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NUCLEAR-CRITICALITY-SAFETY STUDIES OF INTEREST TO TMI-2 RECOVERY OPERATIONS

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ABSTRACT

A series of criticality calculations was made on simple systems representative of possible situations that may be found during recovery operations at TMI-2. While not specific to physical conditions that may be encountered, the effect of oxide fines on the neutron multiplication factor may be estimated from the relative effects observed in the system studied.

INTRODUCTION

Basic criticality data for 2 and 3 wt % ^{235}U in uranium are necessary to describe possible neutron multiplication factors for unusual geometries that may be encountered during re-entry of the TMI-2 reactor. The state of the reactor core is not known, but it is expected that loose oxide (probably as U_3O_8) will have to be removed as well as the fuel bundles. While an absolute definition of criticality is not feasible because of the many uncertainties, the relative effect of the oxide presence on the neutron multiplication factor of a defined condition does have reliability. The effects are explored by validated calculations utilizing the KENO V criticality code and the 27-group cross section sets used in a previous study.[1]

MATERIALS AND METHODS

Fuel pins of sintered UO_2 (r=0.4699 cm) are assumed to contain 3 wt % ^{235}U and to be clad in Zirconium (r_i=0.4788 cm, r_o=0.5461 cm). The density of the UO_2 in the fuel pins was taken as 10.138 g/cm.[3] The oxide-water mixtures assume the UO_2 is converted to U_3O_8 (theoretical density 8.3 g/cm^3) and the compositions described by a simple volume displacement relation.

The atom number densities for the sintered oxide were ^{235}U=6.873-4, ^{238}U=2.194-2 and $^{16}\phi$=4.526-2. Those for the oxide-water mixtures are described in Table 1. The table also presents the mixtures with 1500 and 3500 ppm boron by weight.

The majority of the calculations were performed with the 27 energy-group library developed from ENDF/B-IV data.[2] Cross section preparation utilized the procedures described in Ref. (1) with the exception that configurations with the oxide-water mixtures were processed by the Rolaids code.[2,3] The KENO V criticality program contains options not available in the KENO IV program. An option is the array of arrays capability which permits the description of an arrangement of fuel assemblies by a single description of the fuel pin followed by an array description to define the fuel assembly and a subsequent array specification of the fuel assemblies in the arrangement. Unless noted otherwise, all of the finite systems analyzed in this study were fully reflected with the equivalent of 30 centimeters of water.

CALCULATED DATA

Systems Containing Fuel Pins

The neutron multiplication factor of fuel pins of unlimited length and number (k_∞) was calculated for various lattice spacings. These are described in Table 2 and display the k_∞ response to the removal of the Zr-clad and the addition of boron to the water moderator. The results are summarized graphically in Fig. 1. The k_∞ of the fuel pins at TMI-2 design lattice pitch (1.443-cm) was calculated with the oxide-water-boron mixtures as the moderator. These results are given in Table 3 and in Fig. 2.

Fuel pins having a length of 50 cm were described in a 15x15 matrix at 1.443 cm lattice pitch. These fuel assemblies were then arranged in a 2x2 array of assemblies at the design fuel assembly pitch (21.181 cm) of the TMI-2 reactor. Calculations of this system were performed to display the effect of the oxide-water-boron addition and the Zr-clad on the k_{eff}. These results are given in Table 4 and displayed in Fig. 3.

The 2x2x1 configuration of assemblies with no Zr-cladding and 0-ppmB of Table 4 was calculated as an homogenized mixture in the volume occupied by the four assemblies. Interest is in displaying the effect on the calculated k_{eff}. The result is dependent on the cross-section preparation. The CSAS-1 option in SCALE was used to prepare three different cross section sets for the calculations.

(i) Description of a pin-cell of the fuel assembly to produce cross sections suitable for a detailed description of the fuel assemblies in a KENO-V calculation of k_{eff} (this set was used to produce the results in Table 4),

(ii) Description of a pin-cell of the fuel assembly to produce cell-weighted cross sections to represent smearing the fuel over the region of the fuel assembly in a KENO V calculation of k_{eff}, and

(iii) Producing the cross sections for an infinite homogenous medium using the number densities from the homogenized 2x2x1 core.

The use of the (i) set resulted in the value reported in Table 4, 1.102±0.005. The use of set (ii) when the fuel assemblies are homogenized, i.e., a 2x2x1 array of four separated homogenized regions, resulted in a k_{eff} of 1.096±0.004. The use of set (i) with the entire core homogenized gave a k_{eff} of 1.092±0.004. Finally the use of set (iii) with the entire 2x2x1 core homogenized produced a k_{eff} of 1.047±0.004.

Table 1. Atom Number Densities for $U(3)_3O_8$-Water-Boron Mixtures Used in KENO V Criticality Program

U_3O_8 Density	^{235}U density	$H/^{235}U$	^{235}U	^{238}U	$^{16}\phi$	^{1}H	^{10}B	^{11}B
				0-ppm B				
4.0	1.018-1	132.9	2.6087-4	8.3283-3	4.0245-2	3.4681-2	----	----
2.0	5.09-2	389.6	1.3043-4	4.1642-3	3.6858-2	5.0812-2	----	----
1.5	3.82-2	560.6	9.7825-5	3.1231-3	3.6011-2	5.4844-2	----	----
1.0	2.54-2	902.8	6.5216-5	2.0821-3	3.5165-2	5.8877-2	----	----
0.5	1.27-2	1929.3	3.2608-5	1.0410-3	3.4318-2	6.2909-2	----	----
0.25	6.36-3	3982.2	1.6304-5	5.2052-4	3.3895-2	6.4926-2	----	----
				1500-ppm B				
4.0	1.018-1	132.9	2.6087-4	8.3283-3	4.0226-2	3.4514-2	8.5731-6	3.4769-5
2.0	5.09-2	389.6	1.3043-4	4.1642-3	3.6831-2	5.0566-2	1.2561-5	5.0941-5
1.5	3.82-2	560.6	9.7825-5	3.1231-3	3.5982-2	5.4579-2	1.3558-5	5.4984-5
1.0	2.54-2	902.8	6.5216-5	2.0821-3	3.5133-2	5.8593-2	1.4554-5	5.9027-5
0.5	1.27-2	1929.3	3.2608-5	1.0410-3	3.4284-2	6.2606-2	1.5512-5	6.3070-5
0.25	6.36-3	3982.2	1.6304-5	5.2052-4	3.3859-2	6.4612-2	1.6050-5	6.5091-5
				3500-ppm B				
4.0	1.018-1	132.9	2.6087-4	8.3283-3	4.0202-2	3.4296-2	1.9680-5	7.9815-5
2.0	5.09-2	389.6	1.3043-4	4.1642-3	3.6795-2	5.0248-2	2.8834-5	1.1694-4
1.5	3.82-2	560.6	9.7825-5	3.1231-3	3.5943-2	5.4236-2	3.1122-5	1.2622-4
1.0	2.54-2	902.8	6.5216-5	2.0821-3	3.5091-2	5.8224-2	3.3411-5	1.3550-4
0.5	1.27-2	1929.3	3.2608-5	1.0410-3	3.4240-2	6.2212-2	3.5700-5	1.4478-4
0.25	6.36-3	3982.2	1.6304-5	5.2052-4	3.3814-2	6.4206-2	3.6843-5	1.4942-4

Table 2. Effect of Spacing, Zr-Cladding, and Boron on the Infinite-Lattice Neutron Multiplication Factor of Fuel Pins

Lattice pitch (cm)	Zr clad	k_∞ 0-ppm B	1500-ppm B	3500-ppm B
1.425	No	1.404	1.122	0.900
1.425	Yes	1.373	1.144	0.949
1.776	No	1.383	0.958	0.699
1.776	Yes	1.387	0.996	0.742
2.109	No	1.302	0.792	0.541
2.109	Yes	1.317	0.825	0.570

Table 3. The Effect of $U(3)_3O_8$-Water-Boron Mixtures on the Infinite-Lattice Neutron Multiplication Factor of Fuel Pins at Design Pitch

U_3O_8 density	k_∞ 0-ppm B	1500-ppm B	3500-ppm B
	— Zr clad —		
4.0	1.098	1.039	0.972
2.0	1.232	1.107	0.981
1.5	1.261	1.113	0.971
1.0	1.288	1.117	0.957
0.5	1.318	1.118	0.941
0.25	1.337	1.124	0.933
0.0	1.373	1.144	0.949
	— no Zr clad —		
4.0		1.072	0.994
2.0		1.122	0.977
1.5		1.121	0.958
1.0		1.116	0.934
0.5		1.107	0.905
0.25		1.103	0.891
0.0	1.404	1.122	0.900

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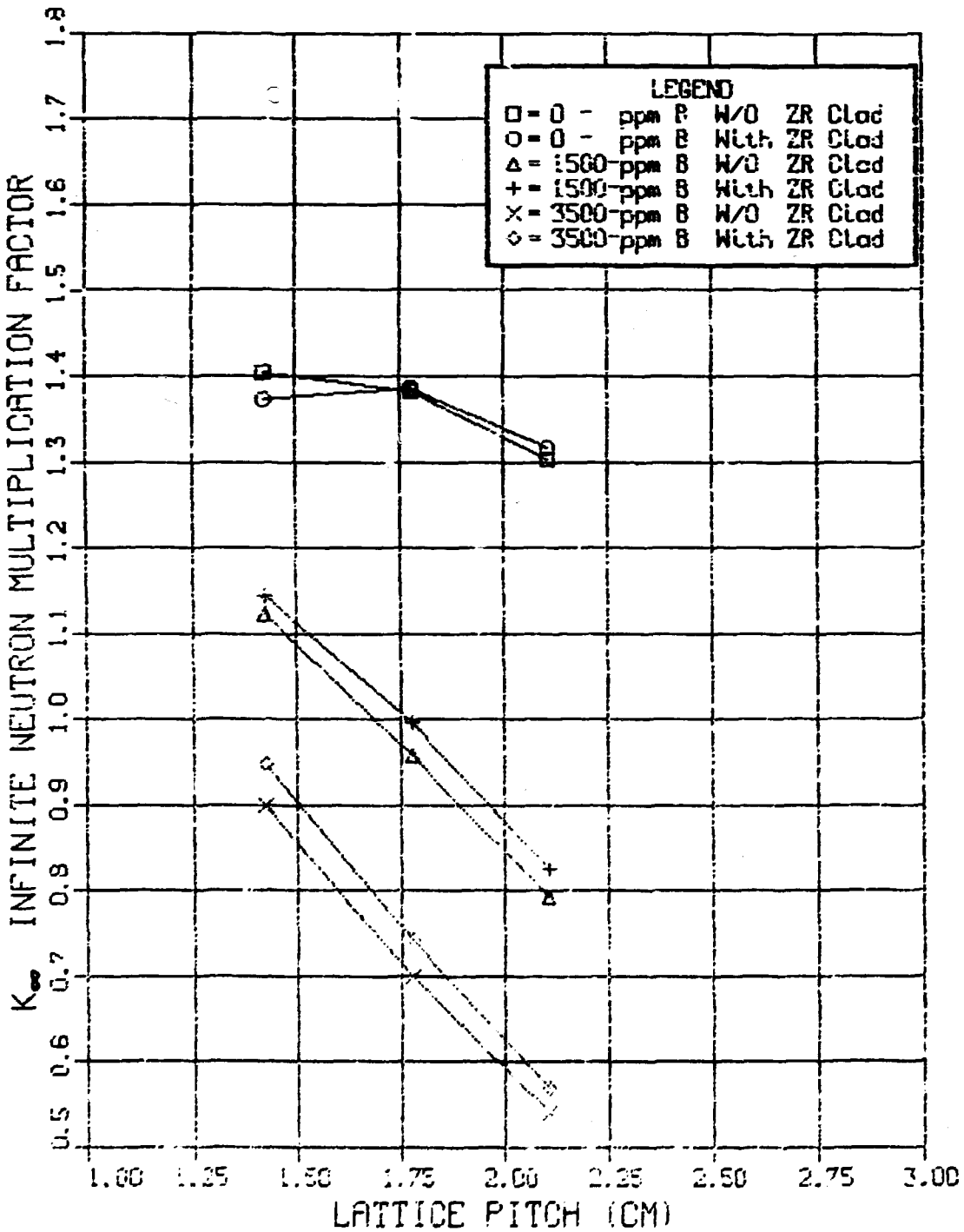

Fig. 1. Neutron multiplication factor of an infinite lattice of fuel pins showing the influence of Zr-cladding and boron concentration in moderator

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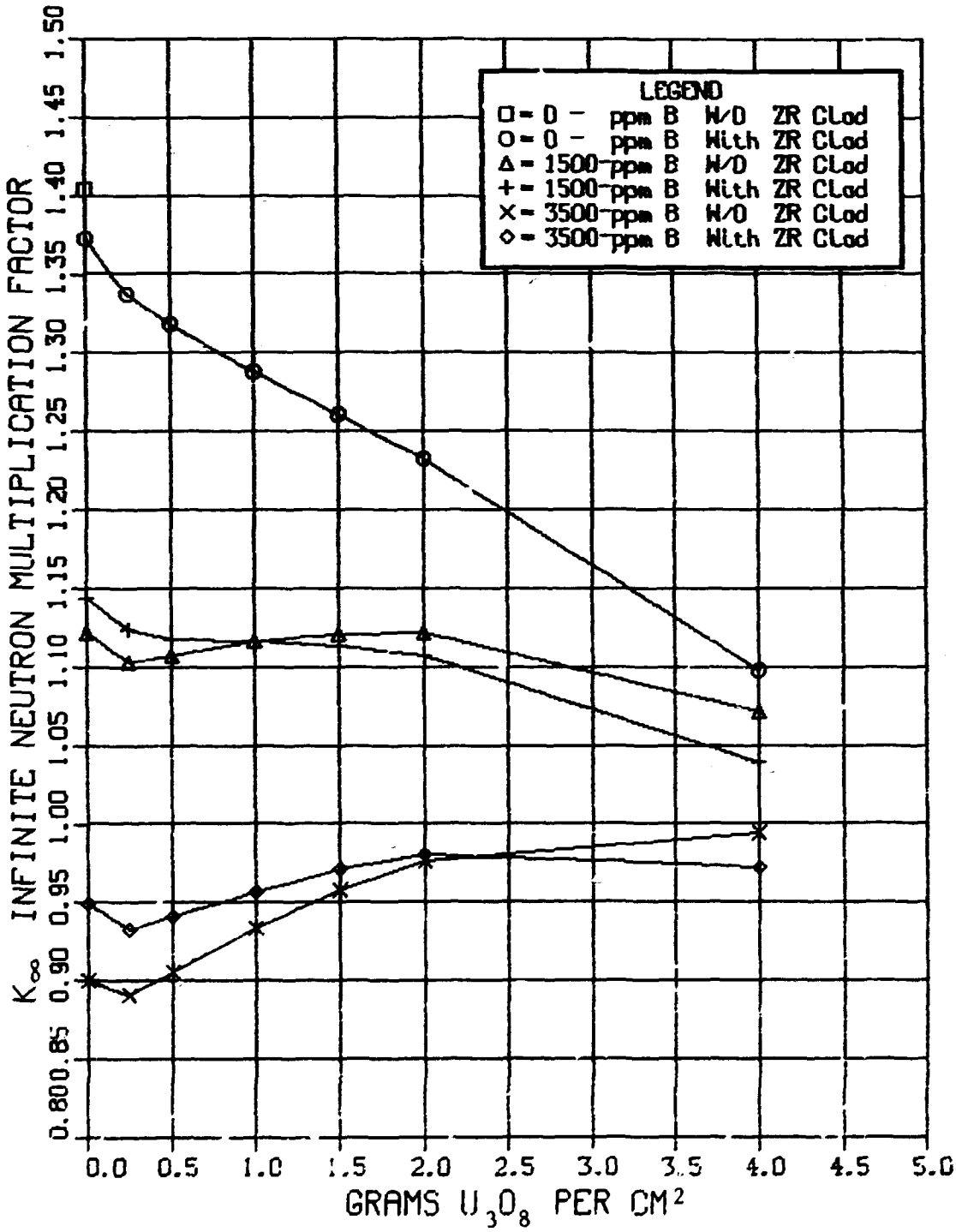

Fig. 2. Neutron multiplication factor of an infinite lattice of fuel pins showing the influence of Zr-cladding and $U(3)_3O_8$-water-boron mixtures as moderator

Table 4. Calculated k_{eff} of a 2x2 System of Fuel Assemblies for Various $U(3)_3O_8$-Water-Boron Mixtures

$U(3)_3O_8$ density	k_{eff}[a] 0-ppm B	1500-ppm B	3500-ppm B
	-- Zr clad --		
4.0	0.813	0.772	0.723
2.0	0.921	0.822	0.727
1.5	0.938	0.841	0.729
1.0	0.972	0.839	0.718
0.5	0.988	0.838	0.704
0.25	1.002	0.832	0.696
0.0	1.033	0.863	0.711
	-- No Zr clad --		
4.0	0.874	0.820	0.759
2.0	0.985	0.866	0.754
1.5	1.006	0.872	0.742
1.0	1.030	0.867	0.725
0.5	1.054	0.858	0.701
0.25	1.074	0.856	0.694
0.0	1.102	0.866	0.701

[a] Standard deviation ± 0.004.

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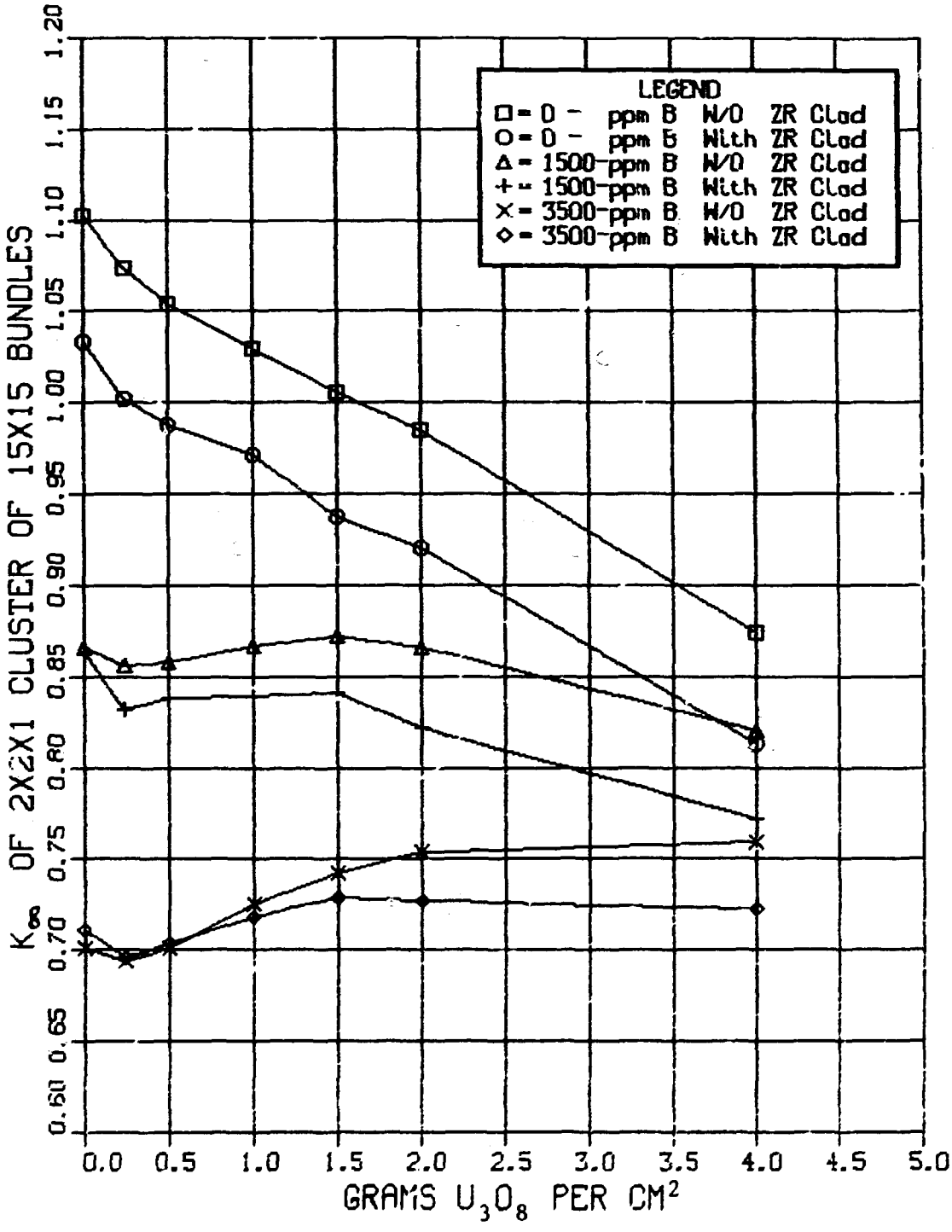

Fig. 3. Neutron multiplication factor of a 2x2 arrangement of "fuel assemblies" showing the influence of Zr-cladding and $U(3)_3O_8$- water-boron mixtures as moderator

Table 5. Calculated k_{eff} of a 3x3 System of Fuel Assemblies with Center Assembly Removed for Various $U(3)_3O_8$-Water-Boron Mixtures

$U(3)_3O_8$ density	k_{eff}[a]		
	0-ppm B	1500-ppm B	3500-ppm B
4.0	0.990	0.905	0.823
2.0	1.080	0.908	0.774
1.5	1.090	0.894	0.745
1.0	1.086	0.874	0.707
0.5	1.077	0.850	0.687
0.25	1.077	0.840	0.675
0.0	1.084	0.848	0.672

[a] Standard deviation ± 0.003.

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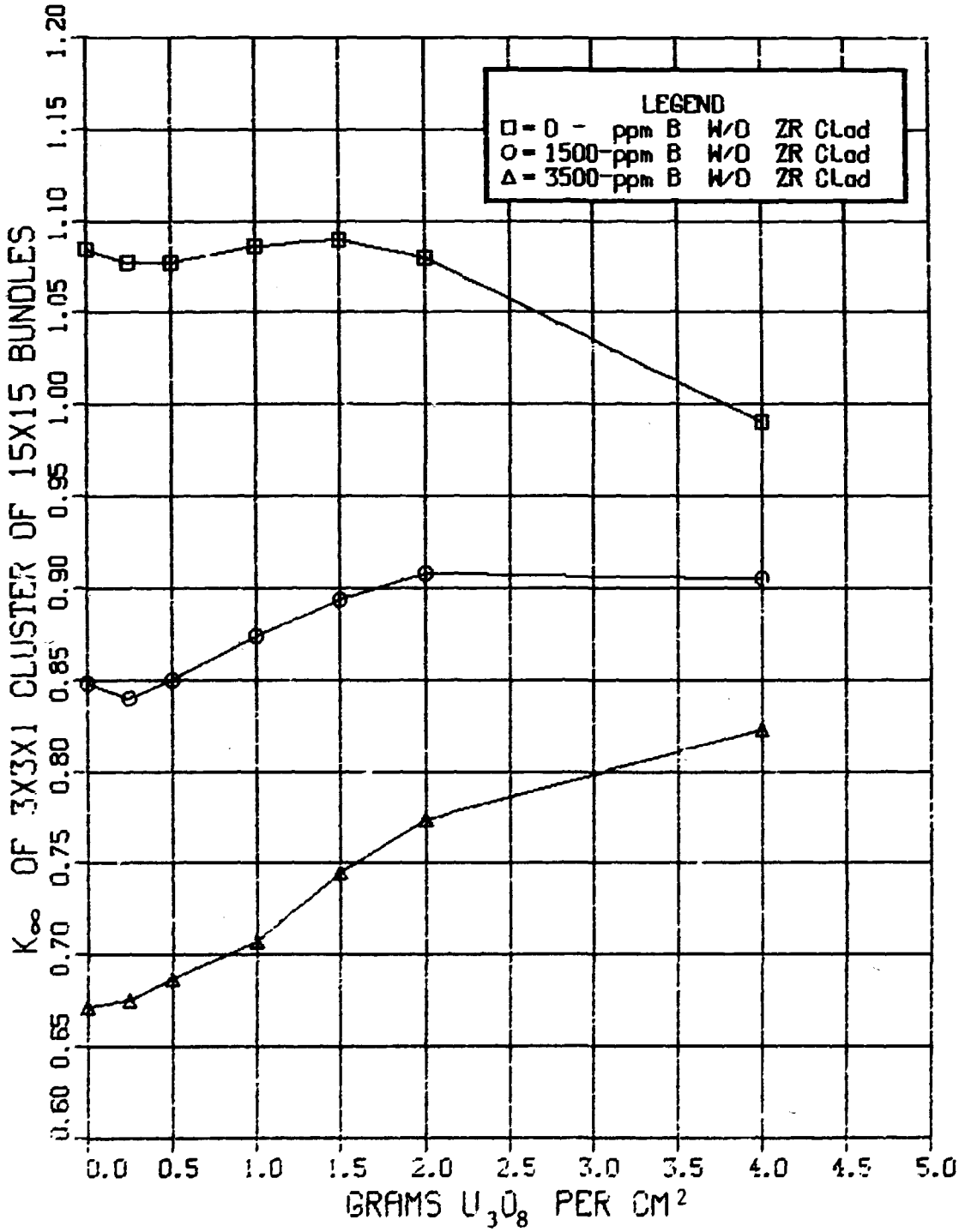

Fig. 4. Neutron multiplication factor of a 3x3 array of "fuel assemblies" with center assembly removed as a function of $U(3)_3O_8$-water-boron mixtures as moderator without Zr-cladding

An additional series of calculations was conducted on a 3x3 arrangement of fuel assemblies with the center assembly absent. These results provide some guidance on the possible significance of a region having a partially or totally destroyed fuel assembly in which oxide may pass or accumulate. The data are presented in Table 5 and are repeated in Fig. 4.

OXIDE-WATER MIXTURE SYSTEMS

The critical dimensions of the oxide-water mixture were calculated for the basic geometries of the sphere and infinite cylinder and slab. These results are given in Table 6. The response of the k_{eff} of these systems to a fractional reduction in the critical dimension is presented in Table 7. With the exception of the reflected slab, the results do not differ significantly.

It should be recognized that the chemical form and initial density of oxide influence the concentration and H:U atomic ratio in description of oxide-water mixtures. As an illustration, the two forms of oxide, $U(3)O_2$ and $U(3)_3O_8$, at 4 g of oxide per cubic centimeter are compared in Table 8.

Two additional calculations of fuel pins were made in the reflected and unreflected geometry of an infinite slab. The pins were of indefinite length, at design lattice pitch, without cladding, and there was no boron in the water moderator. A slab thickness of 17 pin-cells, unreflected, resulted in a k_{eff} of 1.000_9. The water-reflected slab consisted of 11 pin-cells giving a k_{eff} of 0.999_3.

Table 9 presents a comparison of cross sections in calculations of $U(2)O_2$-water mixtures at 0.05 g $^{235}U/cm^3$ ($H:^{235}U=367$). The H-R Mod set refers to corrections of f factors in the Hansen-Roach set which were made to effect agreement between calculations and a large number of experiments at low enrichments. The 27-group set is that used in this study. Finally the Hansen-Roach (HR) set is that used by Stratton.[4] There is reasonable agreement among these results.

Table 6. $U(3)_3O_8$-Water Mixtures: Critical Dimensions[a] for Slabs, Cylinders and Spheres

$U(3)_3O_8$ Density	^{235}U Density	$H:^{235}U$	Unreflected Systems			Reflected Systems		
			Slab	Cylinder	Sphere	Slab	Cylinder	Sphere
4.0	1.018-1	132.9	32.62	26.29	35.13	21.28	20.79	29.76
2.0	5.088-2	386.6	27.21	22.07	29.57	18.65	17.86	25.36
1.5	3.820-2	560.6	28.94	23.39	31.28	20.88	19.40	27.35
1.0	2.544-2	902.8	36.94	29.56	39.39	29.40	25.80	35.67

[a]Dimensions in centimeters.

Table 7. k_{eff} Response of Basic Geometries to Fractional Reduction in Critical Dimensions of Table 6

Fraction Critical Dimension	Unreflected Systems $U(3)_3O_8$ Density 4	2	1.5	1	Reflected Systems $U(3)_3O_8$ Density 4	2	1.5	1
			geom = sphere					
1.00	1.000	1.000	0.999	1.000	1.000	1.000	1.000	1.000
0.95	0.978	0.976	0.978	0.985	0.982	0.980	0.982	0.988
0.90	0.952	0.949	0.954	0.969	0.962	0.957	0.961	0.972
0.85	0.924	0.918	0.926	0.949	0.940	0.932	0.937	0.955
0.80	0.892	0.884	0.896	0.927	0.915	0.904	0.912	0.936
0.75	0.857	0.846	0.861	0.902	0.888	0.874	0.883	0.915
0.70	0.817	0.804	0.822	0.873	0.859	0.841	0.852	0.890
0.65	0.771	0.756	0.778	0.840	0.826	0.804	0.817	0.862
0.60	0.720	0.703	0.728	0.801	0.790	0.763	0.778	0.830
0.55	0.663	0.643	0.671	0.756	0.750	0.717	0.734	0.794
0.50	0.598	0.576	0.607	0.703	0.705	0.667	0.685	0.752
			geom = cylinder					
1.00	1.000	1.000	1.000	1.000	1.000	0.999	0.999	1.000
0.95	0.978	0.976	0.979	0.985	0.983	0.981	0.982	0.988
0.90	0.953	0.949	0.955	0.969	0.965	0.960	0.962	0.974
0.85	0.926	0.920	0.928	0.950	0.945	0.937	0.941	0.958
0.80	0.895	0.887	0.898	0.929	0.923	0.913	0.918	0.940
0.75	0.860	0.850	0.864	0.904	0.900	0.885	0.892	0.920
0.70	0.821	0.809	0.826	0.876	0.874	0.856	0.864	0.897
0.65	0.777	0.762	0.783	0.843	0.845			0.872
0.60	0.727	0.710	0.735	0.805	0.813			
0.55	0.671	0.652	0.680	0.761	0.779			
0.50	0.608	0.587	0.617	0.710	0.740			
			geom = slab					
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.95	0.979	0.977	0.980	0.986	0.986	0.985	0.986	0.990
0.90	0.955	0.952	0.957	0.970	0.971	0.968	0.970	0.977
0.85	0.929	0.924	0.931	0.952	0.956	0.950	0.952	0.964
0.80	0.900	0.892	0.903	0.931	0.939	0.931	0.934	0.949
0.75	0.867	0.857	0.871	0.908	0.922	0.910	0.914	0.932
0.70	0.830	0.818	0.835	0.881	0.903	0.888	0.892	0.913
0.65	0.789	0.775	0.794	0.850	0.882	0.864	0.868	0.893
0.60	0.742	0.726	0.749	0.815	0.860	0.838	0.841	0.870
0.55	0.690	0.671	0.697	0.773	0.836	0.809	0.813	0.844
0.5	0.631	0.610	0.638	0.725	0.810	0.779	0.781	0.815

Table 8. Comparison of the Oxide Forms $U(3)O_2$ and $U(3)_3O_8$ at 4 g Oxide/cc

Oxide Form	$U(3)O_2$	$U(3)_3O_8$
ρ_o(g/cc) (Reference Density) t	10.138	8.3
g ^{235}U/cc	1.057-1	1.018-1
^{235}N	2.711-4	2.6087-4
^{238}N	8.654-3	8.328-3
^{1}N	4.0511-2	3.4681-2
^{16}N	3.8106-2	4.0245-2
H:^{235}U	149.4	132.9
H:U	4.539	4.038
Reflected r_c,cm Sphere	27.42	29.76
Unreflected r_c,cm Sphere	32.48	35.13

Table 9. $U(2)O_2$ - Water Mixtures: Critical Dimension[a] of Slabs, Cylinders, and Spheres

Cross Sections	Unreflected			Reflected		
	Slab	Cylinder	Sphere	Slab	Cylinder	Sphere
H-R-mod.	34.22	27.51	36.69	24.77	22.78	32.00
27 grp	34.56	27.74	36.98	25.49	23.20	32.46
H-R	37.53	30.06	40.06	27.84	25.21	35.22

[a]Dimensions in centimeters.

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