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June 23, 2006

ATTN: Document Control Desk
Director, Spent Fuel Project Office
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Reference:
1. USNRC Docket No. 71-9261 (HI-STAR 100), TAC No. L23796
2. Holtec Project 5014
3. SFPO Letter dated 23 December 2005
4. Holtec Letter 5014592 dated 24 March 2006

Subject: Action Items on Request for Additional Information for HI-STAR 100 Transportation Package

Dear Sir:

By application dated 16 September 2003 and as supplemented by letter dated 23 March 2004, we requested approval of an amendment to the Certificate of Compliance for our HI-STAR 100 Transportation Package (Reference 1). Via letter on 23 December 2005, the SFPO submitted a list of Action Items in relation to RAI clarifications. We herein submit additional information in the form of an updated Appendix 6.A (Draft) of the proposed SAR.

Please contact us if you have any questions or require further clarification.

Sincerely,

Stefan Anton

Stefan Anton, Dr.-Ing.
Licensing Manager

Attachments: Appendix 6.A (Draft) of HI-STAR SAR, Proposed Rev. 12

cc: Mr. Meraj Rahimi, NRC

Document ID: 5014601

NMSS01

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Non-Proprietary Attachment 1

Appendix 6.A (Draft) of HI-STAR SAR, Proposed Rev. 12

(29 pages plus this cover sheet)

APPENDIX 6.A: BENCHMARK CALCULATIONS

6.A.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 cask designs. Two independent methods of analysis were used, differing in cross section libraries and in the treatment of the cross sections. MCNP4a [6.A.1] is a continuous energy Monte Carlo code and KENO5a [6.A.2] uses group-dependent cross sections. For the KENO5a analyses reported here, the 238-group library was chosen, processed through the NITAWL-II [6.A.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., [6.A.3 through 6.A.5]) for calculations with collapsed cross section sets.

The results of the benchmark calculations presented herein are separated into two parts. The first part (Sections 6.A.1 through 6.A.5) presents the calculational bias for fresh fuel calculations and encompasses the benchmark critical experiments numbered 1 through 62 in Table 6.A.1. The second part (Section 6.A.6) presents the calculational bias for burnup credit and encompasses all of the benchmark critical experiments presented in Table 6.A.1.

In cask 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 cask and fuel designs, have a smaller effect, but are also included in the analyses.

Table 6.A.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". 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 energy of the average lethargy causing fission determined (post-processing).

Figures 6.A.1 and 6.A.2 show the calculated k_{eff} for the benchmark critical experiments as a function of the "energy of the average lethargy causing fission" for MCNP4a and KENO5a, respectively (UO_2 fuel only). The scatter in the data (even for comparatively minor variation in

† 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.

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 6.A.1 and 6.A.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		
	Total	Truncated
MCNP4a	0.0009 ± 0.0011	0.0021 ± 0.0007
KENO5a	0.0030 ± 0.0012	0.0036 ± 0.0009

The values of bias shown in this table include both the bias derived directly from the calculated k_{eff} values in Table 6.A.1, and a more conservative value derived by arbitrarily truncating to 1.000 any calculated value that exceeds 1.000. The bias and standard error of the bias were calculated by 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 [6.A.18] (for the number of cases analyzed, the K-factor is ~2.05 or slightly more than 2).

$$\bar{k} = \frac{1}{n}\sum_{i=1}^{n} k_i \qquad (6.A.1)$$

$$\sigma_{\bar{k}}^2 = \frac{\sum_{i=1}^{n} k_i^2 - (\sum_{i=1}^{n} k_i)^2 / n}{n(n-1)} \qquad (6.A.2)$$

$$\text{Bias} = (1 - \bar{k}) \pm K\sigma_{\bar{k}} \qquad (6.A.3)$$

where k_i are the calculated reactivities for 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)); and K is the one-sided multiplier for 95% probability at the 95% confidence level (NBS Handbook 91 [6.A.18]).

[††] 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 [6.A.6] (or the MCNP4a manual) and is the same methodology used in MCNP4a and in KENO5a.

Formula 6.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 6.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, $K\sigma_{\bar{k}}$, which corresponds to σ_B in Section 6.4.3, 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 larger of the calculational biases (truncated bias) was used to evaluate the maximum k_{eff} values for the cask designs.

6.A.2 Effect of Enrichment

The benchmark critical experiments include those with enrichments ranging from 2.46% to 5.74% and therefore span the enrichment range for the MPC designs. Figures 6.A.3 and 6.A.4 show the calculated k_{eff} values (Table 6.A.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 (0.08 for MCNP4a and 0.37 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, the MPC-68 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 6.A.2 and Figure 6.A.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.

6.A.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 cask designs. Of these critical experiments, those performed by B&W are the most representative of the cask 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 6.A.3 lists the subset of experiments using thin neutron absorbers (from Table 6.A.1) and shows the reactivity worth (Δk) of the absorber.†

†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.

No trends with reactivity worth of the absorber are evident, although based on the calculations shown in Table 6.A.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 6.A.6 and Table 6.A.4 for the MPC-68 cask[††] 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).

6.A.4 Miscellaneous and Minor Parameters

6.A.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 6.A.5 (subset of data in Table 6.A.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 cask calculations may be slightly more conservative than otherwise.

6.A.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 cask designs, the fuel pellet diameters range from 0.303 to 0.3835 inches O.D. (0.496 to 0.580 inch lattice spacing) for PWR fuel and from 0.3224 to 0.498 inches O.D. (0.488 to 0.740 inch lattice spacing) for BWR fuel. Thus, the critical experiments analyzed provide a reasonable representation of the fuel in the MPC designs. Based on the data in Table 6.A.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 or the cask designs.

6.A.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 6.A.6. Analyses of the very high boron

[††]The MPC-68 geometry was chosen for this comparison since it contains the greater number of Boral panels and would therefore be expected to be the most sensitive to trends (errors) in calculations.

[†]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 cask design. A lead reflector is also not directly pertinent, but might be used in future designs.

concentration experiments (>1300 ppm) show a tendency to slightly overpredict reactivity for the three experiments exceeding 1300 ppm.

6.A.5 MOX Fuel Critical Experiments

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 6.A.7. Results of these analyses are generally above a k_{eff} of 1.00, indicating that when Pu is present, MCNP4a and KENO5a overpredict the reactivity.

This may indicate that calculation of k_{eff} 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, suggested that a small trend may exist with KENO5a. It is also possible that the overprediction in k_{eff} in 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).

6.A.6 Burnup Credit Benchmark Experiments

The use of burnup credit in a spent fuel transportation cask license requires benchmarking of the appropriate codes to spent fuel critical experiments. However, spent fuel critical experiments are not available, therefore benchmarking with an extended set of mixed oxide fuel critical experiments is performed. ~~Thirty-nine~~*Fifty* MOX fuel critical experiments (31 from reference [6.A.21], ~~and~~ eight additional MOX critical experiments from Section 6.A.5 *and eleven MOX critical experiments from [6.A.22]*) have been selected for validating MCNP4a for burnup credit. The total bias (systematic error, or mean of the deviation from a k_{eff} of exactly 1.000) for MCNP4a for the entire set of ~~87~~*98* critical experiments identified in Table 6.A.1 is shown in the table below.

Calculational Bias of MCNP4a and KENO5a		
	Total	Truncated
MCNP4a	-0.000~~6~~*64* ± 0.000~~9~~*98*	0.0015 ± 0.000~~5~~*54*

The values of bias shown in this table include both the bias derived directly from the calculated k_{eff} values in Table 6.A.1, and a more conservative value derived by arbitrarily truncating to 1.000 any calculated value that exceeds 1.000. The bias and standard error of the bias were calculated with the equations in Section 6.A.1, with the standard error multiplied by the one-sided K-factor for 95% probability at the 95% confidence level from NBS Handbook 91 [6.A.18] (for the number of cases analyzed, the K-factor is ~1.95 or slightly less than 2).

6.A.6.1 Effect of EALF

Figure 6.A.7 shows the MOX fuel calculated k_{eff} values as a function of the calculated EALF from MCNP4a during post-processing as described in Section 6.A.1. Linear regression analysis

for this data confirms that the MCNP4a results do not exhibit any trends with respect to the EALF as evidenced by the low value of the correlation coefficient (~~-0.34~~*-0.03*). Thus there is no correction to the bias as a function of the EALF.

6.A.6.2 Effect of Cladding OD

The MOX critical experiments selected for analysis cover a range of cladding outside diameters from 0.230 to 0.565 inches. In the Holtec cask designs, the allowable cladding outside diameters range from 0.342 to 0.440 inches O.D. for PWR fuel and from 0.378 to 0.563 inches O.D. for BWR and PWR fuel. Thus, the critical experiments analyzed provide a reasonable representation of the fuel in the MPC designs. Linear regression analysis for this data confirms that the MCNP4a results do not exhibit any trends with respect to the Cladding O.D. as evidenced by the low value of the correlation coefficient (~~-0.14~~*-0.17*). Thus there is no correction to the bias as a function of the Cladding O.D.

6.A.7 References

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

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[6.A.19] R. I. Smith and G.J. Konzek, April 1976 and September 1978. *Clean Critical Experiment Benchmarks for Plutonium Recycle in LWRs,* Volumes I and II, EPRI NP-196, Electric Power Research Institute.

[6.A.20] V. O. Uotinen, et al., August 1972. "Lattices of Plutonium-Enriched Rods in Light Water – Part I: Experimental Results," *Nuclear Technology,* 15, 257.

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[6.A.22] "Critical Arrays of Mixed Plutonium-Uranium Fuel Rods with Water-to-Fuel Volume Ratios Ranging from 2.4 to 5.6", from "International Handbook of Evaluated Criticality Safety Benchmark Experiments", NEA/NSC/DOC(95)03, Volume VI, MIX-COMP-THERM-004

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

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
13	B&W-1484 (6.A.7)	Core XVIII	2.46	1.0036 ± 0.0012	0.9931 ± 0.0006	0.1705	0.1708
14	B&W-1484 (6.A.7)	Core XIX	2.46	0.9961 ± 0.0012	0.9971 ± 0.0005	0.2103	0.2011
15	B&W-1484 (6.A.7)	Core XX	2.46	1.0008 ± 0.0011	0.9932 ± 0.0006	0.1724	0.1701
16	B&W-1484 (6.A.7)	Core XXI	2.46	0.9994 ± 0.0010	0.9918 ± 0.0006	0.1544	0.1536
17	B&W-1645 (6.A.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 (6.A.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 (6.A.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 (6.A.9)	Case 1 1337 ppm B	2.46	1.0023 ± 0.0010	NC	0.1531	NC
21	B&W-1810 (6.A.9)	Case 12 1899 ppm B	2.46/4.02	1.0060 ± 0.0009	NC	0.4493	NC
22	French (6.A.10)	Water Moderator 0 gap	4.75	0.9966 ± 0.0013	NC	0.2172	NC
23	French (6.A.10)	Water Moderator 2.5 cm gap	4.75	0.9952 ± 0.0012	NC	0.1778	NC
24	French (6.A.10)	Water Moderator 5 cm gap	4.75	0.9943 ± 0.0010	NC	0.1677	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
25	French (6.A.10)	Water Moderator 10 cm gap	4.75	0.9979 ± 0.0010	NC	0.1736	NC
26	PNL-3602 (6.A.11)	Steel Reflector, 0 cm separation	2.35	NC	1.0004 ± 0.0006	NC	0.1018
27	PNL-3602 (6.A.11)	Steel Reflector, 1.321 cm separation	2.35	0.9980 ± 0.0009	0.9992 ± 0.0006	0.1000	0.0909
28	PNL-3602 (6.A.11)	Steel Reflector, 2.616 cm separation	2.35	0.9968 ± 0.0009	0.9964 ± 0.0006	0.0981	0.0975
29	PNL-3602 (6.A.11)	Steel Reflector, 3.912 cm separation	2.35	0.9974 ± 0.0010	0.9980 ± 0.0006	0.0976	0.0970
30	PNL-3602 (6.A.11)	Steel Reflector, Infinite separation	2.35	0.9962 ± 0.0008	0.9939 ± 0.0006	0.0973	0.0968
31	PNL-3602 (6.A.11)	Steel Reflector, 0 cm separation	4.306	NC	1.0003 ± 0.0007	NC	0.3282
32	PNL-3602 (6.A.11)	Steel Reflector, 1.321 cm separation	4.306	0.9997 ± 0.0010	1.0012 ± 0.0007	0.3016	0.3039
33	PNL-3602 (6.A.11)	Steel Reflector, 2.616 cm separation	4.306	0.9994 ± 0.0012	0.9974 ± 0.0007	0.2911	0.2927
34	PNL-3602 (6.A.11)	Steel Reflector, 5.405 cm separation	4.306	0.9969 ± 0.0011	0.9951 ± 0.0007	0.2828	0.2860
35	PNL-3602 (6.A.11)	Steel Reflector, Infinite separation	4.306	0.9910 ± 0.0020	0.9947 ± 0.0007	0.2851	0.2864
36	PNL-3602 (6.A.11)	Steel Reflector, with Boral Sheets	4.306	0.9941 ± 0.0011	0.9970 ± 0.0007	0.3135	0.3150

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
37	PNL-3626 (6.A.12)	Lead Reflector, 0 cm sepn.	4.306	NC	1.0003 ± 0.0007	NC	0.3159
38	PNL-3626 (6.A.12)	Lead Reflector, 0.55 cm sepn.	4.306	1.0025 ± 0.0011	0.9997 ± 0.0007	0.3030	0.3044
39	PNL-3626 (6.A.12)	Lead Reflector, 1.956 cm sepn.	4.306	1.0000 ± 0.0012	0.9985 ± 0.0007	0.2883	0.2930
40	PNL-3626 (6.A.12)	Lead Reflector, 5.405 cm sepn.	4.306	0.9971 ± 0.0012	0.9946 ± 0.0007	0.2831	0.2854
41	PNL-2615 (6.A.13)	Experiment 004/032 – no absorber	4.306	0.9925 ± 0.0012	0.9950 ± 0.0007	0.1155	0.1159
42	PNL-2615 (6.A.13)	Experiment 030 – Zr plates	4.306	NC	0.9971 ± 0.0007	NC	0.1154
43	PNL-2615 (6.A.13)	Experiment 013 – Steel plates	4.306	NC	0.9965 ± 0.0007	NC	0.1164
44	PNL-2615 (6.A.13)	Experiment 014 – Steel plates	4.306	NC	0.9972 ± 0.0007	NC	0.1164
45	PNL-2615 (6.A.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 (6.A.13)	Exp. 009 1.62% Boron Steel plates	4.306	0.9996 ± 0.0012	0.9982 ± 0.0007	0.1161	0.1173
47	PNL-2615 (6.A.13)	Exp. 031 – Boral plates	4.306	0.9994 ± 0.0012	0.9969 ± 0.0007	0.1165	0.1171
48	PNL-7167 (6.A.14)	Experiment 214R – with flux traps	4.306	0.9991 ± 0.0011	0.9956 ± 0.0007	0.3722	0.3812

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
49	PNL-7167 (6.A.14)	Experiment 214V3 –with flux trap	4.306	0.9969 ± 0.0011	0.9963 ± 0.0007	0.3742	0.3826
50	PNL-4267 (6.A.15)	Case 173 – 0 ppm B	4.306	0.9974 ± 0.0012	NC	0.2893	NC
51	PNL-4267 (6.A.15)	Case 177 – 2550 ppm B	4.306	1.0057 ± 0.0010	NC	0.5509	NC
52	PNL-5803 (6.A.16)	MOX Fuel – Type 3.2 Exp. 21	20% Pu	1.0041 ± 0.0011	1.0046 ± 0.0006	0.9171	0.8868
53	PNL-5803 (6.A.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 (6.A.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 (6.A.16)	MOX Fuel – Type 3.2 Exp. 32	20% Pu	1.0079 ± 0.0011	0.9966 ± 0.0006	0.1339	0.1165
56	WCAP-3385 (6.A.17)	Saxton Case 52 PuO_2 0.52" pitch	6.6% Pu	0.9996 ± 0.0011	1.0005 ± 0.0006	0.8665	0.8417
57	WCAP-3385 (6.A.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 (6.A.17)	Saxton Case 56 PuO_2 0.56" pitch	6.6% Pu	1.0036 ± 0.0011	1.0047 ± 0.0006	0.5289	0.5197
59	WCAP-3385 (6.A.17)	Saxton Case 56 borated PuO_2	6.6% Pu	1.0008 ± 0.0010	NC	0.6389	NC
60	WCAP-3385 (6.A.17)	Saxton Case 56 U 0.56" pitch	5.74	0.9994 ± 0.0011	0.9967 ± 0.0007	0.2923	0.2954

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
61	WCAP-3385 (6.A.17)	Saxton Case 79 PuO_2 0.79" pitch	6.6% Pu	1.0063 ± 0.0011	1.0133 ± 0.0006	0.1520	0.1555
62	WCAP-3385 (6.A.17)	Saxton Case 79 U 0.79" pitch	5.74	1.0039 ± 0.0011	1.0008 ± 0.0006	0.1036	0.1047
		Additional MOX					
63	EPRI Exp22 (6.A.19)	0.700-in. pitch 0 ppm B	2% Pu	1.0065 ± 0.0011	NC	0.5458	NC
64	EPRI Exp23 (6.A.19)	0.700-in. pitch 688 ppm B	2% Pu	1.0069 ± 0.0010	NC	0.7256	NC
65	EPRI Exp24 (6.A.19)	0.870-in. pitch 0 ppm B	2% Pu	1.0037 ± 0.0011	NC	0.1963	NC
66	EPRI Exp25 (6.A.19)	0.870-in. pitch 1090 ppm B	2% Pu	1.0073 ± 0.0011	NC	0.2880	NC
67	EPRI Exp26 (6.A.19)	0.990-in. pitch 0 ppm B	2% Pu	1.0057 ± 0.0010	NC	0.1386	NC
68	EPRI Exp27 (6.A.19)	0.990-in. pitch 767 ppm B	2% Pu	1.0079 ± 0.0010	NC	0.1849	NC
69	WCAP-3385 (6.A.17)	Saxton Case PuO_2 0.735" pitch	6.6% Pu	1.0081 ± 0.0012	NC	0.1843	NC
70	WCAP-3385 (6.A.17)	Saxton Case PuO_2 1.04" pitch	6.6% Pu	1.0085 ± 0.0011	NC	0.0999	NC
71	PUP Exp35 (6.A.20)	8 wt% ^{240}Pu 0.80" pitch	2% Pu	0.9971 ± 0.0010	NC	0.3582	NC
72	PUP Exp36 (6.A.20)	8 wt% ^{240}Pu 0.93" pitch	2% Pu	1.0018 ± 0.0011	NC	0.1883	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
73	PUP Exp37 (6.A.20)	8 wt% ^{240}Pu 1.05" pitch	2% Pu	0.9959 ± 0.0011	NC	0.1377	NC
74	PUP Exp38 (6.A.20)	8 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0017 ± 0.0010	NC	0.1170	NC
75	PUP Exp39 (6.A.20)	8 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0000 ± 0.0010	NC	0.0956	NC
76	PUP Exp40 (6.A.20)	8 wt% ^{240}Pu 1.386" pitch	2% Pu	0.9994 ± 0.0009	NC	0.0908	NC
77	PUP Exp41 (6.A.20)	16 wt% ^{240}Pu 0.93" pitch	2% Pu	1.0042 ± 0.0010	NC	0.1981	NC
78	PUP Exp42 (6.A.20)	16 wt% ^{240}Pu 1.05" pitch	2% Pu	1.0018 ± 0.0010	NC	0.1408	NC
79	PUP Exp43 (6.A.20)	16 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0029 ± 0.0009	NC	0.1200	NC
80	PUP Exp44 (6.A.20)	16 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0019 ± 0.0008	NC	0.0970	NC
81	PUP Exp45 (6.A.20)	24 wt% ^{240}Pu 0.80" pitch	2% Pu	0.9947 ± 0.0010	NC	0.3988	NC
82	PUP Exp46 (6.A.20)	24 wt% ^{240}Pu 0.93" pitch	2% Pu	0.9993 ± 0.0008	NC	0.2006	NC
83	PUP Exp47 (6.A.20)	24 wt% ^{240}Pu 1.05" pitch	2% Pu	1.0014 ± 0.0008	NC	0.1414	NC
84	PUP Exp48 (6.A.20)	24 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0019 ± 0.0009	NC	0.1196	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
85	PUP Exp49 (6.A.20)	24 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0049 ± 0.0008	NC	0.0973	NC
86	PUP Exp50 (6.A.20)	24 wt% ^{240}Pu 1.386" pitch	2% Pu	1.0040 ± 0.0008	NC	0.0917	NC
87	PUP Exp51 (6.A.20)	18 wt% ^{240}Pu 0.85" pitch	4% Pu	0.9993 ± 0.0011	NC	0.3918	NC
88	PUP Exp52 (6.A.20)	18 wt% ^{240}Pu 0.93" pitch	4% Pu	0.9991 ± 0.0010	NC	0.2565	NC
89	PUP Exp53 (6.A.20)	18 wt% ^{240}Pu 1.05" pitch	4% Pu	1.0073 ± 0.0011	NC	0.1757	NC
90	PUP Exp54 (6.A.20)	18 wt% ^{240}Pu 1.143" pitch	4% Pu	1.0065 ± 0.0010	NC	0.1454	NC
91	PUP Exp55 (6.A.20)	18 wt% ^{240}Pu 1.386" pitch	4% Pu	1.0093 ± 0.0009	NC	0.1068	NC
92	PUP Exp56 (6.A.20)	18 wt% ^{240}Pu 1.60" pitch	4% Pu	1.0086 ± 0.0010	NC	0.0932	NC
93	PUP Exp57 (6.A.20)	18 wt% ^{240}Pu 1.70" pitch	4% Pu	1.0106 ± 0.0009	NC	0.0884	NC
94	*MCT004 (6.A.22)*	*2.42Pu Lattics, 59.55 cm Water*	*3% Pu*	*0.9962 ± 0.0007*	*NC*	*0.1461*	*NC*
95	*MCT004 (6.A.22)*	*2.42Pu Lattics, 61.90 cm Water*	*3% Pu*	*0.9959 ± 0.0006*	*NC*	*0.1453*	*NC*
96	*MCT004 (6.A.22)*	*2.42Pu Lattics, 64.06 cm Water*	*3% Pu*	*0.9973 ± 0.0006*	*NC*	*0.1441*	*NC*
97	*MCT004 (6.A.22)*	*2.98Pu Lattics, 61.50 cm Water*	*3% Pu*	*0.9984 ± 0.0006*	*NC*	*0.1196*	*NC*
98	*MCT004 (6.A.22)*	*2.98Pu Lattics, 64.40 cm Water*	*3% Pu*	*0.9980 ± 0.0007*	*NC*	*0.1195*	*NC*
99	*MCT004 (6.A.22)*	*2.98Pu Lattics, 69.40 cm Water*	*3% Pu*	*0.9988 ± 0.0006*	*NC*	*0.1181*	*NC*
100	*MCT004 (6.A.22)*	*4.24Pu Lattics, 60.32 cm Water*	*3% Pu*	*0.9996 ± 0.0006*	*NC*	*0.0929*	*NC*
101	*MCT004 (6.A.22)*	*4.24Pu Lattics, 62.99 cm Water*	*3% Pu*	*0.9998 ± 0.0006*	*NC*	*0.0928*	*NC*
102	*MCT004 (6.A.22)*	*4.24Pu Lattics, 65.63 cm Water*	*3% Pu*	*1.0015 ± 0.0006*	*NC*	*0.0921*	*NC*
103	*MCT004 (6.A.22)*	*5.55Pu Lattics, 62.05 cm Water*	*3% Pu*	*1.0000 ± 0.0006*	*NC*	*0.0800*	*NC*
104	*MCT004 (6.A.22)*	*5.55Pu Lattics, 64.53 cm Water*	*3% Pu*	*1.0025 ± 0.0006*	*NC*	*0.0794*	*NC*

Notes: NC stands for not calculated.

† EALF is the energy of the average lethargy causing fission

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

Table 6.A.2

COMPARISON OF MCNP4a AND KENO5a CALCULATED REACTIVITIES†
FOR VARIOUS ENRICHMENTS (UO_2)

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 MPC-68 with the GE 8x8R

Table 6.A.3

MCNP4a CALCULATED REACTIVITIES FOR
CRITICAL EXPERIMENTS WITH NEUTRON ABSORBERS (UO_2)

Ref.	Experiment		Δk Worth of Absorber	MCNP4a Calculated k_{eff}	EALF† (eV)
6.A.13	PNL-2615	Boral Sheet	0.0139	0.9994 ± 0.0012	0.1165
6.A.7	BAW-1484	Core XX	0.0165	1.0008 ± 0.0011	0.1724
6.A.13	PNL-2615	1.62% Boron-steel	0.0165	0.9996 ± 0.0012	0.1161
6.A.7	BAW-1484	Core XIX	0.0202	0.9961 ± 0.0012	0.2103
6.A.7	BAW-1484	Core XXI	0.0243	0.9994 ± 0.0010	0.1544
6.A.7	BAW-1484	Core XVII	0.0519	0.9962 ± 0.0012	0.2083
6.A.11	PNL-3602	Boral Sheet	0.0708	0.9941 ± 0.0011	0.3135
6.A.7	BAW-1484	Core XV	0.0786	0.9910 ± 0.0011	0.2092
6.A.7	BAW-1484	Core XVI	0.0845	0.9935 ± 0.0010	0.1757
6.A.7	BAW-1484	Core XIV	0.1575	0.9953 ± 0.0011	0.2022
6.A.7	BAW-1484	Core XIII	0.1738	1.0020 ± 0.0011	0.1988
6.A.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 6.A.4
COMPARISON OF MCNP4a AND KENO5a
CALCULATED REACTIVITIES† FOR VARIOUS BORON LOADINGS (UO_2)

^{10}B, g/cm^2	Calcualted $k_{eff} \pm 1\sigma$	
	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
0.030	0.9325 ± 0.0011	0.9338 ± 0.0004
0.035	0.9234 ± 0.0011	0.9251 ± 0.0004
0.040	0.9173 ± 0.0011	0.9179 ± 0.0004

† based on 4.5% enrichment GE 8x8R in the MPC-68 cask.

Table 6.A.5

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH THICK LEAD AND STEEL REFLECTORS† (UO_2)

Ref.	Case	Enrichment, wt%	Separation, cm	MCNP4a k_{eff}	KENO5a k_{eff}
6.A.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
6.A.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
6.A.11	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 6.A.6

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH VARIOUS SOLUBLE BORON CONCENTRATIONS (UO_2)

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

Table 6.A.7

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH MOX FUEL

Reference	Case†	MCNP4a		KENO 5a	
		k_{eff}	EALF†† (eV)	k_{eff}	EALF†† (eV)
PNL-5803 [6.A.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 [6.A.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

† Arranged in order of increasing lattice spacing.

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

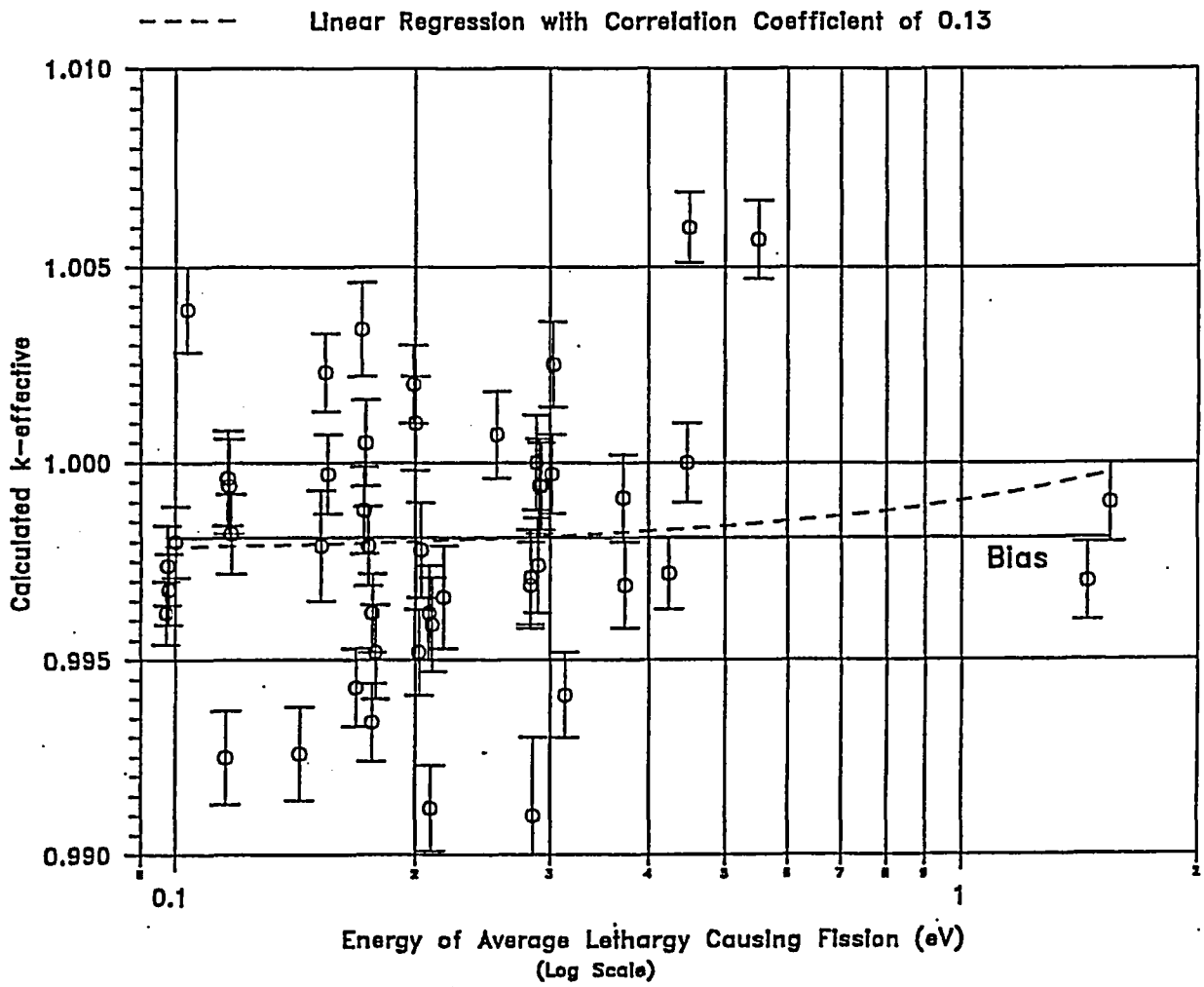

FIGURE 6.A.1 MCNP4a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

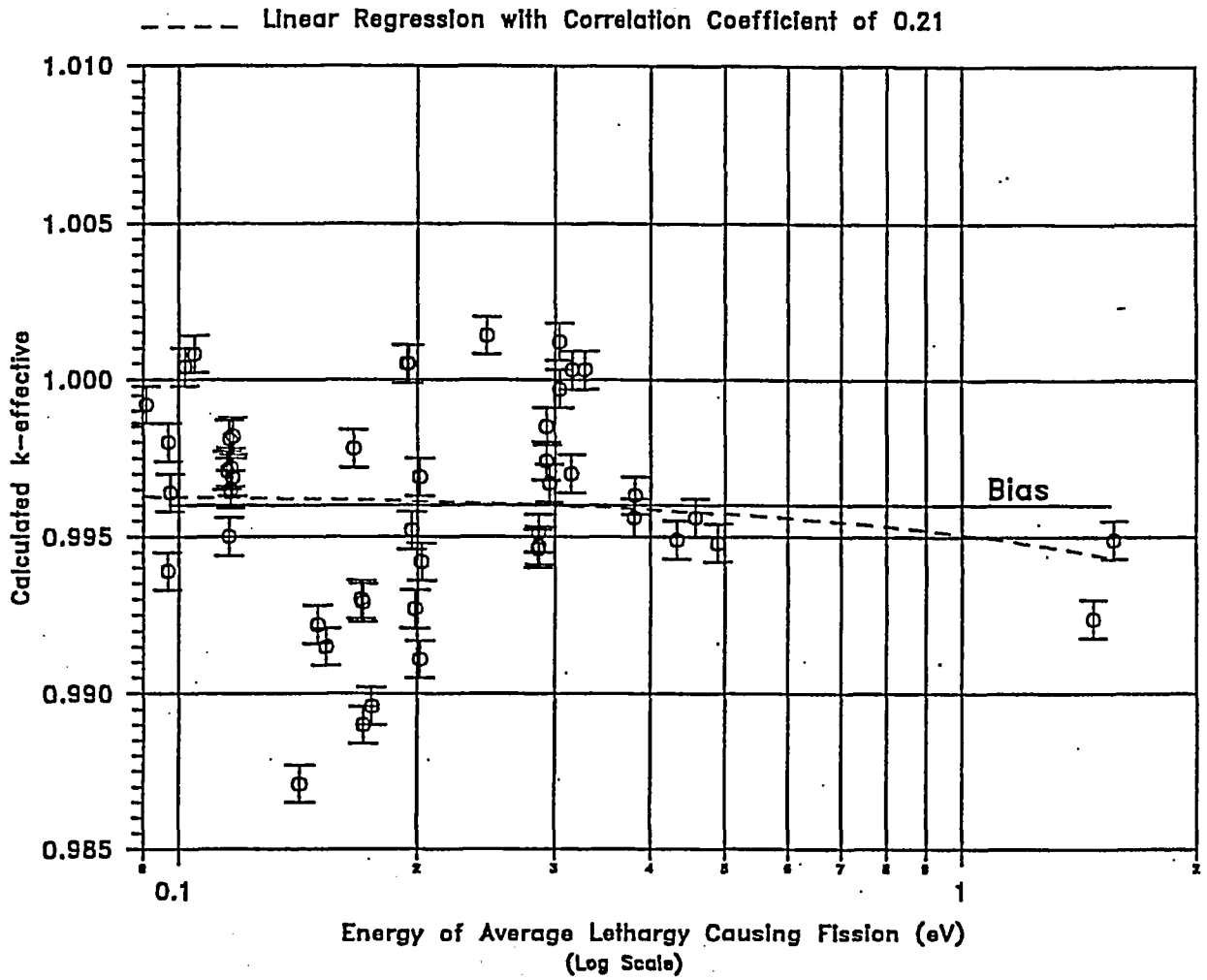

FIGURE 6.A.2 KENO5a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

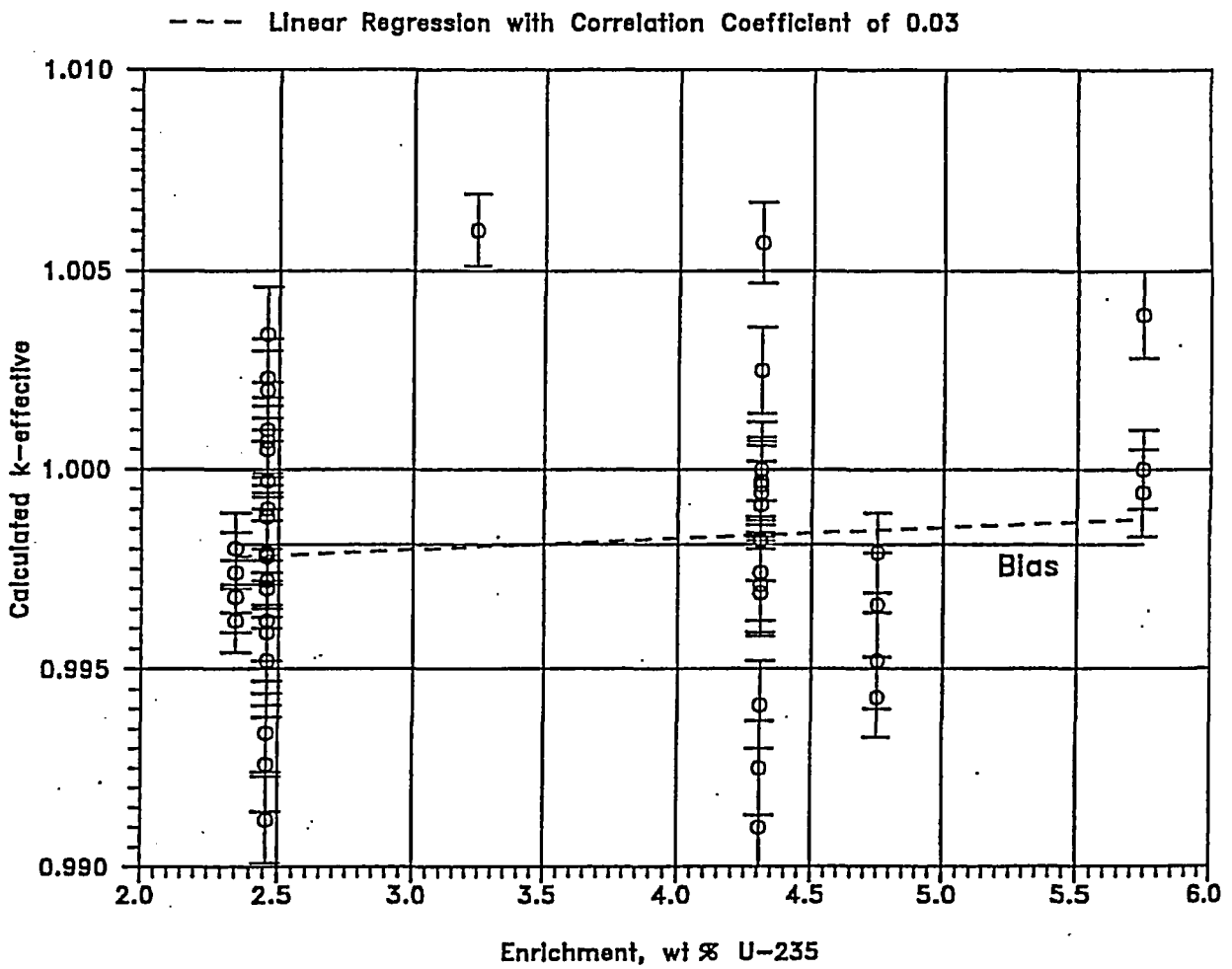

FIGURE 6.A.3 MCNP4a CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

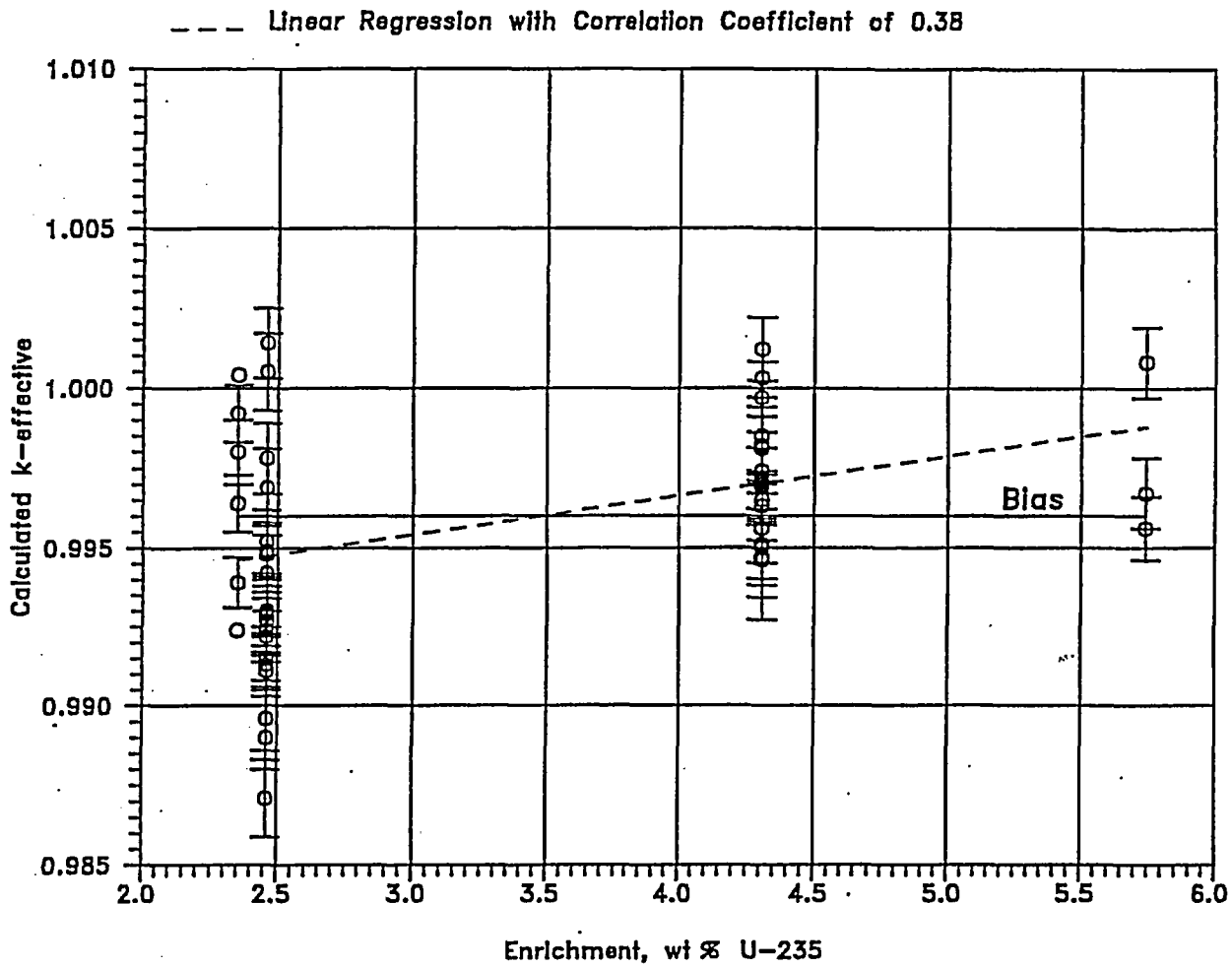

FIGURE 6.A.4 KENO5a CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

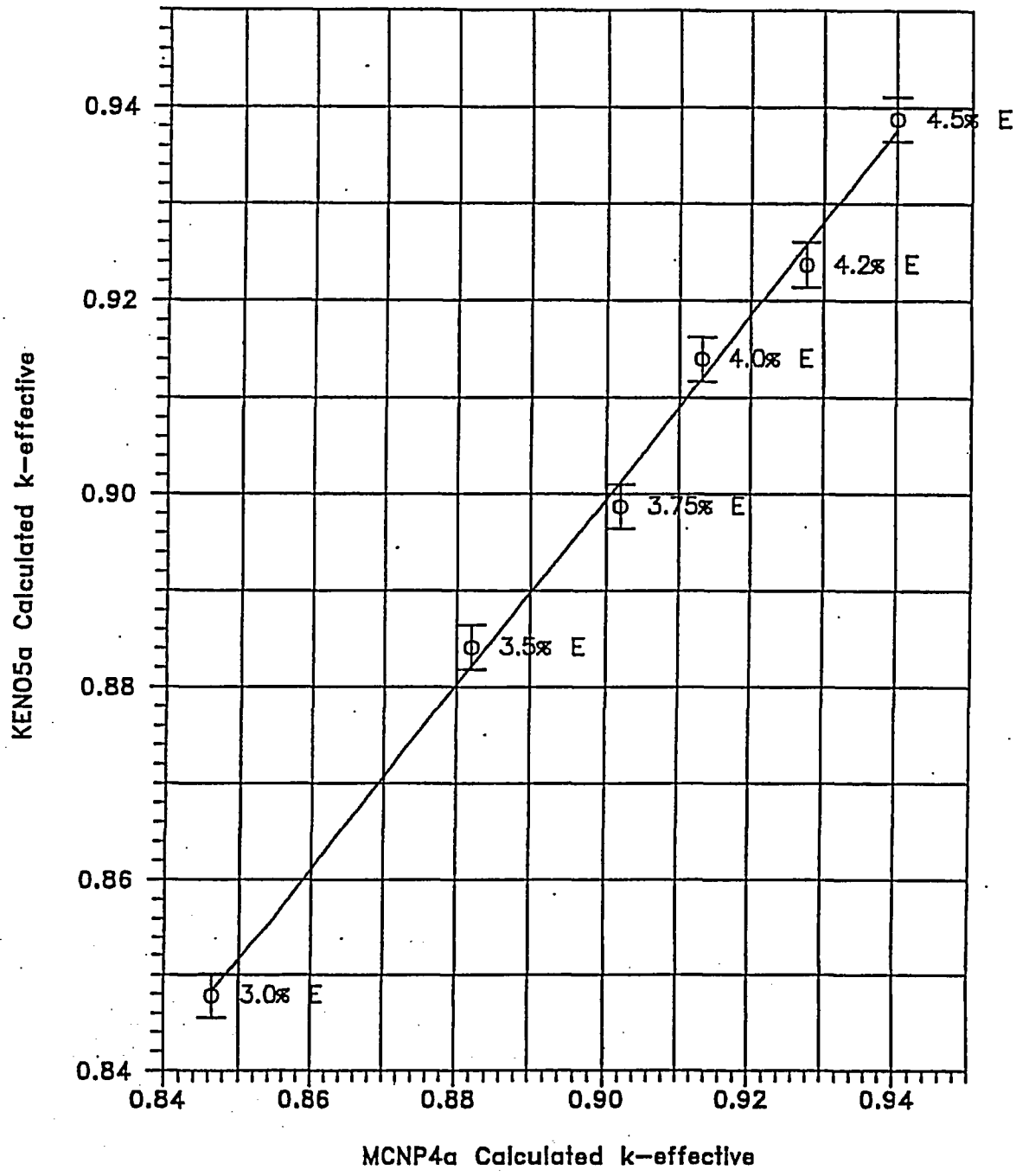

FIGURE 6.A.5 COMPARISON OF MCNP4a AND KENO5a CALCULATIONS FOR VARIOUS FUEL ENRICHMENTS

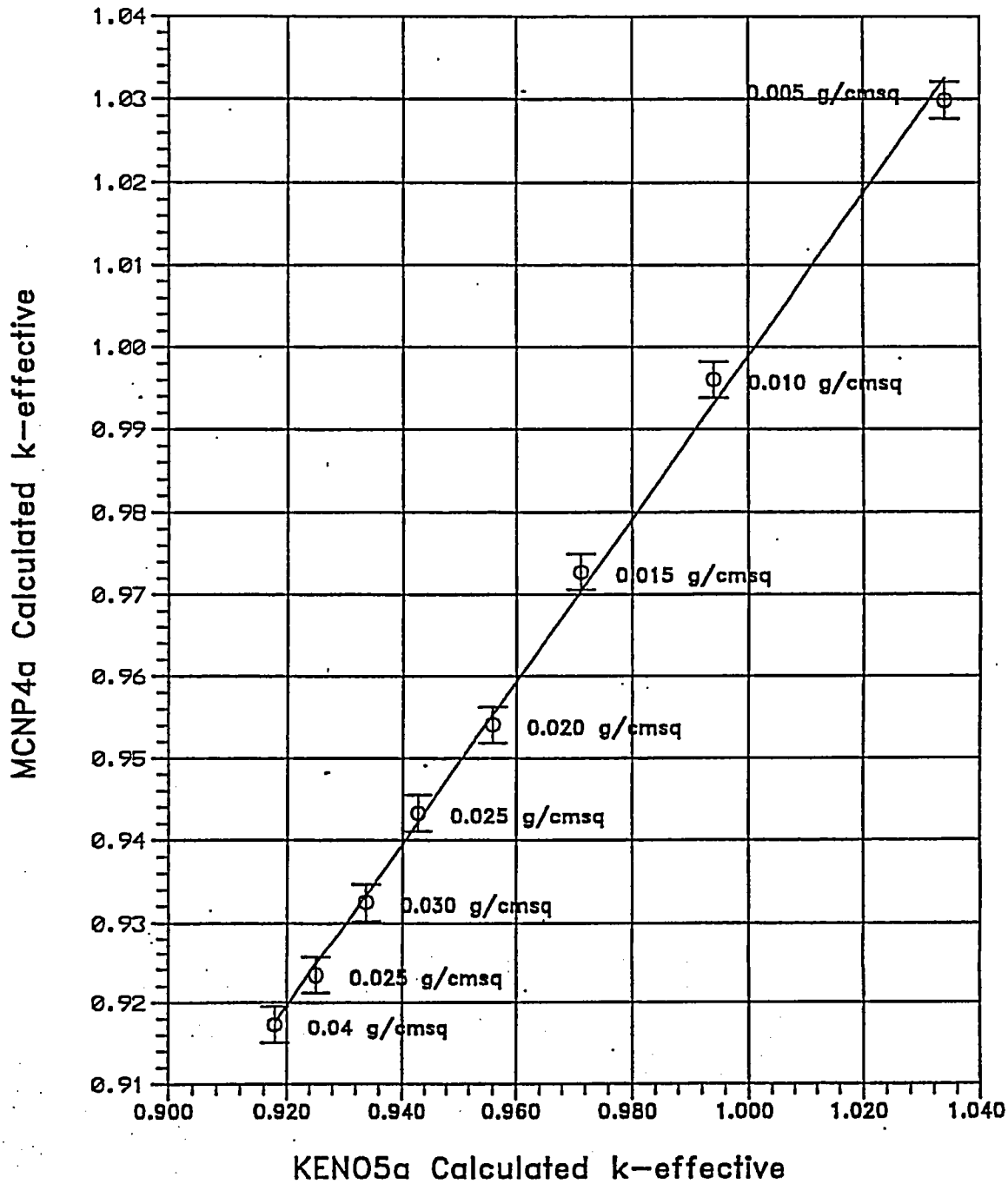

FIGURE 6.A.6 COMPARISON OF MCNP4a AND KENO5a CALCULATIONS FOR VARIOUS BORON-10 AREAL DENSITIES

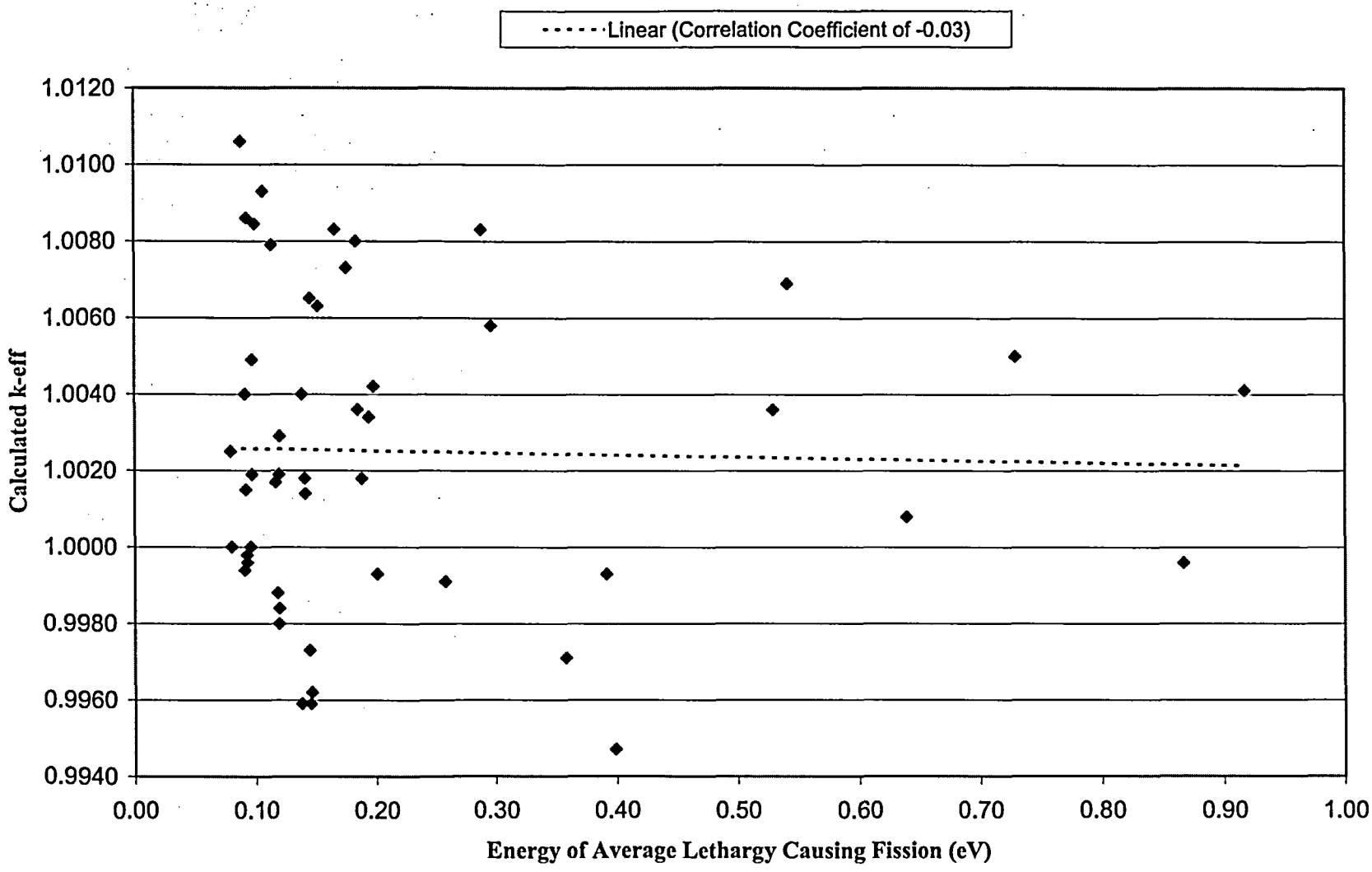

Figure 6.A.7: MCNP4a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX