CRITICALITY SAFETY EVALUATION OF THE

CRYSTAL RIVER UNIT 3 NEW FUEL STORAGE VAULT

WITH FUEL OF 5% ENRICHMENT

Prepared for the

FLORIDA POWER CORPORATION

by

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1.0 INTRODUCTION

In a previous evaluation[1], criticality safety analyses established that the New Fuel Storage Vault at Crystal River Unit 3 could safely accommodate fuel of 4.5% enrichment, with restrictions on the number of useable storage locations. The present study is intended to extend that analysis to confirm the capability of the New Fuel Storage Vault to safely receive and store fuel of 5.0% initial enrichment with the same restriction on useable storage locations. A companion report, HI-931111, documents the capability of Pool A to also accept fuel of 5.0% initial enrichment.

The New Fuel Storage Vault is intended for the receipt and storage of fresh fuel under normally dry conditions where the reactivity is very low. To assure criticality safety under accident conditions and to conform to the requirements of General Design Criterion 62, "Prevention of Criticality in Fuel Storage and Handling", two separate criteria must be satisfied as defined in NUREG-0800, Standard Review Plan 9.1.1, "New Fuel Storage". These criteria are as follows:

- When fully loaded with fuel of the highest anticipated reactivity and flooded with clean unborated water, the maximum reactivity, including uncertainties, shall not exceed a k_{eff} of 0.95.

- With fuel of the highest anticipated reactivity in place and assuming the optimum hypothetical low density moderation, (i.e., fog or foam), the maximum reactivity shall not exceed a k_{eff} of 0.98.

Results of the present evaluation confirms that the New Fuel Storage Vault can safely accommodate fuel of 5.0% enrichment with the restriction that certain storage locations must remain empty of fuel. These locations are the same as those defined in the previous evaluation.

2.0 SUMMARY

The New Fuel Storage Vault normally provides a 6 x 11 cell array of storage locations arranged on a 21.125 inch lattice spacing. Results of the previous evaluation showed that it is necessary to blank-off, and keep empty of fuel, two rows of storage locations as indicated in Figure 1. With the same restriction, the remaining 54 storage locations in the New Fuel Storage Vault can accommodate 5.0% enriched fuel within the two Regulatory guidelines identified above.

Calculations were made with the 27-group NITAWL-KENO-5a code package, a three-dimensional Monte Carlo analytical technique, using the configuration illustrated in Figure 1. Results of the criticality safety analyses are summarized in Table 1 for the two accident conditions. Figure 2 illustrates the variation in k_{eff} with moderator density and shows that the peak reactivity (optimum moderation) occurs at 7.5% moderator density. The maximum reactivity at 7.5% moderator density is a 0.978, including uncertainties, which is within the Regulatory limit of 0.98, thus confirming the acceptability of the NFV for 5.0% fuel.

In the flooded condition (clean unborated water), the storage locations are essentially isolated from each other (neutronically). Under these conditions and with fuel of 5.0% enrichment, the maximum reactivity, including all known uncertainties, is 0.948 which is less than the limiting value of 0.95, thus confirming the acceptability of the NFV for 5.0% fuel.

3.0 CRITICALITY ANALYSES

3.1 Fuel Assembly Specifications

The reference design fuel assembly is a standard Babcock & Wilcox 16 x 15 array of fuel rods, with 17 rods replaced by 16 control guide tubes and one instrument thimble. Table 2 summarizes the fuel assembly design specifications and expected range of significant fuel tolerances.

3.2 New Fuel Storage Rack Design

The racks in the New Fuel Storage Vault include steel lead-ins, although there is no steel in the active fuel region. The storage locations are arranged in eleven rows of six cells each, located on a 21 1/8 ± 1/16 inch lattice spacing, as illustrated in Figure 1. Normally, fuel is stored in the dry condition with very low reactivity.

3.3 Analytical Methods

The criticality analyses were made with the three-dimensional Monte-Carlo code package NITAWL-KENO5a[2] using the 27-group SCALE* cross-section library[3] and the Nordheim integral treatment for U-238 resonance shielding effects. Benchmark calculations, presented in Appendix A, indicate a bias of 0.0103 ± 0.0018 for the NITAWL-KENO-5a code package, at the 95% probability, 95% confidence level[4].

In the calculational model, each fuel rod, cladding, or guide tube were explicitly described. The model also used the standard concrete reflector option available in KENO-5a to describe the

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*"SCALE" is an acronym for Standardized Computer Analysis for Licensing Evaluation, a standard cross-section set developed by ORNL for the USNRC.

concrete walls of the NFV.

Monte Carlo (KENO-5a) calculations inherently include a statistical uncertainty due to the random nature of neutron tracking. To minimize the statistical uncertainty of the KENO-calculated reactivity, a minimum of 500,000 neutron histories in 1000 generations of 500 neutrons each, were accumulated in each calculation. For the flooded case and at optimum low-density moderation, confirmatory calculations were made with 2,500,000 neutron histories. Furthermore, because of the close approach to the limiting reactivity, check calculations for the flooded case and at optimum low-density moderation were made with the 218 neutron group library. Results of these calculations are as follows:

CASE	7.5% Mod. Dens.	Flooded
27-groups	0.9648 ± 0.0006	0.9345 ± 0.0008
218-groups	0.9623 ± 0.0010	0.9320 ± 0.0012

The 218-group calculations resulted in a slightly lower k_{eff} than the reference 27-group library, thus confirming the reference calculations.

3.4 Manufacturing Tolerances

The reactivity uncertainties associated with various manufacturing tolerances were calculated by the difference between KENO-5a calculations, each with the nominal value and a second calculation with each value set at the maximum tolerance. Results are tabulated below:

Tolerance	Δk Uncertainty @ 7% Mod Dens	Δk Uncertainty flooded
± 1/8 in lattice spacing	± 0.0015	± 0.0007
± 0.02 in % enrichment	± 0.0013	± 0.0014
± 0.166 g_{UO2}/cc	± 0.0015	± 0.0015

Statistical Combination	± 0.0025	± 0.022

4.0 Abnormal and Accident Conditions

Normally, the new fuel storage vault is dry with a very low reactivity. The two limiting criticality criteria are accident conditions and no other safety concerns have been identified. Under the double contingency principle of ANSI-N16-1975, endorsed by the April 1978 USNRC position statement, it is not necessary to consider the simultaneous occurrence of independent accident conditions.

5.0 REFERENCES

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Table 1

SUMMARY OF CRITICALITY SAFETY ANALYSES
NEW FUEL VAULT - 5.0% ENRICHED FUEL
(Under Accident Conditions)

	Optimum Moderation	Flooded Condition
Temperature for analysis	20°C (68°F)	20°C (68°F)
Reference k_∞ (KENO5a)	0.9648	0.9345
Calculational bias, δk	0.0103	0.0103
Uncertainties		
In the Bias[1]	± 0.0018	± 0.0018
KENO Statistics[1]	± 0.0010	± 0.0014
Lattice spacing	± 0.0015	± 0.0007
Fuel enrichment	± 0.0013	± 0.0014
Fuel density	± 0.0015	± 0.0015
Statistical combination of uncertainties[2]	± 0.0029	± 0.0032
Total	0.9751 ± 0.0029	0.9448 ± 0.0032
Maximum Reactivity (k_{eff})	0.9780	0.9480
Regulatory Limit	0.98	0.95

(1) With one-sided factor for 95%/95% tolerance (NBS Handbook 91).
(2) Square root of sum of squares.

TABLE 2
FUEL ASSEMBLY SPECIFICATIONS

Fuel Rod Data	
Outside dimension, in.	0.430
Cladding ID, in.	0.377
Cladding thickness, in.	0.0265
Cladding material	Zr-4
Pellet diameter, in.	0.369
UO_2 density, g/cm^2	10.420 ± 0.166
Enrichment, wt.% U-235	5.0 ± 0.02
Fuel Assembly Data	
Number of fuel rods	208 (15x15 array)
Fuel rod pitch, in.	0.568
Control rod guide tube	
Number	16
O.D., in.	0.530
Thickness, in.	0.016
Material	Zr-4
Instrument thimble	
Number	1
O.D., in.	0.493
Thickness, in.	0.026
Material	Zr-4

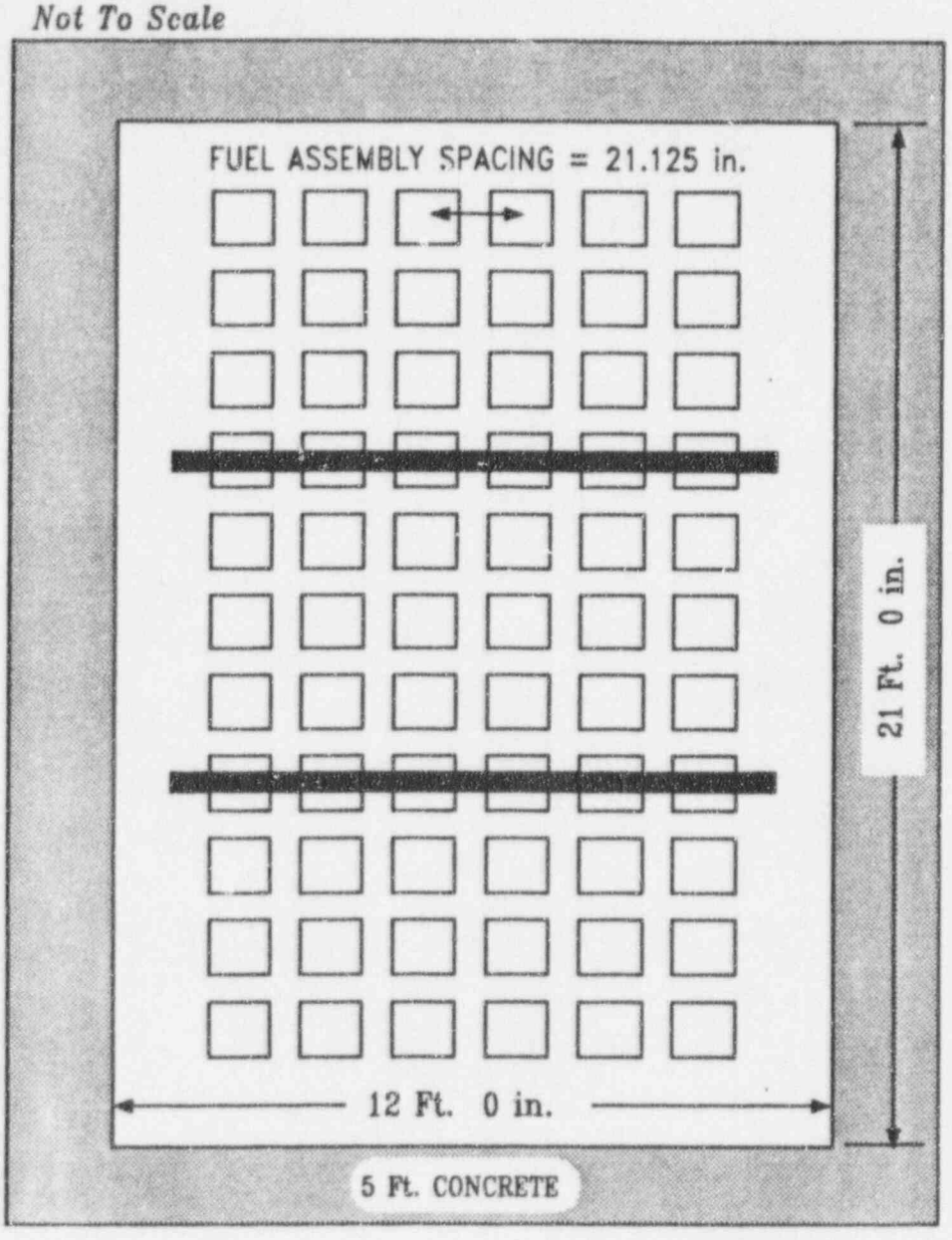

Fig. 1 New Fuel Storage Vault Configuration

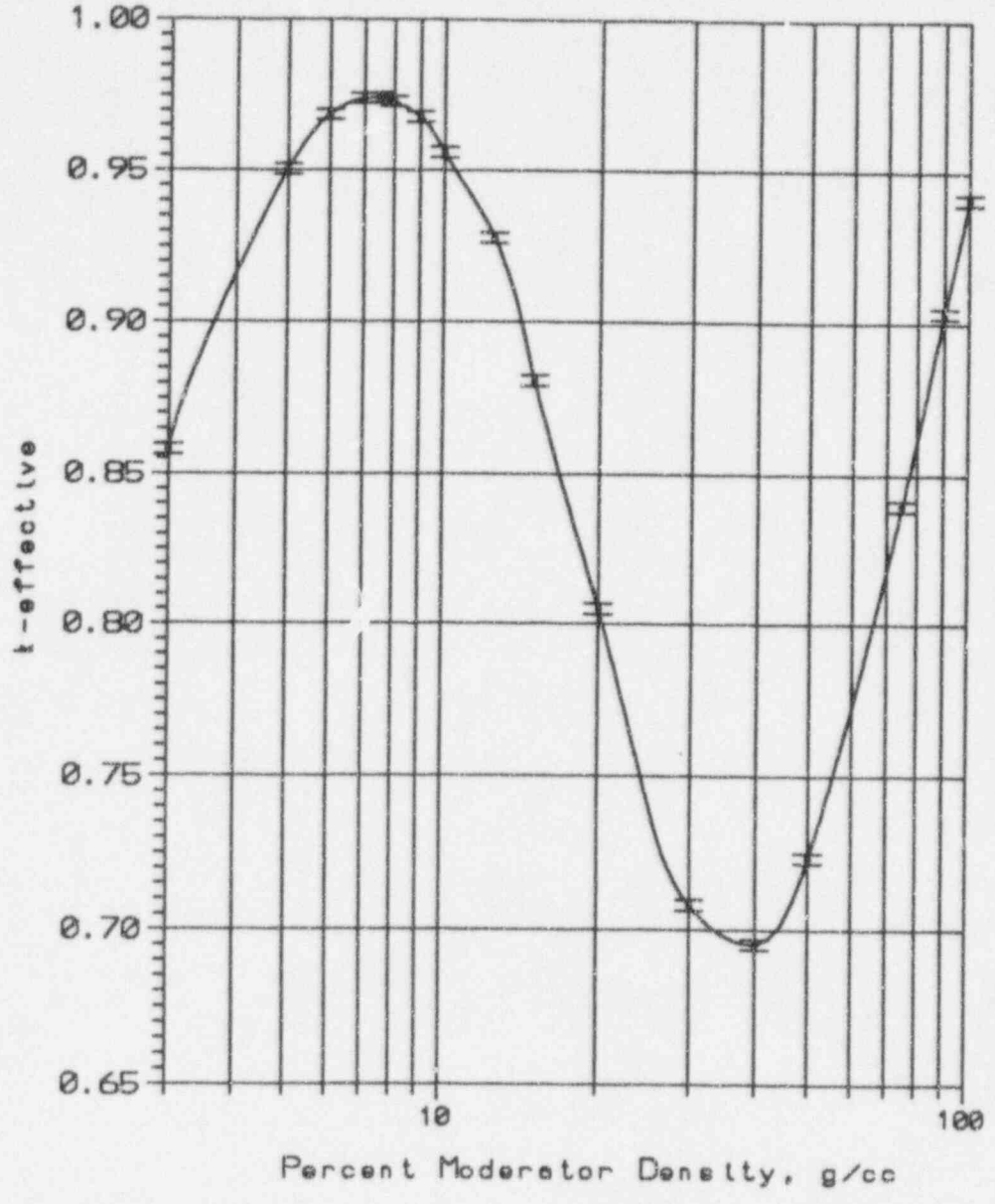

Fig. 2 Reactivity Variation with Moderator Density

APPENDIX A

BENCHMARK CALCULATIONS

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1.0 INTRODUCTION AND SUMMARY

The objective of this benchmarking study is to verify both the NITAWL-KENO5a[1,2] methodology with the 27-group SCALE cross-section library and the CASMO3 code[3] for use in criticality safety calculations of high density spent fuel storage racks. Both 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.

Results of the benchmark calculations show that the 27-group (SCALE) NITAWL-KENO5a calculations consistently underpredict the critical eigenvalue by 0.0103 ± 0.0018 δk (with a 95% probability at a 95% confidence level) for critical experiments[4] that are as representative as possible of realistic spent fuel storage rack configurations and poison worths.

Extensive benchmarking calculations of critical experiments with CASMO3 have also been reported[5], 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.

The benchmark calculations reported here confirm that either the 27-group (SCALE) NITAWL-KENO5a or CASMO3 calculations are acceptable for criticality analysis of high-density spent fuel storage racks. Where possible, reference calculations for storage rack designs should be performed with both code packages to provide independent verification. CASMO3, however, 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[4], including some with absorber panels typical of a poisoned spent fuel rack, is summarized in Table 1, as calculated with NITAWL-KENO5a using the 27-group SCALE cross-section library 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 is 0.9899 ± 0.0028 (1 σ standard deviation of the population). With a one-sided tolerance factor corresponding to 95% probability at a 95% confidence level[6], the calculational bias is + 0.0103 with an uncertainty of the mean of ± 0.0018 for the sixteen critical experiments analyzed.

Similar calculational deviations have been reported by ORNL[7] 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 the 27 group SCALE library, comparable to those previously observed[8] with the 123-group GAM-THERMOS cross-section library.

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 3 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 medium of storage cells, neglecting leakage effects.

CASMO3 is a modification of the CASMO-2E code and has been extensively benchmarked against both mixed oxide and hot and cold critical experiments by Studsvik Energiteknik[5]. Reported analyses[5] 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 calculations were made with CASMO3 and with NITAWL-KENO5a 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) are within the normal statistical variation of KENO5a calculations and confirm the bias of 0.0000 ± 0.0024 (95%/95%) for CASMO3.

Since two 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.

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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".

A second series of CASMO3 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.

4.0 WORKER ROUTINE

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 CASMO3, based on the assumption that two independent methods of analysis would not exhibit the same error. Results of these calculations, shown in Table 4, confirm that the trend with temperature obtained by both codes are comparable. 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.

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 reactivity values differ somewhat 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.

5.0 CLOSE-PACKED ARRAYS

The BAW close-packed series of critical experiments[12] intended to simulate consolidated fuel, were analyzed with NITAWL-KENO5a. Results of these analyses, shown in Table 5, suggest a slightly higher bias than that for fuel with normal lattice spacings. Similar results were obtained by ORNL[13]. Because there are so few cases available for analysis, the maximum bias for close-packed lattices may be taken as 0.0155, including uncertainty. This would conservatively encompass all but one of the cases measured.

6.0 REFERENCES TO APPENDIX A

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12. G.S. Hoovler, et al., "Critical Experiments Supporting Underwater Storage of Tightly Packed Configurations of Spent Fuel Pins", BAW-1645-4, Babcock & Wilcox Company (1981).

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Table 1

RESULTS OF 27-GROUP (SCALE) NITAWL-KENO5a CALCULATIONS OF B&W CRITICAL EXPERIMENTS

Experiment Number	Calculated k_{eff}	σ
I	0.9922	± 0.0006
II	0.9917	± 0.0005
III	0.9931	± 0.0005
IX	0.9915	± 0.0006
X	0.9903	± 0.0006
XI	0.9919	± 0.0005
XII	0.9915	± 0.0006
XIII	0.9945	± 0.0006
XIV	0.9902	± 0.0006
XV	0.9836	± 0.0006
XVI	0.9863	± 0.0006
XVII	0.9875	± 0.0006
XVIII	0.9880	± 0.0006
XIX	0.9882	± 0.0005
XX	0.9885	± 0.0006
XXI	0.9862	± 0.0006
Mean	0.9897	± 0.0007[1]
Bias (95%/95%)	0.0103	± 0.0018

(1) Standard Deviation of the Mean, calculated from the k_{eff} values.

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 AND NITAWL-KENO5a
BENCHMARK (INTERCOMPARISON) CALCULATIONS

Enrichment[1] Wt. % U-235	NITAWL-KENO5a[2]	k_∞ CASMO3	$\lvert\delta k\rvert$
2.5	0.8376 ± 0.0010	0.8386	0.0010
3.0	0.8773 ± 0.0010	0.8783	0.0010
3.5	0.9106 ± 0.0010	0.9097	0.0009
4.0	0.9367 ± 0.0011	0.9352	0.0015
4.5	0.9563 ± 0.0011	0.9565	0.0002
5.0	0.9744 ± 0.0011	0.9746	0.0002
		Mean	0.0008
Expt. No.[3]			
XIII	1.1021 ± 0.0009	1.1008	0.0013
XIV	1.0997 ± 0.0008	1.1011	0.0014
XV	1.1086 ± 0.0008	1.1087	0.0001
XVII	1.1158 ± 0.0007	1.1168	0.0010
XIX	1.1215 ± 0.0007	1.1237	0.0022
		Mean	0.0012

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

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

(3) Central Cell from BAW Critical Experiments

Table 4

Intercomparison of WORKER-NITAWL-KENO5a
and CASMO3 Calculations at Various Temperatures

Temperature	CASMO3	W-N-KENO5a(*)
4°C	1.2276	1.2345 ± 0.0014
17.5°C	1.2322	1.2328 ± 0.0015
25°C	1.2347	1.2360 ± 0.0013
50°C	1.2432	1.2475 ± 0.0014
75°C	1.2519	1.2569 ± 0.0015
120°C	1.2701	1.2746 ± 0.0014

*Corrected for bias

Table 5

Reactivity 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	1.778	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

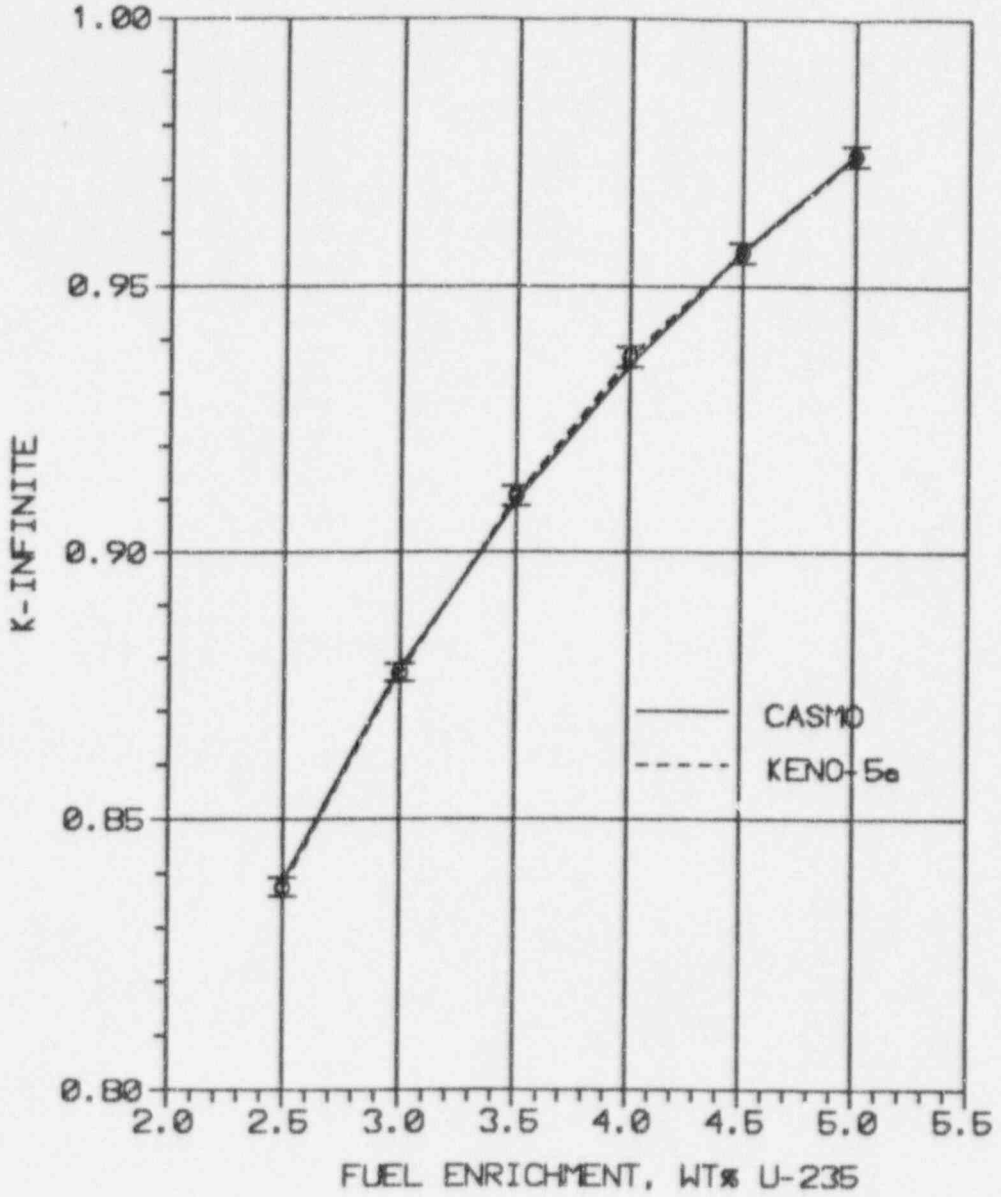

Fig. 1
COMPARISON OF CASMO AND KENO5a CALCULATIONS
AT VARIOUS ENRICHMENTS IN REPRESENTATIVE FUEL STORAGE RACK

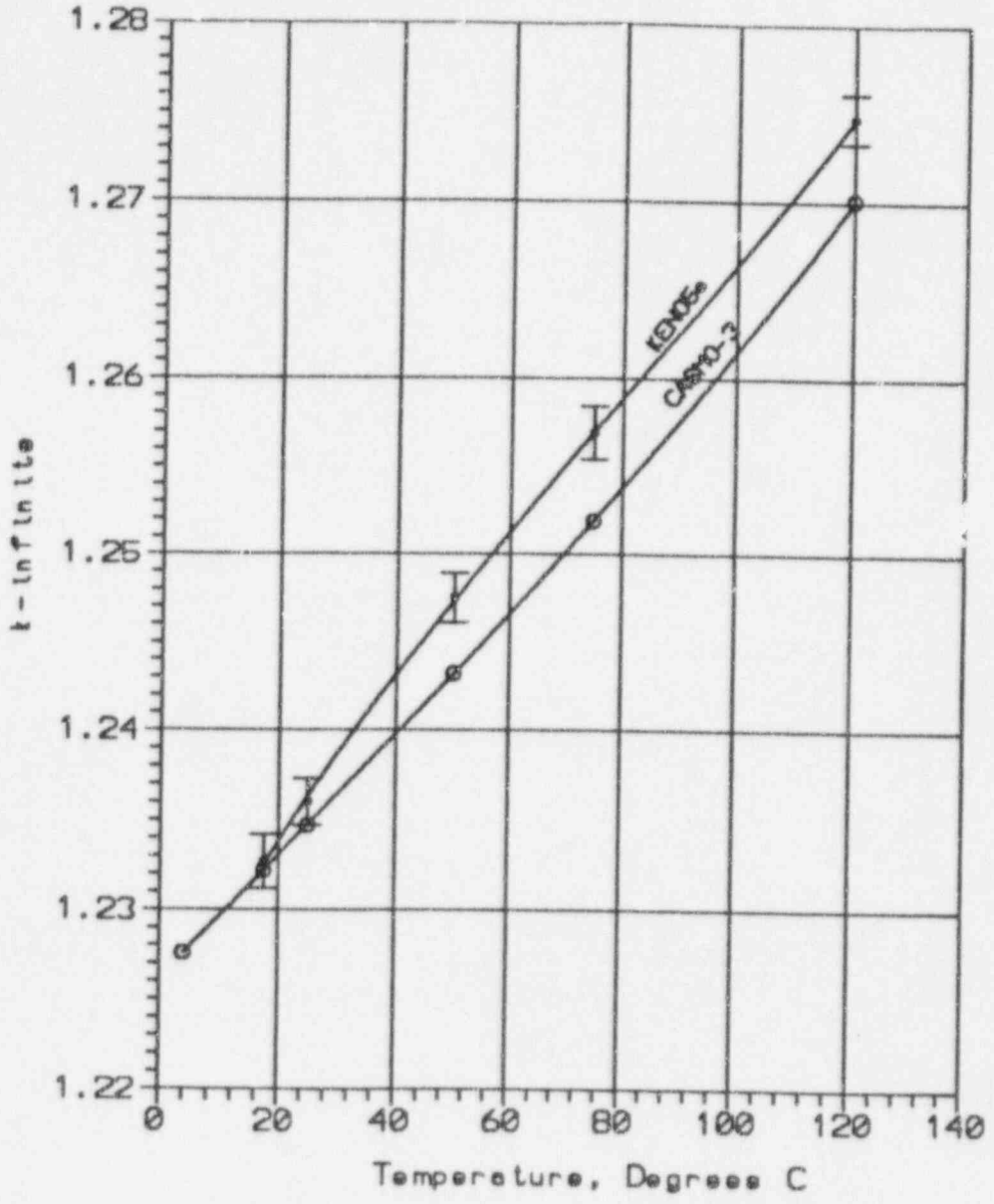

Fig. 2 COMPARISON OF CASMO-3 and KENO5a TEMPERATURE DEPENDENCE

ATTACHMENT 2