CRITICALITY CODE VALIDATION FOR BORATED PLATES

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ABSTRACT

Critical experiments with boral or borated steel plates from the International Handbook of Evaluated Criticality Safety Benchmark Experiments have been used to validate codes for nuclear criticality safety. Thirty-nine experiments from five benchmark evaluations with lattices of low-enriched uranium rods and borated plates are included in this study. The experimental arrangements contained arrays of low enriched uranium (2.35 to 4.7% ^{235}U) UO_2 pins in square lattices. Three of the five sets of experiments were done in the Critical Mass Laboratory at the Pacific Northwest Laboratories and two at the "Service de Recherches et d'Etudes en Criticite" in Valduc France. Some of the measurements had stainless steel plates with a few percent boron impurity and some had boral plates. Validation was done for SCALE 4.4 with the CSAS25 sequence (BONAMI, NITAWL and KENO-Va) with the 27-group ENDF/B-IV and the 238-group ENDF/B-V cross section libraries and with MCNP-4b with the continuous energy ENDF/B-V and ENDF/B-VI cross section sets. The average k_{eff} values, both weighted by the benchmark and Monte Carlo uncertainties, and unweighted, the variance and a lower tolerance limit were calculated for the 39 benchmark experiments containing boron. Criticality limits were calculated and compared with limits from another study for low enriched uranium fuels with enrichments in the range for 2 to 10%.

1. INTRODUCTION

Metal plates containing boron are sometimes used in spent fuel storage racks and in fissile fuel shipping containers. A few critical experiments with boral or borated steel plates have been included in the International Handbook of Evaluated Criticality Safety Benchmark Experiments[1]. This paper includes descriptions of the benchmark critical experiments and generation of code bias values for metal plates with boron.

Boral plates were used in many of the critical measurements. Boral plates contain a core of B_4C-Al between two sheets of an aluminum alloy. Some of the critical experiments include steel with a few percent boron, and one includes boroflex, a borated rubber material. The boron content is often characterized by the surface density, grams-boron/cm^2 or grams-^{10}B/cm^2. In this paper several other parameters to characterize the boron content will be considered, for example the ratio of the linear density of ^{10}B to ^{235}U (^{10}B per cm/^{235}U per cm) and the reactivity effect of ^{10}B (the computed change in k_{eff} when ^{10}B is removed from the system).

Upper subcritical limits and lower tolerance limits (LTL) have been calculated for SCALE 4.4 with the 27-group and the 238-group cross section sets and for MCNP-4b with ENDF/B-V and ENDF/B-VI cross section sets. These limits are values above which the true population of k_{eff} benchmark calculations is expected to lie. The LTL values are calculated for comparison only since the data sets do not test to be normally distributed. The LTL values for the four combinations of code packages and cross section sets are all within 0.3% of each other. The upper subcritical limits with boron plates are compared with lower tolerance limits for low enriched uranium pins in lattice arrangements similar to many of the boron plate lattices. This comparison suggests that an additional 1.5 % margin is appropriate for situations that include borated steel or boral plates in a lattice. This recommendation is applicable for conditions listed below. Several parameters are listed for the boron content. It is intended that any one of the three may be used.

Boron Content	
^{10}B surface density	0.0 – 0.067 g ^{10}B /cm^2
^{10}B to ^{235}U mass ratio	0.0 – 0.080 g ^{10}B /g ^{235}U
Boron reactivity worth	0.0 – 0.22 Δk_{eff}
Other conditions	
Neutron spectrum	Thermal

The upper subcritical limit and margin in k_{eff} for boron plates in an array is calculated from a set of critical experiments with low enriched uranium pins in a water-moderated system. Because the neutron spectrum is well thermalized, it is believed that the uranium enrichment is not an important characteristic and it is recommended that this study is applicable to systems with ^{235}U of all enrichments in well-moderated configurations with no other neutron absorbers.

2. CRITICAL BENCHMARKS

Five benchmark evaluations with lattices of low-enriched uranium rods and borated plates are included in this study, LEU-COMP-THERM (LCT) 009, 016, 034, 040 and 042. Most of these evaluations were approved by the benchmark reviewing committee in meetings in January 1999 and June 1999 and were not in the published handbook when this validation was done (August 1999). They are in the September 1999 edition of the handbook. Thirty-nine experiments with boron containing plates and five with steel plates are included in this analysis. Three of the five sets of experiments were done in the Critical Mass Laboratory at the Pacific Northwest Laboratories (PNL) and two were done at the experimental critical facility at the “Service de Recherches et d’Etudes en Criticite” in Valduc France. A brief description of each set of experiments follows.

2.1 LEU-COMP-THERM-009 Water-Moderated Rectangular Clusters of $U(4.31)O_2$ Fuel Rods (2.54-cm Pitch) Separated by Steel, Boral, Copper, Cadmium, Aluminum, or Zircalloy-4 Plates

This evaluation includes 27 benchmark experiments done at the Critical Mass Laboratory at the Pacific Northwest Laboratory. Eight experiments with steel, borated steel or boral plates are included in this study. The experimental configuration consisted of three 15X8 arrays of UO_2 pins in a square lattice with 2.54-cm pitch. Each pin has a 1.265-cm diameter UO_2 region and 1.415-cm outer clad diameter. The three 15X8 arrays were aligned in a row with the absorber plates and water gaps in the two spaces between the central array and the two outer arrays. The spacings between the absorber plates and the central array and water gap thickness were varied. Characteristics of each array and absorber plate are in Table 1. In these tables the atom ratio $H/^{235}U$ is the ratio for a unit cell in the square-pitch lattice and does not include the water in the gap between the arrays or reflector water. The ratio $g^{10}B /g^{235}U$ is the mass ratio of ^{10}B in the cuboid defined by the width of the array, the length of three arrays plus twice the array separation, and the active fuel height, and the ^{235}U in the three arrays. The ^{10}B surface density, g/cm^2, is the ^{10}B mass density times the active plate thickness. For the boral plates the active thickness does not include the aluminum clad. The benchmark evaluation contained sample KENO and MCNP input files for one case. These files were checked against the benchmark models and additional input files constructed. The benchmark models for all of the cases in this evaluation had $k_{eff} = 1.0000 \pm 0.0021$.

Table 1
LEU-COMP-THERM-009
UO_2 Fuel Rods at 4.31 % Enrichment in 15X8-Rod Arrays with 2.54-cm Pitch

Case	Absorber	Array Separation	Boron	^{10}B	^{10}B / ^{235}U
		Cm	wt %	g/cm^2	
1	Steel	8.58	0.00	0.00	0.00
2	Steel	9.65	0.00	0.00	0.00
3	Steel	9.22	0.00	0.00	0.00
4	Steel	9.76	0.00	0.00	0.00
5	SS 1.1%B	6.10	1.05	0.0046	0.0019
6	SS 1.1%B	8.08	1.05	0.0046	0.0019
7	SS 1.6%B	5.76	1.62	0.0069	0.0030
8	SS 1.6%B	7.90	1.62	0.0069	0.0030
9	Boral	6.72	28.7	0.0670	0.0286

2.2 LEU-COMP-THERM-016 Water-Moderated Rectangular Clusters of U(2.35)O_2 Fuel Rods (2.032-cm Pitch) Separated by Steel, Boral, Copper, Cadmium, Aluminum or Zircaloy-4 Plates

This evaluation includes 32 benchmark experiments done at the Critical Mass Laboratory at the Pacific Northwest Laboratory. Fourteen experiments with steel, borated steel, and boral are included in this study. The experimental configuration consisted of three arrays of UO_2 pins in a square lattice with 2.032-cm pitch. The three arrays were lattices of 20X17 pins for eight of the cases and 20X16 for the balance. Each pin has a 1.1176-cm diameter UO_2 region and 1.27-cm outer clad diameter. The three arrays were aligned in a row with the absorber plates and water gaps in the two spaces between the central array and the two outer arrays. The spacings between the absorber plates and the central array and water gap thickness were varied. Characteristics of each array and absorber plate are in Table 2. The benchmark evaluation handbook contained sample KENO and MCNP input files for all cases. These files were checked against the benchmark models and used as is. The benchmark models for all of the cases in this evaluation had k_{eff} = 1.0000 ± 0.0031.

Table 2
LEU-COMP-THERM-016
UO_2 Fuel Rods at 2.35 % Enrichment in Arrays with 2.032-cm Pitch

Case	Absorber	Array	Array Separation.	Boron	^{10}B	^{10}B /^{235}U
			Cm	wt%	g/cm^2	
1	Steel	20X16	6.88	0.00	0.00	0.00
2	Steel	20X16	7.64	0.00	0.00	0.00
3	Steel	20X16	7.51	0.00	0.00	0.00
4	Steel	20X16	7.42	0.00	0.00	0.00
5	Steel	20X16	7.76	0.00	0.00	0.00
6	Steel	20X17	10.44	0.00	0.00	0.00
7	Steel	20X17	11.47	0.00	0.00	0.00
8	SS 1.1%B	20X17	7.56	1.05	0.0046	0.0017
9	SS 1.1%B	20X17	9.62	1.05	0.0046	0.0017
10	SS 1.6%B	20X17	7.36	1.62	0.0069	0.0025
11	SS 1.6%B	20X17	9.52	1.62	0.0069	0.0025
12	Boral	20X17	6.33	28.7	0.0670	0.0243
13	Boral	20X17	9.03	28.7	0.0670	0.0243
14	Boral	20X16	5.05	28.7	0.0670	0.0243

2.3 LEU-COMP-THERM-034 Four 4.738 % Enriched Uranium Dioxide Rod Assemblies Contained in Cadmium, Borated Stainless Steel or Boral Square Canister Water Moderated and Reflected

This evaluation includes 26 benchmark experiments done at the experimental critical facility at the “Service de Recherches et d’Etudes en Criticite” in Valduc France. Fourteen experiments with borated steel and boral are included in this study. The experimental configuration consisted of four arrays of UO_2 pins in a square lattice with 1.6-cm pitch. Tie rods or instrument channels replaced the four corner pins. Each array consisted of an 18X18 lattice of pins enclosed on the four vertical sides by absorber plates. The four arrays were arranged in a square with a variable water gap between each array and the critical water height was measured for each case. The fuel pins had a 0.79-cm fuel diameter and 0.82-cm outer clad diameter. Characteristics of each array and absorber plate are in Table 3. The benchmark evaluation handbook contained sample input files for the French Monte Carlo code MORET IV. KENO and MCNP input files were constructed for all cases. The benchmark models for the cases in this evaluation had k_{eff} = 1.0000 with uncertainties ranging from 0.0038 to 0.0048.

Table 3
LEU-COMP-THERM-034
UO_2 Fuel Rods at 4.738 % Enrichment in 18X18-Rod Arrays with 1.6-cm Pitch

Case*	Absorber	Water gap	Water Height	Boron	^{10}B	Mass Ratio
		Cm	Cm	wt %	g/cm^2	g^{10}B /g^{235}U
1	SS 1.1% B	0.6	34.33	1.1	0.0025	0.0043
2	SS 1.1% B	1.0	36.54	1.1	0.0025	0.0043
3	SS 1.1% B	2.0	40.01	1.1	0.0025	0.0043
4	SS 1.1% B	3.0	47.15	1.1	0.0025	0.0043
5	SS 1.1% B	4.0	53.87	1.1	0.0025	0.0043
6	SS 1.1% B	5.0	62.86	1.1	0.0025	0.0043
7	SS 1.1% B	6.0	70.73	1.1	0.0025	0.0043
8	SS 1.1% B	7.0	80.66	1.1	0.0025	0.0043
10	Boral	0.3	51.74	22.20	0.0461	0.0799
11	Boral	0.5	53.01	22.20	0.0461	0.0799
12	Boral	1.0	57.43	22.20	0.0461	0.0799
13	Boral	1.5	66.15	22.20	0.0461	0.0799
14	Boral	2.0	72.96	22.20	0.0461	0.0799
15	Boral	2.5	84.14	22.20	0.0461	0.0799

*Cases 9 and 16 in LCT034 are not considered acceptable as benchmarks.

2.4 LEU-COMP-THERM-040 Four 4.738 % Enriched Uranium Dioxide Rod Assemblies Contained in Borated Stainless Steel or Boral Square Canisters, Water Moderated and Reflected by Lead or Steel.

This evaluation includes 10 benchmark experiments done at the experimental critical facility at the “Service de Recherches et d’Etudes en Criticite” in Valduc France. All ten experiments with borated steel and boral are included in this study. The experimental arrangement was the same as in LCT034. This study featured the lead and steel reflectors. The array consisted of four lattices of UO_2 pins in a square array with 1.6-cm-pitch. Tie rods or instrument channels replaced the four corner pins. Each array consisted of an 18X18 lattice of pins enclosed on the four vertical sides by absorber plates. The four arrays were arranged in a square with a water gap between the arrays and the reflectors. For all cases the water gap was 2.0 cm. The critical water height was measured for each case. The fuel pins had a 0.79-cm fuel diameter and 0.82-cm outer clad diameter. Characteristics of each array and absorber plate are in Table 4. The benchmark evaluation handbook contained sample input files for the French Monte Carlo code MORET IV. KENO and MCNP input files were constructed for all cases. The benchmark models for the cases in this evaluation had k_{eff} = 1.0000 with uncertainties ranging from 0.0038 to 0.0045.

Table 4
LEU-COMP-THERM-040
UO_2 Fuel Rods at 4.738 % Enrichment in 18X18-Rod Arrays with 1.6-cm Pitch

Case	Reflector	Absorber	Water Height	Boron	^{10}B	Mass Ratio
			Cm	Wt %	g/cm^2	$g^{10}B / g^{235}U$
1	Water	SS 1.1% B	40.01	1.1	0.0025	0.0043
2	Lead	SS 1.1% B	33.04	1.1	0.0025	0.0043
3	Lead	SS 1.1% B	36.13	1.1	0.0025	0.0043
4	Lead	SS 1.1% B	37.95	1.1	0.0025	0.0043
5	Water	Boral	72.96	22.20	0.0461	0.0799
6	Lead	Boral	53.98	22.20	0.0461	0.0799
7	Lead	Boral	63.85	22.20	0.0461	0.0799
8	Lead	Boral	69.40	22.20	0.0461	0.0799
9	Steel	Boral	51.55	22.20	0.0461	0.0799
10	Steel	Boral	61.84	22.20	0.0461	0.0799

2.5 LEU-COMP-THERM-042 Water-Moderated Rectangular Clusters of $U(2.35)O_2$ Fuel Rods (1.684-cm Pitch) Separated by Steel, Boral, Boroflex, Cadmium, or Copper Plates, With Steel Reflecting Walls

This evaluation includes 7 benchmark experiments done at the Critical Mass Laboratory at the Pacific Northwest Laboratory. Four experiments with steel, borated steel, boral or boroflex plates are included in this study. The experimental configuration consisted of three arrays of UO_2 pins in a square lattice with 1.684-cm pitch. The central array was a lattice of 25X18 pins and each outer array a lattice of 20X18 pins. Each pin has a 1.1176-cm diameter UO_2 region and 1.27-cm outer clad diameter. The three arrays were aligned in a row with the absorber plates and water gaps in the two spaces between the central array and the two outer arrays. The spacings between the absorber plates and the central array and water gap thickness were varied. Characteristics of each array and absorber plate are in Table 5. The benchmark evaluation contained sample KENO and MCNP input files for one case. These files were checked against the benchmark model and additional input files constructed. The benchmark models for all of the cases in this evaluation had $k_{eff} = 1.0000 \pm 0.0018$.

Table 5
LEU-COMP-THERM-042
UO_2 Fuel Rods at 2.35 % Enrichment in Rod Arrays with 1.684-cm Pitch

Case	Absorber	Array Separation	Boron	^{10}B	^{10}B / ^{235}U
		cm	Wt%	g/cm^2	
1	Steel	8.28	0.00	0.00	0.00
2	SS 1.1 %B	4.80	1.05	0.0046	0.0013
3	Boral	2.69	30.36	0.0302	0.0084
4	Boroflex	2.98	32.74	0.0236	0.0065

3. BENCHMARK ANALYSIS

The benchmark cases were run on Digital Equipment Alpha workstations. Cases were run in SCALE 4.4 with the CSAS25 sequence (BONAMI, NITAWL and KENO-Va) with the 27-group ENDF/B-IV and the 238-group ENDF/B-V cross section libraries and with MCNP-4b with the continuous energy ENDF/B-V and ENDF/B-VI cross section sets. For the experiments in LCT009, 016 and 042, sample input files were provided by the evaluators for one case. That file was checked against the benchmark model and additional input files constructed. For the experiments in LCT034 and 040, no KENO or MCNP input files were provided by the evaluators. In all cases material properties were input as atom densities from the benchmark evaluations. In MCNP with ENDF/B-V cross sections the iron cross section 26000.50c was used in all cases. The computed k_{eff} values are in Appendix A.

There are a few trends in the data. In LCT034 there is a trend of decreasing k_{eff} with increased water gap spacing between the lattices. For the borated steel cases, k_{eff} decreases about 0.5% as the water gap increases to 7.0 cm. For the boral plates the decrease in computed k_{eff} is about 1% as the spacing increases to 2.5 cm. There may also be a trend of decreasing k_{eff} with increasing water height in both LCT034 and 040, although the “trend” is dominated by four experiments with the smallest water gaps. The authors of the evaluations note that those experiments with small water gaps are sensitive to the positions of the absorber plates and assign higher uncertainties to these measurements. Also the measurements with lead reflectors in LCT040 tend to calculate lower than the other measurements. These trends are more pronounced with the 27-group cross sections in SCALE than the ENDF/B-V in MCNP. All of the experiments in LCT034 and 040 have the average neutron energy causing fission in a very narrow range and there is not an obvious trend with neutron energy. This implies that the neutron spectrum is not much different among these lattices, even though, with variable water height, some part of the fuel pins is out of the water. The arrangement in LCT034 and 040 is four close lattices in a square, each lattice surrounded by an absorber plate. There are no similar trends in the computed k_{eff} value with water spacing in the PNL measurements, a different lattice arrangement. An attempt to correlate these trends with a useful parameter was not successful and so we are left with a word of caution about the use of boron in absorber plates in lattices with large spacing between units.

In LCT016 the cases 9, 11 and 13 are very little affected by the boron, i.e. the ^{10}B Δk is low. In these three cases the array separation is about 9 cm. The combination of water and boron apparently enhances the isolation of each array so that the boron is less effective. In LCT009 case 6 also has a large spacing between the lattices and the boron change in reactivity is relatively low.

Several average values of k_{eff} calculated for these cases are listed in Table 6. These are unweighted averages (not weighted by the experimental and calculated uncertainties) and are reported with typical standard deviations of the mean of the population.

In another study a set of low enriched uranium (LEU) benchmark experiments from Reference 1 was used for criticality code validation. Many of the experiments were done at PNL with the same pins and lattices as those in the PNL boron measurements. The results for the experiments with LEU fuel (2 to 5 % enriched) are included in the last row of Table 6 as a comparison to similar measurements without absorber plates.

The range of k_{eff} values from the lowest to the highest in Table 6 for one code system and cross section (that is in one column) is 0.0036 which is about the same as the standard deviation from the mean for any set of data. Thus it is hazardous to draw conclusions from any differences in the average k_{eff} values. One thing that could be said is that all of these critical experiments calculate about the same with one code set (SCALE or MCNP). This implies that the bias does not depend on the presence of boron in absorber plates for these cases and it doesn't matter whether the boron is in steel plates or in boral plates. The most extreme values for the two cross-section sets in SCALE are between the French measurements and the PNL measurements. The average k_{eff} values for the French measurements are among the highest for both cross sections in MCNP.

Table 6
Average k_{eff} Values

		SCALE		MCNP		
	# cases	27 gp	238 gp	endf/b-v	Endf/b-vi	1. S.d.
All Cases	51	0.9944	0.9947	0.9974	0.9932	0.0031
Boron Only	39	0.9948	0.9948	0.9980	0.9938	0.0034
Boral	18	0.9945	0.9946	0.9970	0.9931	0.0038
Boron SS	21	0.9950	0.9950	0.9989	0.9944	0.0031
SS Only	12	0.9932	0.9941	0.9953	0.9913	0.0015
PNL	15	0.9932	0.9934	0.9977	0.9925	0.0021
French	24	0.9958	0.9957	0.9983	0.9946	0.0037
LEU	51	0.9957	n.a.	0.9986	n.a.	0.0040

4. BIAS CALCULATION FOR CRITICAL EXPERIMENTS

The 39 benchmark experiments with boron were included in the bias and lower limit analysis. Plots were made of the computed k_{eff} values against the ^{10}B-to-^{235}U mass ratio, against the boron surface density, g ^{10}B /cm^2, and against the reactivity worth of boron, Δk_{eff} with ^{10}B removed from the absorber plate. None of the linear least squares fits to the data was "good", i. e. the coefficient of goodness of fit, r^2, was never better than 0.1. Although the fits were not good, there were no obvious trends to the data. The slopes of the linear fits were small and, in general, the standard error of the slope was such that the range included a slope value of zero. This was true for both the SCALE 27-group and the MCNP ENDF/B-V calculations, the only ones for which these plots were made.

One concern with metal plates containing boron is that, in high boron concentrations, there may be a boron self-shielding effect. This would make the boron less effective in practice than in the calculations, which is not conservative for nuclear criticality. If there were a self-shielding effect in these benchmark experiments, it would appear as a trend of lower computed multiplication with higher boron loading. No such trend is apparent in this data, however the user is cautioned about extending the applicability of this evaluation to higher boron concentrations.

The Shapiro-Wilk test for a normal distribution was used for the 39 cases with boron. Only the MCNP ENDF/B-V results tested normal with a test result of 0.945 compared to test criteria of 0.938. None of the other data sets, MCNP ENDF/B-VI or SCALE with either the 27-group or the 238-group cross sections, tested normal. Each of these data sets appears to be a "two humped" distribution with the PNL results in the lower hump and the French results in the other. Neither the French results nor the PNL results individually test normal for all code sets.

The average k_{eff} values, both weighted by the benchmark and Monte Carlo uncertainties, and unweighted, the variance and a lower tolerance limit are listed in Table 7 for the 39 benchmark experiments containing boron. A lower tolerance limit was calculated for the SCALE results and the MCNP with ENDF/B-VI cross sections although the computed k_{eff} values for these sets did not test to be normal distributions. The better approach is the non-parametric calculation to determine an upper subcritical limit. For this approach, the lowest value of k_{eff} is reduced by the bias uncertainty and by the non-parametric margin. For the number of experiments and a 95% confidence the non-parametric margin is 0.01 for these cases. These values are listed in Table 7. The lower tolerance limit for low enriched uranium (LEU) fuels with enrichments in the range for 2 to 10% is also listed in Table 7.

Table 7
Tolerance Limits

	SCALE		MCNP	
	27-group	238-group	endf/b-v	endf/b-vi
Unweighted k_{eff}	0.9948	0.9948	0.9980	0.9938
Weighted k_{eff}	0.9944	0.9944	0.9979	0.9934
Variance	0.0046	0.0046	0.0042	0.0042
U[a]	2.166	2.166	2.166	2.166
LTL – normal dist.	0.985	0.985	0.989	0.984
USL-non parametric	0.975	0.975	0.978	0.976
LTL LEU	0.988	n.a.	0.987	n.a.

[a] One sided lower tolerance factor

One conclusion from this data is that, for MCNP with ENDF/B-V cross sections, the normal data set, the borated absorber plates have the same bias and lower tolerance limit as the LEU validation. For the data sets that are not normal, SCALE with the 27-group and the 238-group cross sections and MCNP with ENDF/B-VI cross sections, the non-parametric upper subcritical limits are essentially the same. The difference between the USL-non parametric and the LTL for the LEU critical experiments is less than 1.5%. This suggests that at least a 1.5% additional margin for borated steel or boral plates is appropriate.

The applicability for boron conditions for these cases is listed in the following table of area of applicability.

AREA OF APPLICABILITY FOR BORATED PLATE ABSORBERS

^{10}B surface density	0.0025 – 0.067 g ^{10}B /cm^2
^{10}B to ^{235}U mass ratio	0.0013 – 0.08 g ^{10}B /g ^{235}U
Boron reactivity worth	0.002 – 0.22 Δk_{eff}
Neutron spectrum	Thermal

Although lower values are listed for the boron characteristics it is apparent that the lower value can be replaced by zero. Three boron characteristics are listed, all of which are related, and it is not intended that all three be specified. These experiments have a narrow range of average energy of neutrons causing fission in the thermal range and the user should be satisfied that the neutrons are well thermalized. No specification is given for the fissile material, i.e. uranium enrichment. It is contended that in a well-thermalized system the fuel characteristics are not important. This contention is based on the fact that the boron cross section is large and well behaved, that is, no resonance structure, and a “1/v” absorber is less sensitive to neutron spectrum changes than other absorbers. The user should take care in cases where there are large water gaps between fuel assemblies as there appears to be a trend in which the codes are non conservative with larger water spacings.

SUMMARY

Critical measurements with boral or borated steel plates have been considered for validation of nuclear criticality codes. The critical experiments are from the International Handbook of Evaluated Criticality Safety Benchmark Experiments and include measurements made at two laboratories.

Thirty-nine critical benchmark experiments containing either borated stainless steel or boral plates were used to generate code bias values for several code systems and cross section sets. All of the experiments were made with low enriched uranium pin lattices and the bias with boron compared to a bias without borated plates. The results indicate that the borated plates in a lattice increases the code bias by no more than 1.5% in uranium systems.

REFERENCES

1) International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03.

APPENDIX A COMPUTED K_{EFF} VALUES

The computed multiplication factors, one standard deviation uncertainties and average energy group for fission for the 27-group energy structure are in Tables A-1-5. Also listed is a ^{10}B Δk, the reactivity difference computed by SCALE with the 27-group cross sections when the isotope ^{10}B is deleted from the absorber.

Table A-1
LCT009 Computed K_{eff} Values

Case	Absorber	MCNP		SCALE		AEG	^{10}B
LCT009		endf/b-v	endf/b-vi	27-group	238-group.	27-group	delta k
1	Steel	0.9973	0.9935	0.9946	0.9941	23.31	0.0
2	Steel	0.9965	0.9909	0.9945	0.9973	23.32	0.0
3	Steel	0.9937	0.9909	0.9936	0.9953	23.31	0.0
4	Steel	0.9946	0.9938	0.9940	0.9938	23.32	0.0
5	SS-B	1.0006	0.9933	0.9963	0.9950	23.30	0.010
6	SS-B	0.9983	0.9899	0.9924	0.9917	23.30	0.007
7	SS-B	1.0006	0.9940	0.9958	0.9954	23.30	0.005
8	SS-B	1.0000	0.9926	0.9960	0.9945	23.28	0.012
9	Boral	0.9978	0.9926	0.9948	0.9966	23.29	0.018

(All have one standard deviations between 0.001 and 0.002)

Table A-2
LCT016 Computed K_{eff} Values

Case	Absorber	MCNP		SCALE		AEG	^{10}B
LCT016		endf/b-v	endf/b-vi	27-group	238-group.	27-group	delta k
1	Steel	0.9974	0.9899	0.9930	0.9926	23.56	0.0
2	Steel	0.9960	0.9918	0.9892	0.9904	23.56	0.0
3	Steel	0.9979	0.9946	0.9927	0.9942	23.56	0.0
4	Steel	0.9933	0.9917	0.9925	0.9954	23.57	0.0
5	Steel	0.9929	0.9886	0.9921	0.9937	23.58	0.0
6	Steel	0.9954	0.9896	0.9934	0.9950	23.56	0.0
7	Steel	0.9944	0.9918	0.9945	0.9942	23.56	0.0
8	SS-B	0.9973	0.9937	0.9921	0.9929	23.56	0.011
9	SS-B	0.9966	0.9946	0.9931	0.9914	23.56	0.002
10	SS-B	0.9963	0.9917	0.9927	0.9902	23.54	0.006
11	SS-B	0.9972	0.9915	0.9901	0.9938	23.55	0.005
12	Boral	0.9974	0.9913	0.9899	0.9920	23.53	0.032
13	Boral	0.9964	0.9915	0.9952	0.9933	23.55	0.008
14	Boral	0.9967	0.9931	0.9899	0.9941	23.54	0.035

(All have one standard deviations between 0.001 and 0.002)

Table A-3
LCT034 Computed K_{eff} Values

Case	Absorber	MCNP		SCALE		AEG	^{10}B
LCT034		endf/b-v	endf/b-vi	27-group	238-group.	27-group	delta k
1	SS-B	1.0043	1.0017	1.0009	1.0013	22.86	0.099
2	SS-B	1.0062	1.0019	1.0020	1.0031	22.89	0.105
3	SS-B	0.9966	0.9938	0.9938	0.9940	22.94	0.112
4	SS-B	1.0002	0.9963	0.9978	0.9979	23.00	0.112
5	SS-B	0.9996	0.9953	0.9970	0.9973	23.03	0.108
6	SS-B	1.0029	0.9974	0.9987	0.9986	23.07	0.101
7	SS-B	0.9995	0.9980	0.9971	0.9962	23.08	0.095
8	SS-B	1.0010	0.9962	0.9965	0.9963	23.10	0.089
10	Boral	1.0001	0.9982	1.0021	1.0023	22.91	0.192
11	Boral	0.9999	0.9970	1.0010	1.0020	22.91	0.198
12	Boral	0.9974	0.9936	0.9968	0.9965	22.93	0.205
13	Boral	0.9993	0.9947	0.9964	0.9974	22.96	0.214
14	Boral	0.9958	0.9919	0.9920	0.9920	22.98	0.221
15	Boral	0.9941	0.9917	0.9916	0.9916	23.00	0.220

(All have one standard deviations between 0.0003 and 0.0007)

Table A-4
LCT040 Computed K_{eff} Values

Case	Absorber	MCNP		SCALE		AEG	^{10}B
LCT040		endf/b-v	endf/b-vi	27-group	238-group.	27-group	delta k
1	SS-B	0.9965	0.9922	0.9938	0.9942	22.94	0.112
2	SS-B	0.9957	0.9922	0.9925	0.9937	22.76	0.100
3	SS-B	0.9954	0.9922	0.9916	0.9925	22.82	0.112
4	SS-B	0.9958	0.9921	0.9923	0.9926	22.86	0.113
5	Boral	0.9952	0.9908	0.9922	0.9923	22.98	0.221
6	Boral	0.9993	0.9966	0.9978	0.9975	22.90	0.205
7	Boral	0.9961	0.9922	0.9928	0.9922	22.94	0.222
8	Boral	0.9960	0.9915	0.9917	0.9919	22.96	0.223
9	Boral	0.9996	0.9946	1.0001	0.9951	22.89	0.192
10	Boral	0.9918	0.9922	0.9910	0.9895	22.94	0.217

(All have one standard deviations between 0.0003 and 0.0007)

Table A-5
LCT042 Computed K_{eff} Values

Case	Absorber	MCNP		SCALE		AEG	^{10}B
LCT042		endf/b-v	endf/b-vi	27-group	238-group.	27-group	delta k
1	Steel	0.9943	0.9881	0.9945	0.9936	22.76	0.0
2	SS-B	0.9964	0.9926	0.9934	0.9934	22.70	0.031
3	Boral	0.9965	0.9926	0.9928	0.9932	22.64	0.072
4	Boroflex	0.9975	0.9926	0.9929	0.9927	22.65	0.072

(All have one standard deviations between 0.001 and 0.002).