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SUBJECT: RECRITICALITY POTENTIAL OF TMI-2 CORE

A number of KENO Monte Carlo analyses were undertaken to establish the potential of a recriticality in the TMI-2 core. It appears that 3500 ppm natural boron uniformly distributed and maintained in the moderator/coolant will guarantee subcriticality for all credible possible abnormal states of the core. The extreme assumption of complete loss of all movable control rods and all fixed burnable poisons was a condition for all the calculations.

The study indicates also that the highest enriched peripheral region of the core is controlling for criticality when accidental boron (hide out) dilution occurs.

It is also noted that regardless of the boron concentration in the coolant, if a localized 2 percent volume of the core (4 fuel assemblies in square geometric contact) receives unborated water for the full-length of the active core, criticality will be achieved.

The method of analysis, results, and pertinent data are enclosed.

/s/ 168 155-

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Enclosures: As stated

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RECRITICALITY POTENTIAL OF TMI-2 CORE

C. R. Marotta

I. INTRODUCTION AND CONCLUSIONS

This memorandum considers the conditions under which the TMI-2 core may achieve an unplanned criticality (before final dismantling) by analyses of mathematical models of various TMI-2 core configurations and boron concentrations using reasonable conservative scenarios reflecting the recent NRC assessments[1] of core damage. Common to all models in this analysis are the assumptions of complete loss of both ALL movable control rods (Ag-In-Cd; total worth ~ 10% in k) and ALL fixed burnable poison rods (Al_2O_3-B_4C; total worth ~ 4.4% in k). The above assumptions are reasonable (although highly conservative) since from Reference (1) it appears that the temperature of unfueled components lagged the temperature of fuel rods (exceeded 1750°C) by only about 20°F. Consequently, in the hot region of the core, Zr components should have oxidized, and components with Inconel, stainless steel and Ag-In-Cd should have melted. The poison, boron, of the fixed burnable rods is probably also lost since boron is known to leach out of B_4C-Al_2O_3 pellets when exposed to water in a radiation environment. Boric acid in the moderator/coolant is assumed as the only poison keeping the reactor in a subcritical state for all calculations.

[1] Internal NRC memo from R. O. Meyer to R. J. Mattson, April 13, 1979, Subject: CORE DAMAGE ASSESSMENT FOR TMI-2.

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The mathematical-criticality analyses were performed using the KENO Monte Carlo computer program together with the 123 group GAM-THERMOS neutron cross section set. The core was modeled (containing only latticed fuel pellet-clad-moderator) geometrically in 3-D, quarter symmetry, explicitly describing every fuel rod at the pitch under consideration. The central "checkerboard mixture" of 1.98% and 2.64% enriched fuel assemblies were modeled as assemblies having an effective enrichment of 2.31%, occupying two distinct regions: a central square (33% of core) surrounded by a square annulus (33% of core) of identical rods. The outer portion, containing 2.96% enriched fuel assemblies, forms the last square annulus (34% of core). A different boron concentration can be specified for each of these three regions. A two-foot unborated water, all around reflector surrounds the above-described core.

The most reactive core configuration established was that of all 36,816 UO_2 (model assumed 36,864) fuel rods with clad intact and all rods taken at a reduced pitch (from "as built" 1.44 cms to 1.26 cms). This "worst case" of reactivity was arrived at by KENO cell parametric studies of k_∞ versus enrichment, boron concentration and pitch spacing.

Since the TMI-2 coolant will eventually reach room temperature, all criticality analyses were performed at this most reactive (neutronically) temperature. The moderator density was taken as 1.0 gm/cm^3 and the fuel (UO_2) density was assumed as 95% theoretical.

Some confidence is established in the above calculational procedure for the configurations of interest noting the successful KENO run for the critical TMI-2 core (zero power, hot 530°F, clean, all rods out). This critical had a boron level of 1500 ppm. The K_{eff} calculated for this configuration at room temperature was 1.040 ± 0.004. Since the fixed B_4C burnable poison rods were estimated to have worth of 4.5% in k_{eff} and the modeling assumed these rods to be lost, the agreement can be considered excellent. We note here that the 0.3% core volume occupied by stainless steel which is also neglected in the model is not expected to change the final k_{eff} as is the contribution from the moderator temperature coefficient of reactivity + 0.10×10^{-4}, in going from hot (530°F) to room temperature (70°F), i.e., the $\Delta k \sim .0046$ is of the order of the uncertainty in the Monte Carlo calculations.

Conclusions from the above analyses are:

1. A 3500 ppm boron level guarantees subcriticality for all conceivable abnormal states of the TMI-2 core; however 3000 ppm boron is the realistic conservative concentration. It is strongly recommended that this latter concentration be maintained uniformly throughout the core until dismantled.

2. The peripheral highest enriched region of the core is shown to be the most sensitive to boron concentrations. Special boron concentration monitoring (if possibile) of at least this region would be prudent.

3. Regardless of the boron concentration throughout the core, a slug of completely unborated water passing through a minimum of four contiguous (in a square) fuel assemblies, the full length of the core would cause a criticality. Four fuel assemblies corresponds to ~ 2% of the core volume.

II. DESCRIPTION OF CALCULATIONS AND SUMMARY OF RESULTS

a) Preliminary Parametric Study

Figure 1 shows the k_∞ results as a function of boron concentration for an infinite array of TMI-2 fuel assemblies - as built with 208 fuel rods and 17 water holes at the highest TMI-2 enrichment of 2.96% in the U-235 isotope. Since neutron leakage is relatively small in the TMI-2 core, this curve can be interpreted as the maximum k_{eff} of the core without control rods, burnable poisons or fission products. Approximately 2350 ppm boron would guarantee subcriticality for the "as built" TMI-2 core if all fuel rods remain intact and maintain the "as built" pitch. Since the effective enrichment of the core is 2.57%, the above boron level can be considered quite conservative.

b) Pellet-Clad-Moderator Cell Calculations

Figure 2 shows k_∞ results for KENO infinite cylindrical cell calculations for two enrichments (2.31% and 2.96%) as a function of water to fuel (W/F) ratio in the cell for 1000, 2000 and 3000 ppm boron in full density water. Examination of the Figure shows clearly that the 3000 ppm boron would guarantee subcriticality for an infinite system at the as-built pitch, i.e., k_∞ is less than unity for the as-built W/F ~ 1.69 for both enrichments.

All the curves of Figure 2 clearly indicate the reverse trend of k vs W/F for standard LWR undermoderated fuel assemblies in UNborated water. This is due to the heavy absorption in the moderator (when boron is present) giving a positive effect when pitch spacing is reduced. Figure 3 shows the usual trend for the TMI-2 rod (2.96% enriched) in unborated water.

Figure 2 formed the basis in establishing the most reactive lattice pitch. Examination of all the curves show that a reasonable average value of a W/F ~ 1.0 would give a maximum k_∞ for the two enrichments over the range of 2000 to 3000 ppm boron. This W/F of unity translates to a pitch spacing of 1.26 cms from the 1.44 cm as built pitch.

c) 3-Region Modeling of TMI-2 Core

The objective in these calculations was to get some handle on the relative importance of the core regions (radial only) to criticality as a function of the boron concentration. This is the classic boron hide out problem considered for control systems.

Figure 4 is a plan view of the quarter-symmetry of the geometry used in the KENO calculations for all TMI-2 core calculations. There are a total of 55 x 55 (or 3025) fuel rods in region A (~ 14 fuel assemblies of 2.31% enrichment); a total of 78 x 78 - 55 x 55 (or 3059) fuel rods in region B (~ 14 3/4 fuel assemblies of 2.31% enrichment); and a total of 96 x 96 - 78 x 78 (or 3132) fuel rods in region C (~ 15 fuel assemblies of 2.96% enrichment). In this matrix of 9216 rods no water lattices are modeled; in other words, there is slightly more U-235 per cm^3 of core, however, the total mass of

fuel in the core is greater by only 0.1% than actually exists in the TMI-2 core. Since the borated water is replaced by a fuel rod (i.e., the 17 water holes now hold a fuel rod), this represents a conservatism. A mirror boundary condition is applied along the +Y axis and the +X axis giving a total parallelepiped core. A two foot unborated all-around water reflector surrounds the core.

Table 1 gives $k_{eff's}$ calculated for the TMI-2 core at the as-built and the most reactive pitch spacing for a variety of ppm boron in the three separate regions A, B and C. Included in the list is the initial critical configuration achieved by TMI-2 core, all rods out, with a 1500 ppm boron level.

Results from Table 1 indicate that:

(1) For an intact core at the most reactive pitch, 3000 ppm boron uniformily throughout the entire core will guarantee subcriticality.

(2) The presence of Zr clad gives a higher k_{eff}, since it would be replaced (if lost) by borated water - a much stronger neutron absorber.

(3) The outer highest enriched (2.96%) region is most sensitive to boron concentration and appears that maintaining 3000 ppm in 66% of the core but lowering the outer 34% of the core to boron concentrations lower than 1500 ppm can cause the core to become critical.

d) Spherical Pellet Pile

These calculations were performed to estimate the reactivity effects if all the fuel rods were to rupture emptying all their pellets (H/D ∿ 1 gives a spherical pellet radius of .53 cms) into a pile of bare UO_2 spheres with borated water in between. Two KENO k_∞ cases were run using an effective core enrichment of 2.57%. It appears from the results of Table 2 that slightly more than 3500 ppm boron will be needed to avoid criticality here.

e) Local Criticality (4 FA in contact)

These calculations were undertaken to estimate a minimum ppm boron dilution needed for a local isolated criticality in the TMI-2 core. A system composed of four 2.96% enriched fuel assemblies, contact in a square array (represents 2 1/4% of core volume) with unborated water reflector was analyzed for a variety of boron concentrations. Results are given in Table 3 and show that regardless of the amount of boron concentration throughout the core, if ∿ 2% of the core volume receives a slug of unborated water in a localized region a criticality would occur.

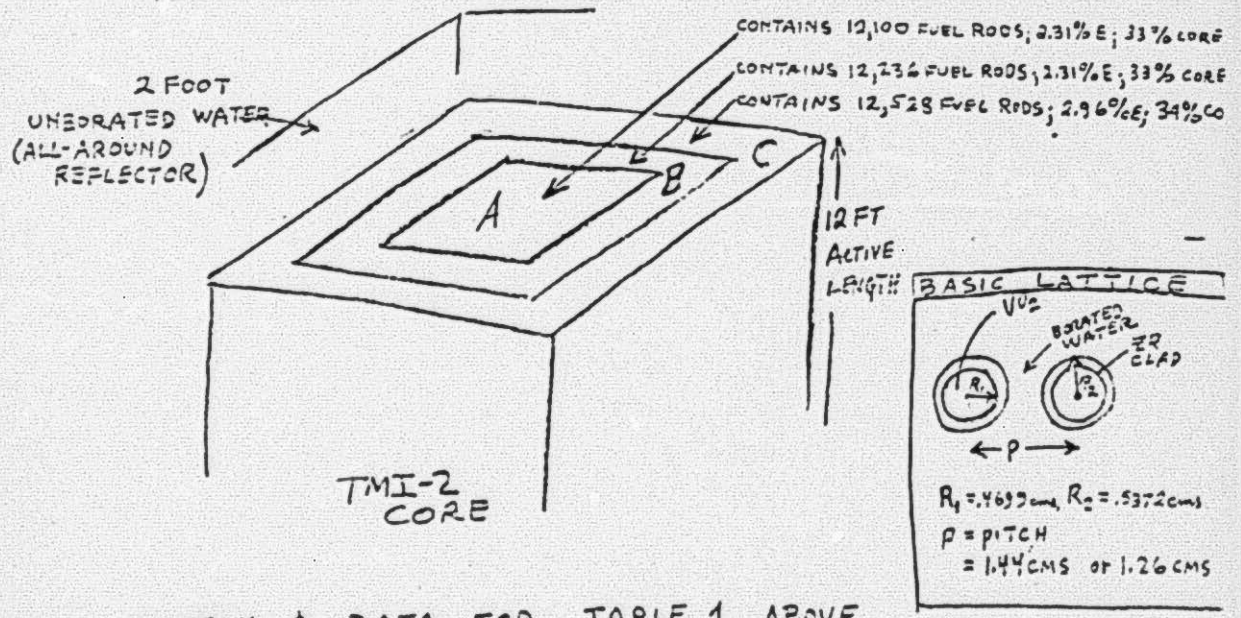
TABLE 1

K_{eff} of TMI-2 Core As Function Of PPM Boron in Water
(No Control Rods or Burnable Poisons)

(Room Temp)

AS BUILT PITCH 1.44 cms PPM BORON					MOST REAC PITCH 1.26 cms PPM BORON				
ZR-CLAD	A	B	C	K_{eff}*	ZR-CLAD	A	B	C	K_{eff}*
YES	1500	1500	1500	1.040	YES	3000	3000	3000	0.944
YES	3000	3000	3000	0.883	YES	3000	3000	2000	0.954
NO	3000	3000	3000	0.857	YES	3000	3000	1500	0.989
					YES	3000	3000	1000	0.992
					NO	3000	3000	3000	0.936
					NO	2500	2500	2500	0.977
					NO	3000	2500	2000	1.000

*All K_{eff} calc. by KENO-123 Gps, using 15,000 neutron histories and all within ± 0.004 in K_{eff} for 1 St.dev.



SKETCH & DATA FOR TABLE 1, ABOVE

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TABLE 2

K^*_∞ for Bare UO_2 Spheres, 2.57% ENR.
In Contact as Function PPM-Boron
Pellet H/D = 1, R_S = 0.538 cms.

PPM	k_∞
3000	1.030 ± 0.004
3500	0.997 ± 0.004

*KENO cell calc., 123 gps, 15,000 neuts hist.

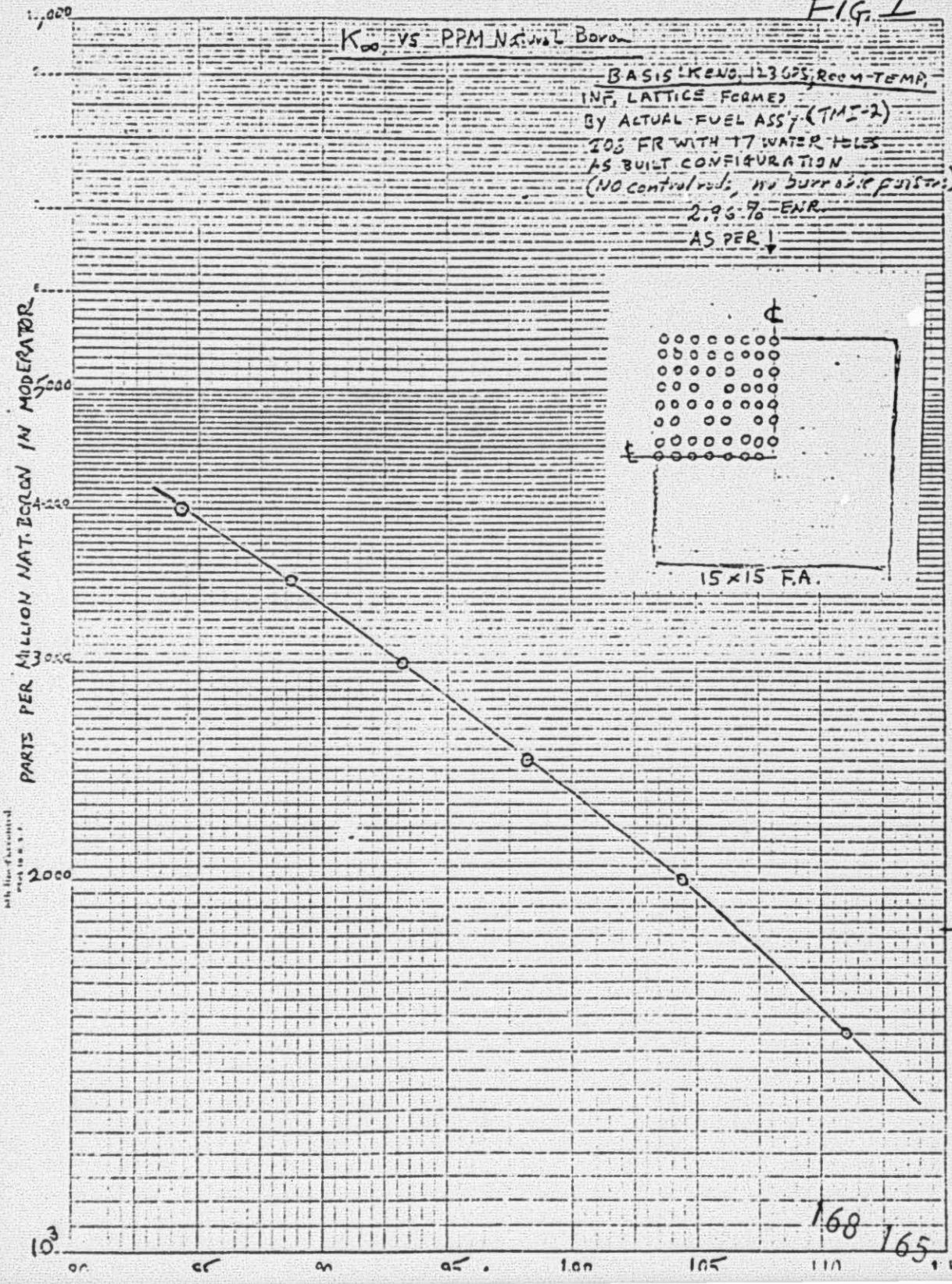
TABLE 3

K^*_{eff} of Four, 2.96% ENR. Fuel Assy's
In Contact Square Array
As Function PPM Boron

PPM	K_{eff}
2500	0.839 ± 0.004
2000	0.866 ± 0.004
1500	0.886 ± 0.004
1000	0.924 ± 0.004
500	0.953 ± 0.004
0	1.000 ± 0.004

*KENO calc.-123 Gps; Explicit Desc. of 900 Fuel Rods in Borated Water surrounded by 1 foot unborated water reflector

FIG. 1


K_∞ vs PPM Natural Boron
BASIS: KENO, 123 GPS, ROOM-TEMP.
INF. LATTICE FORMED
BY ACTUAL FUEL ASS'Y (TMI-2)
208 FR WITH 17 WATER HOLES
AS BUILT CONFIGURATION
(NO control rods, no burnable poisons)
2.96% ENR.
AS PER ↓
PARTS PER MILLION NAT. BORON IN MODERATOR
1,000
2000
3000
4000
10^3
90
95
100
105
110
15 × 15 F.A.
168
165

K_∞ VS W/F

FIG 2

AS A FUNCTION OF PPM NATURAL BORON IN H_2O
FOR 2 ENRICHMENTS
(1) $U(2.31)O_2$ - EFF ENRICH FOR CENTRAL CHECKERBOARD FA's.
(2) $U(2.96)O_2$ - PERIPHERAL FA's.

BASIS FOR CELL CALC: KENO, 123 GPS; SINGLE PIN (.37" diam); Clad ZR (.026"±)
AT ROOM TEMP.

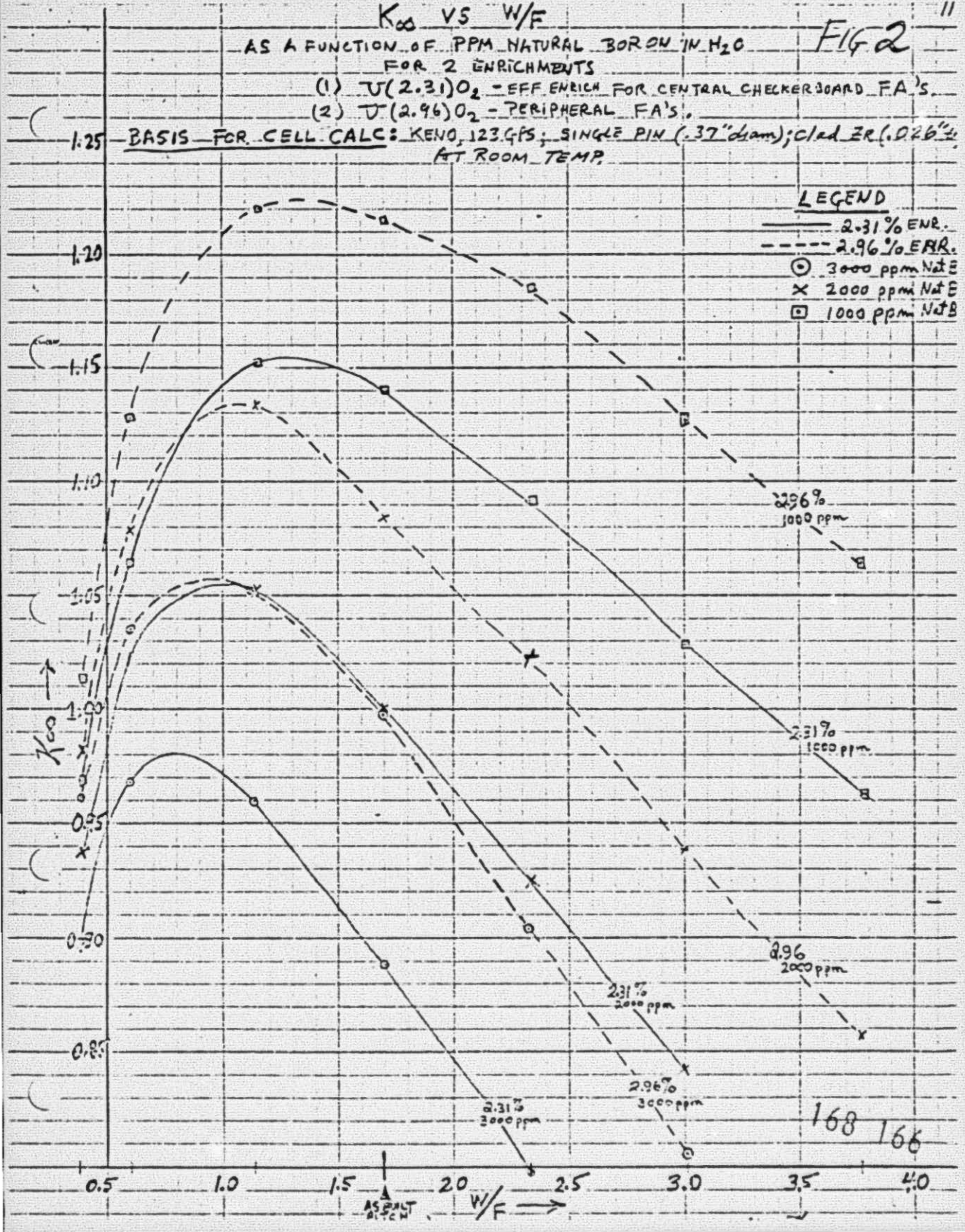


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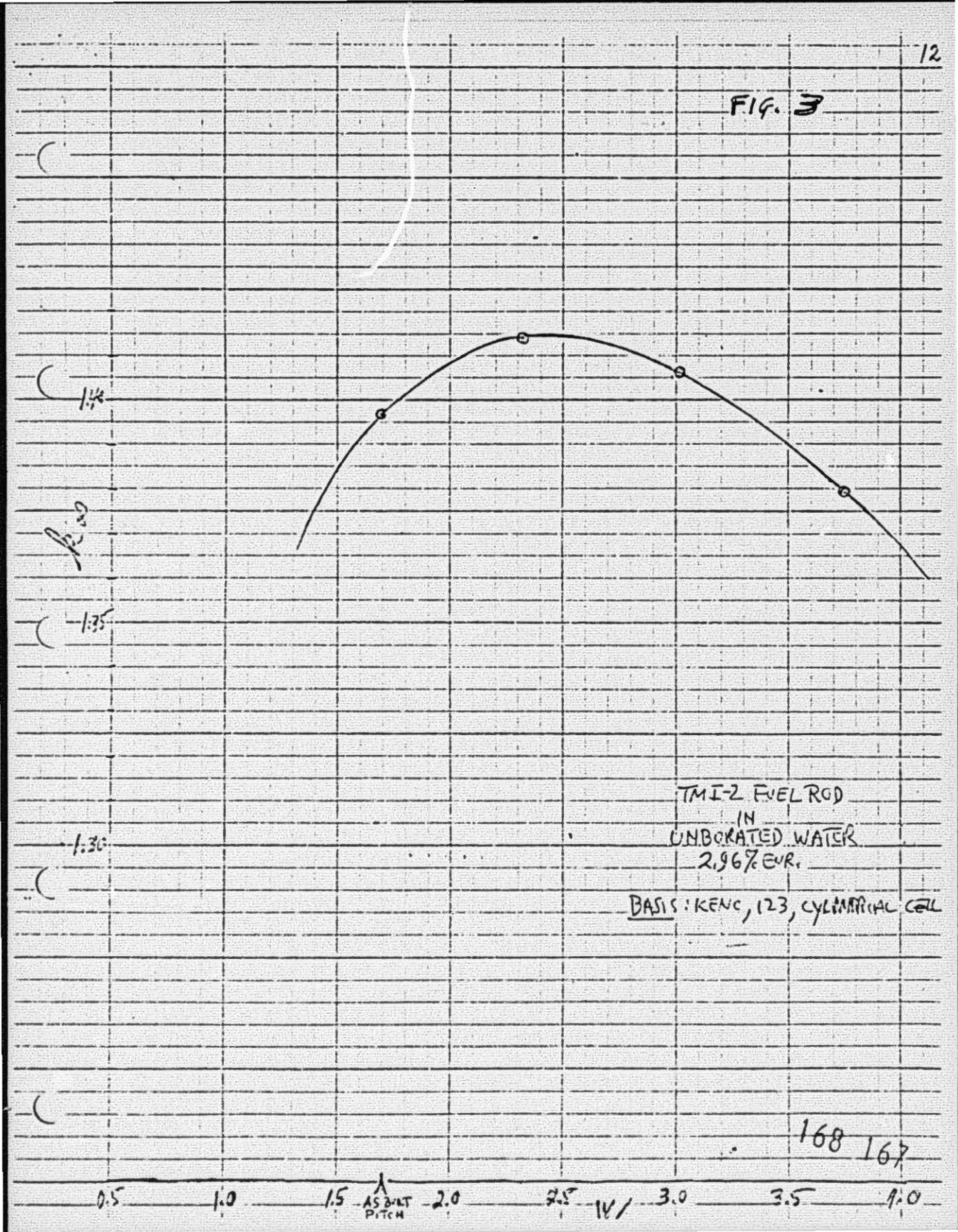
FIG. 3


1.40
1.35
1.30
k_∞
TMI-2 FUEL ROD
IN
UNBORATED WATER
2.96% ENR.
BASIS: KENO, 123, CYLINDRICAL CELL
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
ASSEMBLY PITCH
168
167

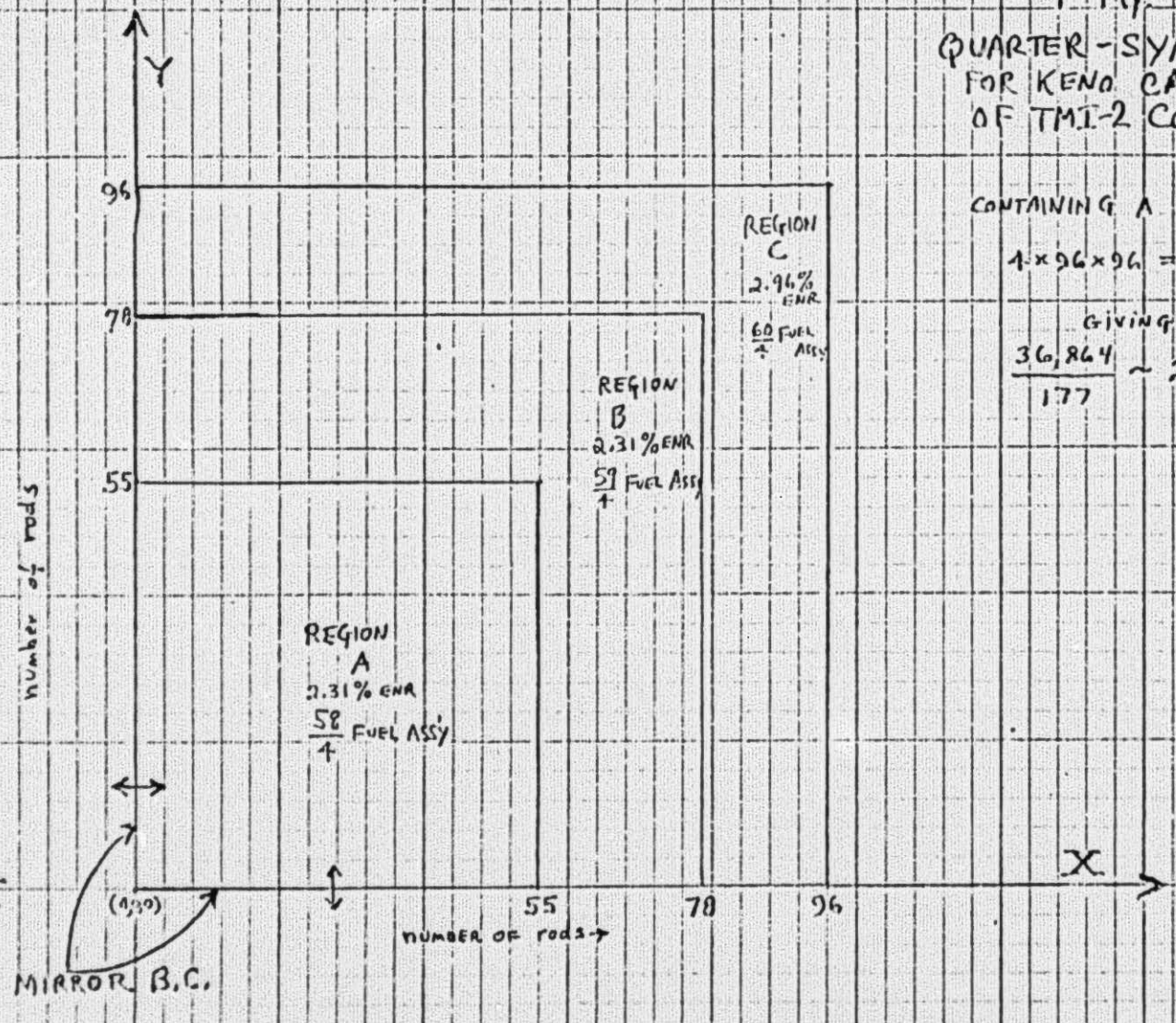


FIG. 4
QUARTER-SYMMETRY
FOR KENO CALCS
OF TMI-2 CORE

CONTAINING A TOTAL OF

$4 \times 96 \times 96 = 36{,}864$ FUEL RODS,

GIVING

$\frac{36{,}864}{177} \sim 208$ rods/FA

FIG. 4.

TABLE 4.3-1.
CORE DESIGN DATA

A. Reactor		
1.	Design heat output, MWt	2772
2.	Vessel coolant inlet temperature, F	557
3.	Vessel coolant outlet temperature, F	607.7
4.	Core coolant outlet temperature, F	610.6
5.	Core operating pressure, psig	2185
B. Core and Fuel Assemblies		
1.	Total No. of fuel assemblies in core	177
2.	No. of fuel rods per fuel assembly	208
3.	No. of control rod guide tubes per assembly	16
4.	No. of in-core instr. positions per fuel assembly	1
5.	Fuel rod outside diameter, in.	0.430
6.	Cladding thickness, in.	0.0265
7.	Fuel rod pitch, in.	0.568
8.	Fuel assembly pitch spacing, in.	8.567
9.	Unit cell metal/water ratio (volume basis)	0.82
10.	Cladding material	Zircaloy-4 (cold worked)
C. Fuel		
1.	Material	UO_2
2.	Form	Dish-end, cylindrical pellets
3.	Pellet diameter, in.	0.370
4.	Active length, in.	144
5.	Density, % of theoretical	92.5

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TABLE 4.3-2.
NUCLEAR DESIGN DATA

Fuel Assembly Volume Fractions	
Fuel	0.303
Moderator	0.580
Zircaloy	0.102
Stainless steel	0.003
Void	0.012
	1.000
Total UO_2 (BOL)	
First core, $mtUO_2$	93.1
Core Dimensions	
Equivalent diameter, in.	128.9
Active height, in.	144.0
Unit Cell H_2O/U Atomic Ratio, Fuel Assembly	
Cold/hot	2.88/2.06
Full-Power Lifetime	
First cycle, days	421
Each succeeding cycle, days	284
Fuel Irradiation	
First cycle avg, MWd/mtU	14,220
Each succeeding cycle, MWd/mtU	9,600
Fuel Loading	
Core avg first cycle, wt% ^{235}U	2.57
Control Data	
Control rod material	Ag-In-Cd
No. of full-length CRAs	61
No. of APSRAs	8
Worth of 61 full-length CRAs, $(\Delta k/k)\%$	11.1
Control rod cladding material	SS304
No. of BPRAs	68 (first cycle only)
BPRA cladding material	Zircaloy-4, cold-worked
BPR poison material	B_4C in Al_2O_3

TABLE 4.3-5.
MODERATOR TEMPERATURE COEFFICIENT

No. of fuel assemblies in core	177
Core avg enrichment, wt% ^{235}U	2.57
Power density, MWt/assembly	15.661
Initial critical condition (hot, full power, clean)	
Boron conc, ppm	1540
CRA inserted worth, %Δk/k	0.7
BPR poison worth, %Δk/k	4.4
Moderator temp coeff, $10^{-4}(\Delta k/k)/F$[a]	+0.10
Threshold value of moderator temp coeff for azimuthal instability, $10^{-4}(\Delta k/k)/F$[b]	
Reference value, 50% flatness	+1.5
Assuming compound errors, 50% flatness	+0.7
Reference value, 25% flatness	+2.2
Assuming compound errors, 25% flatness	+1.2
Moderator temp coeff at end of equil fuel cycle, $10^{-4}(\Delta k/k)/F$	-3.0
Moderator temp coeff at end of first cycle, $10^{-4}(\Delta k/k)/F$	-2.6
Power coeff at BOL with 1230 ppm boron, $10^{-6}(\Delta k/k)/MWt$	-4.34

(a) Two-dimensional isothermal calculations.

(b) Values from modal analysis, three-dimensional calculations show much greater stability; reference BAW-10010.

TABLE 4.3-8.
EXCESS REACTIVITY CONDITIONS

Reactor core condtion[a]	k_{eff}
Cold, 70F, clean	1.252
Hot, 532F, clean, zero power	1.205
Hot, 584F, clean, full power	1.182
Hot, 584F, full power, equilibrium xenon and samarium	1.133
Single fuel assembly[b] (wet)	0.70
Two fuel assemblies[b] (wet)	1.014
Single fuel assembly[b] (dry)	0.03
Two fuel assemblies[b] (dry)	0.04
Cold array[c]	0.90

[a] First cycle at BOL, 68 BPRAs in core.

[b] Based on highest probable enrichment of 3.5 wt%.

[c] A center-to-center assembly pitch of 21 inches is required for this k_{eff} in cold, unborated water with no xenon or samarium.

TABLE 4.3-9.
BOL FIRST CYCLE REACTIVITY
CONTROL DISTRIBUTION

	Reactivity, %Δk/k
Controlled by Soluble Boron	
Moderator temp deficit (70 to 532F)	3.4
Equil Xe and Sm	3.5
Fuel burnup and fission product buildup	10.5
Transient Xe	1.0
Controlled by BPRAs	
Fuel burnup and fission product buildup	4.4
Controlled by Movable CRAs	
Doppler deficit (0 to 2772 MWt)	1.2
Moderator temp deficit (532 to 584F)	0.0
Dilution control	0.2
Shutdown margin	1.0
Xenon undershoot	0.4

TABLE 4.3-11.
SOLUBLE BORON LEVELS AND
WORTH — FIRST CYCLE

Core conditions	BOL boron level, ppm
70F, k_{eff} = 0.99	
No CRAs in	1582
All CRAs in	1057
One stuck CRA (full out)	1327
532F, 0 power, k_{eff} = 0.99	
No CRAs in	1710
All CRAs in	741
One stuck CRA (Full out)	1083
584F, rated power, k_{eff} = 1.00	
No CRAs in	1540
584F, rated power, equil Xe and Sm, k_{eff} = 1.00	
No CRAs in	1175
Boron worth, (%Δk/k)/ppm	
584F, rated power	1/100
70F, zero power	1/75

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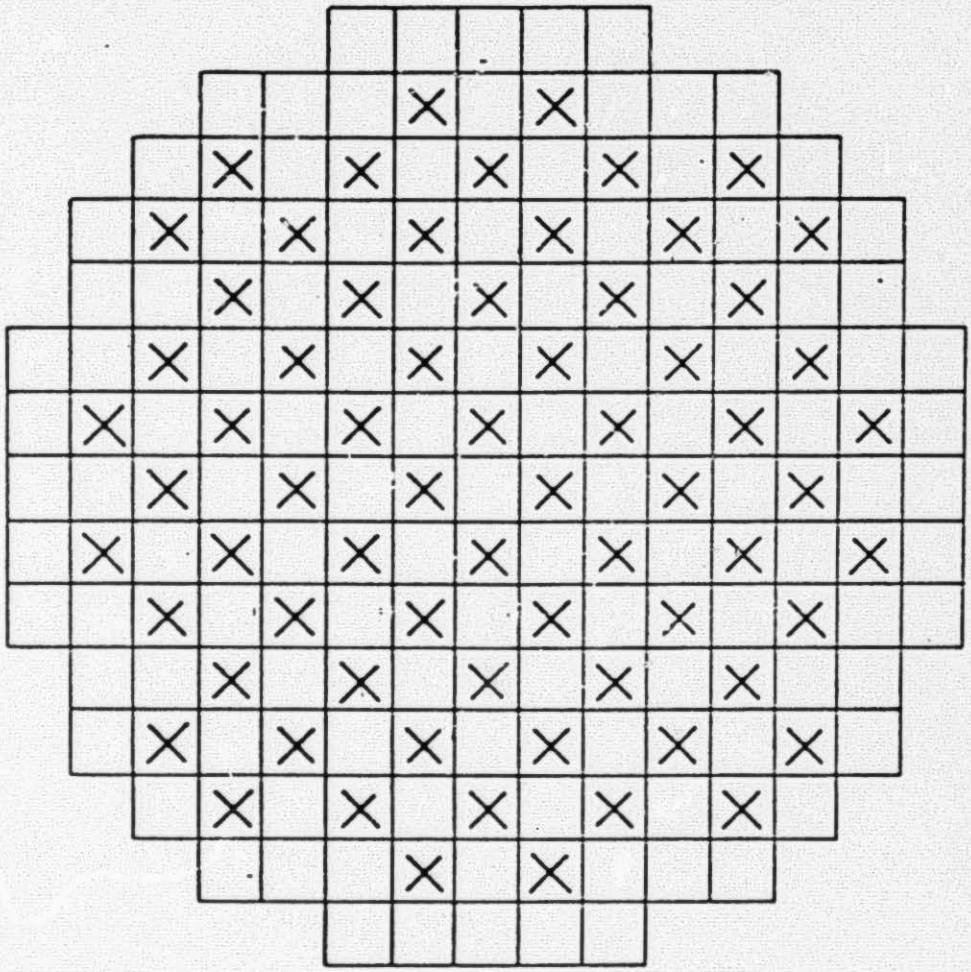
					3	3	3	3	3					
			3	3	3	2	3	2	3	3	3			
		3	3	1	2	1	2	1	2	1	3	3		
	3	3	1	2	1	2	1	2	1	2	1	3	3	
	3	1	2	1	2	1	2	1	2	1	2	1	3	
3	3	2	1	2	1	2	1	2	1	2	1	2	3	3
3	2	1	2	1	2	1	2	1	2	1	2	1	2	3
3	3	2	1	2	1	2	2	2	1	2	1	2	3	3
3	2	1	2	1	2	1	2	1	2	1	2	1	2	3
3	3	2	1	2	1	2	1	2	1	2	1	2	3	3
	3	1	2	1	2	1	2	1	2	1	2	1	3	
	3	3	1	2	1	2	1	2	1	2	1	3	3	
		3	3	1	2	1	2	1	2	1	3	3		
			3	3	3	2	3	2	3	3	3			
					3	3	3	3	3					

Batch No.	W/O U235
1	1.98
2	2.64
3	2.96

FIRST CYCLE CORE

TMI-2



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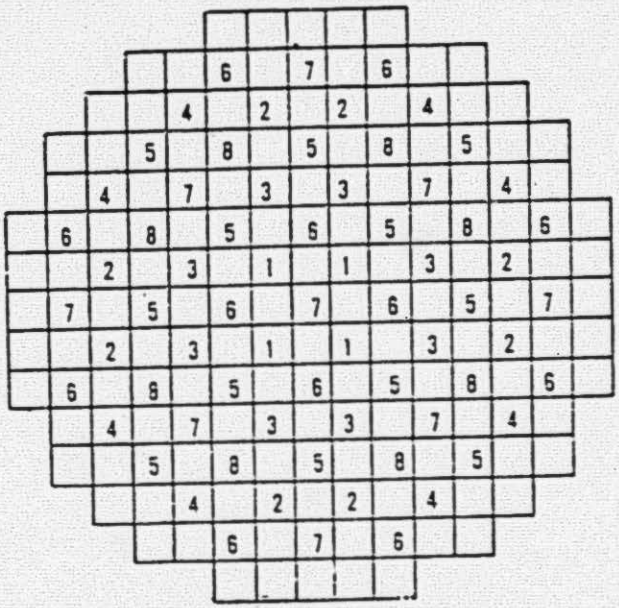
LOCATION OF FUEL ASSEMBLIES CONTAINING BURNABLE POISON RODS

THREE MILE ISLAND NUCLEAR STATION UNIT 2

FIGURE 4.3-2



Bank	No. Rods	Purpose
1	4	Safety
2	8	Safety
3	8	Safety
4	8	Safety
5	12	Regulating
6	12	Regulating
7	9	Regulating
8	8	APSR

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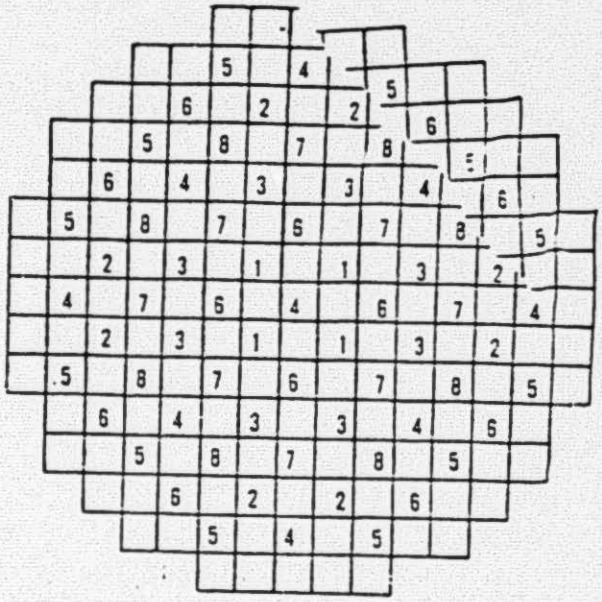
ROD LOCATIONS, 0-200 FPD

THREE MILE ISLAND NUCLEAR STATION UNIT 2

FIGURE 4.3-25



Bank	No. Rods	Purpose
1	4	Safety
2	8	Safety
3	8	Safety
4	9	Safety
5	12	Regulating
6	12	Regulating
7	8	Regulating
8	8	APSR

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ROD LOCATIONS, 200-421 FPD

THREE MILE ISLAND NUCLEAR STATION UNIT 2

FIGURE 4.3-26