly Positioning

The base criticality calculations assume that the fuel assemblies are centered within their respective basket cells. To account for shifting of assemblies within the cell that results in a more reactive configuration, two additional MCNP calculations are performed to obtain an eccentric positioning uncertainty. {

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7.16 MCNP Statistical Uncertainties

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7.2 Off-Normal and Accident Conditions

The effects on reactivity of credible abnormal and accident conditions are examined in this section. None of the abnormal or accident conditions that have been identified as credible cause the reactivity of the storage racks to exceed the limiting reactivity value of $k_{eff} = 0.95$, considering the presence of soluble boron. The double contingency principle of ANSI N16.1-1975 (and the USNRC letter of April 1978) specifies that it shall require at least two unlikely independent and concurrent events to produce a criticality accident. This principle precludes the necessity of considering the simultaneous occurrence of multiple accident conditions.

7.21 Temperature and Density Effects

Water density and temperature effects on reactivity have been calculated {
}. The results show that the spent fuel pool temperature coefficient of reactivity is negative, and that introducing voids in the water internal to the storage cell (to simulate boiling) further decreases reactivity. Therefore the maximum density of water (1.0 g/cc) is used in this analysis.

7.22 Dropped Assembly – Horizontal

For the case in which a fuel assembly is assumed to be dropped on top of an MPC-32, {

}

7.23 Dropped Assembly – Vertical

An event of a vertical drop accident resulting in an assembly leaning immediately adjacent to the HI-TRAC or HI-STAR would have an insignificant effect on reactivity {

}

7.24 Accident Resulting in Misalignment of Active Fuel With Poison Material

Any event resulting in misalignment of the active fuel region with the basket poison material is bound by an extremely conservative accident analysis {

}

7.25 Accident of a Missloaded Fresh Fuel Assembly

The misplacement of a fresh unburned fuel assembly could, in the absence of soluble poison, result in exceeding the regulatory limit (k_{eff} of 0.95). This could possibly occur if a fresh fuel assembly of the highest permissible enrichment (4.95 wt%) were to be inadvertently misloaded into a storage cell intended for spent fuel in the center of the basket. {

}

7.3 Burnup vs Enrichment Requirements

Calculations were performed to determine acceptable minimum burnups for selected initial ^{235}U enrichments from 2.5wt% to 4.95wt%. The burnup vs enrichment values are tabulated in Table 8, and are ploted in Figure 1. Each result is acceptable per the limit in Table 7. A bounding linear equation was established based on this data yielding the following:

$$BU = 9E - 16$$

Where BU = The minimum required burnup in GWd/MTU
And E = Initial assembly enrichment in wt% ^{235}U

8. Computer Files

All input files for the calculations are stored in the directory { } and its subdirectories on the Holtec server. The input file names and descriptions of the { } calculations are listed in the table below.

File name	Code	Description
{ }	{ }	2.2% enriched fresh fuel
{ }	{ }	4.95% enriched fresh fuel, used for depletion uncertainty
{ }	{ }	Accident – { } case with all poison replaced with 950 ppm sb water
{ }	{ }	Accident – { } case with missload of fresh assembly 400 ppm sb
{ }	{ }	Eccentric positioning – { } case with assemblies shifted towards center of basket
{ }	{ }	Eccentric positioning – { } case with assemblies shifted towards periphery of basket.
{ }	{ }	These files all use the convention { } Where { }=enrichment (x 0.1%)* { }=bunup (in GWd/MTU) { }=cooling time (in years) { } { }
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	
{ }	{ }	Tolerance and temperature reactivity effects
{ }	{ }	Depletion 2.5% enriched fuel
{ }	{ }	Depletion 3.0% enriched fuel
{ }	{ }	Depletion 3.5% enriched fuel
{ }	{ }	Depletion 4.0% enriched fuel
{ }	{ }	Depletion 4.5% enriched fuel
{ }	{ }	Depletion 4.95% enriched fuel

9. Conclusion

This report documents the criticality analysis for the storage of CE 16x16 PWR spent nuclear fuel in the Holtec MPC-32 in the ANO Unit 2 spent fuel pool with initial enrichments up to 4.95 wt% ^{235}U. The calculation that determines the maximum permissible k_{eff} from MCNP is provided in Table 7. MCNP results and corresponding minimum burnup requirements were determined at incremental enrichments and are provided in Table 8. Each enrichment case meets the defined acceptance criteria, as summarized in Table 7. A plot and corresponding bounding linear equation was established based on the results in Table 8 and is shown in Figure 1.

The following burnup vs enrichment relationship may be used:

$$BU = 9E - 16$$

Where BU = The minimum required burnup in GWd/MTU
And E = Initial assembly enrichment in wt% ^{235}U

The effects of postulated accident scenarios were also evaluated, where the most limiting case of all poison plates being replaced with water yielded a required a soluble boron concentration of 950 ppm. This is acceptable since it is well below the normal operating level in the ANO Unit 2 spent fuel pool. Results for this accident case and a less limiting case of a missloaded fresh assembly are summarized in Tables 9 and 10 respectively.

10. References[1]

1. M.G. Natrella, Experimental Statistics, National Bureau of Standards, Handbook 91, August 1963.

2. J.F. Briesmeister, Editor, "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4A," LA-12625, Los Alamos National Laboratory (1993).

[1] Note: The revision status of Holtec documents cited above is subject to updates as the project progresses. This document will be revised if a revision to any of the above-referenced Holtec work materially affects the instructions, results, conclusions or analyses contained in this document. Otherwise, a revision to this document will not be made and the latest revision of the referenced Holtec documents shall be assumed to supercede the revision numbers cited above. The Holtec Project Manager bears the undivided responsibility to ensure that there is no intra-document conflict with respect to the information contained in all Holtec generated documents on a safety-significant project. The latest revision number of all documents produced by Holtec International in a safety significant project is readily available from the company's electronic network.

3. M. Edenius, K. Ekberg, B.H. Forssén, and D. Knott, "CASMO-4 A Fuel Assembly Burnup Program User's Manual," Studsvik/SOA-95/1, Studsvik of America, Inc. and Studsvik Core Analysis AB (proprietary).

4. D. Knott, "CASMO-4 Benchmark Against Critical Experiments", SOA-94/13, Studsvik of America, Inc., (proprietary).

5. D. Knott, "CASMO-4 Benchmark Against MCNP," SOA-94/12, Studsvik of America, Inc., (proprietary).

6. Not Used.

7. S.E. Turner, "Uncertainty Analysis - Burnup Distributions", presented at the DOE/SANDIA Technical Meeting on Fuel Burnup Credit, Special Session, ANS/ENS Conference, Washington, D.C., November 2, 1988.

8. HI-2012771 Rev 6, *HI-STAR 100 and HI-STORM 100 Additional Criticality Calculations*, Holtec International.

9. CEO 2001-00284, File No: 104-35, 204-35. Letter from F.H. Smith to J.S. Rowe dated November 9, 2001. (Included as Attachment 1 in this report.)

10. HI-2022864 Rev 5, *Criticality Safety Evaluation of the ANO Unit 2 Spent Fuel Pool Storage Racks,* Holtec International.

11. Holtec Drawing 3752 Rev. 9, *MPC-32 Fuel Basket*, Holtec International.

12. Table A1.18, SA 480, ASME Section II, 1998.

Table 1: Temperature Effects ({ })

Temp (K)	k_{inf}
273	1.15221
277	1.15187
300	1.14917
313	1.14712
343	1.14153
373	1.13470

Table 2: MPC Manufacturing Tolerance Results ({ })

Case	k_{inf}	Δk_{inf}
Reference	1.14917	n/a
min cell ID, red pitch	1.15249	-0.00332
max cell ID, inc pitch	1.14525	0.00392
inc box thick, red cell ID	1.15316	-0.00399
red box thick, inc cell ID	1.14483	0.00434

Note: Negative values indicate an increase in reactivity condition since Δk_{inf} = Ref – Tolerance Case

Table 3: Water Temperature And Density Effects ({ })

Temp (K)	Void Fraction	k_{inf}
300	0.0	1.14917
373	0.1	1.11284

Table 4: Fuel Enrichment Uncertainty ({ })

k_{inf} (5.0 wt% ^{235}U)	k_{inf} (4.95wt% ^{235}U)	Δk_{inf}
1.15118	1.14917	0.00201

Table 5: Depletion Uncertainty ({ })

Maximum Burnup Case	Maximum Burnup k_{eff}	Fresh Fuel Case	Fresh Fuel k_{eff}	Depletion Uncertainty (5% Δk_{eff})
{ }	0.93180	{ }	1.12600	0.00971

Table 6: Eccentric Positioning ({ })

Reference Case	Reference k_{eff}	Eccentric Case	Eccentric k_{eff}	Δk_{eff}
{ }	0.93180	{ }	0.93683	0.00503

Table 7: Maximum Allowable Calculated k_{eff}

Regulaory Limiting k_{eff}	0.95
Uncertainties	
Bias Uncertainty (95%/95%)	0.0011
Calculational Statistics (95%/95%, 2.0×σ)	0.0016
Min Cell ID, Reduced Pitch	0.0033
Increased box thickness, Reduced ID	0.0040
Fuel Enrichment Tolerance	0.0020
Depletion	0.0097
Eccentric Positioning	0.0050
Statistical Combination of Uncertainties	0.0124
Biases	
Calculational Bias (see Appendix A)	0.0009
Temperature Δk (From 300K to 273K)	0.0030
Max Allowable k_{eff} (Regulatory Limiting k_{eff} – biases – combined uncertainties)	**0.9337**

Table 8: { } Burnup vs Enrichment Results

File Name	keff	Initial Enrichment (^{235}U wt%)	Burnup (GWd/MTU)
{ }	0.93299	2.2	0
{ }	0.92027	2.5	5
{ }	0.92200	3.0	10
{ }	0.92485	3.5	15
{ }	0.93106	4.0	19
{ }	0.92891	4.5	24
{ }	0.93180	4.95	28

Table 9: Summary of Poison Replaced With Borated Water Accident

File Name	{ }
Initial Enrichment (wt% ^{235}U)	4.95
Burnup (GWd/MTU)	28
Soluble Boron Level (ppm)	950
Calculated k_{eff} ({ })	0.93234

Table 10: Summary of Missloaded Fresh Assembly Accident

File Name	{ }
Initial Enrichment (wt% ^{235}U)	4.95
Burnup (GWd/MTU)	28
Soluble Boron Level (ppm)	400
Calculated k_{eff} ({ })	0.91704

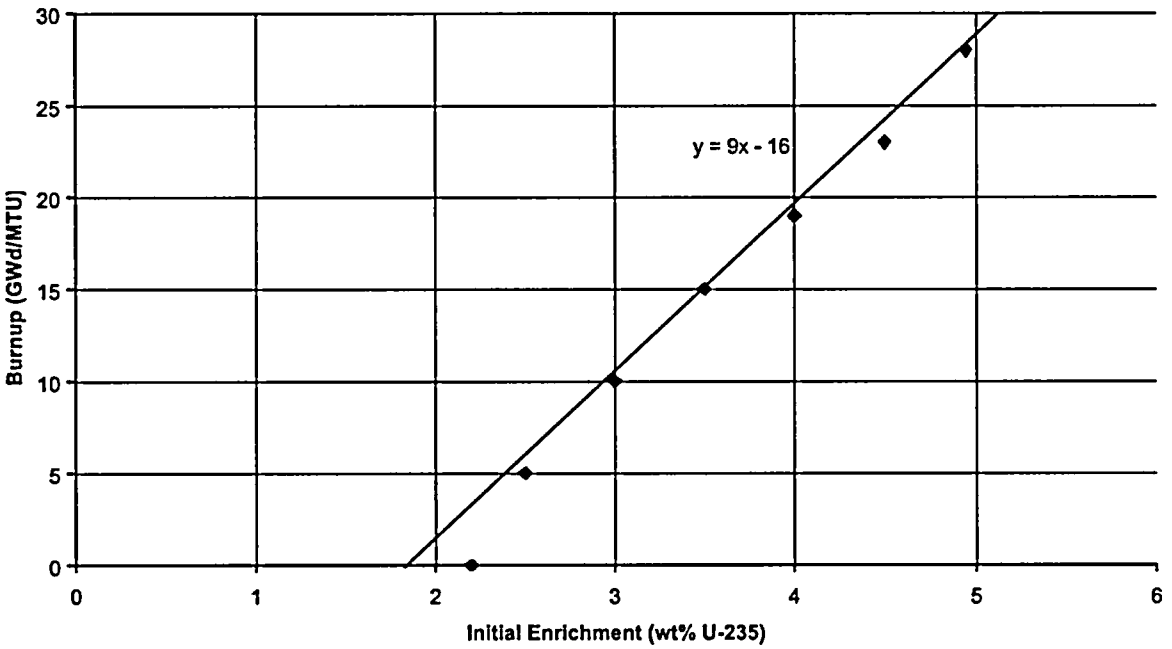

Figure 1: Plot of Burnup vs Enrichment With Bounding Linear Equation

Appendix A

Benchmark Calculations

(total number of pages: 26 including this page)

Note: because this appendix was taken from a different report, 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).

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

† 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.

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

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

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

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Table 4A.1

Summary of Criticality Benchmark Calculations

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

Table 4A.1

Summary of Criticality Benchmark Calculations

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

Table 4A.1

Summary of Criticality Benchmark Calculations

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

Table 4A.1

Summary of Criticality Benchmark Calculations

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

Table 4A.1

Summary of Criticality Benchmark Calculations

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

Notes: NC stands for not calculated.

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

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

Table 4A.2

COMPARISON OF MCNP4a AND KENO5a CALCULATED REACTIVITIES[†] FOR VARIOUS ENRICHMENTS

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

† Based on the GE 8x8R fuel assembly.

Table 4A.3

MCNP4a CALCULATED REACTIVITIES FOR
CRITICAL EXPERIMENTS WITH NEUTRON ABSORBERS

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

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

Table 4A.4

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

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

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

Table 4A.5

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH THICK LEAD AND STEEL REFLECTORS†

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

† Arranged in order of increasing reflector-fuel spacing.

Table 4A.6

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH VARIOUS SOLUBLE BORON CONCENTRATIONS

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

Table 4A.7

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH MOX FUEL

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

Note: NC stands for not calculated

† Arranged in order of increasing lattice spacing.

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

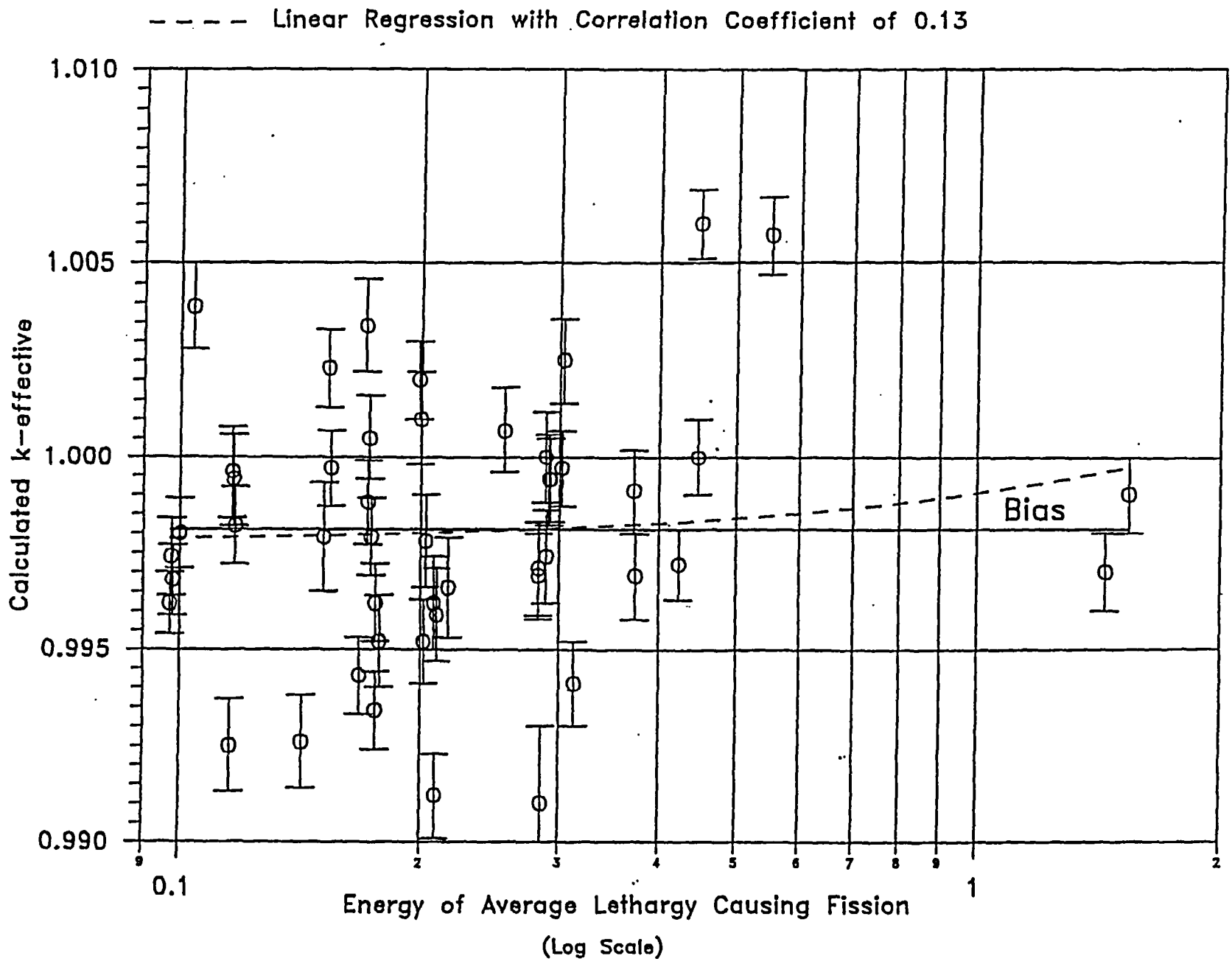


FIGURE 4A.1 MCNP CALCULATED k-eff VALUES for VARIOUS VALUES OF THE SPECTRAL INDEX

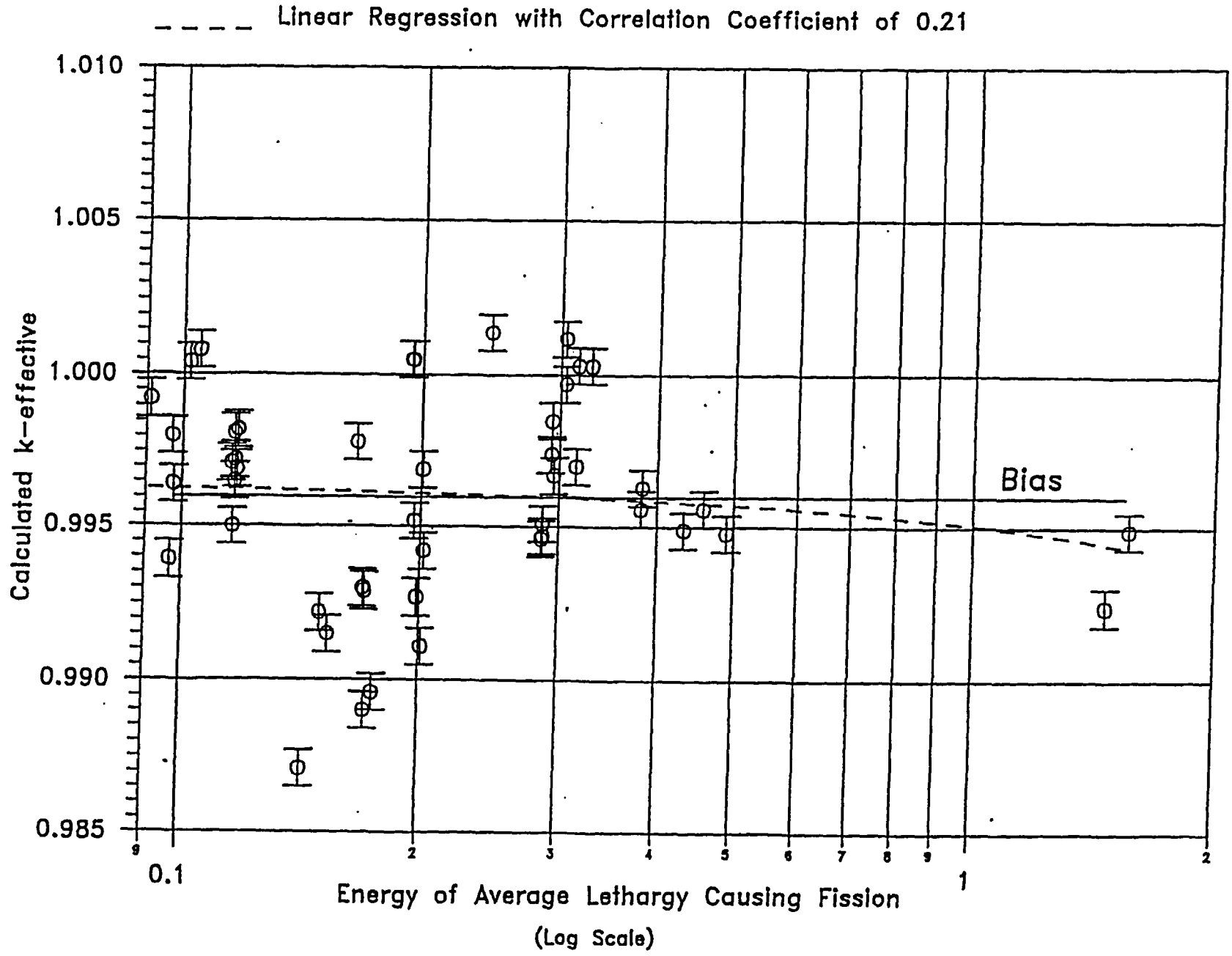


FIGURE 4A.2 KENO5a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

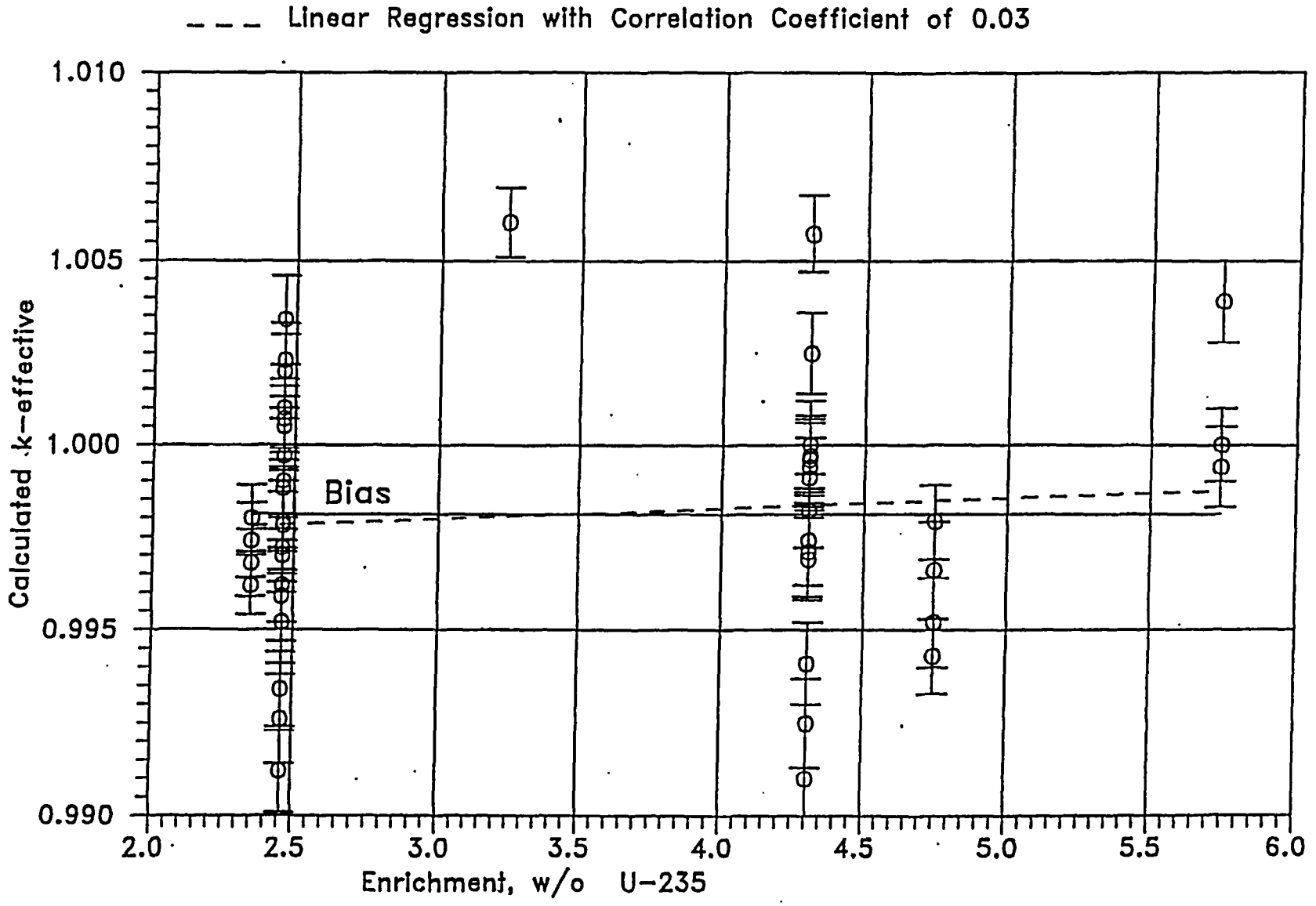


FIGURE 4A.3 MCNP CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

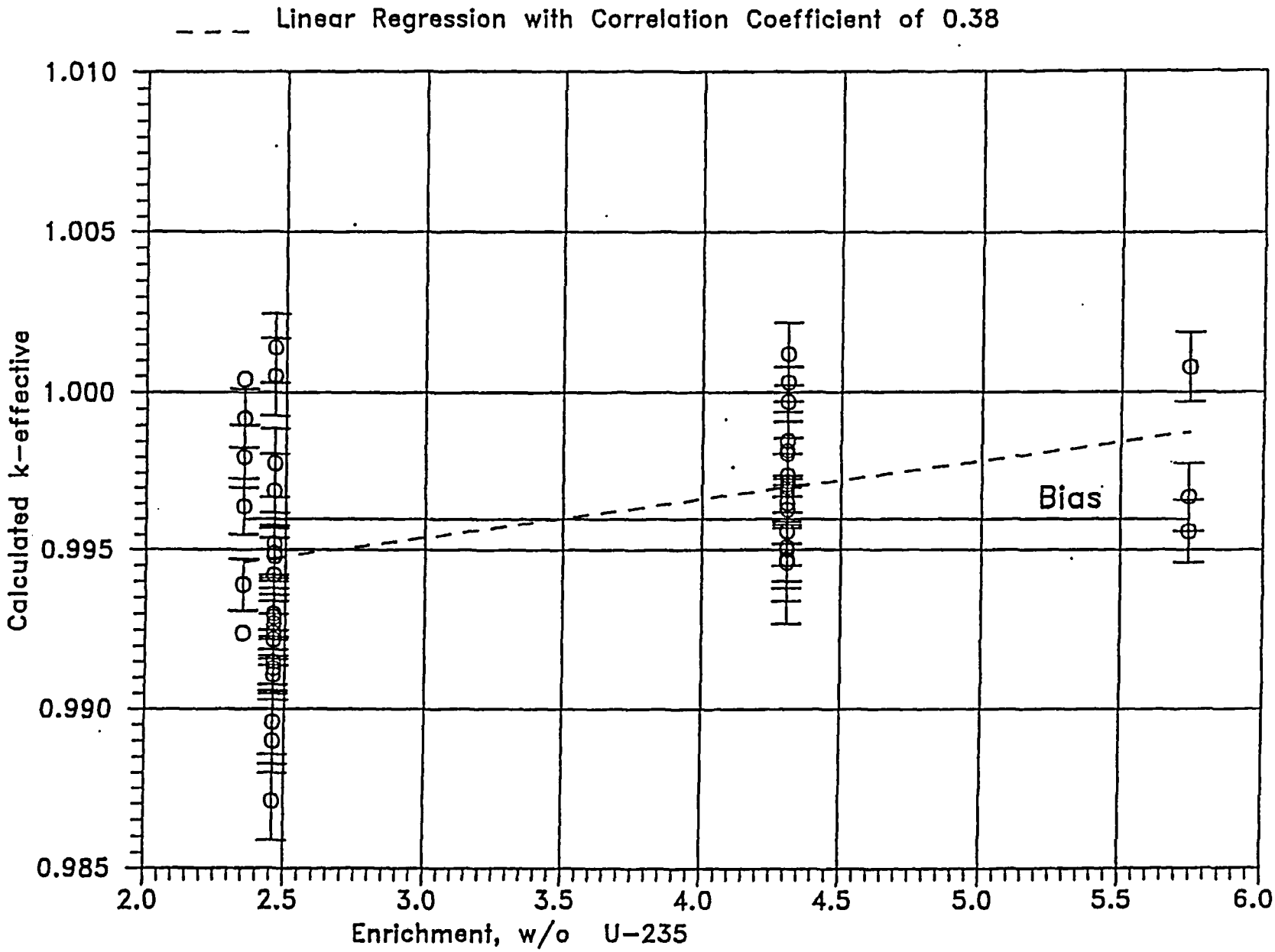


FIGURE 4A.4. KENO CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

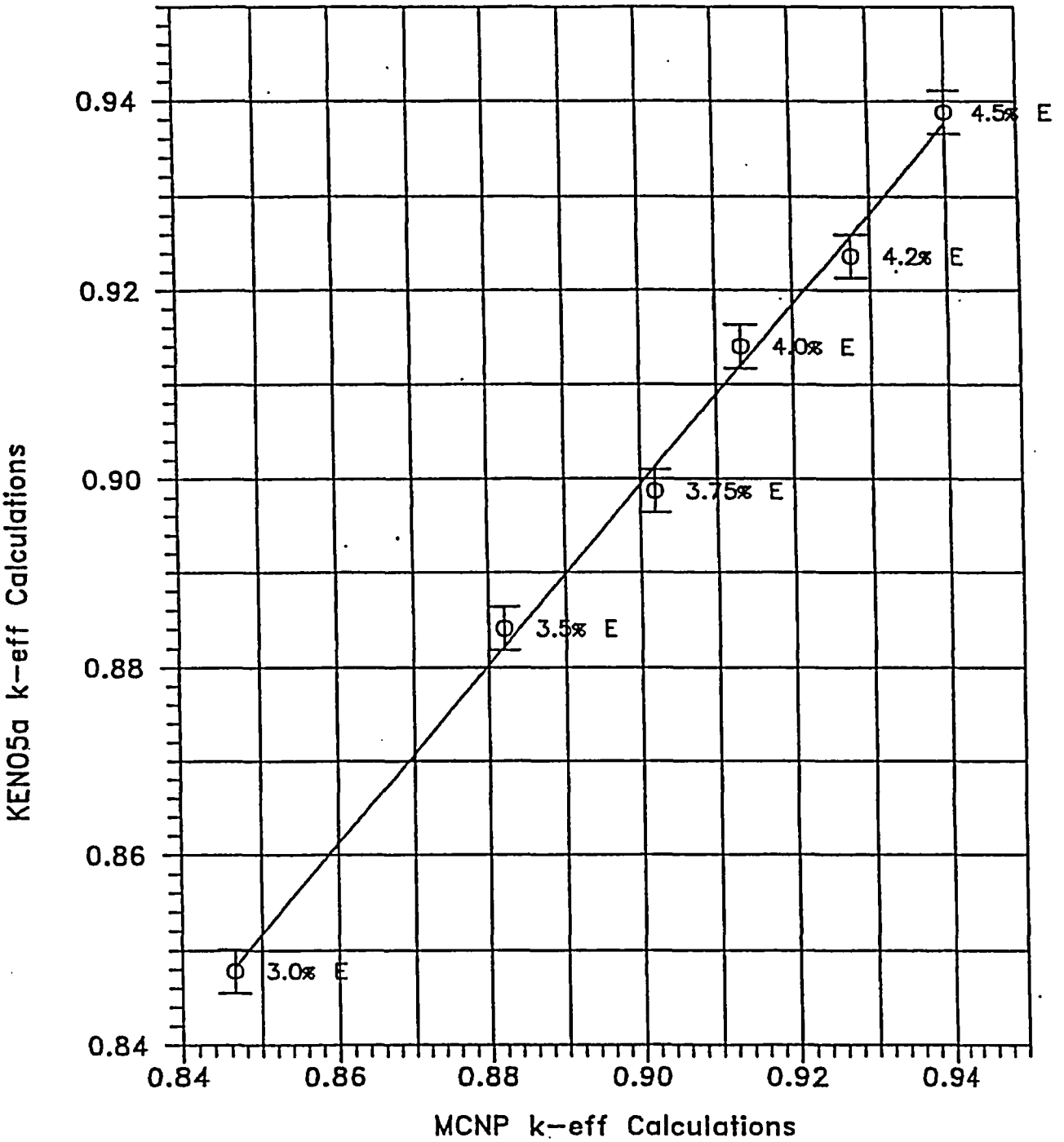


FIGURE 4A.5 COMPARISON OF MCNP AND KENO5A CALCULATIONS FOR VARIOUS FUEL ENRICHMENTS

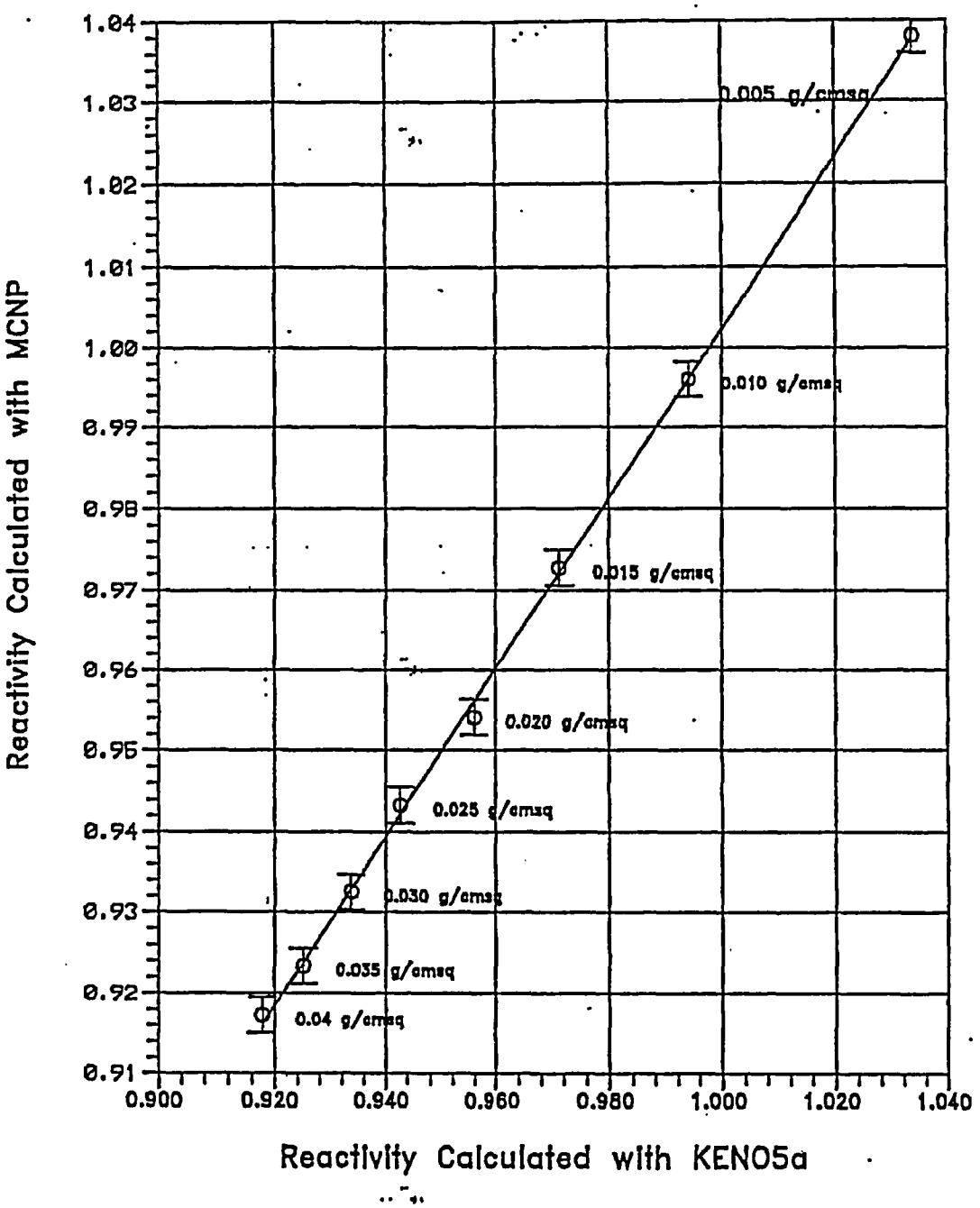


FIGURE 4A.6 : COMPARISON OF MCNP AND KENO5a CALCULATIONS FOR VARIOUS BORON-10 AREAL DENSITIES

Appendix B

Approved Computer Program List

(Total Pages: 6 including this page)

HOLTEC APPROVED COMPUTER PROGRAM LIST		REV. 72 June 29, 2004			
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
ANSYS (A)	5.7,7.0	JZ, ER, PK, CWB, SPA, AIS, IR, SP, AK, SJ, RW, VRP	Windows		
AIRCOOL	5.2I, 6.1		Windows		
BACKFILL	2.0		DOS/ Windows		
BONAMI (Scale)	4.3, 4.4		Windows		
BULKTEM	3.0		DOS/ Windows		
CASMO-4 (A)	1.13.04 (UNIX), 2.05.03 (WINDOWS)	ERD, SPA, DMM, KC, ST,VJB	UNIX/ Windows	Version 1.13.04 should not be used for new projects and should only be used when necessary for additional calculations on previous projects. The user should refer to the error notice documented in c4ser.04-results.pdf located in \generic\library\ nuclear\error notices\ concerning the use of version 1.13.04. Library N should be used with version 2.05.03 for all new reports issued after June 1st, 2003. Revisions to reports issued prior to June 1st, 2003 may continue to use the old Library L.	**2.05.03**
CASMO-3 (A)	4.4, 4.7	ERD, SPA, DMM, KC, ST	UNIX		
CELLDAN	4.4.1		Windows		
CHANBP6 (A)	1.0	SJ, PK, CWB, AIS, SP,AK	DOS/Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST			REV. 72 June 29, 2004		
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
CHAP08 (CHAPLS10)	1.0		Windows		
CONPRO	1.0		DOS/Windows		
CORRE	1.3		DOS/Windows		
DECAY	1.4, 1.5		DOS/Windows		
DECOR	1.0		DOS/Windows		
DR.BEAMPRO	1.0.5		Windows		
DR.FRAME	2.0		Windows		
DYNAMO (A)	2.51	AIS, SP, CWB, PK, SJ	DOS/Windows	Personnel qualified to use MR216 are automatically qualified to use DYNAMO.	
DYNAPOST	2.0		DOS/Windows		
FIMPACT	1.0		DOS/Windows		
FLUENT (A)	4.32, 4.56, 6.1.18	ER, IR, DMM, SPA	Windows	Do not use porous medium with zero velocity.	
FTLOAD	1.4		DOS		
GENEQ	1.3		DOS		
HXFLOW	1.0		DOS/Windows		
INSYST	2.01		Windows		
KENO-5A (A)	4.3, 4.4	ERD, SPA, DMM, KC, ST,VJB	Windows		
LONGOR	1.0		DOS/Windows		
LNSMTH2	1.0		DOS/Windows		
LS-DYNA3D (A)	936, 940, 950, 960, 970	JZ, AIS, SPA, SP, KPS,VRP	Windows		
MAXDISP8	1.8		DOS/Windows		
MAXDIS16	1.0		DOS/Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST			REV. 72 June 29, 2004		
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
MCNP (A)	4A, 4B	ERD, SPA, KC,ST,DMM, VJB, MAP	Windows/ UNIX	CASMO-4 Lumped Fission Products (IDs 401 and 402) and Isotope Pm148M (ID 61248) can be modeled in MCNP 4A using the cross sections documented in HI-2033031. Use of these cross sections is restricted to MCNP 4A, and to material specifications in atom densities.	4A
MASSINV	1.4, 1.5, 2.1		DOS/Windows		
MR2	1.7	AIS, SP, CWB, PK, SJ	DOS/Windows	For use in wet storage analysis only.	
MR216 (A)	1.0, 2.0, 2.2,2.4	AIS, SP, CWB, PK, SJ,AK	DOS/Windows	Versions 2.2 and 2.4 for use in dry storage analyses only. Use DYNAMO for liquefaction problems.	
MSREFINE	1.2,1.3, 2.1		DOS/Windows		
MULPOOLD	2.1		DOS/Windows		
MULTI1	1.3, 1.4, 1.5, 1.54, 1.55		Windows		
NITAWL (Scale)	4.3, 4.4		Windows		
NASTRAN DESKTOP (WORKING MODEL)	6.2, 2001,6.4,2002 , 2003		Windows		
ONEPOOL	1.4.1, 1.5, 1.6		DOS/Windows		
ORIGENS (Scale)	4.3, 4.4		Windows		
PD16	1.1, 1.0,2.1		Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST			REV. 72 June 29, 2004		
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
PREDYNA1	1.5, 1.4		DOS/Windows		
PREMULT8	1.0		DOS/Windows		
PRESPRG8	1.0		DOS/Windows		
PSD1	1.0		DOS/Windows		
QAD	CGGP		DOS/Windows		
SAS2H (Scale)	4.3, 4.4		Windows		
SFMR2A	1.0		DOS/Windows		
SHAPEBUILDER	3.0		DOS/Windows		
SIFATIG	1.0		DOS/Windows		
SOLIDWORKS	2001PLUS, 2003		DOS/Windows	This program may be used to calculate Weight, Volume, Centroid and Moment of Inertia. As a precaution, user should avoid keeping more than one drawing files open at any given time during a Solidworks session. If there is a need for multiples drawing files to be open at once, user should ensure that the part names for all open files are uniquely named (i.e. no two parts have the same name.)	

HOLTEC APPROVED COMPUTER PROGRAM LIST			REV. 72 June 29, 2004		
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
SPG16	1.0, 2.0, 3.0		DOS/Windows		
SHAKE2000	1.1.0, 1.4.0		DOS/Windows		
STARDYNE (A)	4.4, 4.5	SP	Windows		
STER	5.04		Windows		
TBOIL	1.7, 1.9		DOS/Windows	See HI-92832 for restriction on v1.7.	
THERPOOL	1.2, 1.2A		DOS/Windows		
TRIEL	2.0		DOS/Windows		
VERSUP	1.0		DOS		
VIB1DOF	1.0		DOS/Windows		
VMCHANGE	1.4, 1.3		Windows		
WEIGHT	1.0		Windows		

NOTES:
1. XXXX = ALPHANUMERIC COMBINATION
2. GENERAL PURPOSES UTILITY CODES (MATHCAD, EXCEL, ETC.) MAYBE USED ANYTIME.

Attachment 1

Letter from F.H. Smith to J.S. Rowe dated November 9, 2001
(13 Pages, including this one)

Entergy

Inter-Office Correspondence

To: J. S. Rowe

From: F. H. Smith

Date: November 9, 2001

Subject: Inputs for ANO SFP Criticality Analysis, Phase 2

CEO 2001-00284
File No.: 104-35, 204-35

This letter provides transmittal of data for phase two of the ANO spent fuel pool rack analysis. On the attached pages, information on the following topics can be found:

- Fuel parameters (Unit 2)
- Details of axial blankets (Unit 2)
- Reactor specific power (Unit 2)
- Core soluble boron letdown curves (Unit 2)
- Core operating temperatures (Unit 2)
- Radial and Axial Peaking Factors (both units)
- An axial burnup profile for spent fuel (Unit 2)
- Details of integral poison materials in the fuel (Unit 2)

This information has been prepared and documented in accordance with the Headquarters Nuclear Quality Assurance Program governing nuclear safety related analyses.

Please feel free to contact me if you require any additional information.

F. H. Smith
Supervisor, Core Design

FHS/wbb

cc: W. B. Bird (M-ECH-36)
C. D. Walker (N-GSB)
Corporate File [12]

Fuel Parameters

Table 1 presents fuel parameters data. For additional information on guide tubes and instrument tubes for ANO-2 fuel assemblies, please refer to Entergy letter CEXO 2000-00464.

Table 1. Fuel Parameters Data

ROD PARAMETER	ANO-2 VALUE
Assembly type	CE 16x16
Fuel pellet outside diameter (in.)	0.325
Cladding thickness (in.)	0.025
Cladding outside diameter (in.)	0.382
Cladding Material	Zir-4
Maximum stack density (g/cc)	10.412 *
Maximum enrichment, wt% U-235	5.0%
ASSEMBLY PARAMETER	
Array size	16x16
Number of fuel rods	236
Assembly Width (in.)	8.130 - 8.149
Assembly Pitch (in.)	8.180
Fuel rod pitch (in.)	0.506
Number of control rod guide tubes and instrument tubes	5 guide tubes (2x2)
Guide tubes outside diameter (in.)	0.980
Guide tubes inside diameter (in.)	0.900
Active fuel length (in.)	149.61 - 150.0

* A stack density that is 95% of theoretical density should bound future reloads, as well as all previous fuel designs.

Details of Axial Blankets

ANO-2 fuel designs do not utilize axial enrichment blankets.

Core Soluble Boron Concentration

Core soluble boron concentration data is provided in Figure 1 in the form of letdown curves for four recent cycles. These curves are representative of recent cycle operations. However, in order to bound future core designs, please adjust these values to a BOC concentration of 2000 ppm.

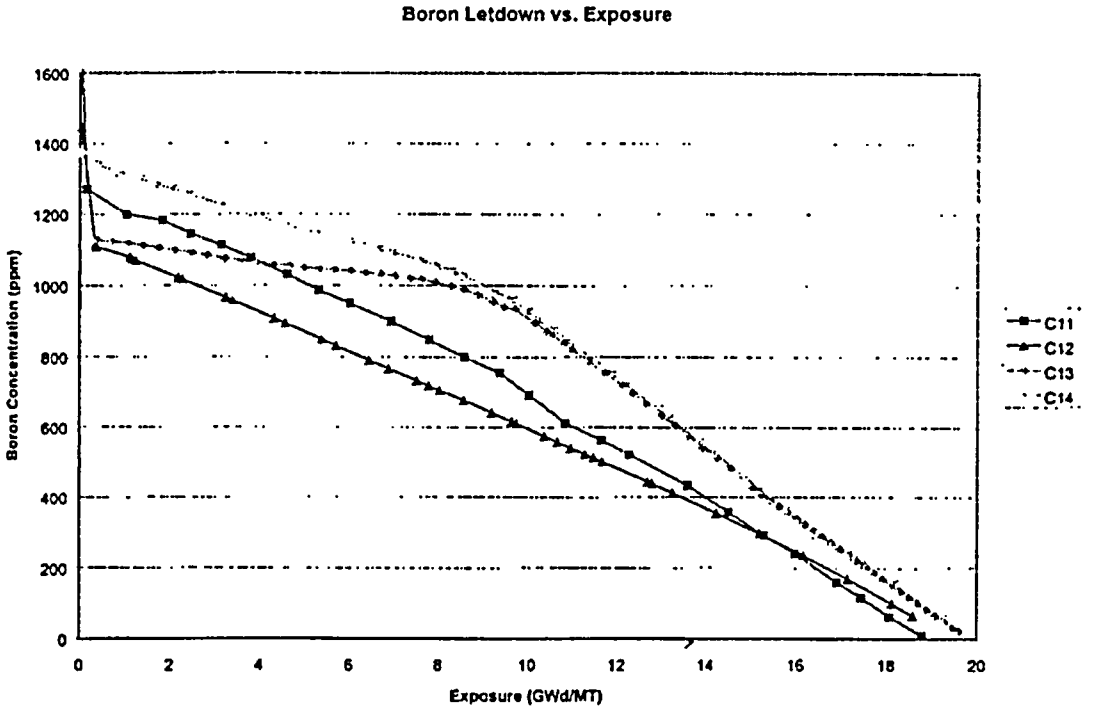


Figure 1. Representative Boron Letdown Curves

Core Operating Conditions

Table 2 documents Core Operating temperatures for ANO-2. Table 3 documents design values for axial and radial peaking at both units.

Table 2. Core Operating Temperatures

PARAMETER	NOMINAL VALUE
Average T_{fuel}	1000–1040 °F
Moderator T_{inlet}	553.5 °F (C1–9) 545.0 °F (C10–14) 549.0 °F (C15) 551.0 °F (C16)
Moderator $T_{average}$	573–578 °F
Moderator T_{outlet}	~604 °F

Table 3. Maximum Radial and Axial Peaking for T/H Analysis

	UNIT 1	UNIT 2
Axial	1.65	1.248
Radial	$F_{\Delta H} = 1.80$	$F_r = 1.65$

The core specific power ranges from approximately 37.0 to 40.0 MW/MTU.

Axial Burnup Profile

EOI has developed an EOC axial burnup distribution for use in the ANO-2 criticality analysis. This burnup profile is shown in Table 4.

Table 4. Generic Axial Burnup Distribution

AXIAL SEGMENT (CM)	RELATIVE BURNUP
0 to 15.24	0.55
15.24 to 30.48	0.82
30.48 to 60.96	1.01
60.96 to 121.92	1.105
121.92 to 182.88	1.105
182.88 to 243.84	1.075
243.84 to 304.80	1.07
304.80 to 335.28	1.02
335.28 to 350.52	0.92
350.52 to 365.76	> 0.72
365.76 to 381	0.47

Integral Poison Materials

For the purposes of the criticality analysis, the presence of a stronger poison during the assembly's core lifetime is conservative. However, since some poison material may remain in the fuel after discharge, a lesser poison loading may result in a more reactive bundle in the SFP. The most limiting poison configuration should be assumed for each burnup requirement. For the criticality analysis, low enriched pins should be modeled as high enriched. This section will summarize the three types of poison material in use at ANO-2.

B_4C

Boron Carbide was used as an integral poison material for cycles 1–12 (fuel batches A–P). These poison rods consist of B_4C in an Al_2O_3 matrix. Boron–10 concentrations vary from 0.004 g/inch to 0.028 g/inch. This corresponds to 0.403 wt% to 4.632 wt% B_4C, with boron–10 comprising approximately 18.3% of the boron present. Between 0 and 16 B_4C rods were used for each lattice. Loading patterns are shown in Figure 2.

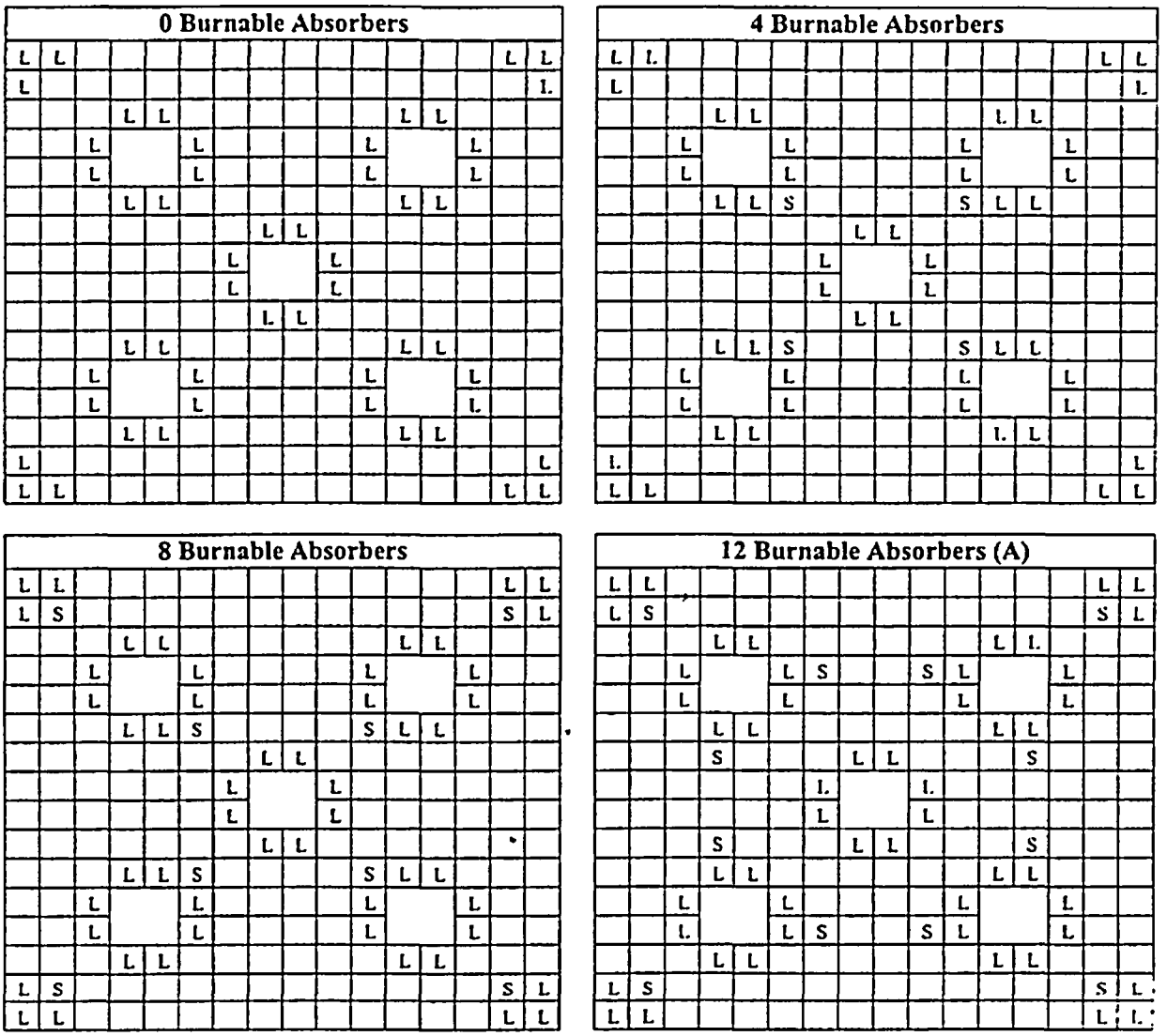
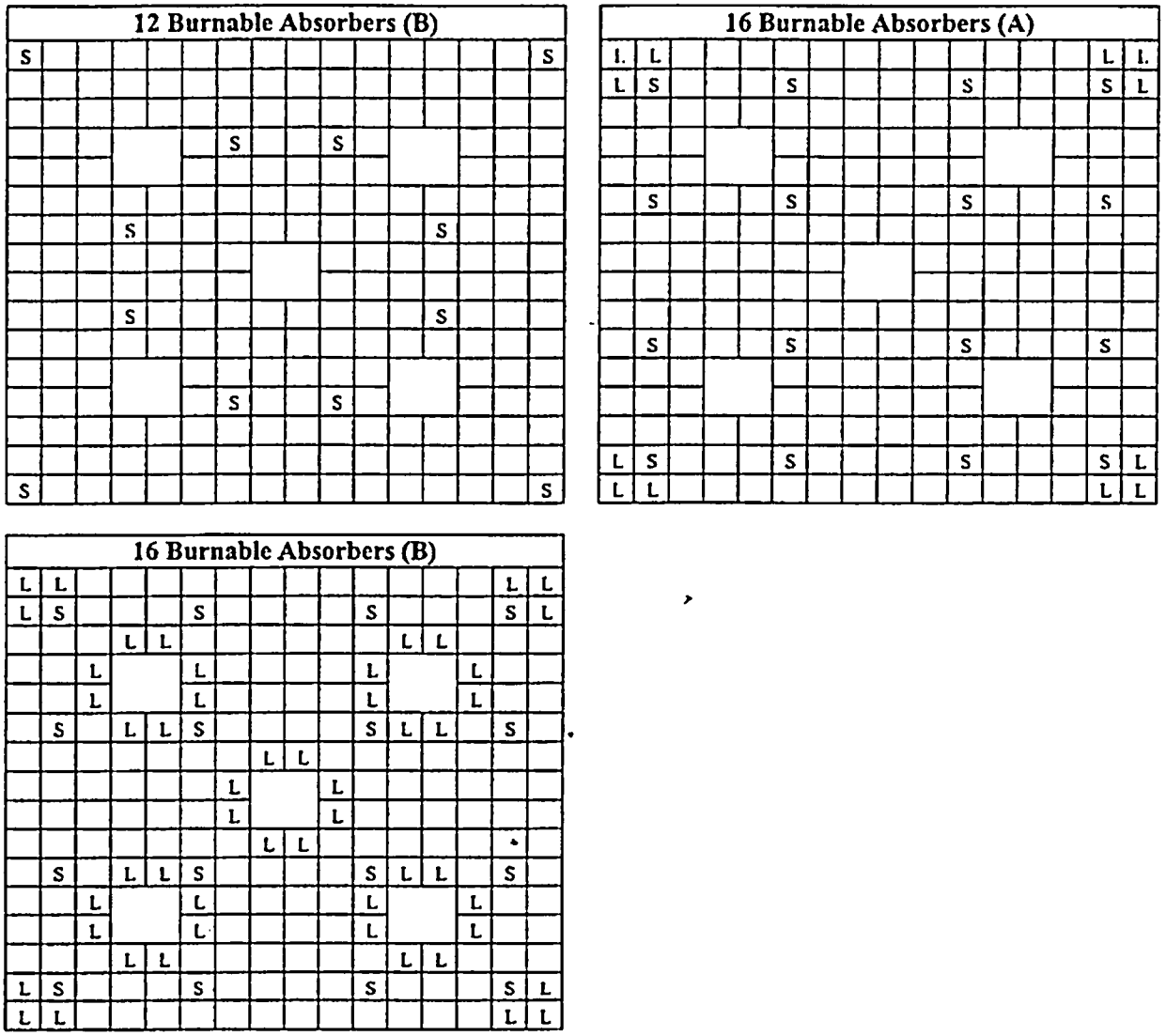


Figure 2a. B4C Loading Patterns

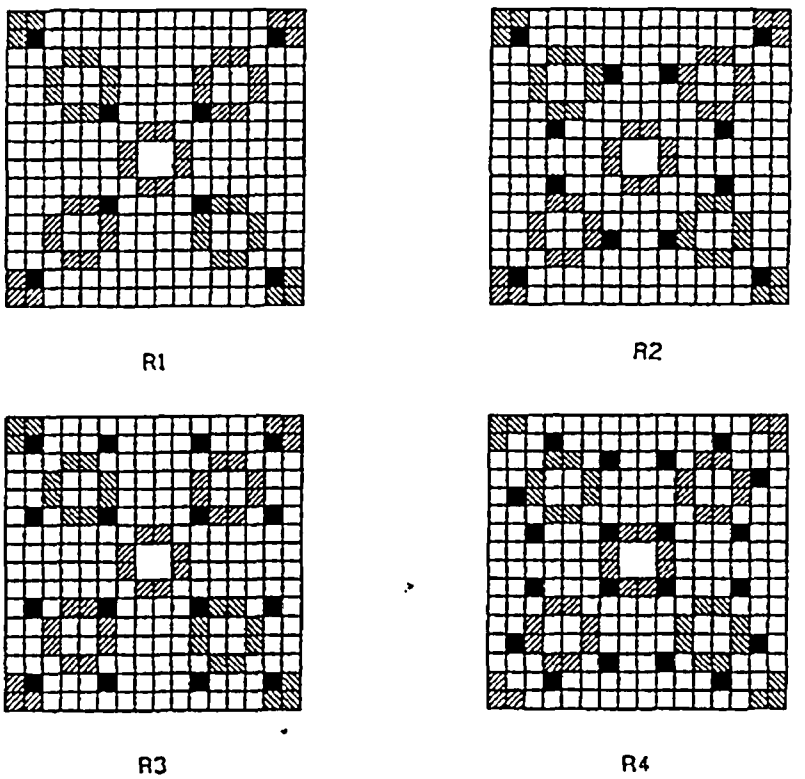


KEY:
L = Low enrichment pin (convert to high enriched for this analysis)
S = B_4C pin

Figure 2b. B4C Loading Patterns

Gadolinium

Cycles 13–15 (fuel batches R, S, and T) utilize Gd_2O_3 poison at 6.0% weight percent. with either 2.3% or 2.5% enriched U_2O_3. The Gadolinia loading patterns are shown on the following pages.

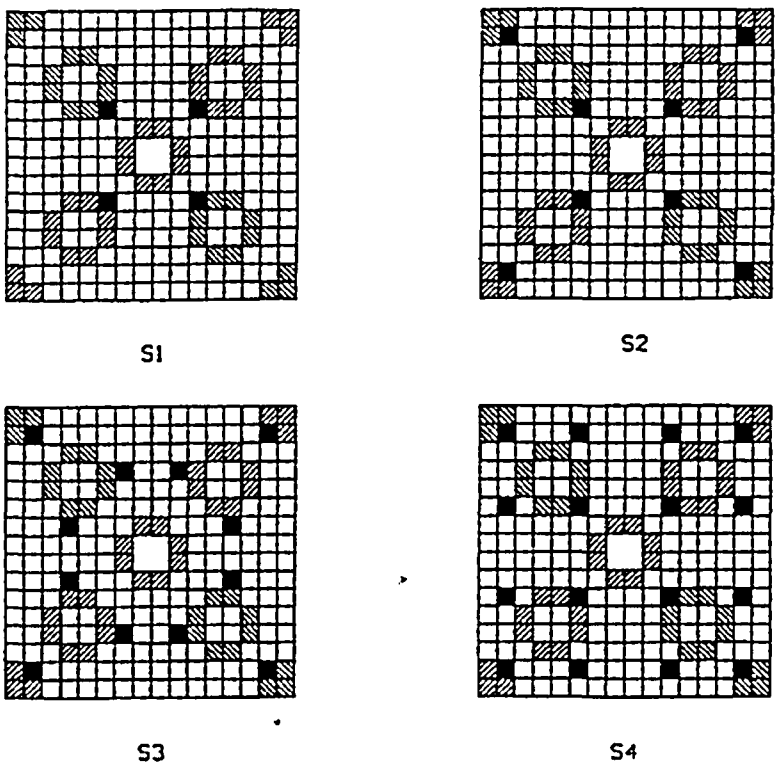


SAR FIGURE NO. 4.3-1C

AMENDMENT-16

ARKANSAS NUCLEAR ONE UNIT 2 RUSSELLVILLE, ARKANSAS	ENTERGY	SCALE : NONE DRAWN : CHARLEY RANKIN DESIGN : ENTERGY CAD NO : 4f3-01c.sar
INTEGRAL BURNABLE POISON SHIM AND ENRICHMENT ZONING PATTERNS FOR BATCH R FUEL ASSEMBLIES	BASED ON DRAWING NO	SHEET: 1 / REV:

Figure 3. Batch R Gad Loading

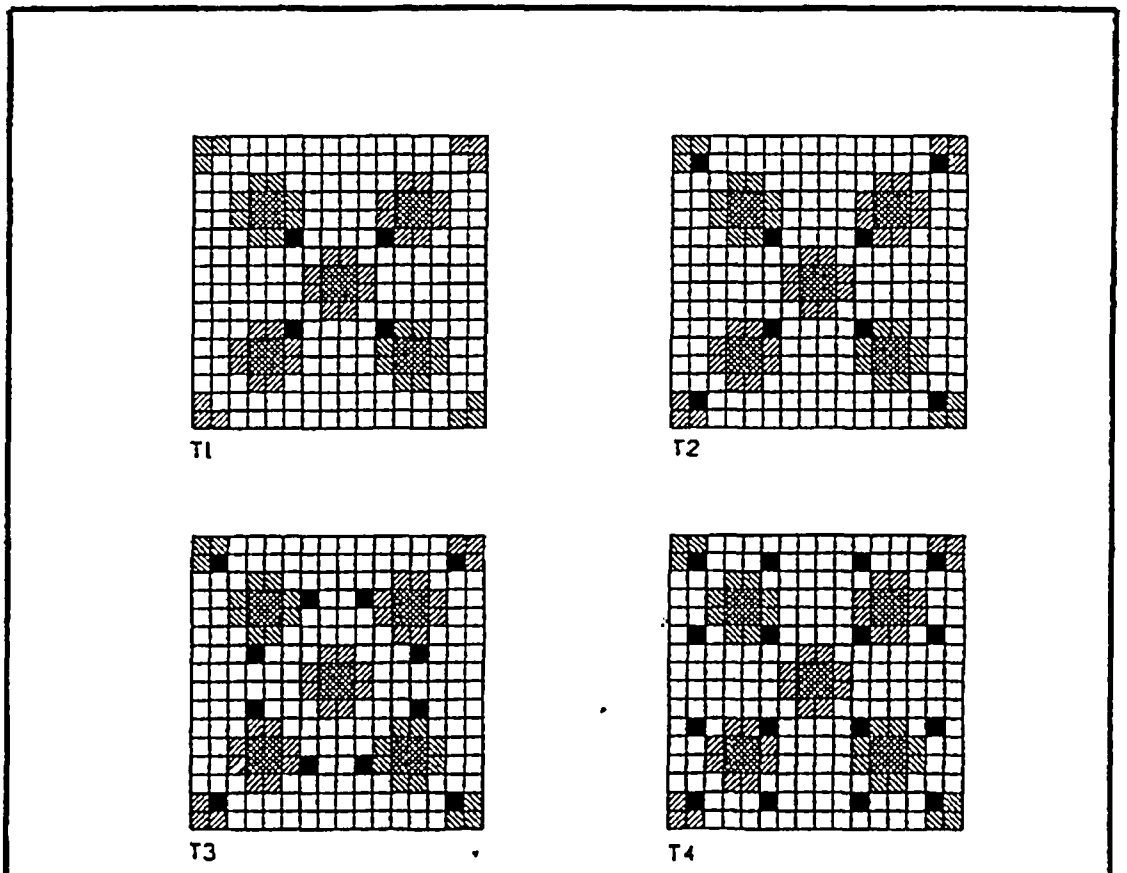


SAR FIGURE NO. 4.3-1B

AMENDMENT-16

ARKANSAS NUCLEAR ONE UNIT 2 RUSSELLVILLE, ARKANSAS	ENTERGY	SCALE : NONE DRAWN : CHARLEY RANKIN DESIGN : ENTERGY CAD NO : 4f3-01b.scr
INTEGRAL BURNABLE POISON SHIM AND ENRICHMENT ZONING PATTERNS FOR BATCH S FUEL ASSEMBLIES	BASED ON DRAWING NO	SHEET: 1 / REV:

Figure 4. Batch S Gad Loading



SAR FIGURE NO.4.3-1A			
AMENDMENT-16			
ARKANSAS NUCLEAR ONE UNIT 2 RUSSELLVILLE, ARKANSAS	ENTERGY	SCALE : NONE DRAWN : CHARLEY RANKIN DESIGN : ENTERGY CAD NO : 4f3-01a.sar	
INTEGRAL BURNABLE POISON SHIM AND ENRICHMENT ZONING PATTERNS FOR BATCH T FUEL ASSEMBLIES	BASED ON DRAWING NO	SHEET	REV
		1	

Figure 5. Batch T Gad Loading

Erbium

Erbium will be utilized as a poison material for future cycles at ANO–2, at 2.1 wt% Er_2O_3. Figure 6 shows the erbium loading patterns that may be used for ANO–2 fuel.

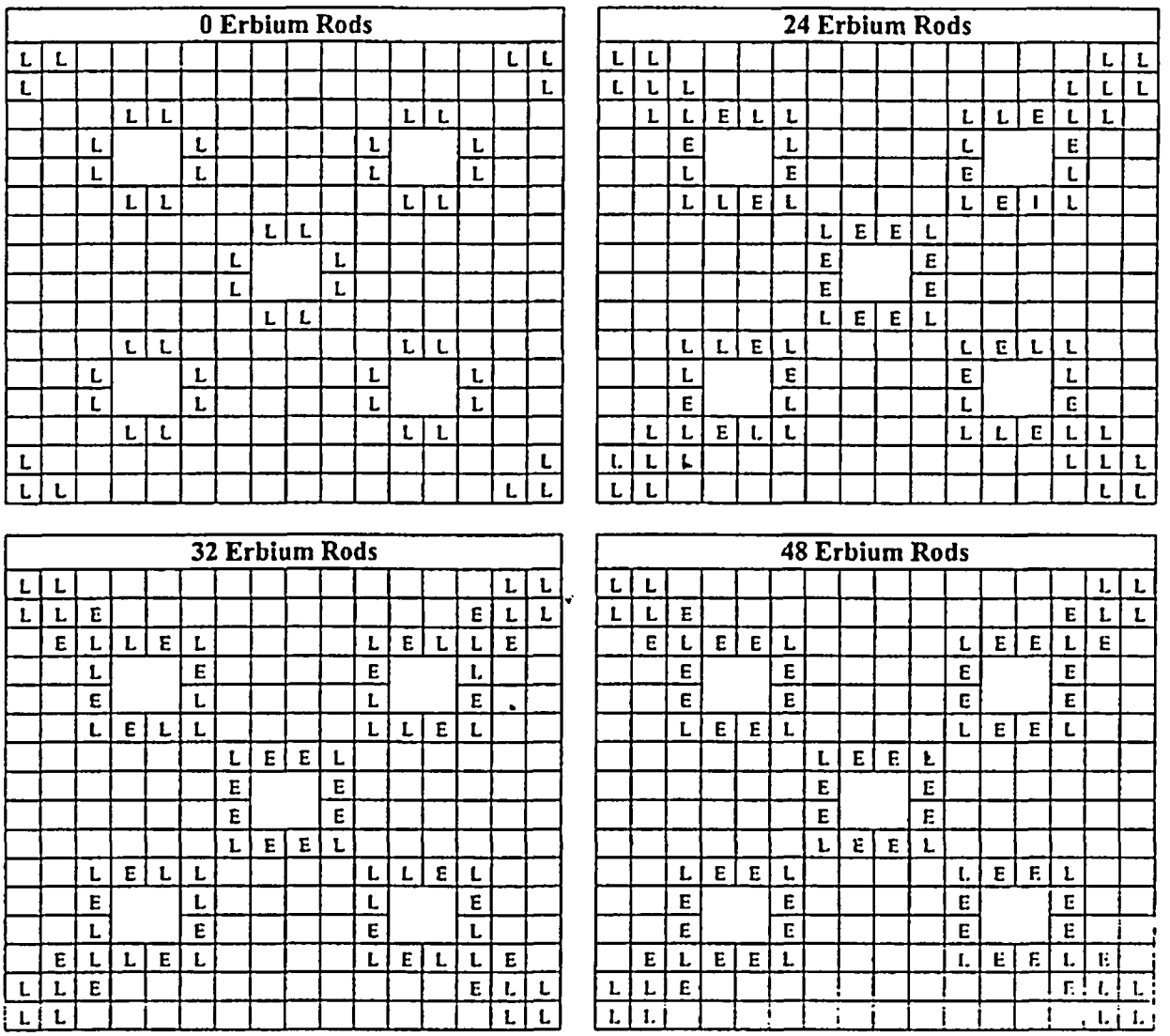


Figure 6a. Erbium Loading Patterns

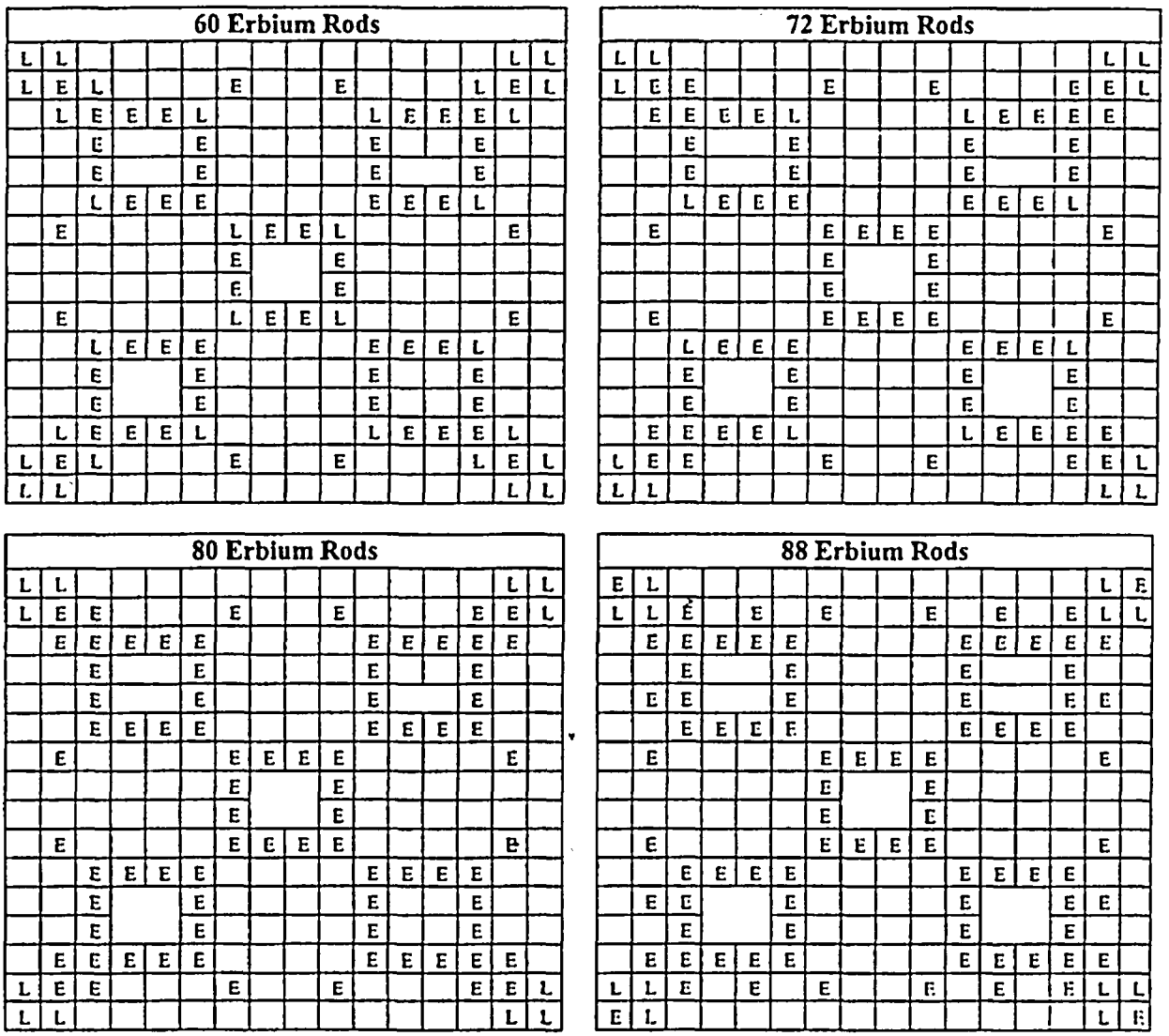


Figure 6b. Erbium Loading Patterns

100 Erbium Rods															
E	E	L			E					E			L	E	E
E	E	E				E			E				E	E	E
L	E	E	E	E	E					E	E	E	E	E	L
		E			E					E			E		
		E			E					E			E		
E		E	E	E	E					E	E	E	E		E
	E					E	E	E	E					E	
						E			E						
						E			E						
	E					E	E	E	E					E	
E		E	E	E	E					E	E	E	E		E
		E			E					E			E		
		E			E					E			E		
L	E	E	E	E	E					E	E	E	E	E	L
E	E	E				E			E				E	E	E
E	E	L			E					E			L	E	E

KEY:

L = Low enriched pin (model as high enriched for the criticality analysis.)
E = Erbium pin (2.1% Er_2O_3, varying uranium enrichments)

Figure 6c. Erbium Loading Patterns

Attachment 3

2CAN080501

Holtec Affidavit Regarding Withholding from Public Disclosure

AFFIDAVIT PURSUANT TO 10CFR2.390

I, Vince Bilovsky, being duly sworn, depose and state as follows:

(1) I am the Holtec International Project Manager for Holtec Project 1104 (ANO Dry Storage) 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 Holtec Report HI-2043262 Rev 0 with the associated computer files.

(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), 2.390(a)(4), and 2.390(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 paragraph 4.a and 4.b, 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. A substantial effort has been expended by Holtec International to develop this information. Release of this information would improve a competitor's position because it would enable Holtec's competitor to copy our technology and offer it for sale in competition with our company, causing us financial injury.

(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 10CFR2.390

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

Mr. Vince Bilovsky, 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 2nd day of August, 2005.

Vince Bilovsky
Holtec International

Subscribed and sworn before me this 2nd day of August, 2005.

MARIA C. MASSI
NOTARY PUBLIC OF NEW JERSEY
My Commission Expires April 25, 2010