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COMPUTING AND TELECOMMUNICATIONS DIVISION
at
Oak Ridge National Laboratory

**THE EFFECT OF BORON AND GADOLINIUM CONCENTRATION
ON THE CALCULATED NEUTRON MULTIPLICATION FACTOR
OF U(3)O₂ FUEL PINS IN OPTIMUM GEOMETRIES**

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Oak Ridge National Laboratory Oak Ridge Y-12 Plant
Oak Ridge Gaseous Diffusion Plant Paducah Gaseous Diffusion Plant
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ABSTRACT

The KENO-Va improved Monte Carlo criticality program is used to calculate the neutron multiplication factor for TMI-U2 fuel compositions in a variety of configurations and to display parametric regions giving rise to maximum reactivity contributions. The lattice pitch of UO_2 fuel pins producing a maximum in k_{eff} is determined as a function of boron concentrations in the coolant for infinite and finite systems. The characteristics of U_3O_8 -coolant mixtures of interest to modeling the rubble region of the core are presented. Several disrupted core configurations are calculated and comparisons made. The results should be useful to proposed defueling of the TMI-U2 reactor.

I. INTRODUCTION

The present work is an extension of a previous study¹ conducted in 1982. The need to understand and document the potential for recriticality at the TMI-U2 reactor during planned defueling operations has stimulated numerous questions of possible parametric changes and geometric configurations that could contribute reactivity to the existing core conditions. In this work the response of the calculated neutron multiplication factor to variations in the following parameters of various systems was examined:

- the uranium ^{235}U enrichment;
- the system geometry;
- the fuel pin lattice pitch;
- the UO_2 and U_3O_8 volume fraction; and
- the boron concentrations in the coolant.

The ^{235}U content of uranium as the oxide was that of the initial TMI-U2 core, i.e., 1.98, 2.64, and 2.96 wt%. Additional ^{235}U enrichments considered were 2.0 wt%, the average for the core, 2.57 wt%, and 3.0 wt%. The UO_2 was in the geometry of the fuel pins at 92.5% of theoretical density. The fuel pin lattice pitch was varied to define the maximum k_{eff} for a system. The variation was conducted for infinite arrays of pins and for finite systems approximately the size of the TMI-U2 core. The infinite system was also used to examine the optimum U_3O_8 -water mixture. These results were applied to represent an upper limit in k_{eff} that may be expected from a region of rubble in a disrupted core model. The effect of boron concentration in the moderator (coolant) on the variation of the parameters was examined. Finally, a limited set of comparative calculations with 3 wt% ^{235}U in uranium was made with gadolinium as the neutron absorber.

The three-dimensional Monte Carlo transport code, KENO V,² was used to calculate the finite systems in disrupted core configurations. The one-dimensional discrete-ordinates transport code, XSDRNPM, was used to calculate the pin lattices and U_3O_8 -coolant mixtures. All calculations were performed in compliance with the ORNL Computer Services Quality Assurance Program. Computational software and data libraries are quality assured through the Configuration Control Management System. Individual case input and output records are retained for future reference and/or reproducibility.

II. CALCULATIONAL METHODS

The computations were performed with the modular code System for performing Standardized Computer Analyses for Licensing Evaluation (SCALE³). Several Criticality Safety Analysis Sequence (CSAS₁) control modules are available in SCALE to calculate a system k_{eff} . CSAS₁ applies a standardized procedure to calculate the number densities of the nuclides in a described composition and prepares the 27-group cross-section sets from the ENDF/B-IV cross-section library. Cross-section preparation may involve the use of the codes NITAWL-S and BONAMI-S to determine the problem-dependent resonance shielding and resonance self-shielding, respectively. CSAS1 is selected for the analysis of one-dimensional geometry problems, i.e., infinite systems. In this case the one-dimensional transport code XSDRNPM is used. CSAS2 is utilized for multi-dimensional problems, i.e., finite geometries, and the analysis is performed with the three-dimensional Monte Carlo transport code KENO V.

As a test of the Monte Carlo code and cross-section preparation, a zero-power startup of the TMI-U2 reactor configuration was calculated. The conditions at critical may be summarized as follows:

- Coolant: 532°F, 2200 psi, $\rho = 0.77$, and 1500 ppm Boron
- Fuel: 532°F
- Control rods: out
- Axial power shaping rods: centered
- Calculated k_{eff} : 0.9973 ± 0.0028

Details of the core description and the code input appear in the Appendix. The resulting k_{eff} is in good agreement with the reported⁴ measurements made in the original TMI-U2 core.

While a test of the critical state for a configuration is necessary to measure the reliability of a method used in analyses, the sufficiency for off-critical states is not established. This problem is fundamental to the adequacy of calculated margins of subcriticality. It follows that more reliance is to be given to Δk_{eff} 's corresponding to parametric changes than to a state characterized by a value of k_{eff} less than unity. The relative interpretation of calculations in conjunction with possible insight on the neutron behavior within a configuration is a more useful basis for safety judgments than is a simple k_{eff} .

III. OPTIMUM LATTICE PITCH GEOMETRIES

A series of calculations was performed with fuel pins having 3 wt% ^{235}U in uranium as the oxide, U(3)O_2 . The calculations were performed with and without the zirconium cladding. Beginning with a definition of the lattice pitch producing the maximum k_{eff} of fuel pins in water as an indefinitely extended system, the effect of boron added to the moderator water was examined. A similar study in finite geometry was conducted. This sequence was repeated with gadolinium as the neutron absorber. Since the effect of absorbers added to the moderator influences the lattice pitch producing the maximum k_{eff} , characterization of this combined parametric change was examined.

A. U(3)O_2 CLAD FUEL PINS

Maximum k_{eff}

The CSAS-1 module produced the calculated k_{eff} of zirconium-clad fuel pins with unlimited length and number as a function of lattice pitch. The results are given in Fig. 1 and define the maximum k_{eff} as occurring in the vicinity of 1.61 cm.

The maximum k_{eff} was defined for a finite geometry approximating that of the TMI-U2 core. Fuel pins at a 3.66-m length were arranged as fuel assemblies in the pattern shown for the TMI-U2 core in Fig. 2. The lattice pitch was varied, but the design spacing between assemblies was maintained. The positions in the configuration occupied by the control rod assemblies and the instruments were replaced by the moderator. The configuration was surrounded by a 30.48-cm thickness of moderator as the reflector. The CSAS-2 sequence produced the results shown in Fig. 3.

Boron and Gadolinium

The system k_{eff} response to the addition of boron to the moderator-reflector water mixture was examined for the infinite and finite geometries at the lattice pitch of 1.61 cm. These results are presented in Fig. 4. The region in this figure common to the two geometries is shown on an expanded scale in Fig. 5. The effect of gadolinium concentration on the k_{eff} of the two geometries is summarized in Fig. 6. The rate of change in k_{eff} with absorber concentration is greater for gadolinium than for the boron absorber. Further, the difference between the finite and infinite systems is more divergent with decreasing k_{eff} values than the boron results of Figs. 4 and 5.

The moderator and absorber number densities used in these calculations are presented in Table 1. The calculated k_{eff} values plotted in Figs. 1 and 3-6 are tabulated in Table 2.

B. U(3)O_2 UNCLAD FUEL PINS

A parametric study defining the maximum k_{eff} for the infinite and finite systems and the influence of neutron absorbers was also conducted for unclad fuel pins. The results are presented graphically and in tabulated form in the same manner as the information for the clad fuel pins.

Maximum k_{eff}

The infinite system is coarsely defined in Fig. 7 where the k_{eff} is shown as a function of the lattice pitch. The maximum k_{eff} is defined as occurring between the lattice pitch values of 1.5 and 1.6 cm. An expanded scale of these results, given in Fig. 8, shows little difference between the 1.52- and 1.53-cm values of lattice pitch. The maximum k_{eff} for the finite geometry occurs near a lattice pitch value of 1.52 cm as depicted in Fig. 9.

Fig. 1. The k_{eff} of an infinite system of clad $U(3)O_2$ fuel pins as a function of lattice pitch.

Fig. 2. Reactor vessel and internal cross section of Three Mile Island Nuclear Station Unit 2.

Fig. 3. The k_{eff} of a finite system of clad $U(3)O_2$ fuel pins approximately the size of the TMI-U2 core as a function of the lattice pitch.

Fig. 4. The k_{eff} of the infinite and finite systems of clad $U(3)O_2$ fuel pins as a function of boron concentration for a fixed lattice pitch of 1.61 cm.

Fig. 5. The k_{eff} of the infinite and finite systems of clad $U(3)O_2$ fuel pins as a function of the boron concentration at a fixed lattice pitch of 1.61 cm. These are data of Fig. 4 with an enlarged scale.

Fig. 6. The k_{eff} of the infinite and finite systems of clad $U(3)O_2$ fuel pins function of the gadolinium concentration at a fixed lattice pitch of 1.61 cm.

Table 1. Atom number densities used in the KENO-V Criticality Program--
 $U(3)O_2$ and mixtures of moderator-reflector water and neutron absorbers

UO ₂			
²³⁵ U	²³⁸ U	Oxygen	Zirconium
6.8676-4	2.1924-2	4.5223-2	4.2518-2

MODERATOR AND REFLECTOR

ppm Boron	Boron-10	Boron-11	Oxygen	Hydrogen
262	2.8829-6	1.1704-5	3.3423-2	6.6803-2
349	3.8439-6	1.5605-5	3.3438-2	6.6817-2
437	4.8049-6	1.9506-5	3.3452-2	6.6832-2
524	5.7659-6	2.3408-5	3.3467-2	6.6846-2
1300	1.4323-5	5.8148-5	3.3597-2	6.6976-2
1500	1.6526-5	6.7094-5	3.3630-2	6.7010-2
1658	1.8258-5	7.4126-5	3.3656-2	6.7036-2
1700	1.8730-5	7.6040-5	3.3664-2	6.7043-2
1800	1.9832-5	8.0513-5	3.3680-2	6.7060-2
1815	1.9997-5	8.1184-5	3.3683-2	6.7062-2
1900	2.0934-5	8.4986-5	3.3697-2	6.7077-2
2000	2.2035-5	8.9459-5	3.3714-2	6.7093-2
2020	2.2256-5	9.0353-5	3.3717-2	6.7097-2
2183	2.4024-5	9.7534-5	3.3744-2	6.7123-2
2200	2.4239-5	9.8405-5	3.3747-2	6.7127-2
2239	2.4645-5	1.0005-4	3.3753-2	6.7133-2
2270	2.5010-5	1.0153-4	3.3759-2	6.7138-2
2505	2.7599-5	1.1204-4	3.3798-2	6.7178-2
2600	2.8646-5	1.1629-4	3.3814-2	6.7194-2
2687	2.9575-5	1.2006-4	3.3828-2	6.7208-2
2844	3.1300-5	1.2707-4	3.3854-2	6.7234-2
2911	3.2039-5	1.3007-4	3.3866-2	6.7245-2
3358	3.6968-5	1.5008-4	3.3940-2	6.7320-2
3492	3.8439-5	1.5605-4	3.3963-2	6.7342-2

Oxygen	Hydrogen
3.337-2	6.675-2
G/L Gadolinium	Gadolinium
0.300	1.1489-6
0.500	1.9149-6
0.575	2.2021-6
0.600	2.2979-6
0.615	2.3553-6
0.650	2.4894-6
0.675	2.5851-6
0.685	2.6234-6
0.700	2.6809-6
0.775	2.9681-6
0.870	3.3320-6
1.000	3.8299-6

Table 2. Summary of calculated values for systems with zirconium-clad fuel pins of $U(3)O_2$

Case	Optimum Pitch Search	
	Pitch(cm)	K-Effective
Infinite System		
CORE1X	1.44272	1.37897
CORE2X	1.48418	1.38786
CORE3X	1.52563	1.39364
CORE4X	1.56709	1.39710
CORE5X	1.60654	1.39843
CORE6X	1.65000	1.39784
Finite System		
CORE1		
PASS 1	1.44272	1.36982 + 0.00310
PASS 2	1.09220	1.09178 + 0.00380
PASS 3	3.19540	0.92230 + 0.00320
PASS 4	2.31900	1.20581 + 0.00280
PASS 5	1.68060	1.36995 + 0.00297

Pitch = 1.60854

Case	ppm Boron	K-Effective
Finite System		
COREB01	1815	0.97232 + 0.00235
COREB02	2020	0.94176 + 0.00299
COREB03	2270	0.91172 + 0.00289
COREB04	2505	0.87824 + 0.00278
Infinite System		
COR5XB01	262	1.32767
COR5XB02	349	1.30578
COR5XB03	437	1.28466
COR5XB04	524	1.26429
COR5XB09	1658	1.05206
COR5XB10	2183	0.978390
COR5XB02*	2239	0.971114
COR5XB03*	2687	0.917579
COR5XB05*	2844	0.900374
COR5XB04*	2911	0.893234
COR5XB01*	3358	0.848712
COR5XB11	3492	0.836383

(*Case was altered without changing case name)

Pitch = 1.60854

Case	Gadolinium (G/L)	K-Effective
Finite System		
COREGD1	0.615	0.96870 + 0.00250
COREGD2	0.685	0.93872 + 0.00302
COREGD3	0.775	0.90400 + 0.00292
COREGD4	0.870	0.86861 + 0.00282
Infinite System		
COR5XGD3	0.3	1.17913
COR5XGD4	0.5	1.07608
COR5XGD2	0.7	0.994783
COR5XGD5	1.0	0.900458

Fig. 7. The k_{eff} of an infinite system of unclad $U(3)O_2$ fuel pins as a function of lattice pitch.

Fig. 8. The k_{eff} of an infinite system of unclad $U(3)O_2$ fuel pins as a function of the lattice pitch. These are data of Fig. 7 with an enlarged scale.

Fig. 9. The k_{eff} of a finite system of unclad $U(3)O_2$ fuel pins approximately the size of the TMI-U2 core as a function of lattice pitch.

Boron and Gadolinium

The effect of the neutron absorber concentration on the calculated k_{eff} for the infinite and finite systems is displayed in Figs. 10 and 11. The information on boron is shown in Fig. 10. The values for the finite system exhibit more scatter than the similar cases with the clad fuel pins. The curve through the points has been drawn to reflect a consistency among the infinite and finite systems. The information with gadolinium as the neutron absorber, as shown in Fig. 11, is again observed to be slightly divergent for the two geometries with decreasing k_{eff} values, although less so than for the clad fuel pins.

The calculated values of k_{eff} appearing in Figs. 7-11 are reported in Table 3.

A summary of the calculated k_{eff} values is presented in Fig. 12 as a function of the boron concentration, cladding, and the two geometries. Figure 13 presents similar results for the gadolinium absorber.

Two additional calculations were performed to examine the effect of temperature on a finite system. The case labeled COREBO5A of Table 3, containing 1700 ppmB and representing room temperature, was repeated for the temperatures of 50° and 32°F. These results are reported in Table 4.

C. COMBINED PARAMETER CHANGES

A series of calculations studied the effect on k_{eff} as a function of both lattice pitch and boron concentration. The results for infinite systems are given in Fig. 14 with the zirconium-clad fuel pins and in Fig. 15 with unclad pins. The calculated k_{eff} values are presented in Table 5. The moderator used in this set of calculations is described in Table 6.

The boron concentration and corresponding lattice pitch producing the maximum k_{eff} were recalculated as finite systems reflected by 30.4 cm of moderator. These cases are presented in Table 7. The fuel pins were uniformly latticed in these calculations. Two of the cases were repeated removing fuel pins from positions where control rods would be located were the fuel pins identified as fuel assemblies. A comparison of the infinite and finite systems producing maximum k_{eff} 's is made in Fig. 16.

The set of finite calculations was repeated with the fuel pins represented as fuel assemblies having a constant surface separation between assemblies equal to that of the TMI-U2 core. These results are given in Table 8 and the graphical comparison made in Fig. 17. Fuel pins occupy all locations in a fuel assembly as in Fig. 16.

Figure 18 compares the results obtained for the maximum k_{eff} produced by the corresponding boron concentration and lattice pitch to the results for the defined maximum k_{eff} at a lattice pitch of 1.61 cm and the effect of boron addition to the k_{eff} .

D. ADDITIONAL ^{235}U ENRICHMENTS

The combined parameter variation was applied to the oxide fuel pins containing 2.57 wt% ^{235}U in the uranium. This value is an average of the ^{235}U content of the uranium in the TMI-U2 core. The calculated k_{eff} values for an infinite system of these fuel pins with and without zirconium cladding are presented in Fig. 19 and tabulated in Table 9. Similar calculations for $\text{U}(2)\text{O}_2$ were performed. A graphical presentation is made in Fig. 20 and the tabulation of values given in Table 10.

Figure 21 compares the maximum k_{eff} observed for infinite systems of the three ^{235}U enrichments as a function of the boron concentration.

Fig. 10. The k_{eff} of the infinite and finite systems of unclad $U(3)O_2$ fuel pins as a function of the boron concentration at a fixed lattice pitch of 1.53 cm.

Fig. 11. The k_{eff} of the infinite and finite systems of unclad $\text{U}(3)\text{O}_2$ fuel pins as a function of gadolinium concentration at a fixed lattice pitch of 1.53 cm.

Table 3. Summary of calculated values for systems with unclad fuel pins of $U(3)O_2$

Case	Optimum Pitch Search Pitch(cm)	K-Effective
Infinite System		
CORE4XA	0.93980	1.01764-CLOSE PACKED
CORE7XA	0.98000	1.09815
CORE9XA	1.00000	1.13087
CORE8XA	1.20000	1.33026
CORE1XA	1.44272	1.40301
CORE12XA	1.50000	1.40645
CORE13XA	1.52500	1.40681-OPTIMUM
CORE15XA	1.53500	1.40680
CORE14XA	1.55000	1.40657
CORE11XA	1.67000	1.40438
CORE5XA	1.80000	1.37785
CORE3XA	2.20000	1.27481
CORE2XA	3.10000	0.982282
CORE6XA	3.20000	0.951233
CORE10XA	3.40000	0.891379
Finite System		
CORE1A		
PASS 1	1.44272	1.38429 + 0.00312
PASS 2	1.09220	1.24375 + 0.00345
PASS 3	3.19540	0.90047 + 0.00306
PASS 4	2.31900	1.18806 + 0.00270
PASS 5	1.57820	1.38492 + 0.00230
Pitch = 1.525		
Case	ppm Boron	K-Effective
Finite System:		
COREB01A	1800	0.98322 + 0.00258
COREB02A	2000	0.94627 + 0.00286
COREB03A	2100	0.92736 + 0.00287
COREB04A	1900	0.97394 + 0.00275
COREB05A	1700	0.99979 + 0.00256
Infinite System		
CO13XB01	1500	1.08454
CO13XB02	1700	1.05334
CO13XB03	1300	1.11784
CO13XB04	2200	0.983482
CO13XB05	2600	0.934647
Pitch = 1.525		
Case	Gadolinium (G/L)	K-Effective
Finite System		
COREGD1A	0.575	0.99748 + 0.00279
COREGD2A	0.600	0.98422 + 0.00281
COREGD3A	0.650	0.96210 + 0.00276
COREGD4A	0.675	0.95410 + 0.00249
COREGD5A	0.700	0.94233 + 0.00277
Infinite System		
CO13XGD3	0.300	1.18723
CO13XGD4	0.500	1.08402
CO13XGD2	0.700	1.00260
CO13XGD5	1.000	0.908104

Fig. 12. The influence of boron on the calculated k_{eff} of idealized systems of $U(3)O_2$ fuel pins with and without zirconium cladding.

Fig. 13. The influence of gadolinium on the calculated k_{eff} of idealized systems of $U(3)O_2$ fuel pins with and without zirconium cladding.

Table 4. Calculated k_{eff} for a finite system of unclad fuel pins at a lattice pitch of 1.53 cm as a function of temperature

Temp. °F	k_{eff}	$\pm \sigma$
68	0.99979	0.00256
50	0.99991	0.00269
32	1.00722	0.00270

Fig. 14. The calculated k_{∞} of infinite lattices of $U(3)O_2$ zirconium-clad fuel pins as a function of boron concentration in the coolant and of the fuel pin lattice pitch.

Fig. 15. The calculated k_{eff} of infinite lattices of $U(3)O_2$ unclad fuel pins as a function of boron concentration in coolant and of the fuel pin lattice pitch.

Table 5. Calculated k_{eff} of $U(3)O_2$ fuel pins in infinite systems with/without zirconium cladding

Case	ppm Boron	ZR	Lattice pitch	H/U	K-inf
1	0	WITH	1.0922	35.86	1.05292
2	"	"	1.2031	71.53	1.23527
3	"	"	1.3140	110.63	1.32680
3A	"	"	1.635		1.39736
	"	"	1.4430		1.3731
	"	"	1.7760		1.3685
	"	"	2.1090		1.3169
4	"	W/O	1.0922	64.94	1.24797
4A	"	"	0.9398	26.55	1.01757
5	"	"	1.2031	105.60	1.33199
6	"	"	1.3140	144.71	1.37863
6A	"	"	1.535		1.40742
	"	"	1.4430		1.4045
	"	"	1.7760		1.3828
	"	"	2.1090		1.3022
7	1500	WITH	1.0922	36.27	1.01900
8	"	"	1.2031	72.33	1.14057
9	"	"	1.3140	111.88	1.16627
	"	"	1.4430		1.1444
	"	"	1.7760		0.9957
	"	"	2.1090		0.8251
10	"	W/O	1.0922	70.73	1.15567
10A	"	"	0.9398	26.85	0.99691
11	"	"	1.2031	106.79	1.17877
12	"	"	1.3140	146.34	1.16391
	"	"	1.4430		1.1216
	"	"	1.7760		0.9582
	"	"	2.1090		0.7921
13	3443.37	WITH	1.0922	36.17	0.97574
13A	"	"	1.19		1.03518
13B	"	"	1.195		1.03577
13C	"	"	1.21		1.03641
14	"	"	1.2031	72.14	1.03878
14A	"	"	1.2200		1.03614
15	"	"	1.3140	111.59	1.01310
	"	"	1.4430		0.9492
	"	"	1.7760		0.7423
	"	"	2.1090		0.5703
16	"	W/O	1.0922	70.54	1.05594
16A	"	"	0.9398	26.78	0.96853
16B	"	"	1.0160	47.84	1.03835
17	"	"	1.2031	106.51	1.03062
18	"	"	1.3140	145.96	0.97611
	"	"	1.4430		0.8998
	"	"	1.7760		0.6996
	"	"	2.1090		0.5406
19	4500	WITH	1.0922	36.27	0.95533
19A	"	"	1.5700		0.990639
19B	"	"	1.1800		0.992669
19C	"	"	1.1900		0.992288
19D	"	"	1.2100		0.989437
19E	"	"	1.1950		0.991831
19F	"	"	1.1850		0.992570
20	"	"	1.2031	72.33	0.99308
21	"	"	1.3140	111.88	0.94857
25	"	"	1.4250	154.96	0.87735
26	"	"	1.7760	314.14	0.65119
27	"	"	2.1090	497.43	0.48914
22	"	W/O	1.0922	70.73	1.01094
22A	"	"	0.9398	26.85	0.95501

Table 5 (continued)

Case	ppm Boron	ZR	Lattice pitch	H/U	K-Inf
22B	"	"	1.0160	47.97	1.00868
22C	"	"	1.0500		1.014340
22D	"	"	1.0100		1.006780
23	"	"	1.2031	106.79	0.96763
24	"	"	1.3140	146.34	0.90082
28	"	"	1.4250	189.42	0.82712
29	"	"	1.7760	348.60	0.61382
30	"	"	2.1090	531.89	0.46483
31	5000	WITH	1.0922	36.31	0.946123
32	"	"	1.2031	72.42	0.970860
32A	"	"	1.1570		0.974901
32B	"	"	1.1700		0.976558
33	"	"	1.3140	112.02	0.919729
34	"	"	1.4250	155.15	0.845926
35	"	"	1.7760	314.53	0.617243
36	"	"	2.1090	498.05	0.459814
38	"	W/O	1.0922	70.82	0.991338
38A	"	"	0.9398	26.89	0.948844
38B	"	"	1.0160	48.03	0.995472
38C	"	"	1.0300		0.997620
38D	"	"	1.0400		0.999484
39	"	"	1.2031	106.92	0.940982
40	"	"	1.3140	146.52	0.869795
41	"	"	1.4250	189.65	0.793810
42	"	"	1.7760	349.03	0.581170
43	"	"	2.1090	532.55	0.43685
128	5500	WITH	1.0922		0.937190
129	"	"	1.11		0.949355
130	"	"	1.12		0.953996
131	"	"	1.14		0.958418
132	"	"	1.15		0.959627
133	"	"	1.16		0.959813
134	"	"	1.17		0.959194
135	"	"	1.18		0.957807
1R	6500	WITH	1.0922		0.919104
2R	"	"	1.2031		0.917126
2RA	"	"	1.1450		0.932744
3R	"	"	1.3140		0.848623
4R	"	"	1.4250		0.765866
5R	"	"	1.7760		0.537420
5RA	"	"	1.1250		0.931670
6R	"	W/O	1.0922		0.937919
7R	"	"	0.9398		0.931159
8R	"	"	1.0160		0.958638
9R	"	"	1.2031		0.870835
10R	"	"	1.3140		0.790376
11R	"	"	1.4250		0.710458
12R	"	"	1.7760		0.503572
13R	7500	WITH	1.0922		0.903864
14R	"	"	1.2031		0.885441
15R	"	"	1.3140		0.808291
16R	"	"	1.4250		0.721851
17R	"	"	1.7760		0.456274
18R	"	"	1.1250		0.910225
44	"	W/O	1.0922	71.25	0.906431
44A	"	"	0.9398	27.05	0.919994
44B	"	"	1.0160	48.33	0.926175
45	"	"	1.2031	107.59	0.830934
46	"	"	1.3140	147.43	0.746483
47	"	"	1.4250	190.82	0.665522
48	"	"	1.7760	351.19	0.463945
49	"	"	2.1090	535.85	0.340169

Table 6. Boron concentration in coolant used in infinite $U(3)O_2$ lattices of fuel pins

ppm Boron	Boron-10	Boron-11	Hydrogen	Oxygen
0			6.6742-2	3.3371-2
1500	1.65481-5	6.71126-5	6.7495-2*	3.3622-2
3443.37	3.79874-5	1.54062-4	6.73181-2	3.39471-2
3500	3.8612218-5	1.5659617-4	6.7327625-2	3.3956625-2
4500	4.9644281-5	2.0133793-4	6.7494947-2	3.4123947-2
5000	5.5160312-5	2.2370881-4	6.7578607-2	3.4207607-2
5500	6.0676343-5	2.4607969-4	6.7662268-2	3.4291268-2
6500	7.1708405-5	2.9082145-4	6.782959-5	3.445859-2
7500	8.2740468-5	3.3556321-4	6.7996911-2	3.4625911-2

*This value is 0.75% too large; the effect on calculated values of k_{eff} is not significant.

Table 7. Description of reflected finite systems defining the maximum k_{eff} for $U(3)O_2$ fuel pins as a uniform lattice

Job Name	ppm B	Lattice Pitch	ZR	K-eff
JCTOPC1A	3443.37	1.2031	WITH	1.01683 + 0.00299
JCTOPC2A	3443.37	1.0922	W/O	1.02902 + 0.00295 98GEN
JCTOPC3A	4500	1.1850	WITH	0.97141 + 0.00238
JCTOPC4A	4500	1.0500	W/O	0.97596 + 0.00331 89GEN
JCTOPC5A	5000	1.1700	WITH	0.95438 + 0.00248
JCTOPC6A	5000	1.0400	W/O	0.95637 + 0.00298
JCTOPC7A	6500	1.1450	WITH	0.91035 + 0.00256
JCTOPC8A	6500	1.0160	W/O	0.92162 + 0.00326
JCTOPC9A	7500	1.1250	WITH	0.89251 + 0.00299
JCTOP10A	7500	1.0160	W/O	0.90469 + 0.00274
WITH VOIDS AT CONTROL ROD LOCATIONS				
Job Name	ppm B	Lattice Pitch	ZR	K-eff
JCTOPC1B	3443.37	1.2031	WITH	1.00831 + .00260
JCTOPC2B	3443.37	1.0922	W/O	1.03035 + .00284 96GEN

Full Lattice Geometry

Fig. 16. Comparison of infinite and finite systems maximum calculated k_{eff} for $U(3)O_2$ unclad and zirconium-clad fuel pins in a uniform lattice as a function of boron concentration in the coolant.

Table 8. Description of reflected finite systems defining the maximum k_{eff} for $\text{U}(3)\text{O}_2$ fuel pins as fuel assemblies without the control rods having the design separation spacing

WITH CONTROL RODS OUT				
Job Name	ppm B	Lattice Pitch	ZR	K-eff
JCTOPTC1	3443.37	1.2031	WITH	1.00306 + 0.00245
JCTOPTC2	3443.37	1.0922	W/O	1.02480 + 0.00271
JCTOPTC3	4500	1.1850	WITH	0.95589 + 0.00277
JCTOPTC4	4500	1.0500	W/O	0.97993 + 0.00313 100GEN
JCTOPTC5	5000	1.1700	WITH	0.93572 + 0.00303
JCTOPTC6	5000	1.0400	W/O	0.96443 + 0.00279
JCTOPTC7	6500	1.1450	WITH	0.89220 + 0.00261
JCTOPTC8	6500	1.0160	W/O	0.92813 + 0.00267
JCTOPTC9	7500	1.1250	WITH	0.86728 + 0.00269
JCTOPT10	7500	1.0160	W/O	0.89979 + 0.00301

Fig. 17. Comparison of infinite and finite systems maximum calculated k_{eff} for $\text{U}(3)\text{O}_2$ unclad and zirconium-clad fuel pins represented as full fuel assemblies as a function of boron concentration in the coolant. Separation of fuel assemblies is constant and equals that in core design.

Fig. 18. Comparison of infinite systems of $^{235}\text{UO}_2$ fuel pins as uniform lattices producing maximum k_{eff} and infinite and finite pins at a constant lattice pitch of ~ 1.61 cm as a function of boron concentration in the coolant.

Fig. 19. Definition of optimum lattice of $U(2.57)O_2$ fuel pins with and without zirconium cladding for different boron concentrations in the coolant.

Table 9. Calculated k_{eff} for infinite lattices of $U(2.57)O_2$ fuel pins with and without zirconium cladding for various boron concentrations in the coolant

Case	ppm B	ZR	Lattice Pitch	H/U	K-inf
50	0	WITH	1.0922	41.87	1.02435
51	"	"	1.2031	83.49	1.20292
52	"	"	1.3140	129.14	1.29154
53	"	"	1.4250	178.86	1.33518
53A	"	"	1.7760	362.60	1.33745
53B	"	"	2.1090	574.17	1.25922
54	"	W/O	1.0922	81.64	1.21928
54A	"	"	0.9398	31.00	0.988136
54B	"	"	1.0160	55.37	1.12782
55	"	"	1.2031	123.27	1.29998
56	"	"	1.3140	168.92	1.34290
57	"	"	1.4250	218.64	1.36164
57A	"	"	1.7760	402.38	1.33293
57B	"	"	2.1090	613.95	1.24619
58	1500	WITH	1.0922	42.34	0.986469
59	"	"	1.2031	84.43	1.09968
60	"	"	1.3140	130.60	1.11901
61	"	"	1.4250	180.88	1.09601
61A	"	"	1.7760	366.70	0.931125
62	"	W/O	1.0922	82.56	1.11809
62A	"	"	0.9398	31.35	0.964799
62B	"	"	1.0160	55.99	1.06840
63	"	"	1.2031	124.66	1.13452
64	"	"	1.3140	170.82	1.11386
65	"	"	1.4250	221.11	1.07306
65A	"	"	1.7760	406.92	0.897948
66	3500	WITH	1.0922	42.23	0.937991
66A	"	"	1.1		0.945926
66B	"	"	1.14		0.976207
66C	"	"	1.17		0.986444
66D	"	"	1.18		0.987945
66E	"	"	1.185		0.988454
66F	"	"	1.19		0.988781
66G	"	"	1.195		0.988925
67	"	"	1.2031	84.23	0.988705
68	"	"	1.3140	130.28	0.955585
69	"	"	1.4250	180.43	0.893393
69A	"	"	1.7760	365.79	0.675884
70	"	W/O	1.0922	82.36	1.00884
70A	"	"	0.9398	31.27	0.932655
70B	"	"	1.0160	55.85	0.997691
71	"	"	1.2031	124.35	0.975625
72	"	"	1.3140	170.40	0.916092
73	"	"	1.4250	220.56	0.847385

Table 9 (continued)

Case	ppm B	ZR	Lattice Pitch	H/U	K-inf
97	4500	WITH	1.0922	42.34	0.917084
97A	"	"	1.18		0.947361
97B	"	"	1.17		0.947819
97C	"	"	1.165		0.947863
97D	"	"	1.16		0.948346
97E	"	"	1.17		0.947819
98	"	"	1.2031	84.43	0.943599
99	"	"	1.3140	130.60	0.893473
100	"	"	1.4250	180.88	0.821113
101	"	W/O	1.0922	82.56	0.964177
101A	"	"	0.9398	31.35	0.918599
101B	"	"	1.0160	55.99	0.967638
102	"	"	1.2031	124.66	0.914651
103	"	"	1.3140	170.82	0.844740
104	"	"	1.4250	221.11	0.770397
114	5500	WITH	1.0922		0.897539
115	"	"	1.2		0.904614
116	"	"	1.3		0.849776
117	"	"	1.4		0.779383
118	"	"	1.5		0.707946
119	"	"	1.15		0.915114
119A	"	"	1.16		0.914487
119B	"	"	1.14		0.914867

Fig. 20. Definition of optimum lattice of $U(2)O_2$ fuel pins with and without zirconium cladding for different boron concentrations in the coolant.

Table 10. Calculated k_{eff} for infinite lattices of $U(3)O_2$ fuel pins with and without zirconium cladding for various boron concentrations in the coolant

Case	ppm B	ZR	Lattice Pitch	H/U	K-inf
74	0	WITH	1.0922	33.80	0.976313
75	"	"	1.2031	107.29	1.14993
76	"	"	1.3140	165.95	1.23107
77	"	"	1.4250	229.84	1.26721
77A	"	"	1.7760	465.94	1.25141
77B	"	"	2.1090	773.81	1.16259
78	"	W/O	1.0922	104.91	1.16762
78A	"	"	0.9398	39.83	0.940240
78B	"	"	1.0160	71.15	1.07982
79	"	"	1.2031	158.40	1.24156
80	"	"	1.3140	217.06	1.27740
81	"	"	1.4250	280.95	1.28968
81A	"	"	1.7760	517.06	1.24493
81B	"	"	2.1090	788.92	1.14909
82	1500	WITH	1.0922	54.40	0.931792
83	"	"	1.2031	108.50	1.03271
84	"	"	1.3140	167.82	1.03996
85	"	"	1.4250	232.43	1.00785
85A	"	"	1.7760	471.20	0.832726
86	"	W/O	1.0922	106.09	1.05219
86A	"	"	0.9398	40.28	0.912305
86B	"	"	1.0160	71.95	1.01062
87	"	"	1.2031	160.19	1.05713
88	"	"	1.3140	219.51	1.02738
89	"	"	1.4250	284.12	0.980247
90	3500	WITH	1.0922	54.27	0.876901
90A	"	"	1.1		0.883861
90B	"	"	1.14		0.908360
90C	"	"	1.17		0.914334
90D	"	"	1.18		0.914561
90E	"	"	1.19		0.914657
91	"	"	1.2031	108.23	0.912311
92	"	"	1.3140	167.40	0.868496
93	"	"	1.4250	231.86	0.801342
94	"	W/O	1.0922	105.83	0.932960
94A	"	"	0.9398	40.18	0.875231
94B	"	"	1.0160	71.77	0.931589
95	"	"	1.2031	159.79	0.889340
96	"	"	1.3140	218.96	0.824430
97	"	"	1.4250	283.42	0.754272

Table 10 (continued)

Case	ppm B	ZR	Lattice Pitch	H/U	K-inf
105	4500	WITH	1.0922	54.40	0.853543
105A	"	"	1.1		0.858517
105B	"	"	1.14		0.873486
105C	"	"	1.17		0.872995
105D	"	"	1.165		0.873593
105E	"	"	1.15		0.874272
105F	"	"	1.155		0.874227
106	"	"	1.2031	108.50	0.864575
107	"	"	1.3140	167.82	0.805507
108	"	"	1.4250	232.43	0.730346
109	"	"	1.7760	471.20	0.517678
110	"	W/O	1.0922	106.09	0.885518
110A	"	"	0.9398	40.28	0.859174
110B	"	"	1.0160	71.95	0.898567
111	"	"	1.2031	160.19	0.827112
112	"	"	1.3140	219.51	0.753854
113	"	"	1.4250	284.12	0.680062
120	5500	WITH	1.0922		0.831951
121	"	"	1.2		0.824290
122	"	"	1.3		0.762484
123	"	"	1.12		0.842100
124	"	"	1.15		0.840976
125	"	"	1.11		0.839861
126	"	"	1.13		0.843082
127	"	"	1.14		0.842041

Fig. 21. Comparison of maximum calculated k_{∞} for infinite systems of U(2), U(2.57)O₂, and U(3)O₂ fuel pins as a function of boron concentration in the coolant.

IV. OPTIMUM U_3O_8 -COOLANT MIXTURES

It is known that the failed fuel assemblies have resulted in a mixture of structural materials, degraded UO_2 pellets, and oxide fines of UO_2 , some of which are converted to U_3O_8 . The uncertainty of the mixture composition leaves one to explore theoretically extreme conditions. An extreme is to assume all the oxide is in the form of U_3O_8 and to examine the neutron production capability of the form of oxide under various conditions.

One-dimensional infinite system calculations were performed to define the optimum k_{eff} value for the three ^{235}U enrichments of the TMI-U2 fuel. These calculations were conducted for the three boron concentrations in the coolant, 1500, 3500, and 4500 ppmB. The results are presented graphically in Fig. 22 as a function of the volume fraction of U_3O_8 in the oxide water mixture. The data points are reported in Table 11. The maxima are observed to be broad indicating that one can expect only slight effects on a systems neutron multiplication factor for significant changes in uranium density.

Fig. 22. Definition of optimum volume fraction of U_3O_8 in borated coolant for various boron concentrations and ^{235}U enrichment in uranium.

Table 11. Calculated k_{eff} (Lambda) for infinite systems of U_3O_8 -coolant mixtures of $U(1.98)_3O_8$, $U(2.64)_3O_8$ and $U(2.96)_3O_8$ for several boron concentrations in the coolant

1.98% Enriched					
Case	U_3O_8 VF	H_2O VF	Boron VF *10-3	% Change in U_3O_8 VF	Lambda
35	0.64394	0.35606	0.4916	---	0.891979
36	0.70833	0.29166	0.4027	+10	0.891850
37	0.57955	0.42045	0.5805	-10	0.873996
38	0.67614	0.32386	0.4471	+5	0.894370
2.64% Enriched					
Case	U_3O_8 VF	H_2O VF	Boron VF *10-3	% Change in U_3O_8 VF	Lambda
39	0.64394	0.35606	0.4916	---	0.975381
40	0.65682	0.34318	0.4738	+2	0.975215
41	0.63106	0.36894	0.5094	-2	0.974832
42	0.67614	0.32386	0.4471	+5	0.973607
2.96% Enriched					
Case	U_3O_8 VF	H_2O VF	Boron VF *10-3	% Change in U_3O_8 VF	Lambda
43	0.64394	0.35606	0.4916	---	1.00699
44	0.67614	0.32386	0.4471	+5	1.00365
45	0.61174	0.38826	0.5361	-5	1.00597
46	0.63106	0.36894	0.5094	-2	1.00709
1.98% Enriched					
Case	U_3O_8 VF	H_2O VF	Boron VF *10-3	% Change in U_3O_8 VF	Lambda
47	0.67321	0.32679	0.5801	---	0.856902
48	0.70687	0.29313	0.5203	+5	0.859864
49	0.63955	0.36045	0.6399	-5	0.848744
50	0.68667	0.31332	0.5562	+2	0.858733
51	0.74053	0.25947	0.4606	+10	0.856994
52	0.72033	0.27967	0.4964	+7	0.859460
2.64% Enriched					
Case	U_3O_8 VF	H_2O VF	Boron VF *10-3	% Change in U_3O_8 VF	Lambda
53	0.67321	0.32679	0.5801	---	0.940131
54	0.70687	0.29313	0.5203	+5	0.938811
55	0.63955	0.36045	0.6399	-5	0.936285
56	0.68667	0.31332	0.5562	+2	0.940237

Table 11 (continued)

2.96% Enriched					
Case	U3O8 VF	H2O VF	Boron VF *10-3	% Change in U3O8 VF	Lambda
57	0.67321	0.32679	0.5801	---	0.972005
58	0.70687	0.29313	0.5203	+5	0.969083
59	0.63955	0.36045	0.6399	-5	0.969861
60	0.65975	0.34025	0.6040	-2	0.971738
1.98% Enriched					
Case	U3O8 VF	H2O VF	Boron VF *10-3	% Change in U3O8 VF	Lambda
61	0.53977	0.46023	0.2723	---	1.00205
62	0.59375	0.40525	0.2404	+10	1.00304
63	0.48579	0.51421	0.3043	-10	0.989704
64	0.56676	0.43324	0.2564	+5	1.00393
2.64% Enriched					
Case	U3O8 VF	H2O VF	Boron VF *10-3	% Change in U3O8 VF	Lambda
65	0.53977	0.46023	0.2723	---	1.08669
66	0.59375	0.40625	0.2404	+10	1.08061
67	0.48579	0.51421	0.3043	-10	1.08187
68	0.52897	0.47103	0.2787	-2	1.08661
2.96% Enriched					
Case	U3O8 VF	H2O VF	Boron VF *10-3	% Change in U3O8 VF	Lambda
69	0.53977	0.46023	0.2723	---	1.11789
70	0.56676	0.43324	0.2564	+5	1.11479
71	0.51278	0.48722	0.2883	-5	1.11833
72	0.48579	0.51421	0.3043	-10	1.11605

V. DISRUPTED CORE CONFIGURATIONS

Only a few peripheral fuel assemblies remain above the seven-foot level in the core. Given that some unknown length of fuel elements remain intact, and that the collapsed portions of the fuel assemblies appear to be approximately uniform across the core, it is appropriate to compute hypothetical situations which would be known to overestimate the possible neutron multiplication factor. In performing this assessment, a number of assumptions are made which conservatively contribute to enhancement of the calculated k_{eff} . These are:

- total inventory of UO_2 in the core preserved;
- rubble composed of a mixture of U_3O_8 and borated coolant only at a concentration producing its maximum k_{eff} , i.e., no structural or other absorber materials present;
- remaining intact portions of the fuel assemblies have the composition and distribution of the TMI-U2 configuration;
- average ^{235}U enrichment of 2.57 wt% used to describe the rubble bed; and
- two-thirds of the fuel of the collapsed portion of the fuel assemblies distributed over remaining portion of the fuel assemblies, and one-third assumed suspended adjacent to the bottom of the fuel assemblies uniformly over the core region.

The calculated k_{eff} as a function of the height of the remaining portion of the fuel assemblies is given in Fig. 23 for 3500 ppmB in the coolant. The calculations were conducted with and without the control rods present. Coolant occupied the control rod positions when these were removed. The U_3O_8 -coolant mixture contained 5.34 gu/cc corresponding to the volume fraction of U_3O_8 , producing the maximum k_{eff} in an infinite system.

The effect of perturbations to two of these systems was explored. The case with the six-foot remaining core height having the control rods present ($k_{eff} = 0.889 \pm 0.003$) was recalculated. The rubble composition was assumed to retain the fuel assembly enrichment in the region of collapse above each assembly. The optimum concentration for each enrichment was that defined in Fig. 22. The resultant k_{eff} was 0.894 ± 0.005 , indicating that the average enrichment used to describe the rubble is satisfactory. The second system considered was the case where the entire core is considered as rubble, i.e., U_3O_8 -borated coolant mixture ($k_{eff} = 0.941 \pm 0.003$). Several perturbations to this system were explored. The first was to demonstrate that the k_{eff} does not change significantly for a slight increase or decrease in the uranium concentration. The core was expanded by 10 vol % to decrease the 5.34 gu/cc to 4.81 gu/cc. This resulted in a calculated k_{eff} of 0.938 ± 0.003 . The initial core was then compressed by 15 vol % to an average density of 6.14 gu/cc, producing a k_{eff} of 0.934 ± 0.003 . These results are consistent with the behavior shown in Fig. 22, the broad maxima, and confirm the assumed mixture to be reasonably defined as that producing the maximum k_{eff} for the mixture. Finally, the enrichment was increased from the average of 2.57 wt% to 3.0 wt%, and this gave a calculated k_{eff} of 0.984 ± 0.003 . This magnitude change is also consistent with Fig. 22 where at 3500 ppmb going from 2.64 wt% to 2.96 wt%, the Δk_{eff} is about 4%.

These data strongly suggested that the calculated k_{eff} was predominantly due to the fictitious rubble region and that the neutron coupling between the core and the two bracketing rubble regions is very weak. A qualitative exploration of these conditions is possible by using the matrix-calculated k_{eff} option in the KENO-V code. In this option, the system being calculated is divided into labeled regions of interest. Three regions selected were the bottom rubble, remaining intact core, and the top rubble regions identified as regions 1, 2, and 3, respectively. The k_{eff} is computed in the usual generation method and also by the matrix method using the regional data. In general,

Fig. 23. Calculated k_{eff} for disrupted core configuration as a function of remaining intact fuel assembly height with 3500 ppmB in coolant.

the two k_{eff} 's agree very well. The matrix elements may be designated as P_{ij} representing the number of next-generation neutrons in region j produced by a neutron born in region i . Thus, P_{22} is the neutron self multiplication of the intact core region of the system, while P_{23} would be a measure of the neutron coupling occurring between regions 2 and 3, representing the neutrons produced in the top rubble region due to neutrons born in the intact core region. Figure 23 presents the disrupted core calculated by the generation method as a function of the remaining intact fuel assembly height. Only information about the total configuration is obtained from these data.

The results of the matrix-calculated k_{eff} for the 3500 ppmB case are presented in Fig. 24 with the control rods in the remaining portion of the fuel assemblies. It is clearly shown that the system k_{eff} follows the neutron multiplication of the top rubble as the remaining core height diminishes. The remaining core, region 2, is seen to be insensitive to its height. The calculations with the control rods removed are given in Fig. 25 where the expected increased k_{eff} for region 2 is evident but without a significant change in the top and bottom rubble regions.

Similar calculations were performed for 4500 and 1500 ppmB in the coolant. These results are presented in Figs. 26-29.

The data points for Figs. 24-29 are summarized in Table 12. Noteable in these data is the absence of recorded events between the top and bottom rubble regions. At the smallest separation of these two regions, 2 feet, no events were recorded where neutrons in either region gave rise to a next-generation neutron in the other. Neutron reproduction is certainly a highly localized effect in coolant having 3500 ppmB or more at these ^{235}U enrichment mixtures.

Finally, a few calculations were conducted to examine the effect were the rubble to be UO_2 rather than the U_3O_8 . The 7-foot height of remaining fuel assemblies was chosen as one region. This region retained the core configuration and ^{235}U enrichments. The rubble region above the fuel assemblies was represented by the average enrichment of the core, 2.57 wt% ^{235}U in the uranium. The UO_2 pellets were homogenized over the region by assuming a geometry of spheres in contact and on a triangular pitch of 1.0724 cm. The cross sections for this configuration were processed using the CSAS2X option in SCALE. The optimum uranium volume fraction in the rubble was determined for boron concentrations of 3500 WPPM (0.58), 4500 WPPM (0.63), and 5500 WPPM (0.66). The 1.98 wt% ^{235}U fuel assemblies of the core contained 2.25 g $\text{U}_3\text{O}_8/\text{cc}$ between the fuel pins at the average ^{235}U enrichment. The base case was calculated at the design pitch for the core and 3500 ppmB. This procedure was repeated with the pins at the optimum pitch for the 3500 ppmB in the coolant, and again for 4500 and 5500 ppmB. The results are presented in Table 13.

Fig. 24. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system with control rods and 3500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $1(2.57)_3O_2$ -coolant mixture.

Fig. 25. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system without control rods and 3500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $U(2.57)_3O_8$ -coolant mixture.

Fig. 26. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system with control rods and 4500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $U(2.57)_3O_8$ -coolant mixture.

Fig. 27. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system without control rods and 4500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $U(2.57)_3O_8$ -coolant mixture.

Fig. 28. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system with control rods and 1500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $U(2.57)_3O_8$ -coolant mixture.

Fig. 29. Calculated matrix- k_{eff} for disrupted core configuration showing system k_{eff} and the k_{eff} of the three regions of the system without control rods and 1500 ppmB in the coolant as a function of remaining intact fuel assembly height. Regions: $i=1$, is bottom rubble, 2 is intact core, and 3 is top rubble. Rubble is $U(2.57)_3O_8$ -coolant mixture.

Table 12. Calculated matrix k_{eff} 's for disrupted core configurations as a function of remaining intact fuel assembly height, boron concentration in coolant, and presence of absorbing rods. Rubble regions are $U(2.57)_3O_8$ -coolant mixture

P_{ij} is the number of next-generation neutrons produced at position j by a neutron born in position i .

i, j - Regions $i, j = 1$ is bottom rubble region
 $i, j = 2$ is remaining intact core
 $i, j = 3$ is top rubble region

1500 ppm Boron without control rods								
Remaining Core Height (ft)	P_{11}	P_{12}	P_{21}	P_{22}	P_{23}	P_{32}	P_{33}	System $K_{eff} \pm \sigma$
7	0.804	0.146	0.0365	0.905	0.0411	0.0782	0.912	0.98243 ± 0.00290
5	0.876	0.0106	0.0276	0.903	0.0392	0.0337	0.976	0.99413 ± 0.00284
4	0.898	0.0927	0.0501	0.891	0.0375	0.0385	0.982	1.0118 ± 0.00297
2								1.01902 ± 0.00292

1500 ppm Boron with control rods								
Remaining Core Height (ft)	P_{11}	P_{12}	P_{21}	P_{22}	P_{23}	P_{32}	P_{33}	System $K_{eff} \pm \sigma$
7	0.822	0.146	0.0205	0.805	0.0805	0.0450	0.950	0.97791 ± 0.00306
5	0.896	0.0106	0.0279	0.803	0.0685	0.0535	0.942	0.96484 ± 0.00309
4	0.896	0.0719	0.0163	0.790	0.0896	0.0282	0.992	1.00264 ± 0.00299
2								1.0185 ± 0.0030
0								1.0398 ± 0.0029

1500 ppm Boron without control rods								
Remaining Core Height (ft)	P_{11}	P_{12}	P_{21}	P_{22}	P_{23}	P_{32}	P_{33}	System $K_{eff} \pm \sigma$
7	0.804	0.146	0.0365	0.905	0.0411	0.0782	0.912	0.98243 ± 0.00290
5	0.876	0.0106	0.0276	0.903	0.0392	0.0337	0.976	0.99413 ± 0.00284
4	0.898	0.0927	0.0501	0.891	0.0375	0.0385	0.982	1.0118 ± 0.00297
2								1.01902 ± 0.00292

1500 ppm Boron with control rods								
Remaining Core Height (ft)	P_{11}	P_{12}	P_{21}	P_{22}	P_{23}	P_{32}	P_{33}	System $K_{eff} \pm \sigma$
7	0.822	0.146	0.0205	0.805	0.0805	0.0450	0.950	0.97791 ± 0.00306
5	0.896	0.0106	0.0279	0.803	0.0685	0.0535	0.942	0.96484 ± 0.00309
4	0.896	0.0719	0.0163	0.790	0.0896	0.0282	0.992	1.00264 ± 0.00299
2								1.0185 ± 0.0030
0								1.0398 ± 0.0029

3500 ppm Boron with control rods								
Remaining Core Height (ft)	P ₁₁	P ₁₂	P ₂₁	P ₂₂	P ₂₃	P ₃₂	P ₃₃	System K-eff $\pm \sigma$
7	0.651	0.107	0.00957	0.669	0.0966	0.0498	0.837	0.862 $\pm$ 0.003
6	0.772	0.0663	0.00794	0.667	0.107	0.0395	0.870	0.889 $\pm$ 0.003
5	0.791	0.0754	0.0132	0.661	0.111	0.0306	0.886	0.902 $\pm$ 0.003
4	0.827	0.0512	0.0205	0.664	0.0990	0.0228	0.899	0.906 $\pm$ 0.003
2	0.844	0.0501	0.0385	0.661	0.111	0.017	0.910	0.918 $\pm$ 0.003

Remaining Core Height (ft)	3500 ppm Boron without control rods							System K-eff $\pm \sigma$
	P ₁₁	P ₁₂	P ₂₁	P ₂₂	P ₂₃	P ₃₂	P ₃₃	
7	0.693	0.106	0.00502	0.769	0.0675	0.0647	0.830	0.872 $\pm$ 0.003
6	0.717	0.114	0.00123	0.754	0.0653	0.0492	0.867	0.898 $\pm$ 0.002
5	0.784	0.0847	0.0244	0.724	0.0698	0.036	0.887	0.905 $\pm$ 0.003
4	0.796	0.0486	0.00818	0.750	0.0900	0.0201	0.909	0.923 $\pm$ 0.003
2	0.856	0.0554	0.0579	0.721	0.0742	0.0156	0.921	0.925 $\pm$ 0.003
0								0.941 $\pm$ 0.003

4500 ppm Boron with control rods								
Remaining Core Height (ft)	P ₁₁	P ₁₂	P ₂₁	P ₂₂	P ₂₃	P ₃₂	P ₃₃	System K-eff $\pm \sigma$
7	0.55	0.190	0.00971	0.725	0.0394	0.116	0.678	0.7792 $\pm$ 0.0025
5	0.686	0.103	0.00683	0.699	0.0889	0.0459	0.833	0.8593 $\pm$ 0.0027
4	0.766	0.0766	0.0158	0.705	0.0768	0.0332	0.852	0.8650 $\pm$ 0.0030
2								0.8931 $\pm$ 0.0024

4500 ppm Boron without control rods								
Remaining Core Height (ft)	P ₁₁	P ₁₂	P ₂₁	P ₂₂	P ₂₃	P ₃₂	P ₃₃	System K-eff $\pm \sigma$
7	0.536	0.181	0.00490	0.822	0.0198	0.136	0.685	0.8436 $\pm$ 0.0024
5	0.708	0.132	0.00146	0.791	0.0455	0.0598	0.823	0.8661 $\pm$ 0.0028
4	0.736	0.0976	0.00207	0.771	0.0570	0.040	0.853	0.8770 $\pm$ 0.0022
2								0.8878 $\pm$ 0.0026
0								0.9059 $\pm$ 0.0027

Table 13. Calculated matrix k_{eff} 's for disrupted core configurations for a 7-foot remaining intact fuel assembly height. Rubble is a $U(2.57)O_2$ -coolant mixture, mass of collapsed fuel is preserved, and $U(2.57)O_2$ is between fuel pins of $U(1.98)O_2$ region of core

P_{ij} is the number of next-generation neutrons produced at position j by a neutron born in position i .

i, j - regions 4 = core
 5 = UO_2 rubble

Base Case					
3500 wppm boron 7-ft core Control rods, axial power shaping rods and burnable poison rods out UO ₂ pellet rubble above core, thickness 67.07 cm U ₃ O ₈ slurry around 1.98% enr. fuel pins					
Design Pitch 1.4427	P4,4 0.773	P4,5 0.0843	P5,4 0.0334	P5,5 0.924	K-Effective 0.9413 ± 0.0030
Optimum rubble, and pitch Boron: 3500 wppm Vol. fraction fuel: 0.58 Rubble thickness: 79.6 cm					
Optimum Pitch 1.2031	P4,4 0.882	P4,5 0.0434	P5,4 0.045	P5,5 0.920	K-Effective 0.9487 ± 0.0029
Optimum rubble, and pitch Boron: 4500 wppm Vol. fraction fuel: 0.63 Rubble thickness: 73.3 cm					
Optimum Pitch 1.1800	P4,4 0.826	P4,5 0.0533	P5,4 0.0358	P5,5 0.894	K-Effective 0.9142 ± 0.0027
Optimum rubble, and pitch Boron: 5500 wppm Vol. fraction fuel: 0.66 Rubble thickness: 70.0 cm					
Optimum Pitch 1.1600	P4,4 0.798	P4,5 0.0512	P5,4 0.0418	P5,5 0.853	K-Effective 0.8783 ± 0.0027

VI. REMARKS

It is possible that the calculated subcritical values of k_{eff} are biased low, by as much as 2%. However, the change in k_{eff} 's associated with a parameter change is more reliable. None of the ideal systems examined in this study exist in the reactor, nor will recovery operations create such conditions.

The representation of the rubble region above an unknown height of remaining portions of the core fuel assemblies by an idealized mixture of U_3O_8 or UO_2 -coolant is unrealistic. Dilution of these mixtures by structural materials will greatly reduce the magnitudes of the k_{eff} 's shown. The information presented by the matrix k_{eff} calculations show clearly the limited range of neutron coupling between regions in the core, less than 2 feet, at 3500 ppmB. This result would be further reduced by debris dilution and reduced inventory by the UO_2 dispersed in the reactor systems. This observation should promote less concern for recovery operations leading to accidental criticality.

An upper limit to the k_{eff} for the present condition of the core would be a few percent in k_{eff} above the calculated neutron multiplication factor shown for the remaining portion of intact fuel assemblies.

REFERENCES

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3. J. A. Bucholz, "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," Oak Ridge National Laboratory, ORNL/NUREG/CSD-2/R1 (1982).
4. "Initial Startup Report," Three Mile Island Nuclear Station, Unit 2, License No. DPR-73, Docket No. 50-320, General Public Utilities Service Corporation, December 28, 1978.

APPENDIX

Code Test Configuration

TMI-U2, Hot, Zero-Power Startup at Critical

Mrs. P. Fox

Conditions at Critical:

Coolant:	Temp 532°F, 2260 psi, $\rho = 0.77$
Fuel:	Temp 532°F
Control Rods:	Out
Axial Power Shaping Rods:	Centered
Boron Concentration:	1500 ppm by wt.

Calculated $k_{eff} = 0.9973 \pm 0.0028$

The code input for this case, as well as the geometric description, is presented in the following pages.

```

COM=LAYER 2=INTACT PINS=NO RUBBLE
UNIT 231
COM=LAYER 2 2.96% ENR. FUEL AND OFFICE ROD ASSEMBLY:
ARRAY 20 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 232
COM=LAYER 2 2.96% ENR. FUEL AND CONTROL ROD ASSEMBLY--OUT:
ARRAY 21 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 233
COM=LAYER 2 2.64% ENR. FUEL AND 1.395% LBP1 ROD ASSEMBLY:
ARRAY 22 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 234
COM=LAYER 2 2.96% ENR. FUEL AND 1.260% LBP2 ROD ASSEMBLY:
ARRAY 23 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 235
COM=LAYER 2 1.98% ENR. FUEL AND CONTROL ROD ASSEMBLY--OUT:
ARRAY 24 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 236
COM=LAYER 2 2.64% ENR. FUEL AND 1.260% LBP2 ROD ASSEMBLY:
ARRAY 25 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 237
COM=LAYER 2 2.64% ENR. FUEL AND 1.060% LBP3 ROD ASSEMBLY:
ARRAY 26 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 238
COM=LAYER 2 1.98% ENR. FUEL AND AXIAL POWER SHAPING ROD ASSEMBLY--OUT:
ARRAY 27 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 239
COM=LAYER 2 2.64% ENR. FUEL AND CONTROL ROD ASSEMBLY--OUT:
ARRAY 28 -10.824 -10.824 -210.34
CUBOID 10 1 4P10.90549 2P210.34
UNIT 300
ARRAY 30 -54.52745 -21.81098 -210.34375
CUBOID 6 1 2P54.528 21.811 -23.716 2P210.3438
UNIT 310
ARRAY 31 -54.52745 -21.81098 -210.34375
CUBOID 6 1 2P54.528 23.716 -21.811 2P210.3438
UNIT 320
ARRAY 32 -21.81098 -10.90549 -210.34375
UNIT 330
ARRAY 33 -21.81098 -54.52745 -210.34375
CUBOID 6 1 21.811 -23.716 2P54.528 2P210.3438
UNIT 340
ARRAY 34 -21.81098 -54.52745 -210.34375
CUBOID 6 1 23.716 -21.811 2P54.528 2P210.3438
UNIT 350
ARRAY 35 -10.90549 -21.81098 -210.34375
COM=UNITS FOR SS CORE FORM:
UNIT 400
CUBOID 6 1 2P11.85 2P.9525 2P210.34
UNIT 410
CUBOID 6 1 2P.9525 2P20.85 2P210.34
UNIT 420
CUBOID 6 1 2P.9525 2P9.94 2P210.34
UNIT 430
CUBOID 6 1 2P22.76 2P.9525 2P210.34
UNIT 440
CUBOID 6 1 2P.9525 2P10.91 2P210.34
UNIT 500
ARRAY 100 -119.961 -119.961 -210.34
CYLINDER 10 1 179.07 2P220.34
MOLE 300 0.0 -141.78 0.0
MOLE 310 0.0 141.78 0.0
MOLE 320 -76.34 -130.87 0.0
MOLE 320 76.34 -130.87 0.0
MOLE 320 -76.34 130.87 0.0
MOLE 320 76.34 130.87 0.0
MOLE 330 -141.78 0.0 0.0
MOLE 340 141.78 0.0 0.0
MOLE 350 -130.87 76.34 0.0
MOLE 350 130.87 76.34 0.0
MOLE 350 -130.87 -76.34 0.0
MOLE 350 130.87 -76.34 0.0
MOLE 400 -153.65 -55.50 0.0
MOLE 400 153.65 -55.50 0.0
MOLE 400 -153.65 55.50 0.0
MOLE 400 153.65 55.50 0.0
MOLE 400 131.84 -99.13 0.0
MOLE 400 -131.84 -99.13 0.0
MOLE 400 131.84 99.13 0.0
MOLE 400 -131.84 99.13 0.0
MOLE 400 -110.03 120.93 0.0
MOLE 400 110.03 120.93 0.0
MOLE 400 -110.03 -120.93 0.0
MOLE 400 110.03 -120.93 0.0
MOLE 410 142.74 -77.31 0.0
MOLE 410 -142.74 -77.31 0.0
MOLE 410 142.74 77.31 0.0
MOLE 410 -142.74 77.31 0.0
MOLE 420 120.92 -110.03 0.0
MOLE 420 -120.92 -110.03 0.0
MOLE 420 120.92 110.03 0.0
MOLE 420 -120.92 110.03 0.0
MOLE 420 99.11 -131.83 0.0
MOLE 420 -99.11 -131.83 0.0
MOLE 420 99.11 131.83 0.0
MOLE 420 -99.11 131.83 0.0
MOLE 430 77.29 -142.74 0.0
MOLE 430 -77.29 -142.74 0.0
MOLE 430 77.29 142.74 0.0
MOLE 430 -77.29 142.74 0.0
MOLE 440 55.49 -154.61 0.0
MOLE 440 -55.49 -154.61 0.0
MOLE 440 55.49 154.61 0.0
MOLE 440 -55.49 154.61 0.0

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CYLINDER 6 1 184.15 20220.34
CYLINDER 10 1 186.69 20230.34
CYLINDER 6 1 191.77 20230.34
CYLINDER 10 1 217.77 250.82 -220.34
CYLINDER 6 1 239.17 250.82 -220.34
CUBOID 0 1 6239.17 250.82 -220.34
UNIT 600
MEMISPM=Z 10 1 217.17
MEMISPM=Z 0 1 239.17
CUBOID 0 1 6239.17
END GEOMETRY

READ ARRAY-
ARA=20 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.96% ENRICHED FUEL ORIFACE ROD ASSEMBLY
FILL 30R21 5R21 20 2R21 187 3R21 20 4R21 187 15R21
2R21 20 2R21 20 2R21 187 15R21 7R21 29 18112 END FILL
'.....'
ARA=21 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.96% ENRICHED FUEL CONTROL ROD ASSEMBLY
FILL 30R21 5R21 29 2R21 187 3R21 29 4R21 187 15R21
2R21 29 2R21 29 2R21 187 15R21 7R21 29 18112 END FILL
'.....'
ARA=22 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.64% ENRICHED FUEL LBP1(1.395%) ROD ASSEMBLY
FILL 30R22 5R22 26 2R22 187 3R22 26 4R22 187 15R22
2R22 26 2R22 26 2R22 187 15R22 7R22 29 18112 END FILL
'.....'
ARA=23 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.96% ENRICHED FUEL LBP2(1.26%) ROD ASSEMBLY
FILL 30R23 5R23 27 2R23 187 3R23 27 4R23 187 15R23
2R23 27 2R23 27 2R23 187 15R23 7R23 29 18112 END FILL
'.....'
ARA=24 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 1.98% ENRICHED FUEL CONTROL ROD ASSM WITH RUBBLE
FILL 30R23 5R23 29 2R23 187 3R23 29 4R23 187 15R23
2R23 29 2R23 29 2R23 187 15R23 7R23 29 18112 END FILL
'.....'
ARA=25 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.64% ENRICHED FUEL LBP2(1.26%) ROD ASSEMBLY
FILL 30R22 5R22 27 2R22 187 3R22 27 4R22 187 15R22
2R22 27 2R22 27 2R22 187 15R22 7R22 29 18112 END FILL
'.....'
ARA=26 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.64% ENRICHED FUEL LBP3(1.06%) ROD ASSEMBLY
FILL 30R22 5R22 28 2R22 187 3R22 28 4R22 187 15R22
2R22 28 2R22 28 2R22 187 15R22 7R22 29 18112 END FILL
'.....'
ARA=27 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 1.98% ENR. FUEL AXIAL POWER SHAPING ROD ASSEMBLY
FILL 30R23 5R23 28 2R23 187 3R23 28 4R23 187 15R23
2R23 28 2R23 28 2R23 187 15R23 7R23 29 18112 END FILL
'.....'
ARA=28 NUX=15 NUY=15 NUZ=1
COM=LEVEL 2 ARRAY DESCRIBING 2.64% ENRICHED FUEL CONTROL ROD ASSEMBLY
FILL 30R22 5R22 29 2R22 187 3R22 29 4R22 187 15R22
2R22 29 2R22 29 2R22 187 15R22 7R22 29 18112 END FILL
'.....'
ARA=30 NUX=5 NUY=5 NUZ=1
FILL 5*231 232 233 232 182 END FILL
'.....'
ARA=31 NUX=5 NUY=5 NUZ=1
FILL 232 233 232 233 232 5*231 END FILL
'.....'
ARA=32 NUX=2 NUY=1 NUZ=1
FILL 5*231 END FILL
'.....'
ARA=33 NUX=2 NUY=5 NUZ=1
FILL 231 232 231 233 231 232 185 END FILL
'.....'
ARA=34 NUX=2 NUY=6 NUZ=1
FILL 232 231 233 231 232 231 185 END FILL
'.....'
ARA=35 NUX=1 NUY=2 NUZ=1
FILL 231 231 END FILL
'.....'
ARA=100 NUX=11 NUY=11 NUZ=1
COM=TM1 CRITICAL CORE 1500WPPM
FILL 231 236 235 236 235 236 185
235 237 235 237 235 236 185
236 238 235 238 235 235 185
235 238 235 233 235 233 185
236 238 236 235 233 236 1860
END FILL
ARA=200 NUX=1 NUY=1 NUZ=2 GBL=200
FILL 600 500 END FILL
END ARRAY
READ PLOT TTL=X-Y SLICE THROUGH Z=10.0
XUL=0.0 XUL=220.00 ZUL=10.0 XLW=220.00 YLR=0.0 ZLR=10.0
UAX=1.0 VDN=-1.0 MAX=390 NCM= 123456789
END PLOT
END DATA
END

```

ORIFACE ROD
UNIT 20

$$R = .60906$$

304SS MIXT 6

H₂O MIXT 10

FUEL ROD
UNIT 21, 22, OR 23

± .72136

R1 = .4699	FUEL	MIX
R1 = .4699	1, 2, 3
R2 = .48768	GAP	0
R2 = .48768
R3 = .5461	ZR	4
R3 = .5461
H ₂ O		10

UNIT 21 - 2.96%

UNIT 22 - 2.64%

UNIT 23 - 1.98%

BURNABLE POISON ROD

UNITS

26 LBP1 1.395 MIXT 7
 27 LBP2 1.26 MIXT 8
 28 LBP3 1.06 MIXT 9

AXIAL POWER SHAPING ROD

REACTOR VESSEL

THREE MILE ISLAND NUCLEAR STATION UNIT 2

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