CRITICALITY SAFETY EVALUATION OF THE

FT. CALHOUN SPENT FUEL STORAGE RACKS

FOR MAXIMUM ENRICHMENT CAPABILITY

Prepared for the

OMAHA PUBLIC POWER DISTRICT

by

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1.0 INTRODUCTION and SUMMARY

The Ft. Calhoun spent fuel storage racks were originally designed[1] to accommodate fresh fuel of 4.2% enrichment in Region 1 or spent fuel of 4.2% initial enrichment burned to 32 MWD/KgU in Region 2, using Boral as the poison material. There was an appreciable margin available below the NRC Regulatory limit and the present study was undertaken to upgrade the capability of the racks to accommodate fuel of higher enrichments. The previous criticality safety evaluation had established that:

- Westinghouse fuel results in a higher reactivity than the fuel manufactured by either Combustion Engineering or ANF,
- the temperature and void coefficients of reactivity are negative, and
- the reactivity effect of eccentric fuel positioning is negative.

In the present evaluation, the analyses were extended to (1) assess the maximum enrichment capability of the racks and (2) to evaluate the additional reactivity control required to enable the racks to safely accommodate fuel with enrichments up to 5%. Result of the analyses established that Region 1 of the racks can safely accommodate fuel of 4.75% enrichment with a maximum reactivity within USNRC Guidelines ($\leq$0.95 k_{eff}), without any restrictions. For fuel with enrichments greater than 4.75%, there are three possible restrictions for storage in Region 1, any one of which will assure the maximum k_{eff} (95% probability, 95% confidence level) will be maintained less than the regulatory limit under normal storage conditions. These include (1) the presence of soluble boron in the pool water, (2) checkerboarding of fuel assemblies, and (3) credit for very limited fuel burnup. In Region 2, credit for burnup was included, extending the previous burnup limit curve to encompass fuel up to 5% enrichment. In addition, the criticality safety evaluation included (1) the use of existing spent control rods (CEA's) in Region 2 and (2) the consequence of postulated accident conditions in both storage regions.

For each region, the reactivity uncertainty associated with manufacturing tolerances and calculational uncertainties were re-evaluated for the higher enrichment fuel and found to be essentially the same as that from the previous analysis[1].

Based upon the criticality safety analyses reported here, the following conclusions may be made:

Any one of the following criteria are acceptable for determining the safe storage of fuel in Region 1:

- **Fuel assemblies with an enrichment of 4.75% or less, or**
- **Fuel assemblies with enrichments up to 5.0%, provided a minimum soluble boron concentration of 75 ppm or more is maintained, or**
- **Fuel assemblies with enrichments up to 5.0% which have attained a minimum burnup of 1000 MWD/MTU (or more), or**
- **Fuel assemblies with enrichments up to 5.0% stored in a three-out-of four checkerboard pattern with the fourth cell filled with water (or non-fuel bearing materials).**

Any one of the following criteria are acceptable for determining the safe storage of fuel in Region 2:

- **Fuel assemblies with enrichments up to 5.0% which have attained a minimum burnup within the acceptable domain of Figure 1, or**
- **Unirradiated fuel assemblies with enrichments up to 4.7% with full-length CEA Rods inserted, or**
- **Unirradiated fuel assemblies with enrichments up to 5.0%, stored in a two-out-of-four checkerboard pattern with alternate cells filled with water (or non-fuel bearing materials).**

To assure criticality safety under all conditions and to conform to the requirements of General Design Criterion 62, "Prevention of Criticality in Fuel Storage and Handling", the definitive criteria contained in the April 14, 1978 USNRC letter and in draft Regulatory Guide 1.13 (Rev. 2) are applicable. Credit for the soluble poison normally present in the pool water is permitted under accident conditions (double contingency principle).

Evaluation of postulated accident conditions in both Region 1 and Region 2 resulted in the following conclusions:

A minimum concentration of soluble boron in the pool water of 200 ppm is recommended to assure that, under all postulated conditions, the maximum k_{eff} will be maintained less than the Regulatory limit (0.95 k_{eff}). The single exception is the use of a checkerboard loading pattern in Region 2, for which a minimum of 500 ppm soluble boron is recommended to protect against a fuel mis-loading accident.

2.0 CRITICALITY SAFETY ANALYSES

2.1 Region 1

The fuel storage racks in the Ft. Calhoun spent fuel storage pool Region 1 use Boral absorber material and a water-gap between cells (flux-trap) to augment reactivity control. Calculations of Region 1 with Westinghouse fuel of various enrichments are shown in Figure 2 where the upper curve represents the maximum reactivity, including bias and uncertainties (at the 95% probability, 95% confidence level[2]) and with credit for the finite axial length of the active fuel. The maximum k_{eff} begins to exceed the acceptable limit (k_{eff} of 0.95) above an enrichment of 4.75%. The presence of axial blankets does not increase reactivity or alter the acceptance criteria, provided the assemblies are evaluated for the enrichment of the active zone (without averaging to include the blanket enrichment).

Results of the criticality safety analyses for 4.75% fuel in Region 1 are summarized in Table 1. These data show a maximum k_{eff} of 0.9498 for fuel of 4.75% enrichment, including bias and uncertainties. In addition, the reactivity effects of soluble boron, fuel burnup and checkerboard loading patterns were also evaluated. For 5.0% enriched fuel, a soluble boron concentration of 75 ppm reduces the maximum k_{eff} to less than 0.95. A three-out-of-four checkerboard loading pattern is also acceptable for storage of 5.0 enriched fuel, with a maximum k_{eff} of 0.900.

Fuel burnup is an alternative way of safely accommodating fuel with enrichments greater than 4.75% in Region 1. Calculations (with CASMO3, using the re-start option) were made for fuel of 5% initial enrichments. From these calculations, it was determined that a burnup of 850 MWD/MTU would reduce the reactivity to the equivalent of 4.75% enrichment, and therefore acceptable for storage in Region 1. For conservatism, the minimum required burnup was rounded up to 1000 MWD/MTU.

For protection against a fuel handling accident in Region 1, a minimum 100 ppm soluble boron concentration would be necessary. This concentration would allow unrestricted storage of 5% fuel in Region 1 with assurance that the maximum k_{eff}, including uncertainties, will be maintained less than the regulatory limit (0.95) for all conditions. However, Region 2 requires a minimum soluble boron concentration of 150 ppm, which would encompass the Region 1 requirement.

2.2 Region 2

For Region 2, the previous criticality analyses were extended to encompass fuel of 5% initial enrichment , including the consequence of a representative axial burnup distribution. Results of these analyses are shown in Figure 1 (and in Table 2) which defines the burnup domain for acceptable storage of spent fuel with initial enrichments up to 5.0%. Fuel which has attained a burnup within the acceptable domain of Figure 1 may be safely stored in Region 2 with a calculated maximum k_{eff} of 0.935 as indicated in Table 1. Data shown for Region 2 in Table 1 is for fuel of 4.75% initial enrichment burned to 38,900 MWD/MTU. For 5.0% enriched fuel, the corresponding limiting burnup (equivalent reactivity) is 42,300 MWD/MTU. Fuel of other enrichments will have an equivalent maximum reactivity for the corresponding limiting burnup shown in Figure 1. Axial blankets would reduce reactivity in Region 2 (because of the axial burnup distribution) provided the assemblies are evaluated for the enrichment in the central active zone, without averaging in the blanket enrichment.

The data in Figure 1 may be described by an empirical equation as a function of initial enrichments (E,%), up to 5%, as follows:

Region 2 Minimum Burnup, MWD/MTU

$$-35520 + (27920 * E) - (4600 * E^2) + (426 * E^3)$$

In addition, it was determined that a checkerboard loading arrangement with a 2-out-of-four

pattern in Region 2 was acceptable for fresh unburned fuel up to 5.0% enrichment, with a maximum k_{eff} (including bias and uncertainties) of 0.823. Soluble boron is necessary in Region 2 as protection against a fuel handling accident (mis-placed assembly - see Section 2.4).

Evaluation of spent control rods (CEA's) was also made for storage in Region 2 of the racks, using the same design and criteria as in the initial analyses. Results of this analysis, listed below, show that fuel up to 4.7% enrichment may be safely stored with the CEA rods installed. Enrichments above 4.7%, however, would exceed the reactivity limit and would require additional reactivity control.

Enrichment, %	Reactivity with CEA Rods Installed
4.2	0.923
4.5	0.939
4.7	0.949 (Interpolated)
4.75	0.951

2.3 Peripheral Cells (Region 3)

The peripheral cells (high-neutron leakage area in Region 2, called Region 3) were initially qualified for fuel with burnups less than that required for unconditional storage in Region 2. Extending the enrichment evaluation for these cells resulted in the lower curve shown in Figure 1, with the same maximum reactivity as before. Limiting fuel burnups for the peripheral cells (Region 3) have also been calculated and the results fitted to a polynomial expression over the range from 2% to 5% enrichment, as follows:

Region 3 Minimum Burnup, MWD/MTU

$$-23760 + (14160 * E) - (489 * E^2)$$

2.4 Accident/Abnormal Conditions

As determined in the original evaluation[1], the temperature and void coefficients of reactivity are negative in both regions. Consequently, the maximum reactivity occurs at a water density of 1.0 g/cc and 4°C was therefore used as the design basis temperature. This conclusion was re-affirmed by specific calculations at the higher enrichments for both Region 1 and Region 2.

Other accident conditions were also evaluated in the original analysis. However, the increase in enrichment capability necessitated re-evaluation of the fuel handling accident in which a new-fuel assembly of 5.0% enrichment might be accidentally loaded into, or outside of, a Region 1 or Region 2 cell when all other cells filled with fuel of the maximum permissible reactivity. Analysis of the postulated fuel handling accidents, listed in Table 3, show that a soluble boron concentration of 425 ppm is required to protect against the most severe credible accident (mis-loading of a 5% enriched assembly when using the checkerboard option). For the more usual storage configurations in Region 2, the most severe accident is the mis-loading of a 5% enriched assembly into a cell with all other cells filled with fuel of the maximum permissible reactivity. This accidrnt would require a minimum of 180 ppm boron, rounded up to 200 ppm to allow for uncertainty in measuring the boron concentration.

2.5 Soluble Boron Considerations

Soluble boron is normally maintained in the spent fuel pool water at approximately 2000 ppm. At this concentration, the normal reactivity of the storage racks is very low (k_{eff} of about 0.76) and the soluble boron would be sufficient to compensate for any credible accident condition. However, the racks were analyzed under the single failure assumption of the complete loss of all soluble boron. Under other accident conditions, credit for the presence of the soluble boron is permissible under the double contingency principle. Some soluble boron is necessary to protect against adverse consequences of postulated accidents and the minimum concentrations required have been evaluated for credible accident conditions (see Section 2.4).

Low concentrations of soluble boron could be used to enable the Region 1 racks to safely accommodate fuel assemblies with up to 5% enrichment. CASMO and KENO5a calculations of the reactivity effect of soluble boron are shown in Figure 3 for fuel of 5% enrichment. Over a range up to 200 ppm boron, the soluble boron has a reactivity "worth" of approximately 0.0125 Δk per 100 ppm boron. Figure 3 shows that, for fuel of 5.0% enrichment, a soluble boron concentration of about 65 ppm would be required for a k_{eff} of 0.95 in Region 1. For conservatism, the required boron concentration was rounded up to 75 ppm.

A minimum soluble boron concentration of 100 ppm is required in Region 1 and 180 ppm in Region 2 to mitigate the consequences of a fuel mis-loading accident (except for the checkerboard configuration in Region 2 which requires 425 ppm boron). A minimum boron concentration of 200 ppm (rounded up from the calculated 180 ppm) would allow unrestricted storage of fuel up to 5.0% in enrichment in both Region 1 and Region 2, subject only to the burnup requirements in Region 2 (as defined in Figure 1), and assuming that a checkerboard loading configuration is not used in Region 2. If a checkerboard configuration is used in Region 2 for 5.0% unirradiated fuel storage, the calculated minimum boron concentration of 425 ppm should be rounded up to 500 ppm for conservatism and to allow for uncertainty in measurement.

3.0 ANALYTICAL BASES

3.1 Fuel Assembly Specifications

The reference fuel assembly used for the analyses is the Westinghouse 14 x 14 fuel assembly with 20 rods replaced by control thimbles - the same as used in the original analyses, which had also determined that this assembly gave a higher reactivity than the available alternate designs. Table 4 lists the design specifications for the fuel used in the analyses.

An axial blanket of UO_2 with an enrichment less than the normal fuel enrichment (e.g., 2%) would result in slightly lower and more conservative reactivities. Fuel enrichments, as used in this report, refer to the enriched fuel zone in the assembly without consideration of any axial blankets that might be present.

3.2 Storage Rack Specifications

3.2.1 Region 1

The nominal spent fuel storage cell used for the criticality analyses of Region 1 storage cells is shown in Figure 4. The rack is composed of Boral absorber material on the outside of a 8.46-inch I.D., 0.075-inch thick stainless steel box. The fuel assemblies are centrally located in each storage cell on a nominal lattice spacing of 10.363 ± 0.080 inches in one direction and 9.821 ± 0.080 inches in the other direction. Stainless steel channels connect one storage cell box to another in a rigid structure and define a water flux-trap between the two (thermal-neutron opaque) Boral absorber panels. The 7.25-inch wide Boral absorber has a nominal thickness of 0.075 ± 0.004 inch and a nominal B-10 areal density of 0.0151 ± 0.0011 g/cm^2 .

3.2.2 Region 2

In Region 2, the storage cells are composed of a single Boral absorber panel between the stainless steel walls of adjacent storage cells. These cells, shown in Figure 5, are located on a lattice spacing of 8.652 ± 0.040 inches. The Boral absorber has a thickness of 0.075 ± 0.004 inch and a nominal B-10 areal density of 0.0151 ± 0.0011 g/cm^2 (minimum of 0.014 g/cm^2).

3.3 Manufacturing Tolerances and Uncertainties

The small reactivity increments associated with manufacturing tolerances developed in the previous evaluation were verified to assure that the higher 5.0% enrichment would result in a significantly different tolerance uncertainty than that from the previous evaluation. Results, shown in Table 1 are consistent with the previous analysis.

3.4 Calculational Methodology

3.4.1 Computer Codes

The principal method of analysis was the CASMO-3[3] code, a two-dimensional multi-group transport code for assemblies and the NITAWL-KENO[4] code package, a three dimensional Monte Carlo code package, using the 27-group SCALE cross-section library. Supplementary analyses for independent verification were performed with the 218-group cross-section library in KENO5a and with the MCNP code[5] (a continuous energy Monte Carlo code developed by the Los Alamos National Laboratory). Benchmarking of the codes, summarized in Appendix A, resulted in the following bias values (at the 95% probability, 95% confidence level[2]):

CASMO-3	0.0000 ± 0.0024
NITAWL-KENO5a	
27-Group Library	0.0103 ± 0.0018
218-Group Library	0.0128 ± 0.0020
MCNP	0.0032 ± 0.0020

In the geometric model used in the calculations, each fuel rod and its cladding were described explicitly. Reflecting boundary conditions (zero neutron current) were used in the radial direction which has the effect of creating an infinite array of storage cells in X-Y directions. In the KENO-5a and MCNP models, the actual fuel assembly length was used in the axial direction, assuming thick (30 cm) water reflectors top and bottom. Since Monte Carlo (KENO-5a and MCNP) calculations inherently include a statistical uncertainty due to the random nature of neutron tracking, a minimum of 1×10^6 neutron histories were accumulated in each calculation.

CASMO3 was used for depletion analyses and in the evaluation of the small reactivity effects of manufacturing tolerances. As in the previous analysis, an uncertainty in depletion calculations equal to 5% of the reactivity decrement from the beginning of life to the burnup of interest was assumed. CASMO3 was also used to determine equivalent enrichments corresponding to 10 zones of the axial burnup distribution. Three-dimensional KENO5a calculations, with the 10 axial zones, enabled the reactivity effect of the distribution in burnup to be determined.

3.4.2 Verification Calculations

Independent verification calculations were made with both the 27-group and the 218-group SCALE cross-section libraries in KENO5a, and with MCNP and CASMO3 for selected cases. These results are shown below (maximum k_∞, including bias and uncertainties):

CASE	CASMO3	MCNP	27-Group	218-Group
Region 1 with 4.75% Fuel	0.9498	0.9486	0.9493	0.9483
Region 1 with 5.0% Fuel	0.9586	0.9573	0.9589	0.9579
Region 2 with 1.6513% Fuel*	0.9438	0.9437	0.9450	0.9454

* Equivalent to 4.75% Enriched Fuel @ 37,500 MWD/MTU

The good agreement for these various cases tend to confirm the validity of the analytical results reported here.

4.0 REFERENCES

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

Table 1

Summary of Criticality Safety Analyses

	Region 1	Region 2
Design Basis	4.75% enrichment	4.75 % enrichment at 38,900 MWD/MTU
Temperature for analysis	4°C	4°C
Reference k_∞ (CASMO-3)	0.9392	0.9016
Uncertainties		
In Bias	± 0.0024	± 0.0024
B-10 loading	± 0.0031	± 0.0032
Boral width	± 0.0008	± 0.0006
Inner box dimension	± 0.0009	± 0.0011
Water gap thickness	± 0.0093	NA
SS thickness	± 0.0004	± 0.0002
Fuel enrichment[1]	± 0.0018	± 0.0018
Fuel density[1]	± 0.0022	± 0.0022
Eccentric position	Negative	Negative
Statistical combination of uncertainties[2]	± 0.0106	± 0.0051
Burnup Uncertainty	NA	± 0.0153
Axial Burnup Distribution	NA	+ 0.0130
Total	0.9392 ± 0.0106	0.9299 ± 0.0051
Maximum Reactivity (k_∞)	0.9498	0.935

(1) For fuel tolerances, uncertainties in Region 2 assumed to be the same as those for Region 1.

(2) Square root of sum of squares.

Table 2
Evaluation of the Minimum Burnup Requirements in Region 2

Initial Enrichment	Calculated k_{eff}	Depletion Uncert. Δk	Axial Burnup Dist. Δk	Limiting Burnup
2.0%	0.9232	0.0025	0.0	5,270[1]
2.5%	0.9197	0.0060	0.0	12,100[1]
3.0%	0.9169	0.0088	0.0	18,310[1]
3.5%	0.9148	0.0109	0.0	24,240[1]
4.0%	0.9130	0.0127	0.0	29,810[1]
4.2%	0.9124	0.0133	0.0038	32,000[1]
4.5%	0.9074	0.0143	0.0082	35,600
4.75%	0.9016	0.0153	0.0130	38,890
5.0%	0.8958	0.0161	0.0180	42,290

[1] From initial analysis

Table 3
Evaluation of the Consequences of Fuel Handling Accidents

Case	Maximum k_{eff}	Soluble Boron Required
Region 1		
5% E Assembly positioned outside and adjacent to Region 1	0.962	100
5% E Assembly mis-loaded into an otherwise filled Region 1 Rack	0.950	None
5% E Assembly misplaced within a Region 1 Checkerboard	0.918	None
Region 2		
5% E Assembly positioned outside and adjacent to Region 2	0.944	None
5% E Assembly mis-loaded into an otherwise filled Region 2 Rack	0.980	180
5% E Assembly misplaced within a Region 2 Checkerboard	1.000	425

Table 4

Design Basis Fuel Assembly Specifications

FUEL ROD DATA	Westinghouse Fuel
Outside diameter, in.	0.440
Cladding inside diameter, in.	0.384
Cladding material	Zr-4
Pellet density, % T.D.	95
Stack density, g UO_2/cc (± 0.20)	10.29
Pellet diameter, in.	0.376
Enrichment, wt % U-235 (±0.05)	4.75 - 5.0
ASSEMBLY DATA	
Fuel rod array	14x14
Number of fuel rods	176
Fuel rod pitch, in.	0.580
Number of control rod guide and instrument thimbles	5
Thimble O.D., in. (nominal)	1.115
Thimble I.D., in. (nominal)	1.035

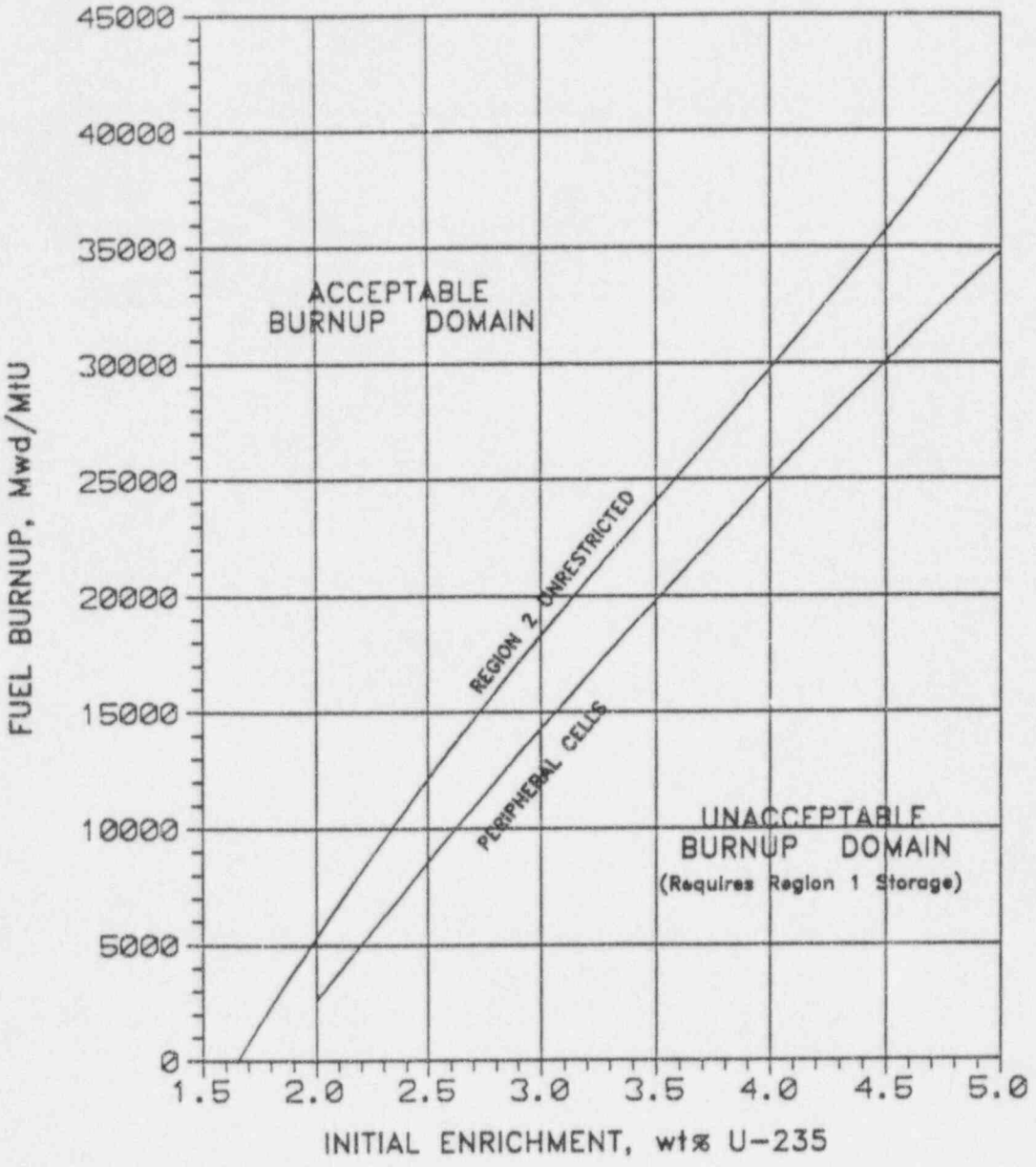

Fig. 1 LIMITING BURNUP CRITERIA FOR ACCEPTABLE STORAGE IN REGION 2

Notes:

(1) Any fuel assembly (≤ 4.7% average U-235 enrichment), mechanically coupled with a full length CEA, may be located anywhere in Region 2.

(2) Peripheral cells are those adjacent to the spent fuel pool wall or the cask laydown area.

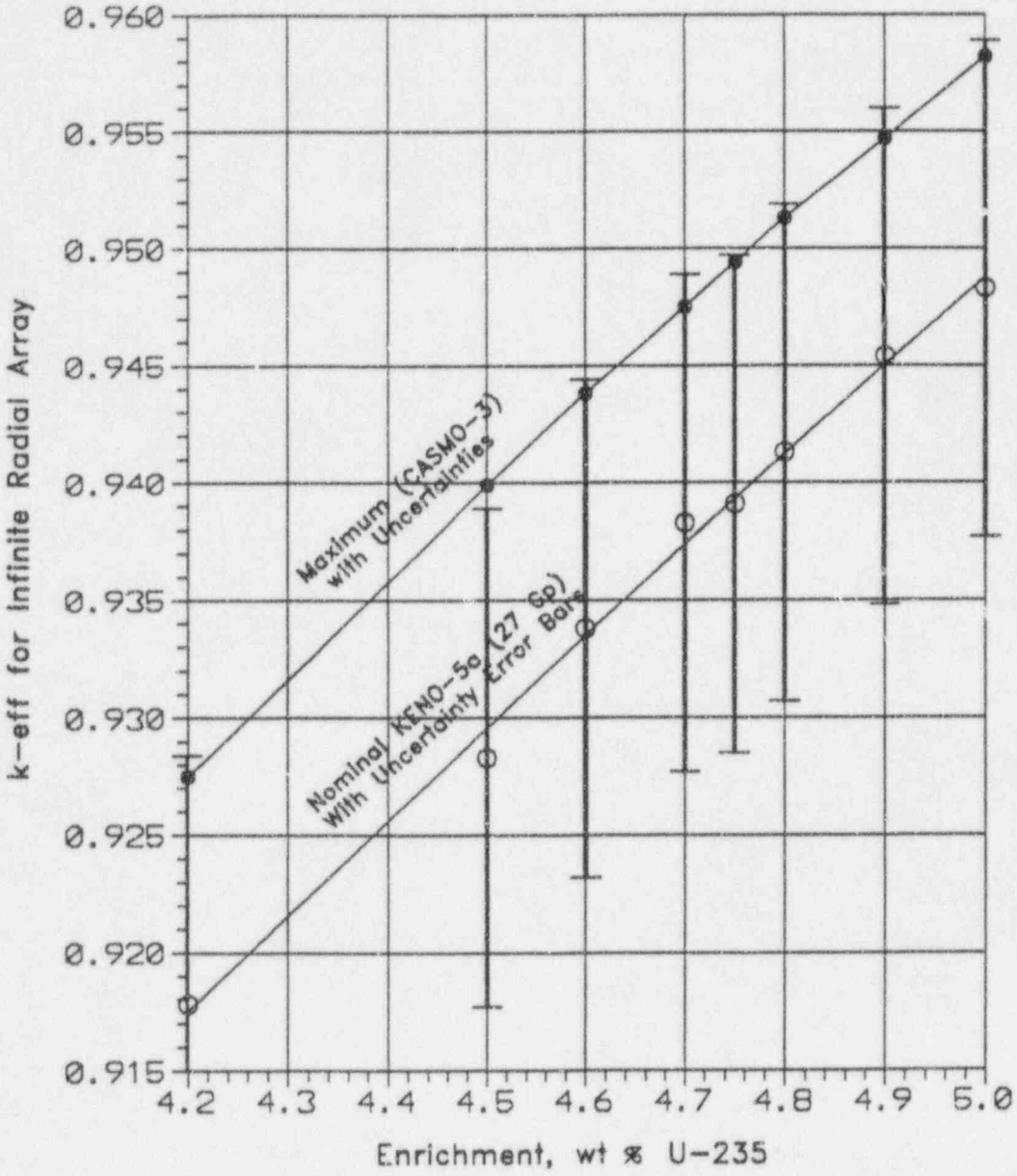

Fig. 2 Effect of Enrichment on Region 1 Reactivity

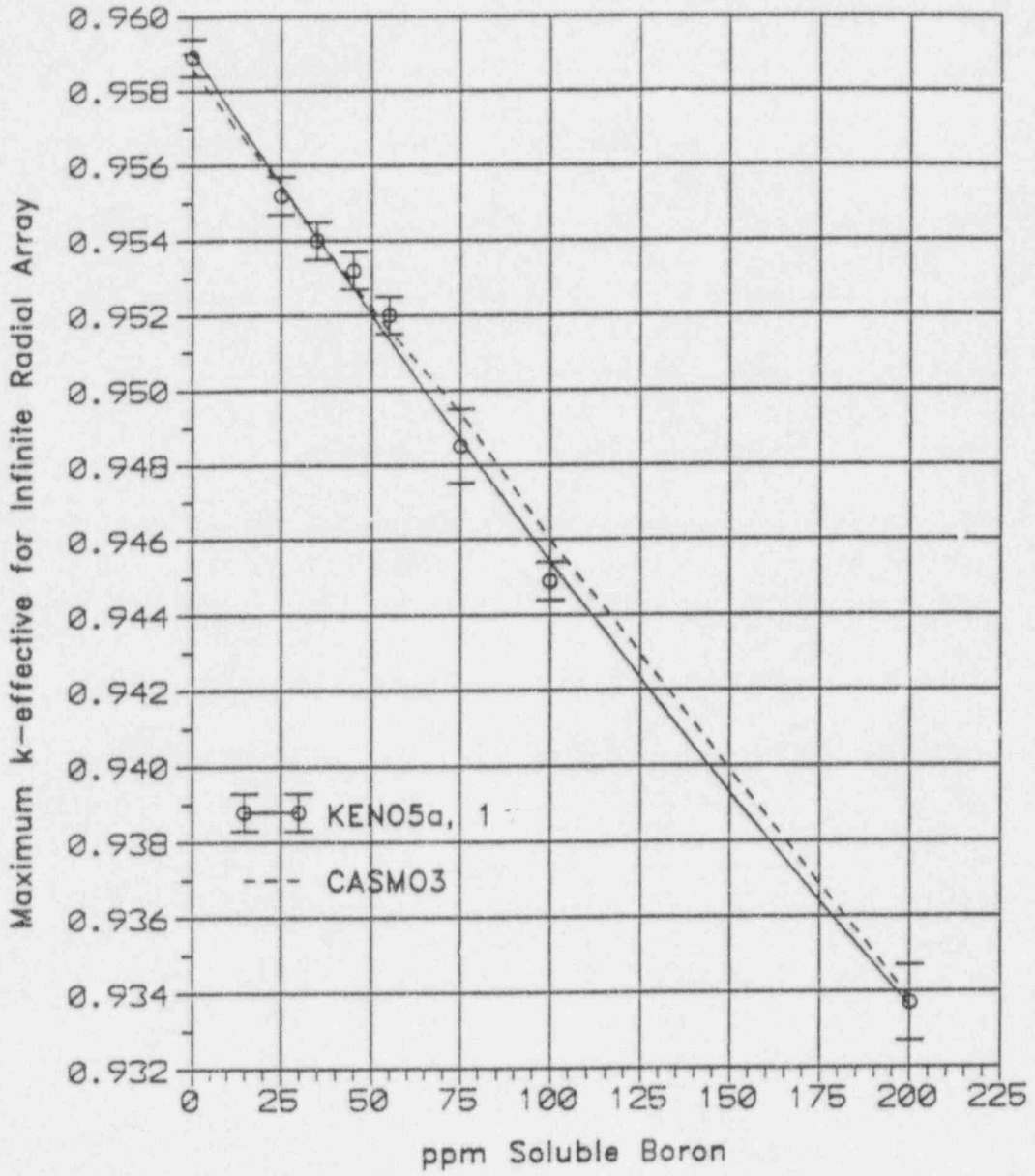

Fig. 3 Reactivity Effect of Soluble Boron (5% Enriched Fuel)

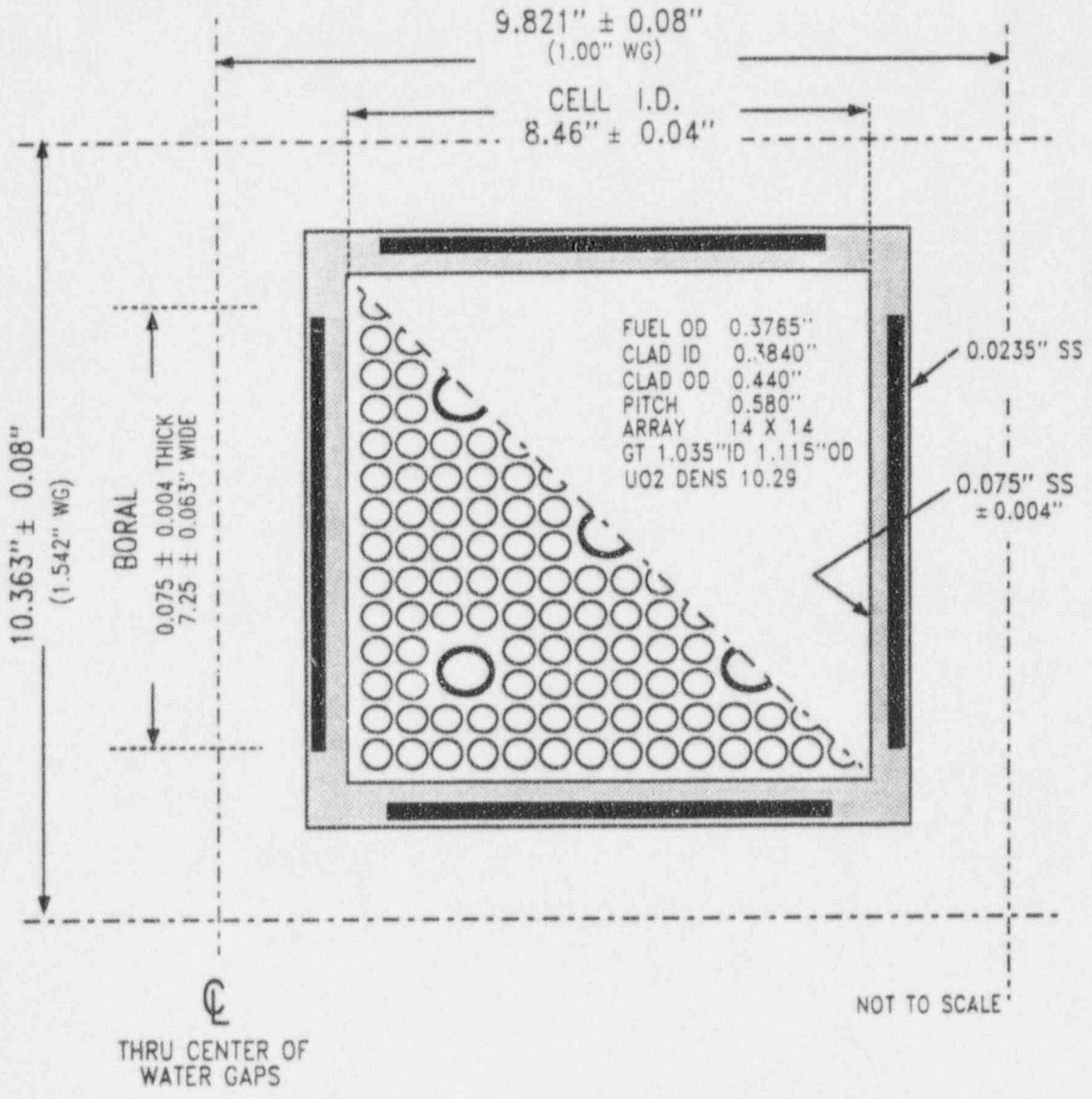

Fig. 4 Region 1 Cross-Section View

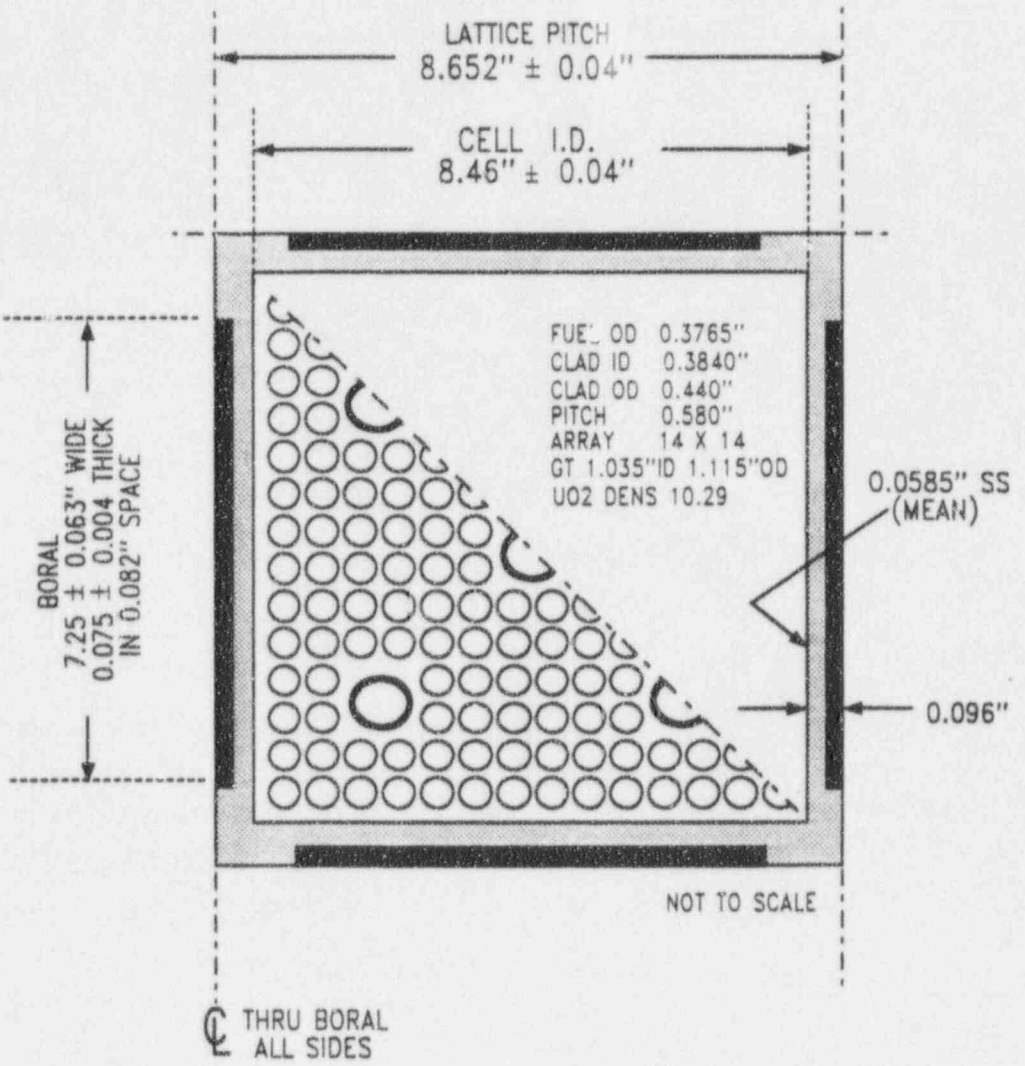

Fig. 5 Region 2 Cross-Section View

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1.0 INTRODUCTION AND SUMMARY

The objective of this benchmarking study is to verify the NITAWL-KENO5a[1,2] methodology (WORKER-NITAWL-KENO5A), the CASMO3 code[3] and MCNP[4] for use in criticality safety calculations of high density spent fuel storage racks. These calculational methods are based upon transport theory and have been benchmarked against critical experiments that simulate typical spent fuel storage rack designs as realistically as possible. Results of these benchmark calculations with both methodologies are consistent with corresponding calculations reported in the literature.

Three different cross-section libraries have been benchmarked for use with KENO5A. Results of these calculations show that NITAWL-KENO5a calculations consistently underpredict the critical eigenvalue for all three of the cross-section libraries. These libraries and their related calculational bias (for 95% probability at a 95% confidence level)[5] determined from critical experiments[6] are the following:

- 27 group Library (27GROUPNDF4) 0.0103 ± 0.0018
- 27group with fission products (27BURNUPLIB) 0.0095 ± 0.0016
- 218 group library (218GROUPNDF4) 0.0128 ± 0.0020

For CASMO-3, extensive benchmarking calculations of critical experiments have also been reported[7] in the literature, giving a mean k_{eff} of 1.0004 ± 0.0011 for 37 cases. With a K-factor of 2.14[6] for 95% probability at a 95% confidence level, and conservatively neglecting the small overprediction, the CASMO3 bias then becomes 0.0000 ± 0.0024. CASMO3 and NITAWL-KENO5a intercomparison calculations of infinite arrays of poisoned cell configurations (representative of typical spent fuel storage rack designs) show very good agreement, confirming that 0.0000 ± 0.0024 is a reasonable bias and uncertainty for CASMO3 calculations. Reference 5 also documents good agreement of heavy nuclide concentrations for the Yankee core isotopics, agreeing with the measured values within experimental error.

MCNP (a Los Alamos continuous energy Monte-Carlo code) has also been benchmarked against critical experiments, giving a calculational bias of 0.0032 ± 0.0020. Several cross-section libraries are available for MCNP and for the analyses reported here the library identified as "50.C" was used (for a few nuclides, the recommended library was identified as "55.C" or "56.C"). Calculations at Los Alamos have demonstrated that MCNP can readily handle complex geometries with consistent and accurate results. In general, however, MCNP tends to yield slightly lower reactivity values relative of KENO5A.

The benchmark calculations reported here confirm that either the NITAWL-KENO5a, MCNP or CASMO-3 calculations are acceptable for criticality analysis of high-density spent fuel storage racks, provided the appropriate calculational bias is used. Where possible, reference calculations for storage rack designs should be confirmed with an alternative analysis using either different cross-section libraries or different methods of analysis (or both), to provide independent verification. It should be noted, however, that CASMO-3 is not reliable when large water gaps (> 2 or 3 inches) are present.

2.0 NITAWL-KENO5a BENCHMARK CALCULATIONS

Analysis of a series of Babcock & Wilcox critical experiments[6], including some with absorber panels typical of a poisoned spent fuel rack, is summarized in Table 1, as calculated with NITAWL-KENO5a using the three available SCALE cross-section libraries and the Nordheim resonance integral treatment in NITAWL. Dancoff factors for input to NITAWL were calculated with the Oak Ridge SUPERDAN routine (from the SCALE[2] system of codes). The mean for these calculations for each of the four cross-section sets are shown in Table 1 together with the standard deviation of the mean). The calculational bias, shown above and in Table 1, were calculated with a one-sided tolerance factor (2.523) corresponding to 95% probability at a 95% confidence level[5] for the sixteen critical experiments analyzed.

Similar calculational deviations have been reported by ORNL[8] for some 54 critical experiments (mostly clean criticals without strong absorbers), obtaining a mean bias of 0.0100 ± 0.0013 (95%/95%). These published results are in good agreement with the results obtained in the present analysis and lend further credence to the validity of the 27-group NITAWL-KENO5a calculational model for use in criticality analysis of high density spent fuel storage racks. No abnormal deviations in k_{eff} with intra-assembly water gap, with absorber panel reactivity worth, with enrichment or with poison concentration were identified with either the 27 group or the 218-group SCALE library or with MCNP. CASMO was found to be unreliable for the larger water-gaps.

Additional benchmarking calculations were also made for a series of French critical experiments[9] at 4.75% enrichment and for several of the BNWL criticals with 4.26% enriched fuel. Analysis of the French criticals (Table 2) showed a tendency to overpredict the reactivity, a result also obtained by ORNL[10]. The calculated k_{eff} values showed a trend toward higher values with decreasing core size. In the absence of a significant enrichment effect (see Section 5.2 below), this trend and the overprediction is attributed to a small inadequacy in NITAWL-KENO5a in calculating neutron leakage from very small assemblies.

Similar results were observed for the BNWL series of critical experiments[11], which are also small assemblies (although significantly larger than the French criticals). In this case (Table 2), the calculated mean k_{eff} was 0.9959 ± 0.0013 (1 σ population standard deviation). Because of the small size of the BNWL critical experiments (compared to the B&W criticals used to determine the KENO5a bias) and the absence of any significant enrichment effect, the results also suggest a small inadequacy of NITAWL-KENO5a in treating large neutron leakage from very small assemblies.

Since the analysis of high-density spent fuel storage racks generally does not entail neutron leakage, the observed inadequacy of NITAWL-KENO5a is not significant. Furthermore, omitting results of the French and BNWL critical experiment analyses from the determination of bias is conservative since any leakage that might enter into the analysis would tend to result in overprediction of the reactivity.

3.0 CASMO3 BENCHMARK CALCULATIONS

The CASMO3 code is a multigroup transport theory code utilizing transmission probabilities to accomplish two-dimensional calculations of reactivity and depletion for BWR and PWR fuel assemblies. As such, CASMO3 is well-suited to the criticality analysis of spent fuel storage racks, since general practice is to treat the racks as an infinite radial array of storage cells, neglecting leakage effects.

CASMO3 has been extensively benchmarked against both mixed oxide and hot and cold critical experiments by Studsvik Energiteknik[7]. Reported analyses of 37 critical experiments indicate a mean k_{eff} of 1.0004 ± 0.0011 (1σ). To independently confirm the validity of CASMO3 (and to investigate any effect of enrichment), a series of intercomparison calculations were made (see Section 5) with CASMO3, NITAWL-KENO5a and MCNP on identical poisoned storage cells representative of high-density spent fuel storage racks. Results of these intercomparison calculations* (shown in Table 3 and in Figure 1) show very good agreement and confirm the bias of 0.0000 ± 0.0024 (95%/95%) for CASMO3.

A second series of CASMO3, MCNP, and KENO5a intercomparison calculations consisting of five cases from the BAW critical experiments were analyzed for the central cell only. The calculated results, also shown in Table 3, indicate a mean difference within the 95% confidence limit of the KENO5a calculations. This lends further credence to the recommended bias for CASMO3.

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* Intercomparison between analytical methods is a technique endorsed by Reg. Guide 3.41, "Validation of Calculational Methods for Nuclear Criticality Safety".

4.0 MCNP BENCHMARK CALCULATIONS

MCNP (Monte Carlo N-Particle) is a continuous energy Monte Carlo code with very flexible geometry capabilities. For these benchmark calculations, the recommended "50.C" library was used except for two nuclides whose cross-section libraries have been corrected - iron (55.C) and zirconium (56.C).

MCNP was benchmarked against the same set of critical experiments as KENO5A and the comparison is shown in Table 1. These benchmark calculations gave a bias of 0.0032 $\pm$ 0.0020. Independent calculations confirmed that there is no significant dependence on enrichment or temperature (see Section 5).

5.0 INTERCOMPARISON CALCULATIONS

5.1 Enrichment Effect

Calculations were made with CASMO-3, MCNP, and KENO5A (27-Group) for various fuel enrichments in a representative high-density (poisoned) spent fuel storage rack cells. Results of these calculations, shown in Table 3 and illustrated in Figure 1, show very good agreement for the three independent methods of analysis. Since three independent methods of analysis would not be expected to have the same error function with enrichment, results of the intercomparison analyses (Table 3) indicate that there is no significant effect of fuel enrichment over the range of enrichments involved in power reactor fuel.

5.2 Temperature Effect

The WORKER routine was obtained from ORNL and is intended to interpolate the hydrogen scattering matrices for temperature in order to correct for the deficiency noted in NRC Information Notice 91-66 (October 18, 1991). Benchmark calculations were made against MCNP and CASMO3, based on the assumption that independent methods of analysis would not exhibit the same error. Results of these calculations, shown in Table 4 and in Figure 2, confirm that the slope with temperature obtained by CASMO3 and KENO5a are essentially the same. This agreement establishes the validity of the WORKER routine, in conjunction with NITAWL-KENO5a, in calculating reactivities at temperatures between 20°C and 120°C. MCNP is comparable but does not incorporate the Doppler effect which accounts for the slight difference in slope.

The deficiency in the NITAWL hydrogen scattering matrix at temperatures above 20 °C does not appear except in the presence of a large water gap where the scattering matrix is important. However, the absolute value of the k_∞ from CASMO3 is not reliable in the presence of a large water gap, although the relative values should be accurate. In the calculations shown in Table 4 and in Figure 2, the absolute CASMO-3 reactivity values differ somewhat from the other calculations, but the trends with temperature are sufficiently in agreement to lend credibility to the WORKER routine over the temperature range from 20°C to 120°C.

5.3 Effect of Water-Gap Size

Calculations were made for a fuel assembly suspended in water for the reactivity with various water-gap spacings between assemblies. Results, shown in Table 5, indicate good agreement between MCNP and KENO5A. CASMO-3, however, showed significant deviations for 4 inch or larger water-gaps, depending upon the number of mesh intervals specified in the CASMO-3 calculations. For this reason, CASMO-3 is not considered reliable for water-gap spacing greater than about 2 to 3 inches, although differential calculations for small design variations (e.g., tolerances) would be acceptable.

6.0 CLOSE-PACKED ARRAYS

The BAW close-packed series of critical experiments[12] intended to simulate consolidated fuel, were analyzed with NITAWL-KENO5a (27-Group). Because there are so few cases available for analysis, results of these analyses, shown in Table 6, suggest the possibility of a slightly larger bias than that for fuel with normal lattice spacings. Similar results were obtained by ORNL[13]. Therefore, the maximum bias for close-packed lattices may be taken as 0.0155, including uncertainty, which would very conservatively encompass all but one of the cases measured.

7.0 REFERENCES TO APPENDIX A

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Table 1

Results of NITAWL-KENO5a and MCNP
Benchmark Calculations

Expt Number	$k_{eff} \pm 1\sigma$			
	27-Group	27-group Burn	218-group	MCNP
I	0.9922 ± 0.0006	0.9919 ± 0.0006	0.9886 ± 0.0006	0.9918 ± 0.0010
II	0.9917 ± 0.0005	0.9924 ± 0.0005	0.9896 ± 0.0005	0.9995 ± 0.0010
III	0.9931 ± 0.0005	0.9923 ± 0.0005	0.9907 ± 0.0005	0.9988 ± 0.0010
IX	0.9915 ± 0.0006	0.9912 ± 0.0006	0.9884 ± 0.0006	0.9881 ± 0.0009
X	0.9903 ± 0.0006	0.9915 ± 0.0006	0.9871 ± 0.0006	0.9951 ± 0.0009
XI	0.9919 ± 0.0005	0.9917 ± 0.0005	0.9904 ± 0.0005	0.9991 ± 0.0009
XII	0.9915 ± 0.0006	0.9929 ± 0.0006	0.9898 ± 0.0006	0.9883 ± 0.0009
XIII	0.9945 ± 0.0006	0.9951 ± 0.0006	0.9904 ± 0.0006	1.0004 ± 0.0009
XIV	0.9902 ± 0.0006	0.9910 ± 0.0006	0.9885 ± 0.0006	0.9974 ± 0.0010
XV	0.9836 ± 0.0006	0.9858 ± 0.0006	0.9800 ± 0.0006	0.9925 ± 0.0010
XVI	0.9863 ± 0.0006	0.9855 ± 0.0006	0.9817 ± 0.0006	0.9916 ± 0.0010
XVII	0.9875 ± 0.0006	0.9885 ± 0.0005	0.9853 ± 0.0006	0.9958 ± 0.0009
XVIII	0.9880 ± 0.0006	0.9892 ± 0.0006	0.9857 ± 0.0006	0.9985 ± 0.0010
XIX	0.9882 ± 0.0005	0.9899 ± 0.0005	0.9858 ± 0.0006	0.9939 ± 0.0009
XX	0.9885 ± 0.0006	0.9887 ± 0.0006	0.9859 ± 0.0006	0.9981 ± 0.0010
XXI	0.9862 ± 0.0006	0.9909 ± 0.0006	0.9878 ± 0.0006	1.0006 ± 0.0009
Mean[1]	0.9897 ± 0.0007	0.9905 ± 0.0006	0.9872 ± 0.0008	0.9968 ± 0.0008
Bias[2]	0.0103 ± 0.0018	0.0095 ± 0.0016	0.0128 ± 0.0020	0.0032 ± 0.0020

(1) Standard Deviation of the Mean, calculated from the individual k_{eff} values.
(2) Bias at the 95% Probability / 95% Confidence level.

Table 2

Results of 27-Group (SCALE) NITAWL-KENO5a Calculations of French and BNWL Critical Experiments

French Experiments

Separation Distance, cm	Critical Height, cm	Calculated k_{eff}
0	23.8	1.0302 ± 0.0008
2.5	24.48	1.0278 ± 0.0007
5.0	31.47	1.0168 ± 0.0007
10.0	64.34	0.9998 ± 0.0007

BNWL Experiments

Case	Expt. No.	Calculated k_{eff}
No Absorber	004/032	0.9942 ± 0.0007
SS Plates (1.05 B)	009	0.9946 ± 0.0007
SS Plates (1.62 B)	011	0.9979 ± 0.0007
SS Plates (1.62 B)	012	0.9968 ± 0.0007
SS Plates	013	0.9956 ± 0.0007
SS Plates	014	0.9967 ± 0.0007
Zr Plates	030	0.9955 ± 0.0007
Mean		0.9959 ± 0.0013

Table 3

Results of CASMO3, MCNP, AND NITAWL-KENO5a
Benchmark (Intercomparison) Calculaltions

Enrichment[1] Wt. % U-235	k_∞ (Bias Corrected)		
	NITAWL-KENO5a[2]	CASMO3	MCNP[3]
2.5	0.8371 ± 0.0010	0.8386	0.8350 ± 0.0010
3.0	0.8776 ± 0.0010	0.8783	0.8750 ± 0.0011
3.5	0.9082 ± 0.0010	0.9097	0..9075 ±0.0010
4.0	0.9370 ± 0.0011	0.9352	0.9326 ± 0.0011
4.5	0.9561 ± 0.0011	0.9565	0.9557 ± 0.0011
5.0	0.9747 ± 0.0011	0.9746	0.9717 ± 0.0012
Expt. No.[4]			
XIII	1.1021 ± 0.0009	1.1008	1.1030 ± 0.0010
XIV	1.0997 ± 0.0008	1.1011	1.1032 ± 0.0008
XV	1.1086 ± 0.0008	1.1087	1.1104 ± 0.0009
XVII	1.1158 ± 0.0007	1.1168	1.1177 ± 0.0008
XIX	1.1215 ± 0.0007	1.1237	1.1235 ± 0.0008

(1) Infinite array of assemblies typical of high-density spent fuel storage racks.

(2) k_∞ from NITAWL-KENO5a corrected for bias (+0.0103).

(3) MCNP calculation corrected for bias (+0.0032)

(3) Central cell of BAW Critical Experiments (Ref. 6).

Table 4
Intercomparison of Calculations[1] at Various Temperatures with MCNP, KENO5A and CASMO3

Temperature	MCNP ($S(\alpha,\beta)$ at 300 °K)	CASMO3	W-N-KENO5a[2]
4°C	1.2320 ± 0.0008	1.2276	1.2345 ± 0.0014
17.5°C	1.2342 ± 0.0008	1.2322	1.2328 ± 0.0015
25°C	1.2346 ± 0.0008	1.2347	1.2360 ± 0.0013
50°C	1.2431 ± 0.0018[3]	1.2432	1.2475 ± 0.0014
75°C	1.2540 ± 0.0009[3]	1.2519	1.2569 ± 0.0015
120°C	1.2779 ± 0.0010	1.2701	1.2746 ± 0.0014

[1] Bias Corrected
[2] WORKER-NITAWL-KENO5a Code Package.
[3] Interpolated between $S(\alpha,\beta)$ at 27 °C and $S(\alpha,\beta)$ at 127 °C; Doppler effect not included.

Table 5

Intercomparison of Calculations[1] at Various Water Gaps with MCNP, KENO5A and CASMO3

Interassembly Water Gap, in.	MCNP	CASMO3[2]	W-N-KENO5a[3]
1.0	1.4755 ± 0.0007	1.467 - 1.468	1.4655 ± 0.0010
2.0	1.3244 ± 0.0008	1.321 - 1.326	1.3169 ± 0.0012
4.0	1.0791 ± 0.0010	1.088 - 1.102	1.0769 ± 0.0014
6.0	0.9871 ± 0.0011	0.983 - 1.008	0.9893 ± 0.0015
8.0	0.9591 ± 0.0011	0.916 - 0.986	0.9622 ± 0.0015
12.0	0.9469± 0.0013	0.844 - 0.979	0.9476 ± 0.0016

(1) Bias Corrected
(2) Range due to different mesh intervals used.
(3) WORKER-NITAWL-KENO5a Code Package.

Table 6

KENO5A (27-Group) Calculations for Close-Packed Critical Experiments

Calc. No.	BAW Expt. No.	Pin Pitch cm	Module Spacing cm	Boron Conc. ppm	Calculated k_{eff}
KS01	2500	Square 1.4097	1.792	1156	0.9891 ± 0.0005
KS02	2505	Square 1.4097	1.792	1068	0.9910 ± 0.0005
KS1	2485	Square Touching	1.778	886	0.9845 ± 0.0005
KS2	2491	Square Touching	0.778	746	0.9849 ± 0.0005
KT1	2452	Triang. Touching	1.86	435	0.9845 ± 0.0006
KT1A	2457	Triang. Touching	1.86	335	0.9865 ± 0.0006
KT2	2464	Triang. Touching	2.62	361	0.9827 ± 0.0006
KT3	2472	Triang. Touching	3.39	121	1.0034 ± 0.0006

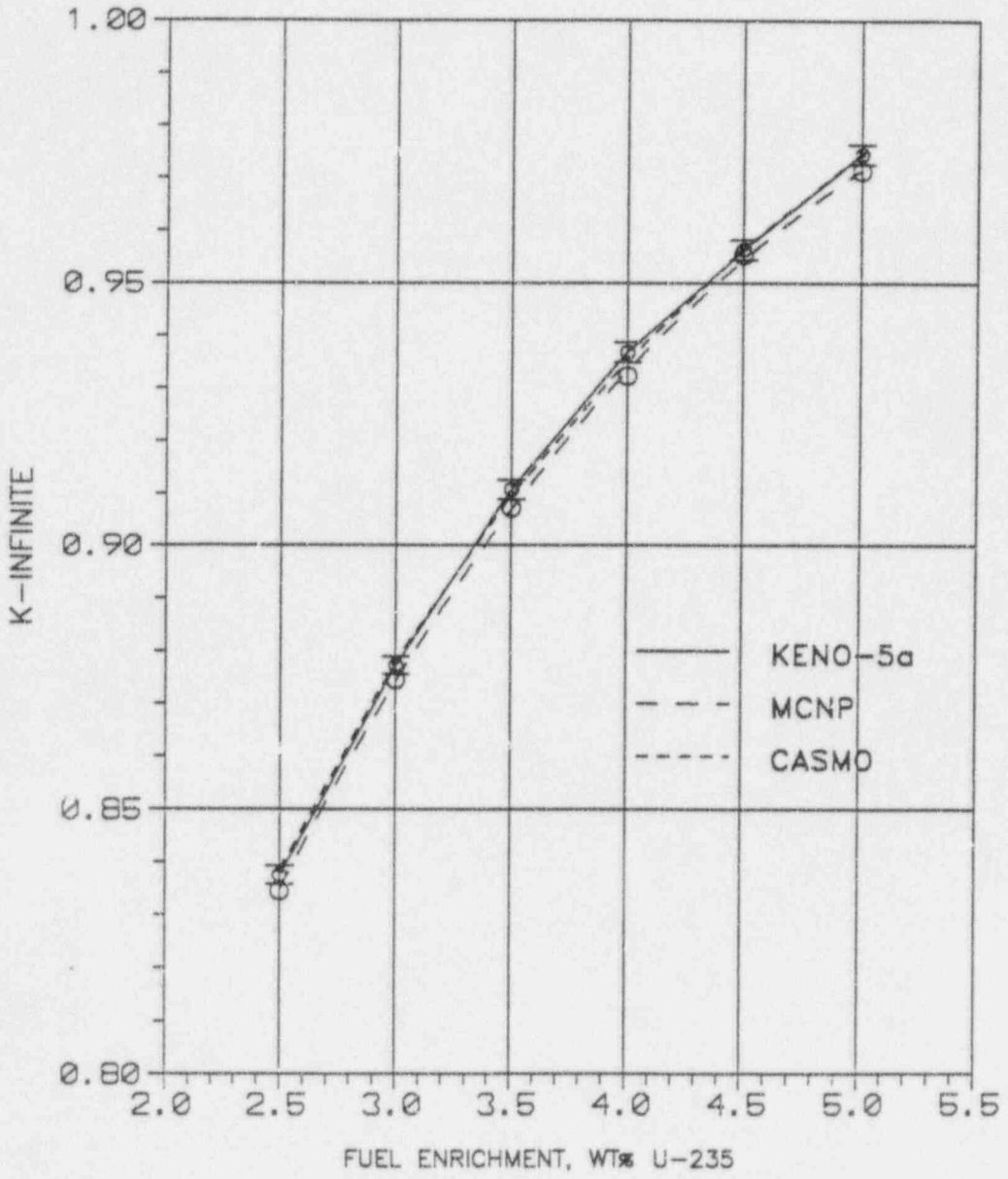

Fig. 1 Intercomparison of CASMO-3, MCNP, and KENO-5a for Fuel of Various Enrichments

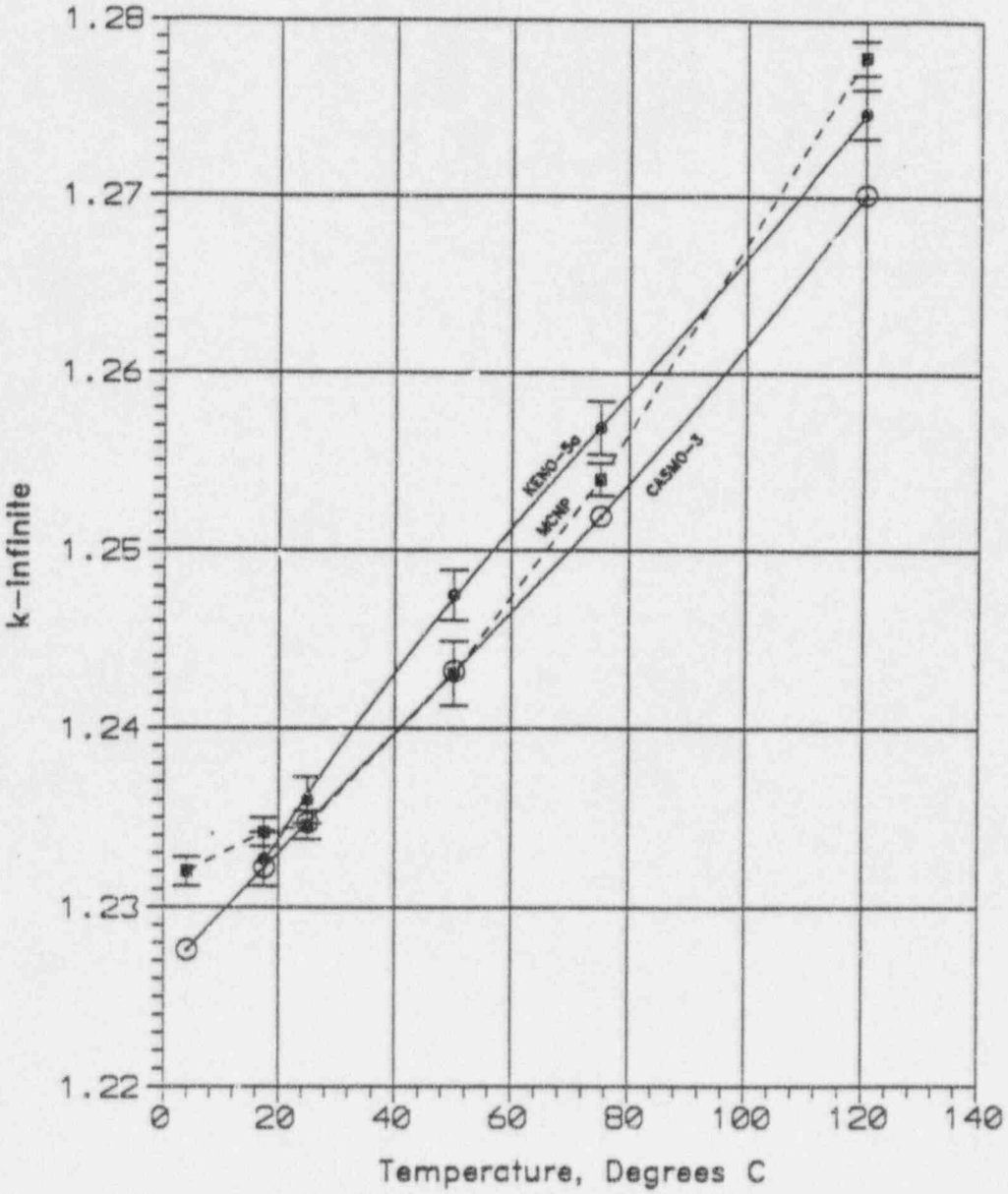

Fig. 2 COMPARISON OF TEMPERATURE DEPENDANCE FOR CASMO-3, MCNP, AND KENO-5A