CEND-155

ABWR DESIGN AND DEVELOPMENT QUARTERLY PROGRESS REPORT, JANUARY 1 THROUGH MARCH 31, 1962

April 15, 1962

Nuclear Division
Combustion Engineering, Inc.
Windsor, Connecticut

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REACTOR TECHNOLOGY

ABWR

QUARTERLY PROGRESS REPORT

January 1 through March 31, 1962

DESIGN AND DEVELOPMENT

April 15, 1962

Contract AT(11-1)-1062

U. S. ATOMIC ENERGY COMMISSION

Approved:

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NUCLEAR DIVISION

COMBUSTION ENGINEERING, INC.

Windsor Connecticut

PREFACE

This report presents the Combustion Engineering Design and Development progress in the Army Boiling Water Reactor Program during the third quarter of fiscal year 1962.

The work described in this report satisfies requirements established by U. S. Atomic Energy Commission Contract AT(11-1)-1062.

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I. REACTOR DEVELOPMENT AND EVALUATION

A. CONTROL ROD DRIVE MECHANISM

1. Component Test Program

a. Face Seal

The face seal used in the mechanism actuator is a Garlock Mechanipak Seal. Torque tests were performed on the seal assembly with the actuator dry and with the actuator wet and pressurized. The tests show that the assembled actuator requires approximately 14 inch pounds of torque to overcome all internal friction. Since a theoretical torque of 107 inch pounds is available, a margin of 93 inch pounds exists. A test was performed at operating conditions to determine if rod scram would occur when no motion is imparted to the seal for an extended period of time. After 64 hours at static operating conditions the seal operated satisfactorily and scram motion occurred. The maximum seal leakage during the period was 0.28 lb/hr of water.

b. Nozzle Bushing

The nozzle bushing had a radial clearance with the extension shaft of 0.0025 inches. During test it was found that a water level of 17 inches above the buffer could be maintained with a supply rate of 0.28 gpm. Scram tests produced galling of the stainless steel extension shaft which caused binding of the extension shaft in the bushing thereby preventing a satisfactory scram. The extension shaft has been reduced in diameter to increase the radial clearance and chrome plating has been added to improve the resistance to galling. It is anticipated that the mechanism will now require a water supply rate of at least double the initial test rate in order to maintain water in the hydraulic buffer.

c. Position Indication

The rod position indication system was manufactured by Scientific-Atlanta, Inc. The system was calibrated to determine the accuracy of indication with respect to true rod position. A maximum variation of 0.154 inches between rod withdrawal and insertion was obtained. This is within the allowed 0.200 inch.

d. Limit Switches

The limit switch assembly is being used to actuate the automatic controls as well as to prevent damage to the system due to rod over-travel. The switches require approximately 5 inch pounds of torque to actuate and trip consistently at the same point when set to actuate in a particular direction of rod travel.

e. Electromagnetic Clutch

The electromagnetic clutch has operated satisfactorily. The clutch requires 1.4 amperes of 24 V DC current when operating. No burring of clutch face teeth has been noticed.

f. Buffer Piston

The design of a scram buffer assembly was initiated when preliminary mechanism testing showed that, during normal operating conditions, a sufficiently high water level could be maintained in the mechanism to guarantee proper operation of a buffer. Because of space limitations, a short stroke buffer design was selected which could be installed in place of the hard-stop. Analysis showed that the buffer would reduce the impact velocity at the end of rod travel by 50%. Since the shock factor is directly proportional to this impact velocity, the resulting impact loads are correspondingly reduced.

2. Accelerated Life Test

After all actuator components had been received the test loop was assembled and checked. The checks included complete operation of the automatic equipment to insure shutdown in the event of either system over-pressure or over-temperature, the setting of an operating pressure band, hydrostatic testing at 1100 psi, and checkout of the automatic cycle operation. Initial scrams showed that a rigid, common mounting plate was required for the motor and clutch housing since the drive gear loading caused relative movement between the components. When the circulating pump was operated pressure surges in excess of $\pm$ 150 psi were obtained. These pressure surges caused failure of a 60 durometer Buna N "O" ring in the seal. No ring failure was encountered when a ring of 80 durometer silicone rubber was installed. In order to overcome pressure surges, a surge tank was installed in the pump discharge line and charged with 100 psig air prior to operation. Subsequent problems with the loop were caused by crud from the pump packing and rust from a sight glass. Both occurrences required the loop to be flushed and scrubbed. A filter was installed in the loop having an 8 micron particle retention capability and the sight glass has been nickel plated to prevent further crud from accumulating in the actuator.

B. PLANT SIMULATION

The simulation runs were completed covering the PL-2 steam demand transient capability. Conservatively a 30% step decrease from full power steam demand can be sustained without exceeding the over-power scram setting of 140% of full power. The high power level occurs almost immediately following the step change in steam demand and is of short duration. This transient corresponds to a step change in electric load of approximately 375 KW, which appears to be greater than normally expected at any intended application for PL-2.

The results are reported in detail in Vol. VI of IDO-19030,"PL-2 Final Design Report" to be issued in April, 1962.

C. CORE EVALUATION

1. Fuel Assembly

Required design changes to the PL fuel assembly have been completed and a set of interim drawings produced. These drawings have been released to the manufacturing department for fabrication of the final PL lead fuel assembly. After manufacturing feasibility has been established by fabrication of the lead assembly, the design changes will be incorporated in the PL fuel assembly drawings.

The principal design changes in the fuel assembly may be summarized as follows:

a. The upper tube sheet flow area was increased by removal of some of the ligaments between the flow holes. A lower flow resistance is thus provided.

b. The upper lifting fixture was changed to a threaded male connector similar to the control rod blade connector. This change eliminated the previous spider-like casting, thus resulting in a reduction in flow resistance.

c. The removable feature of the boron-containing tubes has been eliminated from the design since the current critical experiments make possible a prefabrication determination of the core boron loading. The new fixed boron-containing tubes eliminate the many separate parts which were required by the removable type.

2. Control Rods

A final drawing of the PL control blade has been completed (Figure 1) which incorporates changes dictated by recent tests and analysis. Most of the changes were made to increase the blade resistance to mechanical or thermal shock. The blade connector has been changed to a modified Whitworth-thread which should sustain 8000 full scrams compared to the 1000 scram limitation with the previous Acme thread.

The thickness of Ag-In-Cd poison filler in the control rod blade was increased from .135 inches to .175 inches to increase the nuclear worth. Other significant changes in the blade were an increase in the number of tie pins which connect the sheathing and an increase in the number of vent holes in the blade. These changes increase the blade's resistance to thermal shock by 1) increasing its structural resistance to a rapid build-up of internal steam pressure and 2) by improving the capability to relieve internally formed steam.

3. Core Structure

Work is nearly complete on revisions to the PL core support structure. The basic change is the incorporation of a vibration suppressor within the riser section above the core. The suppressor protects withdrawn control blades from excessive buffeting of the core effluent by shrouding each blade within a sheet metal scabbard. Since the new riser must be removed for refueling, a remotely operated, positive lock-down device was designed to secure it to the lower core structure.

D. PL PRODUCTION FUEL ELEMENTS

During the period covered by this report, the assembly of PL fuel elements was completed and finished elements were delivered to the Critical Experiment Facility for use in the PL core critical experiments. A total of 1572 elements of power quality were fabricated. This is sufficient to complete one PL core and two spare fuel assemblies.

Generally the fabrication of the fuel elements proceeded without significant problems. Minor difficulties were encountered in only two areas: 1) several hundred pieces of 348 stainless steel tubing was slightly out of specification and 2) chipping of UO_2 pellets was a little more severe than expected.

In the case of the out-of-specification tubing, it was found that insignificant increases in stress levels during service would result from the minor variations which had been detected in the internal diameter and wall thickness of the deviated tubing. These deviations were therefore accepted under a specification wiaver and were used in fuel element fabrication.

The excessive chipping of the UO_2 pellets was resolved by re-defining the surface condition criteria in the pellet specification in such a way that performance of finished elements would remain satisfactory. This was accomplished by revising the criteria to allow a slightly larger single chip while retaining the limitation on total fraction of defective surface and on depth of any defect. The resulting new criteria were as follows:

1. No single surface chip shall be greater than 1/8 inch in any dimension parallel to the surface or greater than 1/32 inch deep, except that a narrow chip may be 1/4 inch long if its width is 1/16 inch or less.

2. A broken circular edge is permissible provided that the resulting imperfection does not extend beyond the bounds of a 1/32 x 1/32 chamfer nor violate the area provisions in Paragraph 5.4.

Since the minimum volume of any pellet remains the same under these new criteria, there is no effect on uranium loading in the finished core, thus the new criteria will not effect the nuclear characteristics of the core.

The revised pellet surface condition criteria was also investigated from a thermal standpoint to determine whether the larger allowable surface chips could result in excessive local fuel temperature, or heat flux.

CE-WIND, a two-dimensional heat conduction code, was used to find the temperature distribution in an idealized model of a chipped pellet. This model, shown in Figure 2, consists of a fuel element section with a pellet having a 1/8 inch wide by 1/32 inch deep circumferential groove. This groove simulates a chip, or a series of chips, with a maximum width of 1/8 inch. A continuous groove was used in the analytical model because it reduced the problem to two dimensions; that is, two coordinates, R and Z, were sufficient to describe the geometry. As a result the final temperature distribution is conservative.

The following operating conditions, based on PL-2 calculations for 140% power at beginning of life, were used:

1. Heat generation rate $q''' = 4.88 \times 10^7$ Btu/hr-ft^3
2. Radial gas gap = 0.00127 inches
3. Saturation temperature = 499°F
4. Gas composition in gap - pure helium
5. Surface heat flux, $q'' = 383{,}000$ Btu/hr-ft^2 (unchipped pellet)
6. $\Delta T_{J.L.}$ (boiling film drop) = 32°F

The following thermal properties were used:

1. Thermal conductivity of UO_2 = 1.25 Btu/hr-ft °F
2. Thermal conductivity of clad = 10.6 Btu/hr-ft °F
3. Thermal conductivity of helium = .152 Btu/hr-ft -°F
4. Equivalent film coefficient $= \dfrac{q''}{\Delta T_{J.L.}} = 12{,}000$ Btu/hr-ft^2-°F

The basic assumptions in the analysis were:

1. The pellet is homogeneous (no cracking).
2. The pellet and clad are concentric.
3. The thermal conductivity of UO_2 is constant.
4. There is no axial variation in the gas gap due to tolerances or non-uniform thermal expansion of the pellet.

Based on the beginning of life conditions at the hottest point in the core and at 140% of full power, the maximum pellet centerline temperature would be 4520°F compared to the nominal temperature without a groove of 3930°F. The peak heat flux of 440,000 Btu/hr-ft^2 would exceed the nominal hot spot heat flux by 15%. Based on this analysis, then, it appears that the thermal limitations of the fuel element system (5000°F and 1.3×10^6 Btu/hr-ft^2) are not exceeded; therefore, the chip criteria as now specified in satisfactory from a thermal standpoint. The results of this analysis are shown in Figures 3 and 4. Figure 3 shows the variation of pellet centerline temperature, pellet surface temperature, and inside clad temperature as a function of distance from the center of the groove. Figure 4 shows the variation of heat flux at the clad-water interface at the surface of the pellet.

II. PLANT DEVELOPMENT AND EVALUATION

A. REFUELING

This task was completed and the report issued as a Supplement to Vol. I, "PL Final Design Report" IDO-19030.

B. RADIOACTIVE GAS HANDLING

This task was completed and the report issued as a Supplement to Vol. I, "PL Final Design Report", IDO-19030.

C. PL-2 COST ESTIMATE

The cost estimate and manhours required to erect the PL-2 plant at a prepared snow tunnel site was completed and "PL-2 Cost Report", CEND-154, was issued.

D. SHIELDING

The primary shield analysis was prepared for inclusion in Vol. VI, "PL Final Design Report", IDO-19030, which will be issued in April, 1962.

E. PL-2 START-UP AND SHUTDOWN PROCEDURE

The procedures as outlined in the last progress report have been written and are being issued in April in Vol. VI of the "PL Final Design Report", IDO-19030.

III. CRITICAL EXPERIMENT PROGRAM

A. INTRODUCTION

Initial criticality was achieved on January 17, 1962 in a minimum critical mass core containing only 248 fuel rods. This was the first in a series of steps before loading up to the full size cold mock-up of the PL-2 core. Figure 5 is a drawing of the entire core showing the fuel boxes, control rods, and positions of the fuel and poison elements. The PL-2 fuel rods, containing uranium dioxide enriched to 4.8% U-235, are being used in these experiments. In addition to the nine cruciform control rods of Ag-In-Cd alloy called for by the design, four blade rods which are used as safeties in the experiment are also shown in the center four boxes. The critical experiment program is intended to check the analysis methods used in the PL-2 design and, in particular, to check the effects of the control rods and the boron-stainless steel pins on reactivity and power distribution. In some experiments, a simulation of the reduction in water density in the hot operating condition is obtained by the insertion of concentric aluminum displacers around the fuel and boron-stainless rods.

B. SMALL CORES WITH LOW EXCESS REACTIVITY

1. Square Geometry

The first core assembled, Core I-A-7, with the center four fuel boxes filled with fuel rods, had an excess reactivity of 70¢. Three fuel rods were then removed from each corner forming Core I-A-8, Figure 6, and reducing the excess reactivity to 24¢. The excess reactivities in all these cores were obtained by integrating the worth of the control rods that remained near the top of the core. Criticality data for Cores I-A-7 and I-A-8 are given in Table I.

Core II-A-3, a 20 x 20 square array with eight extra fuel elements centered on each face of the array, with 1.1 w/o boron-stainless steel rods in the design positions, had an excess reactivity of 84¢. The excess was reduced to 51¢ in Core II-A-4 with only four fuel elements centered on each face of the 20 x 20 array, Figure 7. Criticality data for these two cores are given in Table II.

It was desired to obtain an experimental estimate of the worth of the 1.1 w/o boron-stainless steel rods as early in the program as possible. The four boron-stainless steel rods in the center of Core II-A-4 were removed forming Core II-A-5, Figure 8. A reactivity change of $6.0 was inferred by measuring the differential worth of the control rods at their critical positions in each core, and multiplying the average of these worths by the change in critical rod positions. The four boron-stainless steel rods around the center control rod were then put back and the four boron-stainless steel rods located in the center of the four fully filled fuel boxes were exchanged for fuel thus forming Core II-A-6, Figure 9. The

TABLE I

CRITICALITY DATA FOR LOW EXCESS SQUARE CORES WITH NO BORON

Core	Rod Loading		Control Rods		Water Level Control(1)		
	Fuel	B-SS	Critical Position in. from bottom of core	Worth	Critical Height	Worth	Excess React.
I-A-7	248	0	Center at 30.37"; Others out	20.7¢/in. at 31.28"	32.43"	21¢/in. at 32.6"	$0.71
I-A-8	236	0	Center at 34.72"; Others out	12.0¢/in. at 35.98"	36.32"	14.2¢/in at 36.63"	$0.24

(1) Control rods completely withdrawn

TABLE II

CRITICALITY DATA FOR LOW EXCESS SQUARE CORES
WITH 1.1 w/o BORON-STAINLESS STEEL IN DESIGN POSITION

Core	Loading: Fuel	Loading: B-SS	Rods: Positions (1)	Rods: Worth	Water Level Control (2): Critical Height	Water Level Control (2): Worth	Water Level Control (2): Excess React.
II-A-3	392	24 - 1.1 3/0	5 rods at 30.4"		32.02"	20.57¢/in.at 32.40"	$0.84
			4 side rods at 28.08"; Center out	4.34¢/in. at 28.93" each			
			Center at 28.71" Side rods out	Center worth 21.5¢/in. at 28.91"			
II-A-4	376	24 - 1.1 w/o	5 rods at 33.09"		34.61"		$0.51
			4 sides at 31.08: Center out	Side rod 1.75¢/in. each at 34.69"			
				Each side rod worth from 31.08" to all out; 12.7¢			
			Center at 31.61"; Others out				
II-A-5	380	20 - 1.1 w/o	5 rods at 18.40"				
			4 rods with Center at 13.31"	55.8¢/in. for 4 rods at 12.26"			
II-A-6	380	20 - 1.1 w/o	4 rods with Center out at 19.32"	53.0¢/in. for 4 rods at 17.97"			

(1) Distance from bottom of fuel
(2) Control rods completely withdrawn

worth of this change relative to Core II-A-4 was about $3.0. Criticality data for Cores II-A-5 and II-A-6 are given in Table II.

2. Slab Geometry Cores with Varying Concentrations of Boron

A series of small unrodded slab cores were assembled with low excess reactivity. The slab thickness - two fuel boxes - remained the same for all cores and criticality was adjusted by changing the length of the slab and the water height. Unless otherwise noted, boron-stainless steel rods of various natural boron concentrations were located in each box in the PL-2 design positions. The criticality data are given in Table III.

Core II-B-4, shown in Figure 10, contained boron-stainless rods of 1.1 w/o boron and was $3\frac{1}{2}$ fuel boxes long, with eight extra fuel elements centered at one end. In the partially filled fuel boxes, the boron rods in the center position were replaced by fuel. Core II-B-5, shown in Figure 10, was identical to II-B-4 except that the boron content of the boron-steel rods was 0.50 w/o.

Core II-B-7, shown in Figure 11, was $3\frac{1}{4}$ fuel boxes long, and contained 0.25 w/o boron-stainless steel. The length of the assembly was shortened to three fuel boxes in Core II-B-8, Figure 12. For Core II-B-9, shown in Figure 12, the 0.25 w/o boron-stainless steel rods in Core II-B-8 were replaced with plain stainless steel rods.

3. Analysis of Square Cores - Predicted Reactivity

In the reactivity prediction, the cores were represented in explicit X-Y geometry using the IBM-704 diffusion code, PDQ, in two groups. Fast group macroscopic cross sections were obtained by using the MUFT code, and thermal microscopic cross sections were averaged over a Maxwellian energy spectrum. Flux disadvantage factors were obtained for the fuel, cladding, boron-stainless steel, and associated cell water using the cylindrical P_3 approximation code CEPTR. Resonance escape probabilities were obtained using the Bell method to determine the effective chord length, and the QUERY code to find the effective absorption cross sections for the U-238 resonances. The fuel rods were homogenized with their associated water and similarly the boron pins with their associated water. An axial buckling was specified which was based on the core height augmented by the reflector savings. There is, of course, some uncertainty in the top and bottom reflector savings which were assumed to be 7 cm at the bottom and 3 cm for the top, rodded reflector. This provides, at most, an uncertainty of 0.2% in reactivity.

For Core I-A-8, the effective multiplication factor, k_{eff}, by use of the method described above was 1.0203 with water above the top reflector and control rods at the top of the fuel. Under the same conditions, the core had a measured excess of 24¢ which gives a k_{eff} of 1.0017 using a β of .007. This shows that the calculated reactivity is about 1.8% greater than that measured.

TABLE III

CRITICALITY DATA FOR SMALL SLAB CORES CONTAINING VARIOUS CONCENTRATIONS OF BORON-STAINLESS STEEL IN THE DESIGN POSITIONS

Core	Rod Loading		Control Rods		Water Level Control(2)		
	Fuel	B-SS	Positions(1)	Worth	Critical Height	Worth	Excess React.
II-B-4	422	20 - 1.1 w/o	4 rod bank with Center out, 33.68"	Two opposite rods to full out, 12.63¢	36.50"	13.8¢/in. at 37.0"	25.26¢
II-B-5	422	20 - 1/2 w/o	4 rod bank with Center out, 24.72"	-	29.09"	28.8¢/in. at 29.26"	-
II-B-7	382	20 - 1/4 w/o	4 rod bank with Center out, 24.86"	Each, 8.93¢/in. at 25.32"	-	-	-
II-B-8	354	18 - 1/4 w/o	4 rod bank with Center out, 31.09"	Two opposite rods 6.4¢/in. at 31.71"	34.68"	17.09¢/in. at 35.00"	43.0¢
II-B-9	354	4 - 0 w/o	4 rod bank with Center out, 19.21"	4 rods worth 42.25¢/in. at 19.33"	-	-	-
			5 rod bank, 22.35"				

(1) Distance from bottom of fuel
(2) Control rods completely withdrawn

For Core II-A-4, the calculated k_{eff} with water above the top reflector and control rods at the top of the fuel was 1.0209. The measured excess was 51¢, and the corresponding k_{eff} was 1.0036. In this case, the calculated reactivity is about 1.7% greater than that measured.

4. Estimates of Reactivity Worths of Fuel and Boron in Small Cores

The method described earlier for obtaining reactivity changes from the change in critical rod bank position was used to estimate the worth of fuel and boron in the various small slab and square cores. These worths are summarized in Table IV.

C. FULL SIZE REFERENCE LOADING

The full size core with 1.1 w/o boron-stainless steel was built up in three loading steps through Cores II-C-1, II-C-2, and II-C-3(a). Diagrams of these cores are given in Figures 13, 14 and 15, and criticality data are presented in Table V. Core II-C-3(a) was the first fully loaded core, and differed from the reference design in two relatively unimportant respects; the stainless steel shroud surrounding the core was not in place, and 27 of the 72 stainless steel jackets that contain the boron-stainless steel rods were left off. These jackets were in place for all subsequent measurements.

1. Variation of Boron Concentration and Determination of Shutdown Margin with the Center Rod Out

In this phase of the program, the boron loading was systematically reduced and the shutdown margin with the center rod out was measured for each loading. The stainless steel shroud that surrounds the core was installed during this sequence. Measurements made in the same core, with and without the shroud, gave a reactivity worth of only 12¢ by the difference in the rod bank position.

Core III-A-1, Figure 15, identical to II-C-3 except for the full complement of steel jackets around the poison rods, had three 1.10 w/o boron-stainless steel rods in each fuel box. In Core III-A-2, Figure 15, the boron concentration was reduced to 0.50 w/o. The boron concentration was further reduced to 0.25 w/o in Core III-A-3, Figure 15. In Core III-A-4, Figure 16, the 0.25 w/o boron-stainless steel in the center of each fuel box was reduced to 0 w/o; i.e., replaced with boron-free stainless steel rods of the same diameter. In Core III-A-6, the 0.25 w/o boron-stainless steel in all positions in the core was replaced by plain stainless steel rods. Core III-A-5 was an intermediate step in the substitution of plain stainless steel rods for the 0.25 w/o boron. To carry the reduction of poison still further, the stainless steel rods in the corners of the fuel boxes were replaced with 0.25 w/o boron-stainless steel, and the stainless steel rods in the center of the fuel boxes were replaced with fuel elements. The resulting core III-A-7, is shown in Figure 17.

TABLE IV

REACTIVITY WORTH OF FUEL AND BORON IN SMALL CORES

Change	Cores Initial / Final	Reactivity Change Total	Per Fuel Rod	Per Poison Rod	Comments
Removal of 12 fuel rods from corners of core	I-A-7 / I-A-8	68-80¢	6.2	-	$\Delta\rho$ /fuel rod averaged from water height and rod position measurements
Enlarged core and addition of 1.1 w/o	I-A-8 / II-A-3	$1.07	Not applicable	Not applicable	Rough estimate; sizable change in core size
Addition of 4 fuel elements on each face of 20 x 20	II-A-3 / II-A-4	$0.33	1.0¢	-	Calculated from change in excess reactivity
1.1 w/o Boron-stainless steel at center of core replaced with fuel, 4 pins	II-A-4 / II-A-5	$6.07	-	$1.52	Worth includes addition of fuel to boron-stainless steel position
1.1 w/o boron-stainless steel at center of fuel assemblies replaced with fuel, 4 pins	II-A-4 / II-A-6	$3.90	-	$0.98	Worth includes addition of fuel to boron-stainless steel positions
1.1 to 0.5 w/o boron-stainless steel	II-B-4 / II-B-5	$2.10	-	-	By change in critical water height. Core cross sections identical.
1.1 - 0.25 w/o boron-stainless steel and addition of fuel	II-B-4 / II-B-7	$2.16	-	-	By rod bank position. Core length changes.
0.25 - 0.00 w/o boron-stainless steel	II-B-8 / II-B-9	$3.37	-	-	By rod bank position. Core cross sections identical

TABLE V

CRITICALITY DATA FOR INTERMEDIATE SIZE CORES
WITH 1.1 w/o BORON-STAINLESS STEEL IN REFERENCE POSITIONS

Core	Rod Loading Fuel	Rod Loading B-SS	Control Rod Positions (inches from bottom of core)	
II-C-1	708	36 - 1.1 w/o	Nine rod bank at 14.5 inches	Eight rod bank with center out at 12.5 inches
II-C-2	944	48 - 1.1 w/o	Nine rod bank at 11.97 inches	Eight rod bank with center out at 10.14 inches
II-C-3-a[1]	1416	72 - 1.1 w/o	Nine rod bank at 10.16 inches	Eight rod bank with center out at 8.53 inches
			Center out, #2 at 25.54 inches; Others in	Center out, #8 out, #6 at 19.51 inches, others in.

(1) 27 of the boron-stainless steel rods did not have their stainless steel jackets.

The reactivity shutdown of these assemblies with the center control rod completely withdrawn was measured by three basic techniques: control rod calibration, boron substitution, and rod drop.

The shutdown margin using rod calibration can be estimated in a number of ways which depend on the configuration of the remaining control rods. Two rod configurations were chosen which gave maximum and minimum values of reactivity shutdown for Core III-A-1, the first full size core in which these measurements were made. In one configuration, the side rod, #2, is calibrated with the center rod out, compensating with the remaining seven-rod bank. A curve of the differential worth of the side rod is obtained as a function of its position and is integrated from all-in to the eight-rod critical bank position. The relative worth of the rod bank to the side rod is then measured so that the worth of the bank can be inferred from the worth of the side rod. The integrated worth of the eight-rod bank from all-in to the eight-rod bank critical position is then the shutdown margin.

In the second configuration, the side rod, #2, is calibrated with the center rod out, compensating with opposite corner rods 7 and 8, with the remaining five rods in. The differential worth of the side rod is then integrated from fully in to its critical position when rods 7 and 8 are in. The shutdown is this integrated worth. Figure 14 shows the shutdown values obtained by these two methods as a function of the critical position of rod #2, with all other rods in. The corresponding boron concentrations and the calculated shutdown for the PL-2 is included. Shutdown values measured by integrating rod calibration curves are suspect for two reasons. First, the differential worth versus position curves obtained by either method are affected by the motion of the compensating rods. Second, the coupling between rods may not be the same as it would be in a shut down core where all control rods but the center one are fully inserted.

In the boron substitution method, the perturbing effects of the compensating rods are avoided by building a succession of cores with different boron contents and different critical bank heights. The differential worth of the bank, or individual control rods, is measured at the critical height. In this way, the boron compensates for the control rod movement, and the rod is calibrated with the remaining control rods in a fixed configuration. The shutdown for a particular core is then the integrated worth of the rods from fully in to their critical position. In this work, two distinct sets of differential rod worths were used to determine the shutdown in the manner described above: (a) the differential worth of the side rod, at its critical position, with the center rod out and all other rods in, and (b) the differential worth of the eight-rod bank, at its critical position, with the center rod out. Integrated values of these differential worths are included in Figure 18.

The shutdown margin by the rod-drop method is given in Table VII, and plotted in Figure 18. The uncertainties here arise from a possible change

TABLE VI

CRITICAL ROD CONFIGURATIONS FOR VARIOUS BORON CONCENTRATIONS
WITH POISON ELEMENTS IN REFERENCE POSITIONS

Core	III-A-1(a)	III-A-1(b)	III-A-2(a)	III-A-2(b)	III-A-3	III-A-6
w/o Nat. boron in boron-stainless steel	1.10	1.10	0.50	0.50	0.25	0
Figure number	14	14	14	14	14	14
Shroud present	No	Yes	No	Yes	Yes	Yes
Rod Positions (in.)						
9 rods	10.16	10.25	-	9.56	9.08	8.10
8 rods (1)	8.53	8.50 (5)	-	7.66	6.83	.98
7 rods (2)	9.42	-	-	8.42	7.47	1.01
Side rod #2 (3)	25.71	26.20	19.52	19.89	16.19	3.05
Rod worths near critical positions $/inch						
Side rod #2 (3)	$0.204	-	-	0.330	0.382	0.044
7 rod bank (4)	1.55 at 9"	-	-	1.47 at 8.04"	1.27 at 7.15"	-

(1) With the center rod out.
(2) With the center rod out and side rod #2 in.
(3) With the center rod out and the remaining seven rods in.
(4) With the center rod out, and side rod #2 moving from all-in to the eight-rod bank.
(6) Estimated from eight-rod bank versus center rod calibration curves.

TABLE VII

CRITICAL ROD CONFIGURATIONS FOR VARIOUS BORON ARRANGEMENTS

Combinations of Fuel and Boron-stainless steel in Design Positions
All Rod Positions Measured from Bottom of Fuel

Core	III-A-4	III-A-5	III-A-7
w/o Boron-stainless steel	0.25, 0.00	0.25, 0.00	0.25
Figure Number	15	16	15
Remarks	0.25 w/o boron in corners; 0 w/o in centers of fuel assemblies	0 w/o boron in all outside corners and in half of remaining positions, 0.25 elsewhere	0.25 w/o boron in corners, fuel in centers of fuel assemblies
Rod positions in inches			
9 rods	8.67	8.39	8.25
8 rods (1)	5.84	4.80	3.82
7 rods (2)	-	-	4.14
Side rod #2(3)	12.99	-	8.29
Rod worths near critical (Dollars/inches)			
Side rod #2(3)	0.380	-	0.178
7 rod bank (4)	-	-	0.356 at 3.98"

(1) With the center rod out.
(2) With the center rod out and side rod #2 in.
(3) With the center rod out and the remaining seven rods in.
(4) With the center rod out, and side rod #2 moving from all-in to the eight-rod bank.

in flux distribution during the rod drop, and an accompanying change in the effective sensitivity of the neutron detectors.

The shutdown curves in Figure 18 show an interesting behavior. Shutdowns obtained by the integration of rod calibration curves show a large difference from one to another, depending upon the particular method in which the calibration curves were obtained. Shutdown values by boron substitution calculated in two different manners agree very well with each other and with shutdown by rod drop. This agreement is encouraging and, for this reason, the reactivity shutdown estimates obtained by rod drop were taken as the best estimates.

As evident in Figure 20, the calculated shutdown margin for boron concentrations from 0.25 to 1.0 w/o is always about \$2.30, or 1.6% Δ k less than that measured by rod drop, or boron substitution. This difference is approximately the same as that found between measured and calculated reactivities of small, unrodded cores II-A-8 and II-A-3. It appears that the calculational method over-estimates reactivities by about 1.6 to 1.8% Δ k.

Core III-A-3, with 0.25 w/o boron-stainless steel rods in the reference design positions, contains sufficient shutdown margin with the most important rod stuck out. This shutdown can be expressed as at least \$2.82, or about 2.0% reactivity; or by 16.2 inches of withdrawal of the next most important rod before criticality is reached. The possibility of losing this shutdown later in life, as the boron burns out, is unlikely since it has been demonstrated in Core III-A-6 that with no boron, with fresh fuel and without fission products the reactor shuts down by a small margin. All subsequent measurements in the full size core were made with 0.25 w/o boron-stainless steel rods in the reference design positions.

A summary of the control rod worths, critical positions, and configurations for cores in which boron-stainless steel rods of uniform concentrations were in the design positions is given in Table VI. Table VII contains similar data measured in cores which had various combinations of born-stainless steel and fuel elements in the design positions.

2. Measurements in the Core Containing 0.25 w/o Boron-Stainless Steel

The critical assembly is an extremely faithful mock-up of the PL-2 core since it uses the identical fuel elements and control rods. The only significant difference between the design core and the critical core is the substitution in the criticals of mild steel for stainless steel stanchions. A much smaller difference arises from the absence in the criticals of the stainless steel ferrules (spacers) between the fuel rods. It is estimated that the critical mock-up is about one-half percent more reactive than the design core. This reactivity difference makes the nine-rod bank position in the mock-up about 0.3 inch lower than in the design core and the shutdown margin about 0.5% greater in the design core than in the mock-up. In view of this close similarity between the cores, the extrapolation from one to the other is small and rather simple.

Reactivity Measurements: Table VIII gives rod bank positions for various rod configurations. With the center rod in, the core is critical with the remaining eight rods at 11.21 inches which demonstrates that the core would operate with its most important rod stuck in. The data also show that the core can be shut down with any rod stuck out of the core. Table IX gives relative rod worths, reactivity equivalence factors between individual control rods and the eight and nine rod banks and differential worths of the banks and individual rods. The worth of the nine rod bank is taken as the sum of the worths of the eight rod bank and the appropriate individual rod.

The sign and magnitude of the void coefficient of reactivity near the central axis of the core are of safety significance since any substantial power transient would generate or increase the generation of steam bubbles in this region. Aluminum tubing, 0.628" O.D. and 0.065" wall, was placed around all fuel and poison elements in the center four fuel boxes. The reduction in water content inside the fuel boxes was 31.3% and the observed reactivity change was -$3.60. If the absorption and scattering effects from the aluminum are considered negligible, and if it is then assumed that most of the reactivity change is due to the decrease in effective water density, the resultant void coefficient for the center of the core is -0.08% per percent void. This indicates that in addition to the doppler effect there exists a second important built-in shutdown mechanism for quenching reactivity accidents.

Power Distributions: The power distribution in the cold mock-up was measured to test the calculational methods. The prediction of the rod bank position and the axial power distribution would require a three-dimensional synthesis calculation. However, a radial calculation has been performed, and the predicted radial power distribution compares very well with the measured radial power distribution. The calculation was an X-Y PDQ which represented the lower part of the core, below the control rod bank.

The experimental power distribution was obtained by measuring the activation along the length of fuel rods taken from the core after a power run. Three separate runs on three successive days were made to obtain a complete power mapping in an octant of the core; because of symmetry, this is adequate for obtaining a representation of the entire core. The nine-rod bank position remained at 9.07 inches for each run; however, there was an unexplained change of several percent in the apparent axial activation shape from the first to the second day exhibited by the monitor fuel rods. These rods were used for power normalization and for monitoring the symmetry of the core.

Figure 19 shows the measured and calculated radial peaking factors in an octant of the core. These factors were obtained by integrating the power

TABLE VIII

CRITICAL ROD CONFIGURATIONS AND BANK POSITIONS IN THE REFERENCE CORE WITH 0.25 w/o BORON-STAINLESS STEEL

(All Positions in inches, Measured from the Bottom of the Fuel)

Rod Configuration	Center Rod #1	Side Rod #2	Corner Rod #8	Three Side Rods	Three Corner Rods
Nine rod bank	9.08	9.08	9.08	9.08	9.08
Bank position with center rod out	38.30	6.82	6.82	6.82	6.82
Bank position with center rod in	.19	11.21	11.21	11.21	11.21
Bank position with side rod in	9.84	.19	9.84	9.84	9.84
Bank position with Corner rod in	9.45	9.45	.19	9.45	9.45
5 rod bank with corner rod out	5.17	5.17	38.30	5.17	38.30
4 side rod bank with center and corner rods in	.19	18.69	.19	18.69	.19
Side rod with center out and all others in	38.30	16.19	.19	.19	.19
Center rod with side #2 and corner #8 out, all others in	13.94	38.30	38.30	.19	.19

The stainless steel cladding around the central rod poison material limits the insertion of a rod to 0.19 inches from the bottom of the fuel.

TABLE IX

CONTROL ROD WORTHS IN REFERENCE CORE WITH
0.25 w/o BORON-STAINLESS STEEL. ALL VALUES
FOR THE 9 ROD CRITICAL BANK POSITION OF 9.07"

	Relative Differential Control Rod Worths at 9.07"	
	8 Rod Bank	9 Rod Bank
Bank-to-center rod	3.3	4.3
Bank-to-side rod	6.8	7.8
Bank-to-corner rod	14.3	15.3

	Bank Worths at 9.07", $/in.	
	8 Rod Bank(1)	9 Rod Bank
Excluding center rod	2.1	2.8)
Excluding side rod	2.2	2.5)(2.6 Avg.)
Excluding corner rod	2.5	2.6)

Rod Worths

Rod	Differential ($/in.)(1) at 9.07"	Integrated Worth (Dollars) Total	From In to 9.07"	From 9.07" to Out
Center	0.64	9.03	4.17	4.86
Side	.32	5.65	1.75	3.90
Corner	.17	2.68	.92	1.76

Relative Rod Worths

Rod	Relative Differential Worth at the 9 Rod Bank Position(1)	Relative Integrated Rod Worths Total	From In to 9.07"	From 9.07" to Out
Center	3.8	3.4	4.5	2.8
Side	1.9	2.1	1.9	2.2
Corner	1.0	1.0	1.0	1.0

(1) Values obtained slightly below and slightly above the bank agree with each other.

over the total length of the fuel elements, and in this manner the axial power shift was cancelled out. The agreement between the measured and calculated values is within five percent. In Figure 20 are compared the calculated and measured local peaking factors in a central fuel box. The measured values were taken at the axial power peak, and since all measurements in this box were made on the same day, no normalization was necessary. The agreement between calculated and measured values is within eight percent.

Radial Zoning of Boron: The core was divided into four zones: a central zone comprised of fuel boxes 9, 10, 15 and 16 (see Figure 5); an inner zone containing boxes 4, 5, 8, 11, 14, 17, 20 and 21; a corner zone containing boxes 3, 6, 19,and 22; and an outer zone consisting of boxes 1, 2, 7, 12, 13, 18, 23, and 24. Boron-stainless steel rods of 0.25 w/o boron were removed from the center zone, replaced with fuel rods, and criticality data were obtained. The poison rods were then returned to the center zone and those from the inner zone replaced with fuel. This process was repeated for all four zones in turn, and for a fifth peripheral zone which consisted of the outer and corner zones - all fuel boxes next to the reflector. Table X gives a summary of the criticality data measured in this sequence, and includes for comparison similar data from the reference core.

In Table XI the shutdown margin with the center rod out and the reactivity change relative to the design core are given. The shutdown margin was measured by the rod-drop technique, and also by the calibration of a side rod compensated with two opposite corner rods, with all other rods in. The latter method yields the smallest shutdown value as discussed previously. Core IV-A-7, with boron-stainless steel removed from all peripheral fuel boxes, contains only one-half as much boron as the reference design; yet its shutdown margin has only decreased by $0.4 from rod calibration, or $0.6 from rod-drop measurements. The core reactivity has, however, increased by $1.5 as measured by the change in critical position of the center control rod with the remaining rods fixed at 9.07 inches. This core may prove to be a simple improvement over the reference design.

Further measurements in Core IV-A-7 show that the center rod is still reactivity-wise the most important rod in the core. These measurements are reported in Table XII. In the first three configurations, the center rod, a side rod, and a corner rod were withdrawn in turn from a bank position of 8.21 inches to a critical position. The withdrawal of these rods were 1.57 inches, 2.44 inches, and 3.94 inches, respectively, indicating that this is the order of worth of the rods for this configuration. In the last three configurations, it is apparent that the core is subcritical with any one control rod completely withdrawn. The center rod is still the more valuable; however, the corner rod appears to be somewhat more valuable than a side rod.

TABLE X

CRITICALITY DATA FOR VARIOUS ARRANGEMENTS OF 0.25 w/o BORON PINS

(Rod Positions Measured from the Bottom of the Fuel)

Core	III-A-3	IV A-3	IV-A-4	IV-A-5	IV-A-6	IV-A-7
Zone in which boron-stainless steel was replaced by fuel	Reference Design	Center	Inner	Corner	Outer	Peripheral
Fuel boxes from which boron-stainless steel was replaced by fuel	Reference Design	9, 10, 15, 16	4, 5, 8, 11, 14, 17, 20, 21	3, 6, 19, 22	1, 2, 7, 12, 13, 18,23, 24	1, 2, 3, 6, 7, 12, 13, 18, 19, 22, 23,24
9 rod bank positin, in.	9.07	8.01	8.08	8.80	8.78	8.53
8 rod bank at 9.07", position of center rod, in.	9.07	5.76	3.99	7.93	7.78	6.59
Worth of center rod in above configuration, $/in.	0.64 at 9.07"	1.00 at 5.82"	Not measured	0.72 at 8.00"	0.68 at 7.86"	0.60 at 6.67"
Position of side rod #2 with center rod out and all others in, inches	16.19	(1)	12.57	14.88	15.68	14.51
Worth of side rod in above configuration, $/in.	0.38 at 16.33"	(1)	0.45 at 12.69"	0.44 at 15.00"	0.39 at 15.84"	0.45 at 14.64"

(1) Reactor critical with center rod withdrawn 21.35 inches and all other rods inserted.

TABLE XI

SPATIAL REACTIVITY WORTH OF 0.25 w/o BORON AND EFFECT ON SHUTDOWN MARGIN

Core	III-A-3	IV-A-3	IV-A-4	IV-A-5	IV-A-6	IV-A-7
Zone from which boron-stainless steel was removed	Reference Design	Center	Inner	Corner	Outer	Peripheral (corner plus outer)
Fuel boxes from which boron-stainless steel was removed	Reference Design	9, 10, 15, 16	4, 5, 8, 11, 14, 17, 20, 21	3, 6, 19, 22	1, 2, 7, 12, 13, 18, 23, 24	1, 2, 3, 6, 7,12, 13, 18, 19, 22, 23, 24
Reactivity worth of change relative to Reference Design						
(a) By center rod	-	$2.72	-	$0.78	$0.85	$1.54
(b) By side rod	-	$3.20	$2.72	$0.72	$0.84	$1.56
Shutdown with center rod out						
(a) By rod calibration(2)	$2.8	(1)	$2.0	$2.6	$2.5	$2.4
(b) By rod drop	$3.7	(1)	$2.6	-	$2.9	-

(1) Reactor critical with center rod withdrawn 21.35 inches and all other rods inserted.
(2) By method which gives the lowest result; compensation by two side rods.

TABLE XII

CRITICAL ROD CONFIGURATIONS IN CORE II-A-7 - REFERENCE DESIGN
WITH 0.25 w/o BORON-STAINLESS STEEL IN INNER 12 FUEL BOXES.
BORON-STAINLESS STEEL REPLACED BY FUEL IN 12 PERIPHERAL FUEL BOXES

Configuration Number	Center Rod	Side Rods					Corner Rods		
	#1	#2	#3	#4	#5	#6	#7	#8	#9
1	9.78	8.21	8.21	8.21	8.21	8.21	8.21	8.21	8.21
2	8.21	10.65	8.21	8.21	8.21	8.21	8.21	8.21	8.21
3	8.21	8.21	8.21	8.21	8.21	8.21	8.21	12.15	8.21
4	38.30	7.00	5.64	7.00	5.64	5.64	7.00	7.00	5.64
5	7.00	38.00	5.75	7.00	5.75	5.75	7.00	8.70	5.75
6	7.00	7.00	5.75	7.00	5.75	5.75	7.00	38.30	5.75

D. EFFECT ON CORE PERFORMANCE OF CHANGING THE BORON CONTENT FROM 1.0 w/o to 0.25 w/o

As discussed in the previous section, the reactivity shutdown margin is sufficient with the center rod out and with 0.25 w/o boron-stainless steel. Furthermore, since it was estimated earlier that the critical mock-up may be about one-half percent more reactive than the design core due to the substitution of carbon steel for stainless steel in the stanchions, the shutdown margin in the design core would be somewhat larger than that measured in the mock-up.

Preliminary estimates indicate that although the greatest local peaking factor shifts to the fuel rod nearest a boron-stainless steel rod, a power peaking factor problem will not develop as the boron burns out. This would have to be investigated in more detail in a core depletion analysis.

The effects on reactivity and lifetime have been estimated using curves of boron worth, self-shielding factors, reactivity versus lifetime, and fuel and poison depletions given in IDO-19030, CEND-135, Vol. IV of VI, "Reactor Design." The decrease of boron concentration affects the core life for several reasons:

1. The reactivity gained by the reduction of boron is about 1.8% in the cold core with the center rod out. In the hot core, with a nine-rod bank, the corresponding reactivity increase is about 3.5%.

2. With a lower boron concentration, the poison rods are less self-shielded, and a greater fraction of the boron burns out during life. Estimates of the amount of boron, the reactivity controlled by the boron, and the average flux in the boron relative to that in the fuel for the first three years of full power operation have been made and are given in Table XIII.

TABLE XIII

BORON DEPLETION AFTER THREE FULL POWER YEARS IN CORES INITIALLY CONTAINING 1.0 AND 0.25 w/o BORON-STAINLESS STEEL RODS

	1.0 w/o Boron		0.25 w/o Boron	
	Beginning of Life	After 3 Yrs	Beginning of Life	After 3 Yrs
Boron Concentration	1.0 w/o	0.50 w/o	0.25 w/o	0.06 w/o
Reactivity Controlled by Boron in Hot Core	8.0%	6.0%	4.5%	1.2%
Average Flux in Boron Relative to Average Flux in Fuel	0.47	0.70	1.06	~1.3

On comparing the two cores in Table XIII, it is apparent that after three full power years the core with the initial boron loading of 0.25 w/o would be 4.8% more reactive. If 1.8% of this reactivity is used to remove the reactivity bias described earlier, this still leaves 3% extra reactivity, which corresponds to about 1-1/2 additional full power years of operation, for a total full power lifetime of 4-1/2 years. A more exact estimate would come from a detailed core depletion analysis.

It should also be noted that the reactivity worth of the steel in the boron-stainless steel rods increases by one-half percent at end of life. However, this is probably compensated for by further depletion of boron after the three year point in core life.

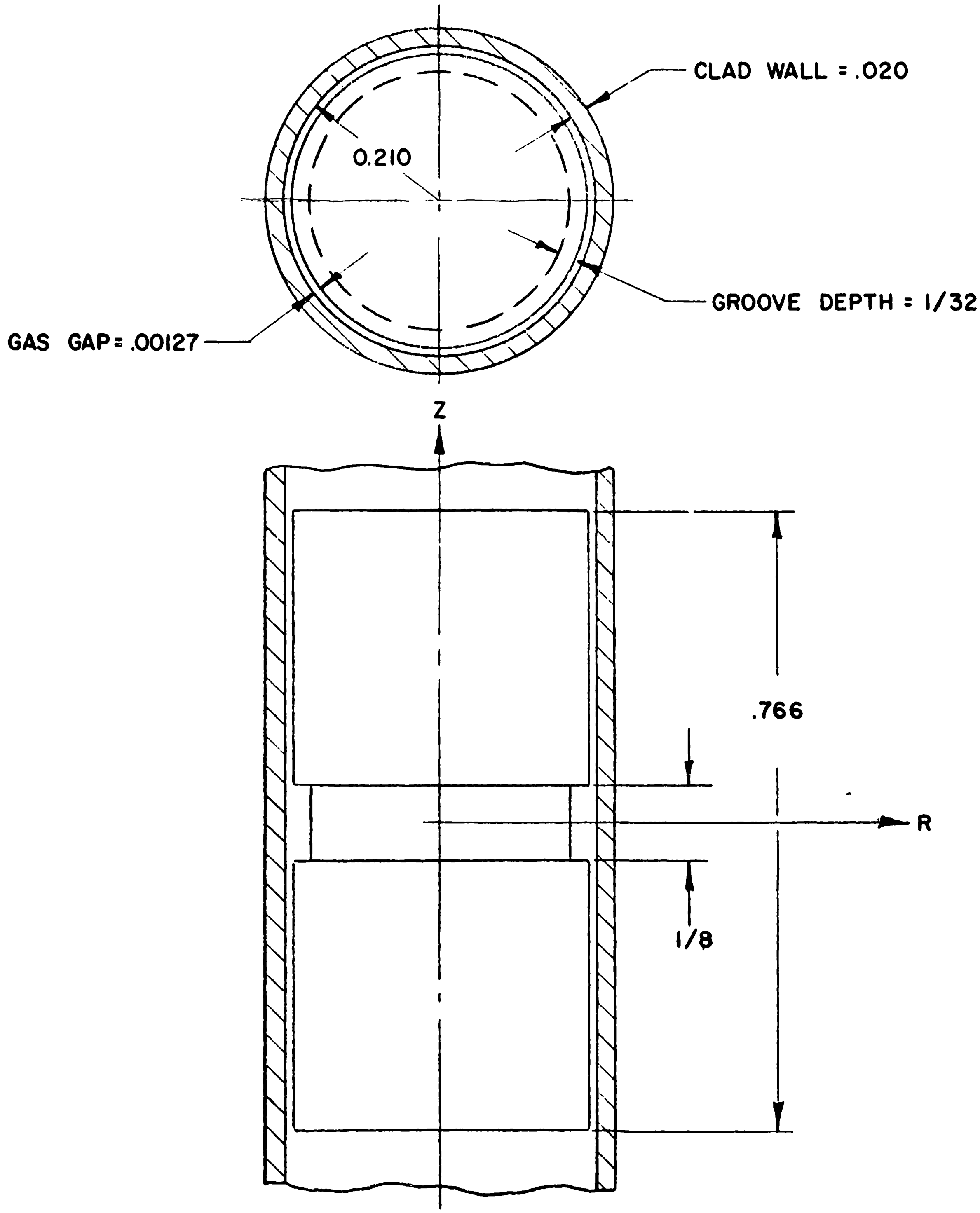
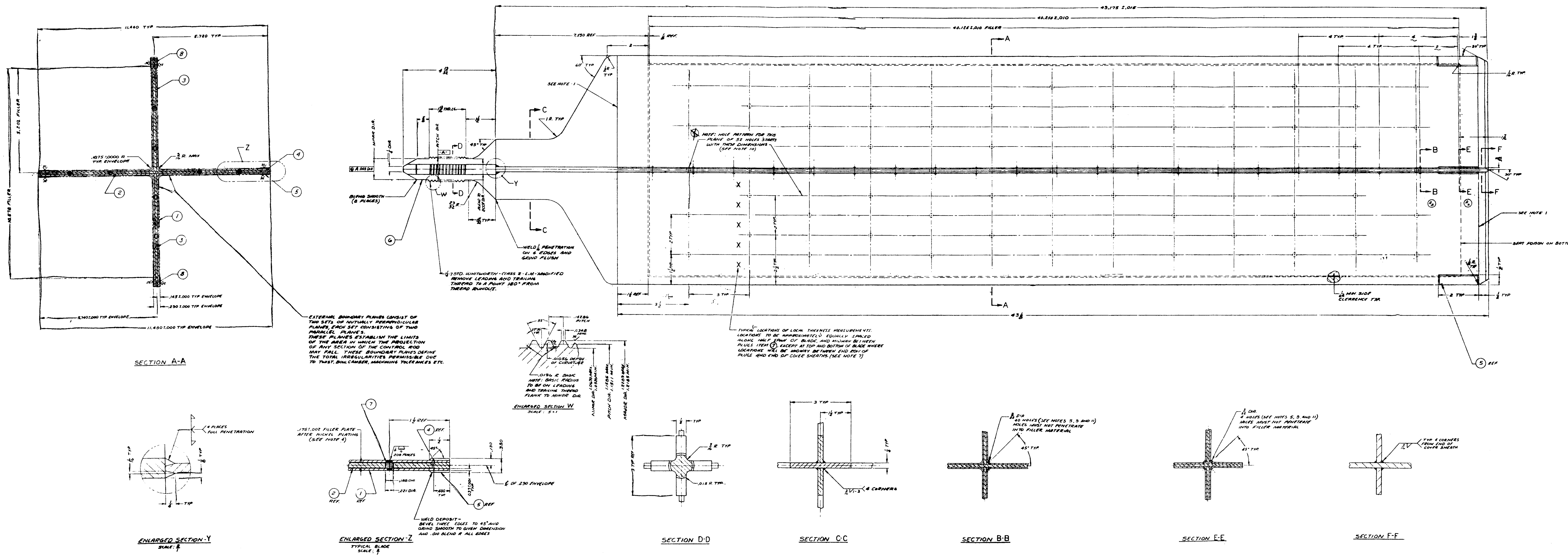
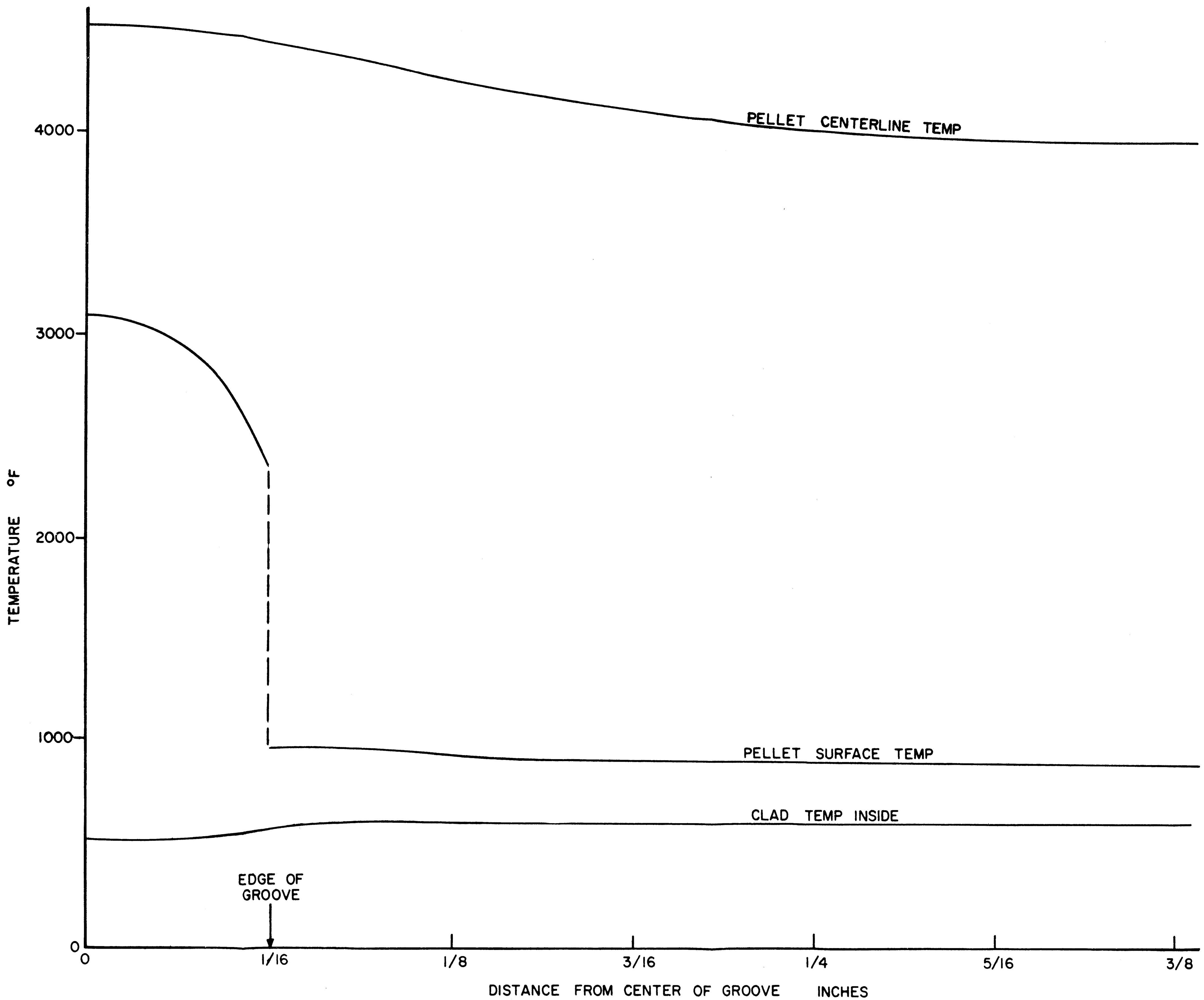


FIGURE 2

ANALYTICAL MODEL
FOR CHIPPED PELLET
CALCULATION

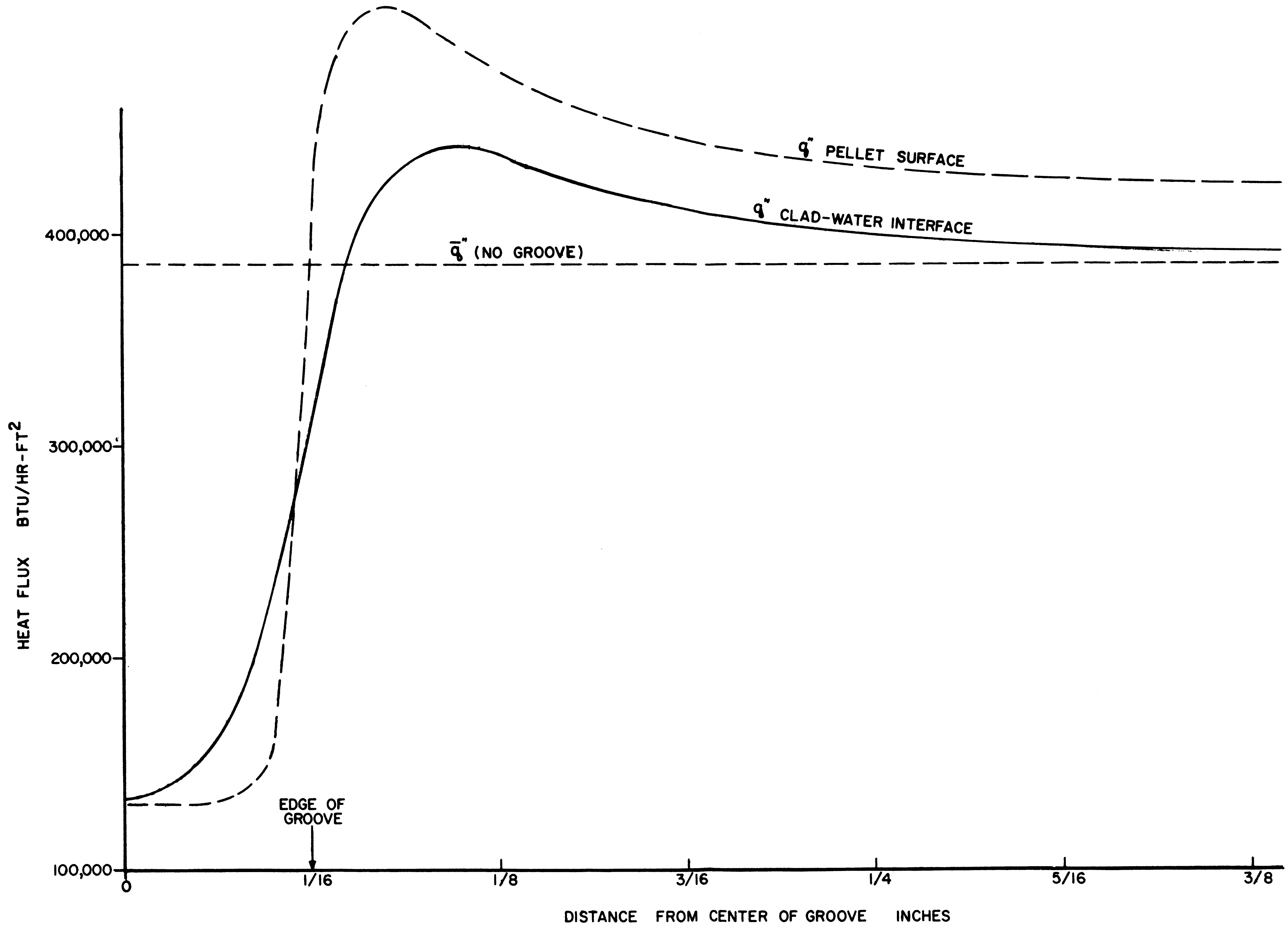


REVISED PL CONTROL ROD BLADE FIGURE I



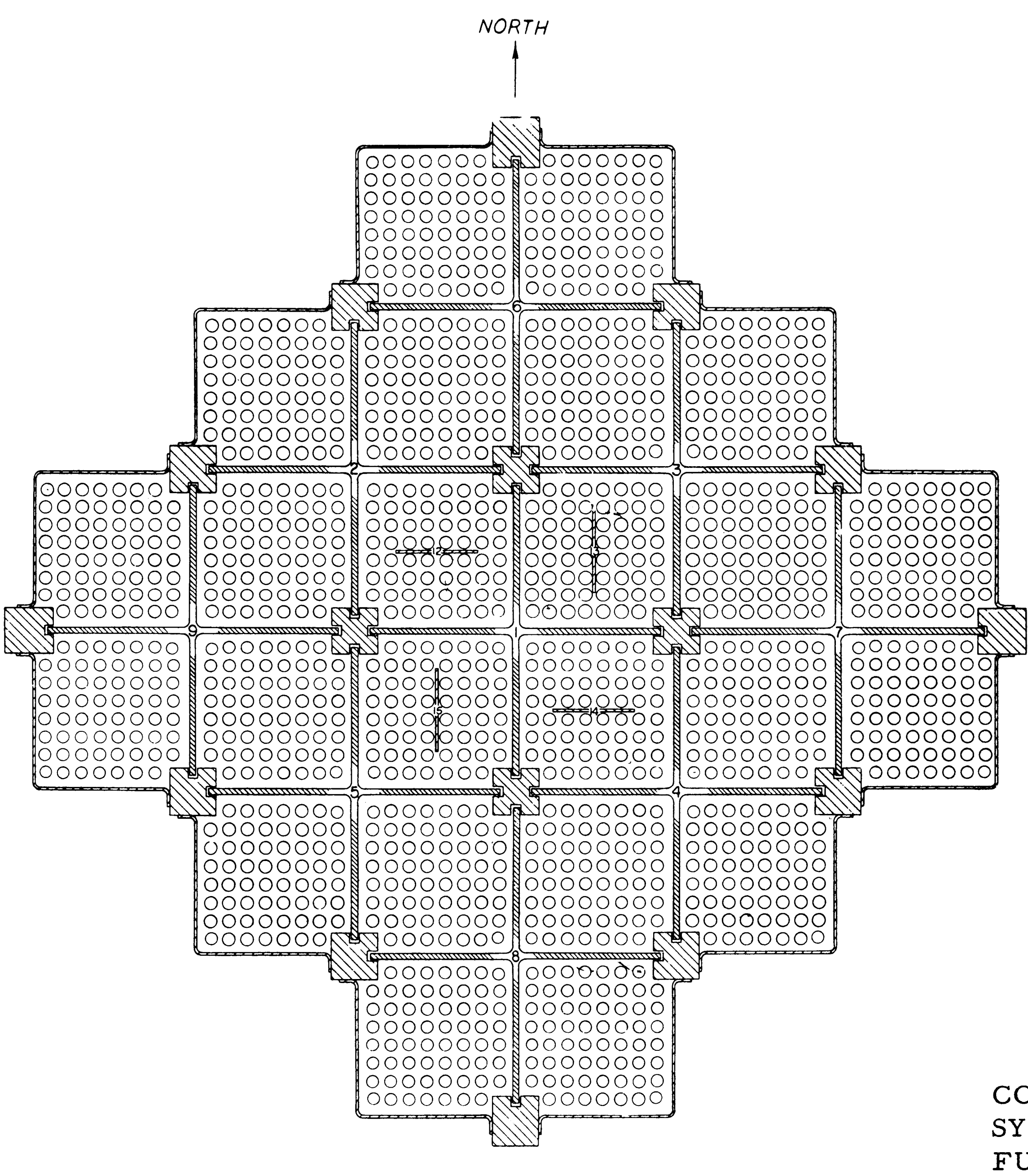
TEMPERATURE VARIATION IN CHIPPED PELLET

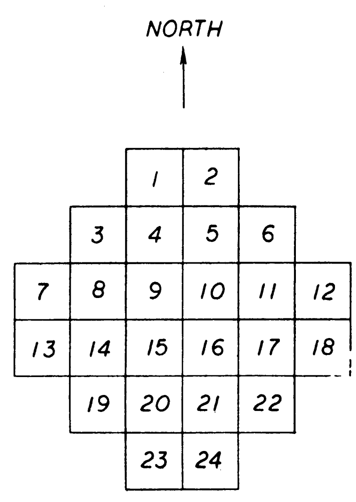
FIGURE 3

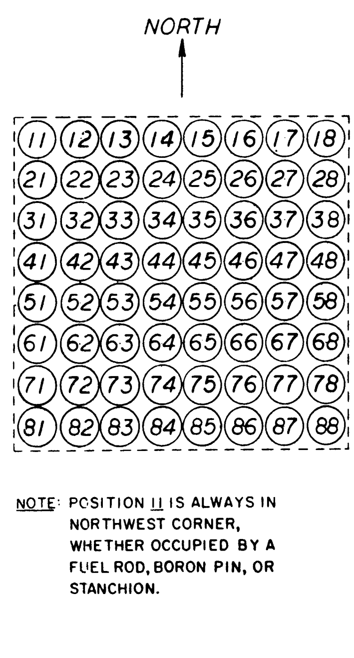


HEAT FLUX VARIATION IN CHIPPED PELLET

FIGURE 4



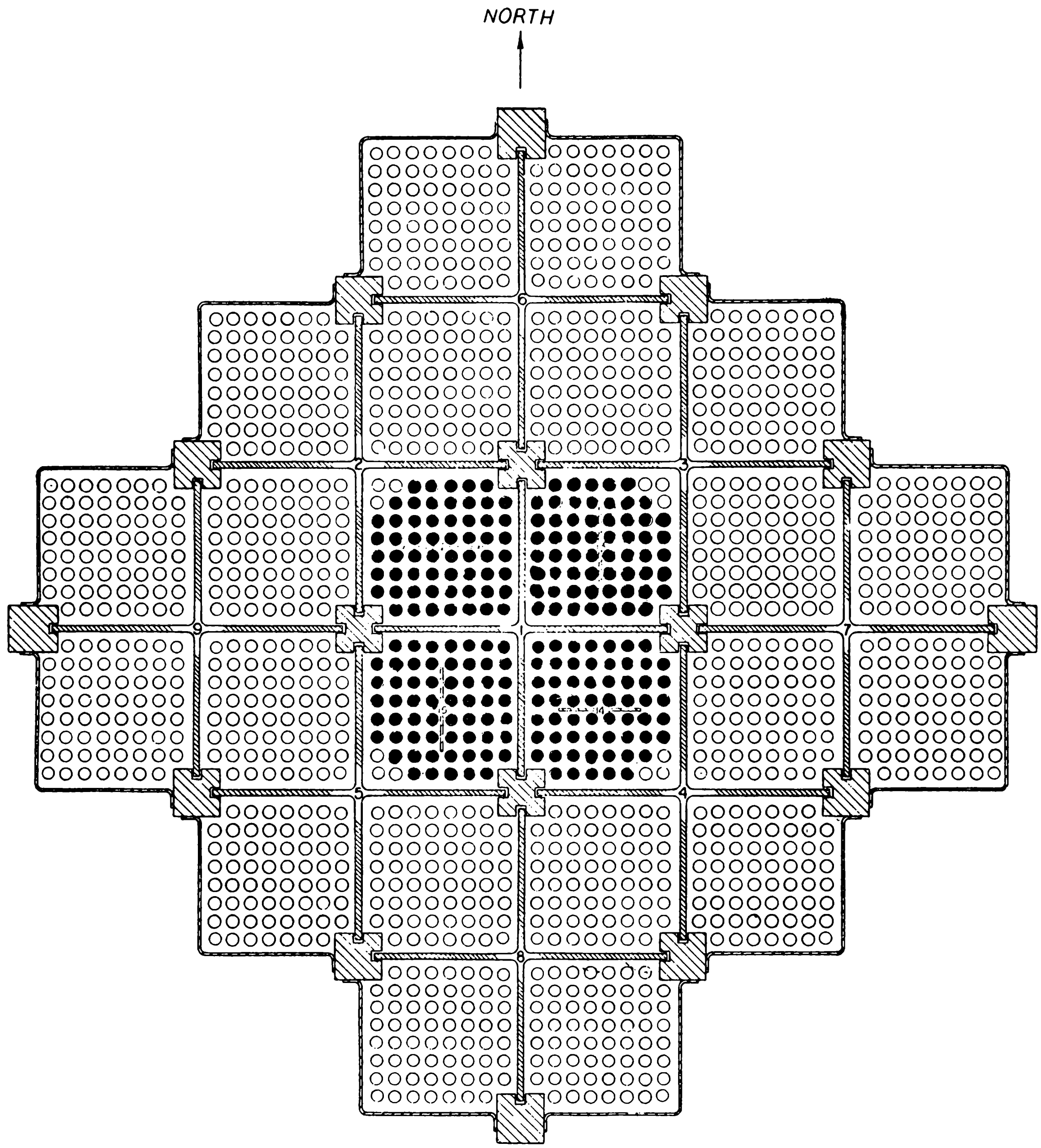




NOTE: POSITION 11 IS ALWAYS IN NORTHWEST CORNER, WHETHER OCCUPIED BY A FUEL ROD, BORON PIN, OR STANCHION.

CORE SECTION SHOWING NUMBERING SYSTEM FOR FUEL ELEMENTS, FUEL BOXES, AND CONTROL RODS

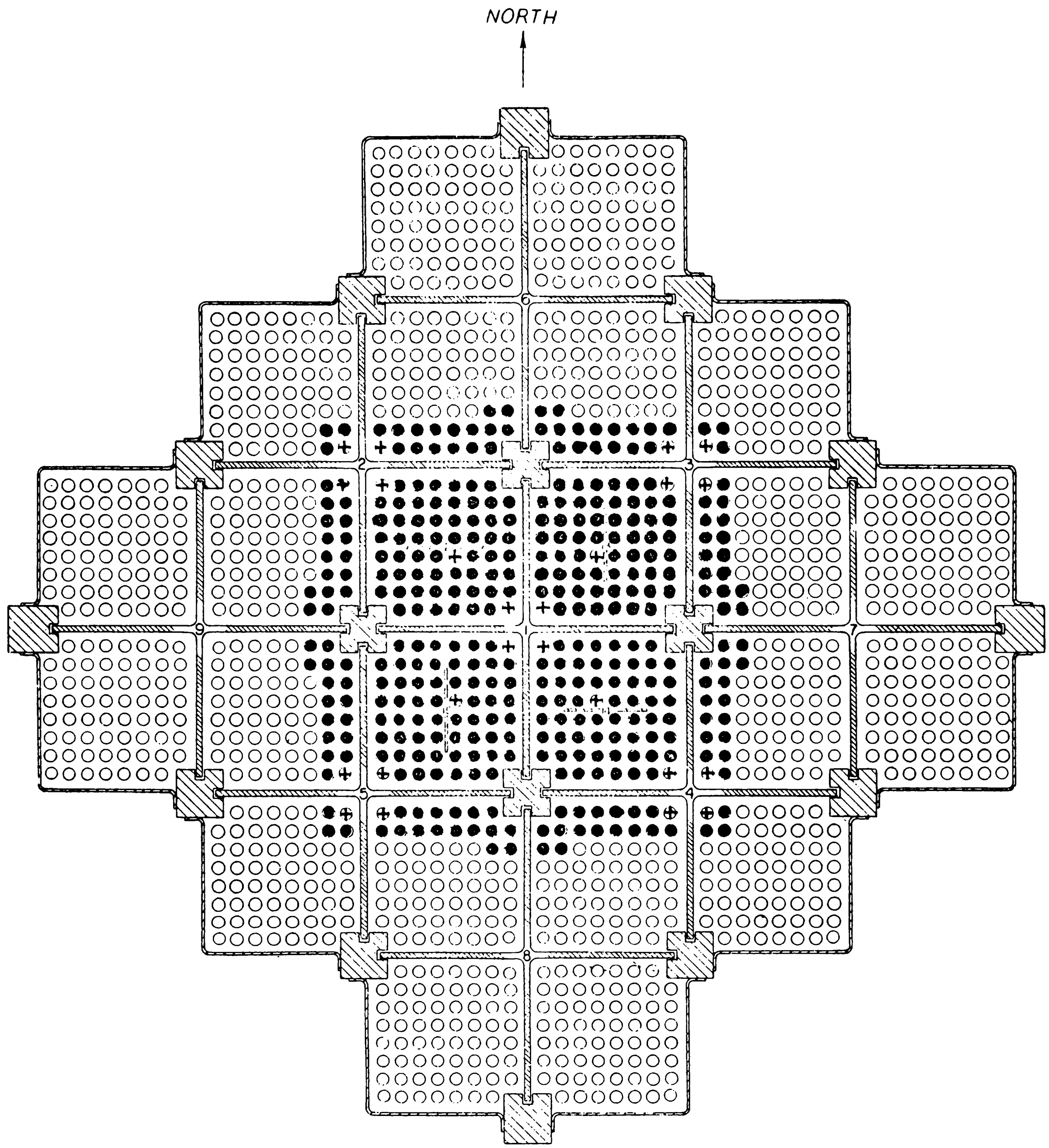
Figure 5



CORE I-A-8. CLEAN CRITICAL, NO BORON,
CONTROL RODS OUT, CRITICAL WATER HEIGHT: 36.32"

● - Fuel Elements

Figure 6

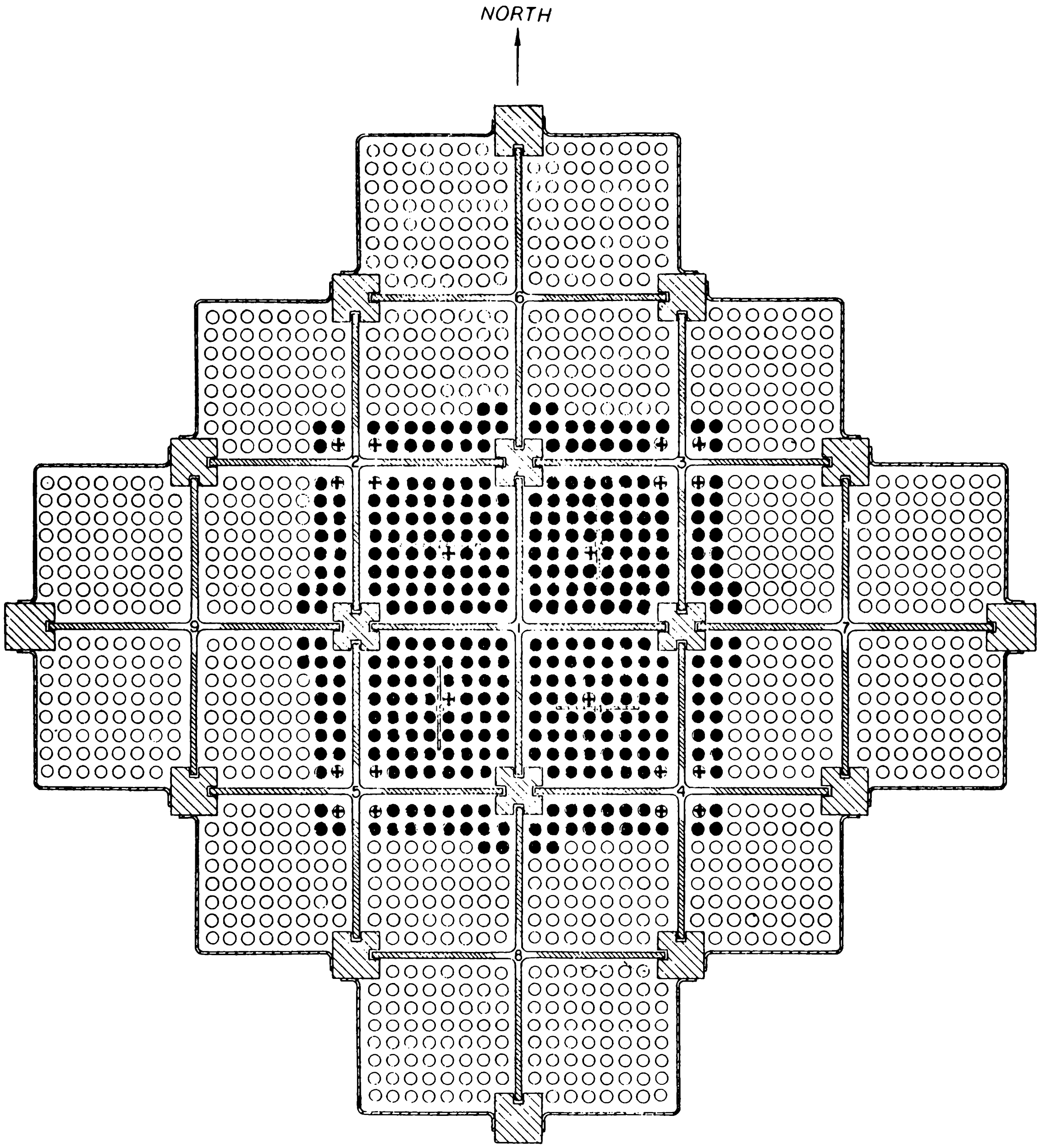


CORE II-A-4. CLEAN CRITICAL WITH 1.1 w/o BORON-STAINLESS STEEL.
CONTROL RODS OUT, CRITICAL WATER HEIGHT: 34.61"

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel

Figure 7

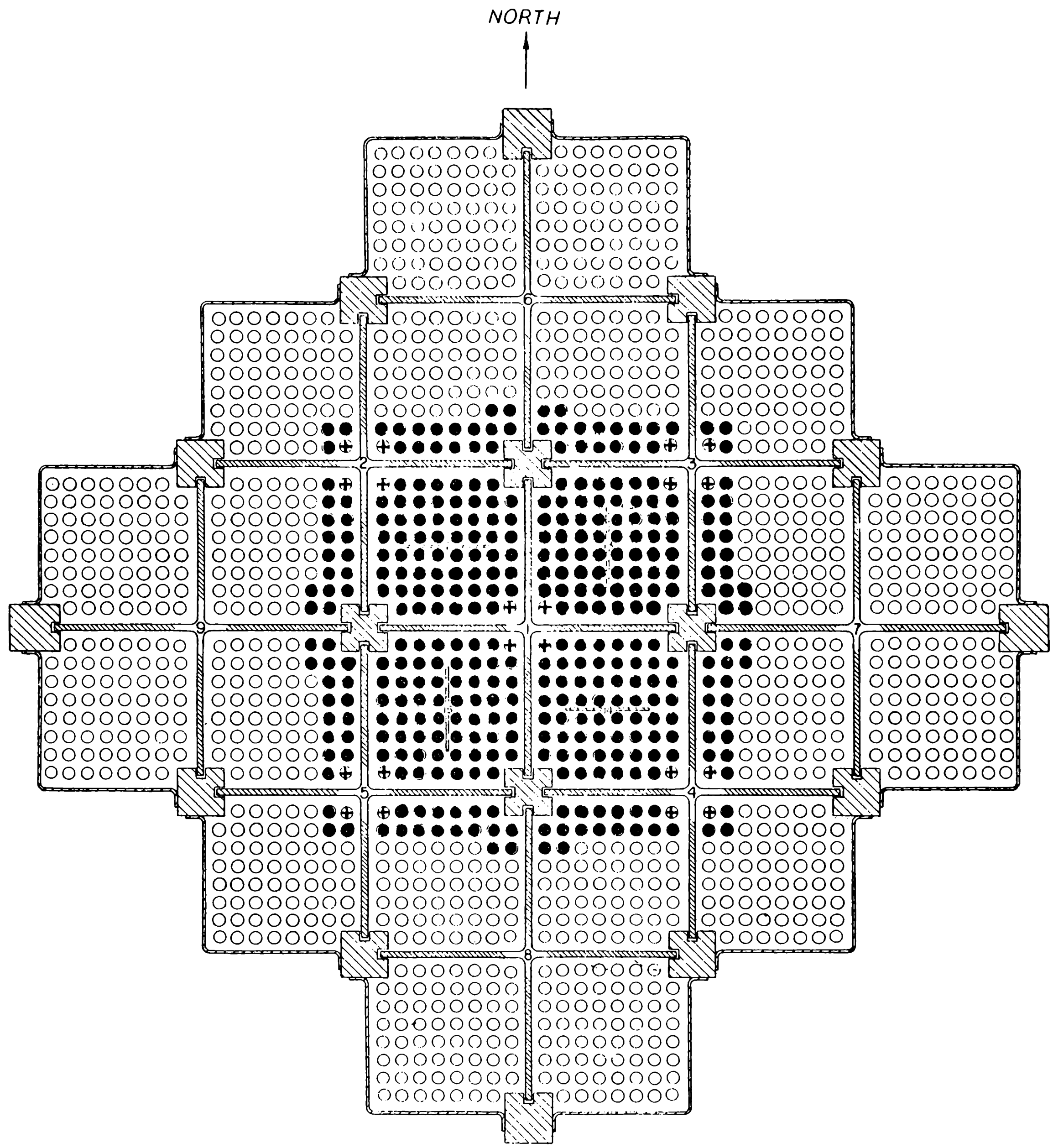


CORE II-A-5. 1.1 w/o BORON-STAINLESS STEEL IN FOUR CENTRAL POSITIONS REPLACED BY FUEL. CONTROL RODS OUT.

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel

Figure 8

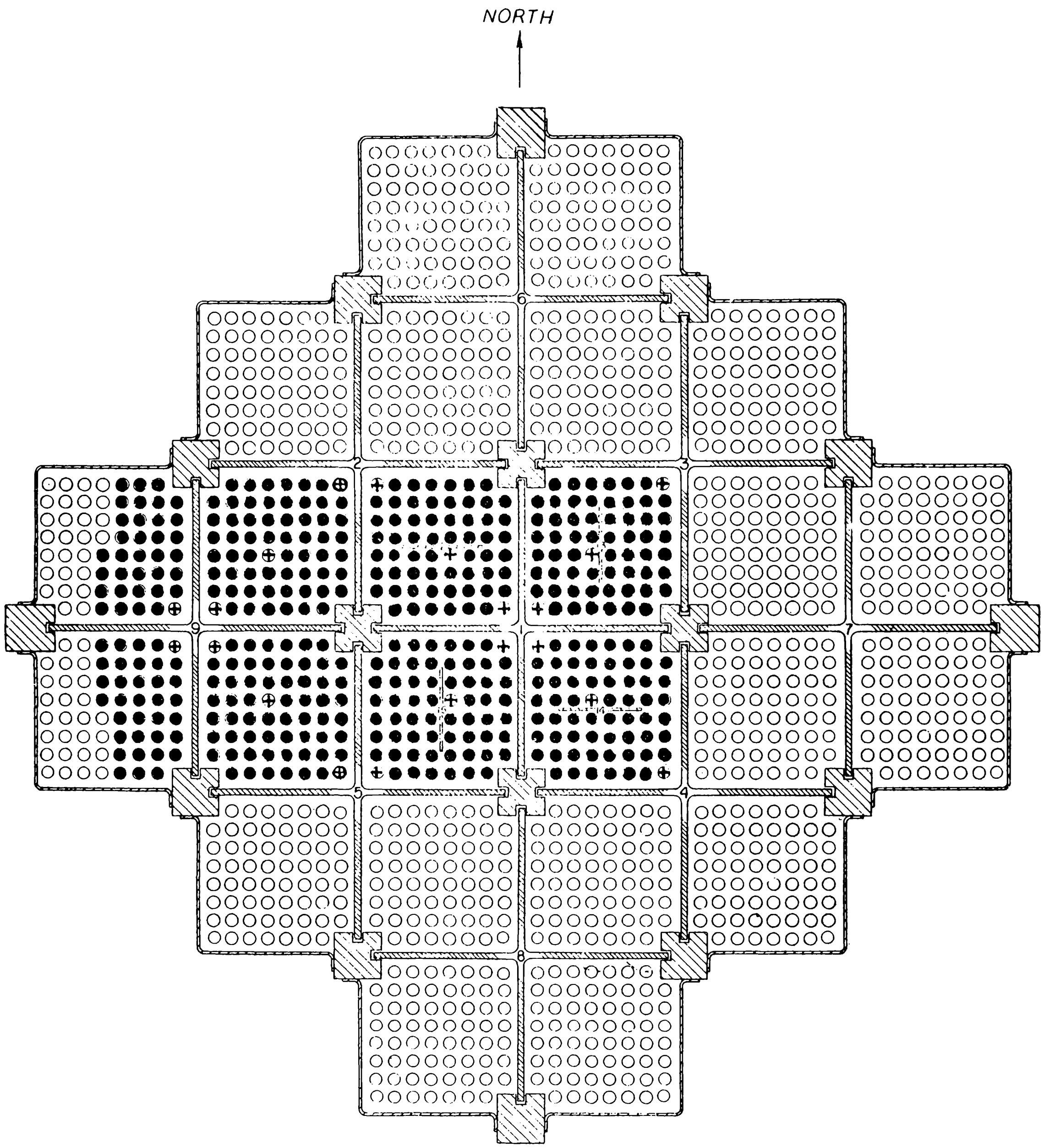


CORE II-A-6. 1.1 w/o BORON-STAINLESS STEEL IN CENTERS OF FUEL BOXES REPLACED BY FUEL, CONTROL RODS OUT.

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel

Figure 9

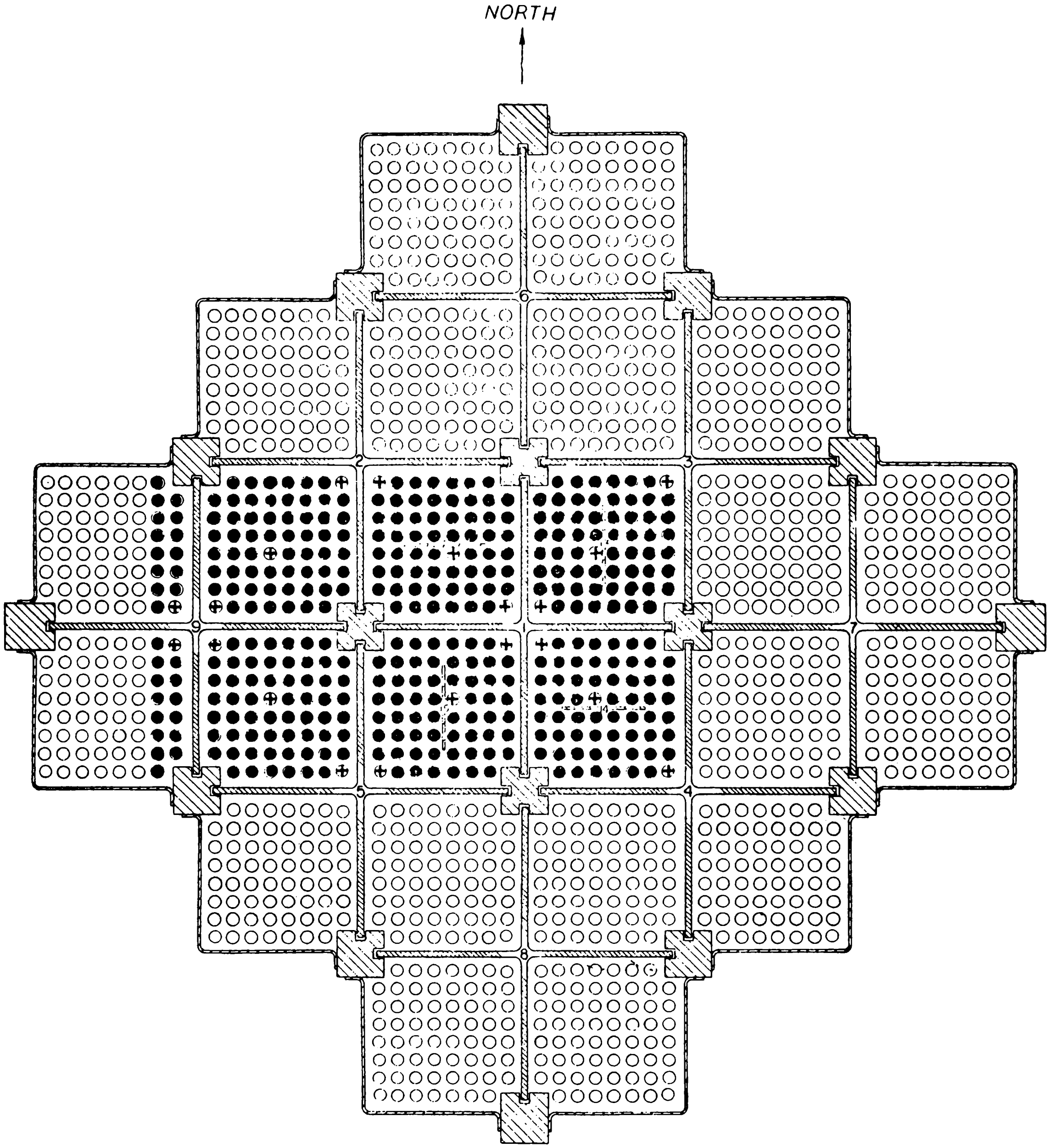


CORES II-B-4, II-B-5. SLAB CORES WITH 1.1 AND 0.5 w/o
BORON-STAINLESS STEEL, CONTROL RODS OUT

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel, Core II-B-4; Critical Water Height: 36.50"
0.5 w/o Boron-Stainless Steel, Core II-B-5; Critical Water Height; 29.09"

Figure 10

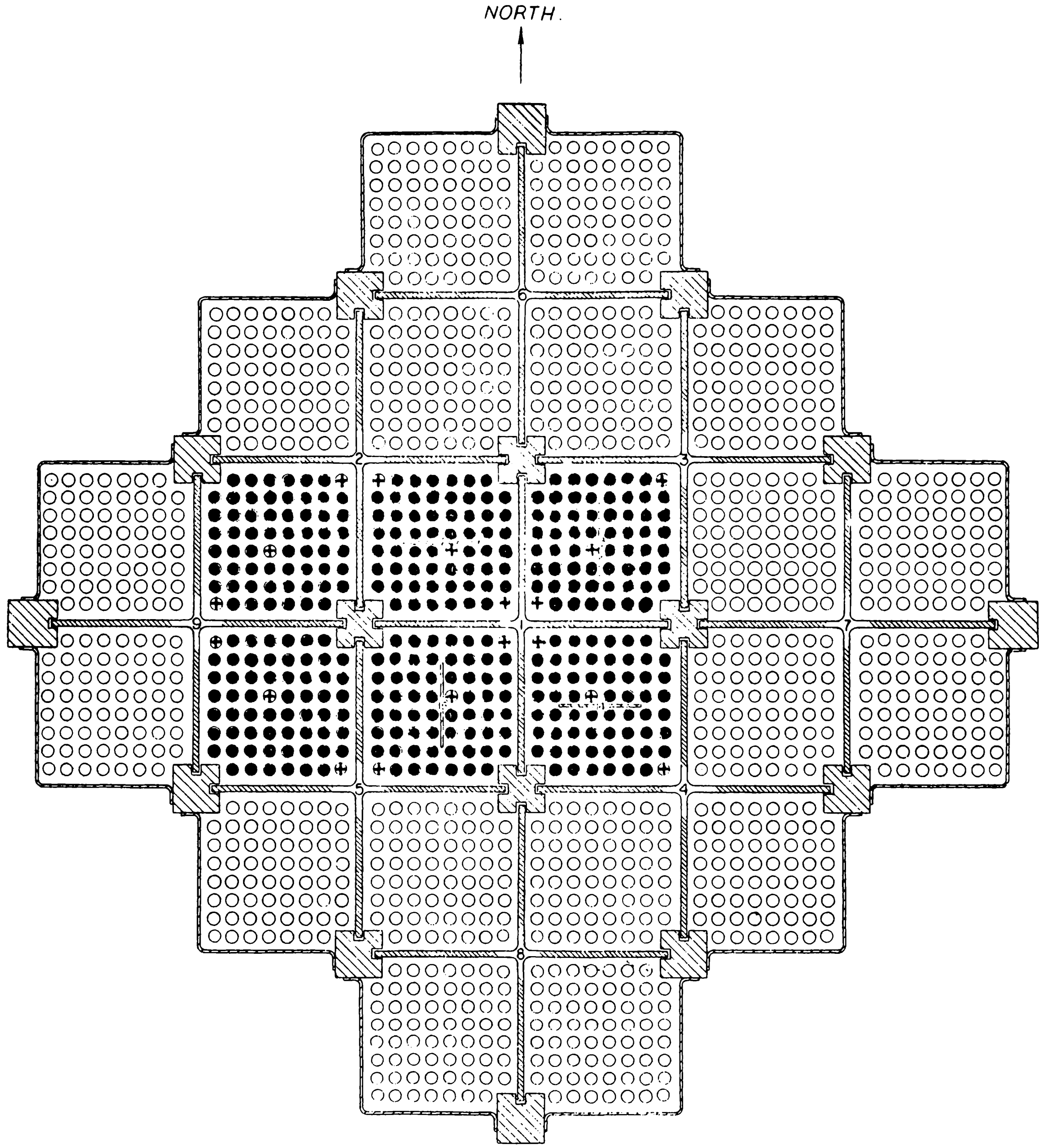


CORE II-B-7. SLAB CORE WITH 0.25 w/o BORON-STAINLESS STEEL. CONTROL RODS OUT.

● - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 11

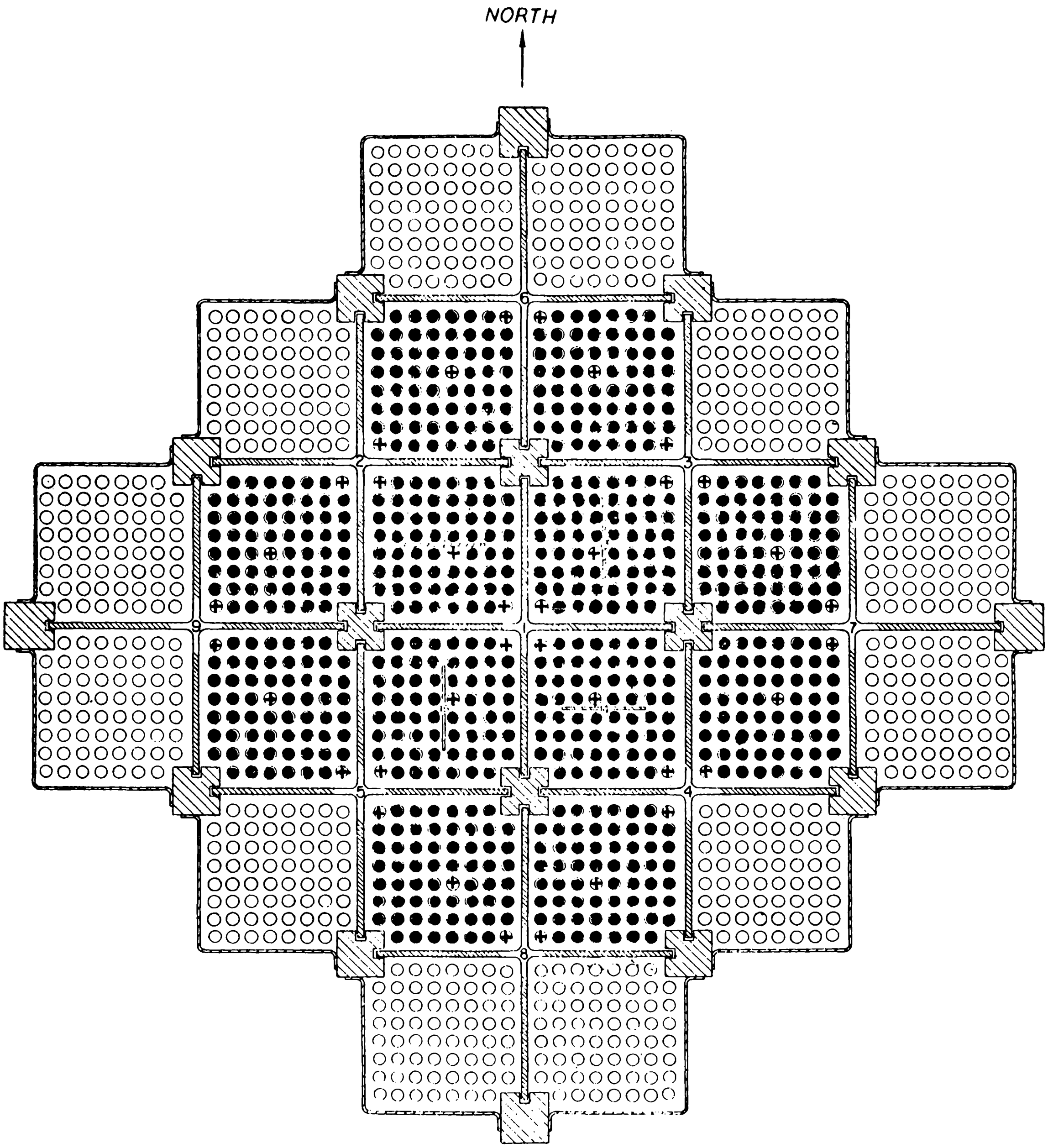


CORES II-B-8, II-B-9. SLAB CORES WITH 0.25 AND 0 w/o BORON-STAINLESS STEEL, CONTROL RODS OUT.

● - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel, Core II-B-8. Critical Water Height: 34.68"
0.00 w/o Boron-Stainless Steel, Core II-B-9

Figure 12

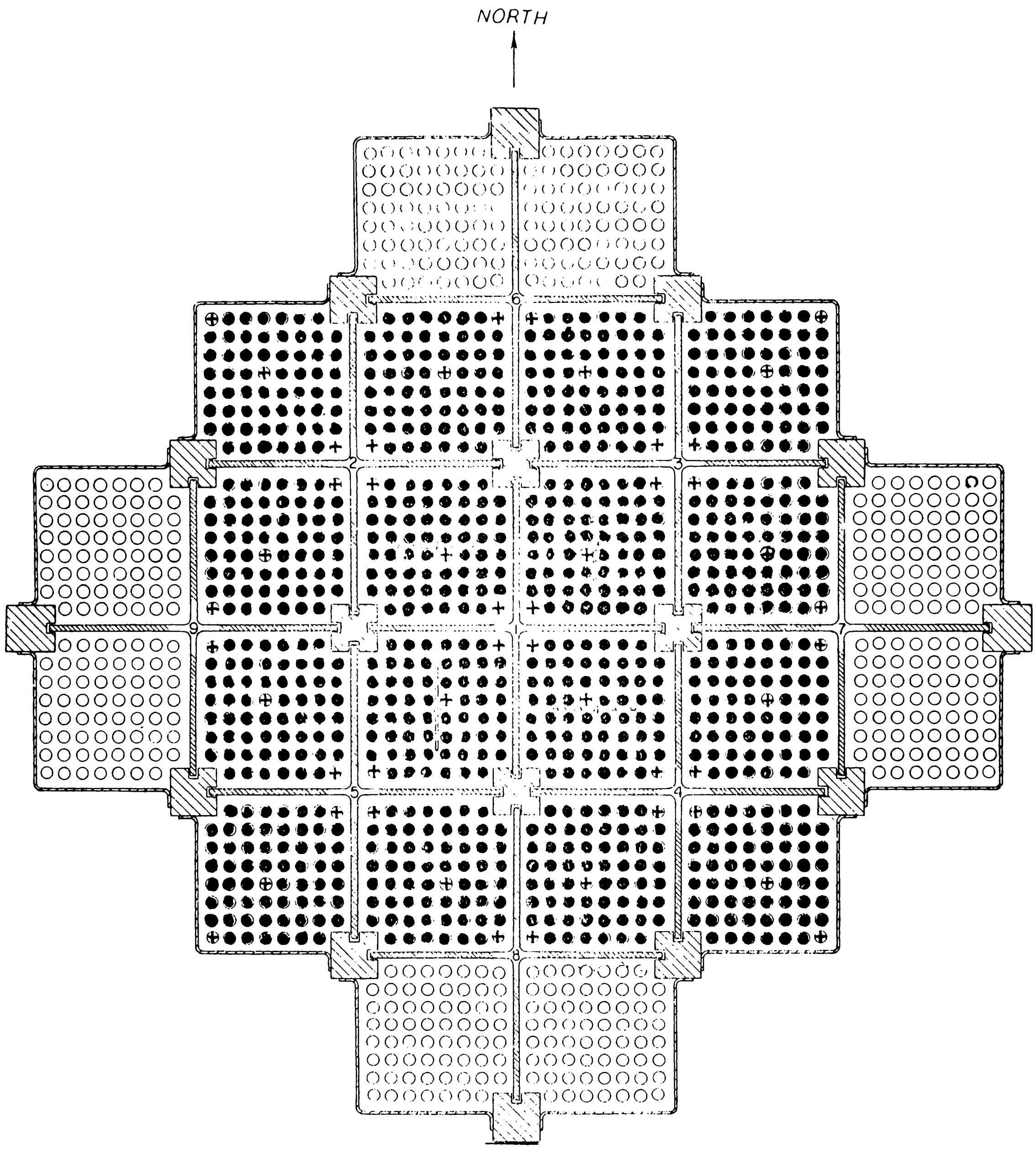


CORE II-C-1. LOADING TO REFERENCE DESIGN WITH 1.1 w/o BORON-STAINLESS STEEL. CRITICAL BANK POSITION: 14.50"

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel

Figure 13

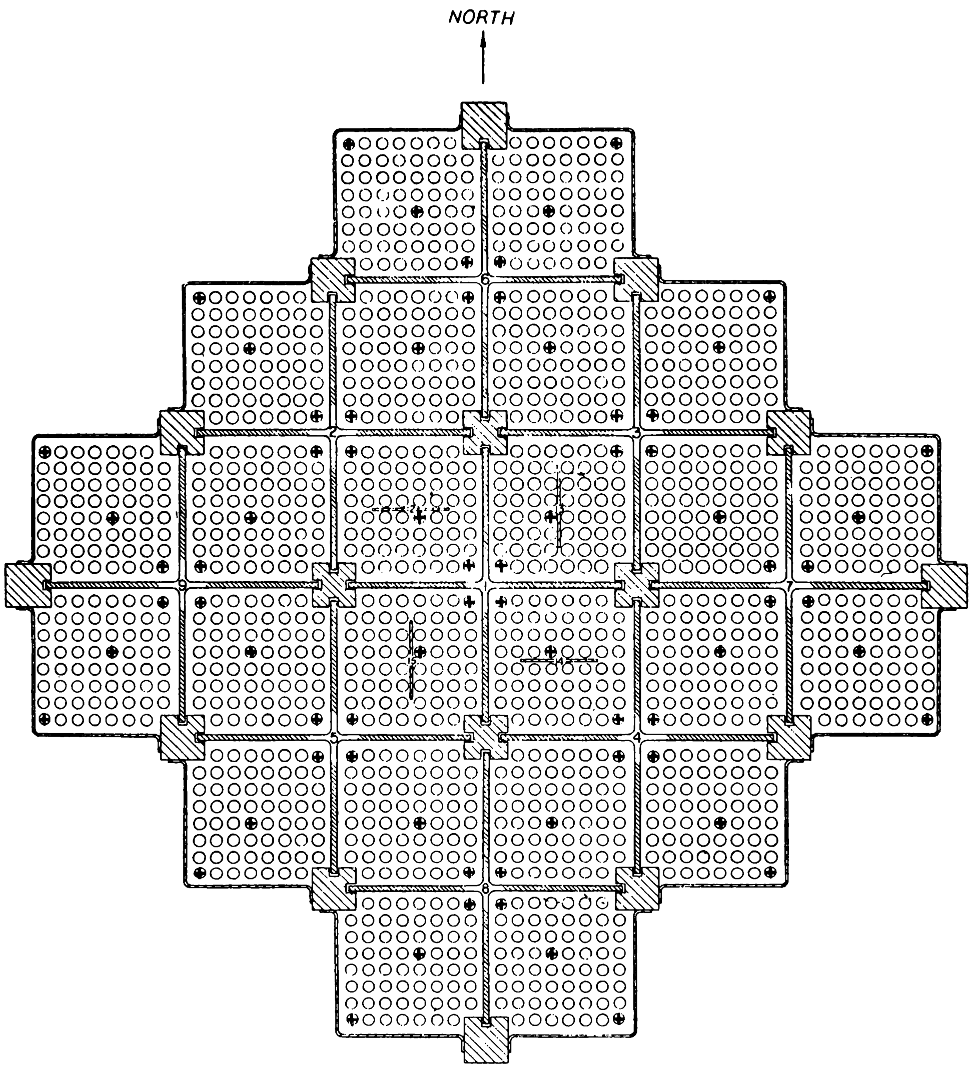


CORE II-C-2. LOADING TO REFERENCE DESIGN WITH 1.1 w/o BORON-STAINLESS STEEL. CRITICAL BANK POSITION: 11.97"

● - Fuel

⊕ - 1.1 w/o Boron-Stainless Steel

Figure 14

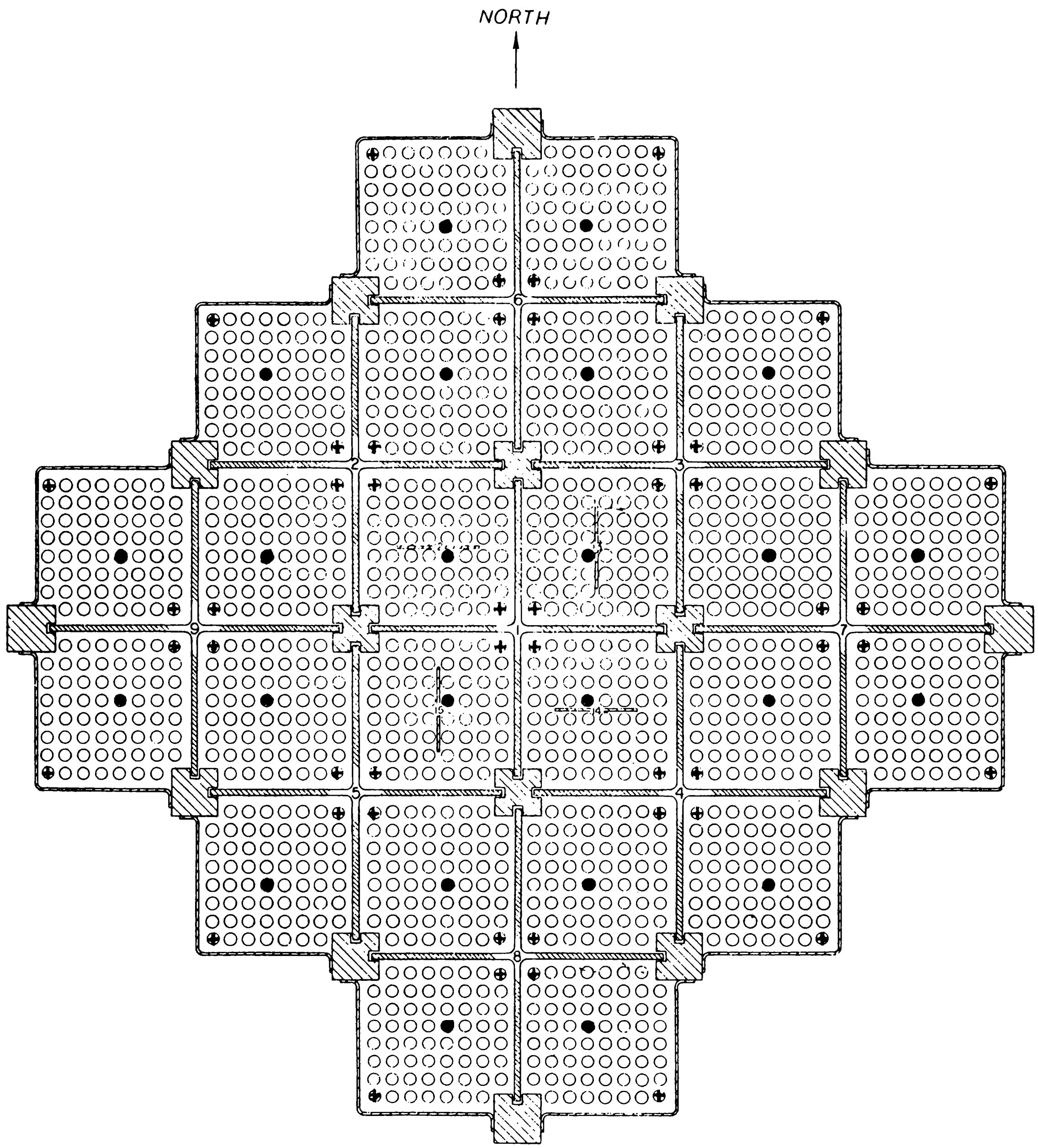


REFERENCE DESIGN WITH VARIOUS BORON CONCENTRATIONS

⊕ -
1.1 w/o Boron-Stainless Steel, Core II-C-3, III-A-1, Critical Bank Position: 10.16"
0.5 w/o Boron-Stainless Steel, Core III-A-2, Critical Bank Position: 9.56"
0.25 w/o Boron-Stainless Steel, Core III-A-3, Critical Bank Position: 9.08"
0.00 w/o Boron-Stainless Steel, Core III-A-6, Critical Bank Position: 8.10"

O - Fuel

Figure 15



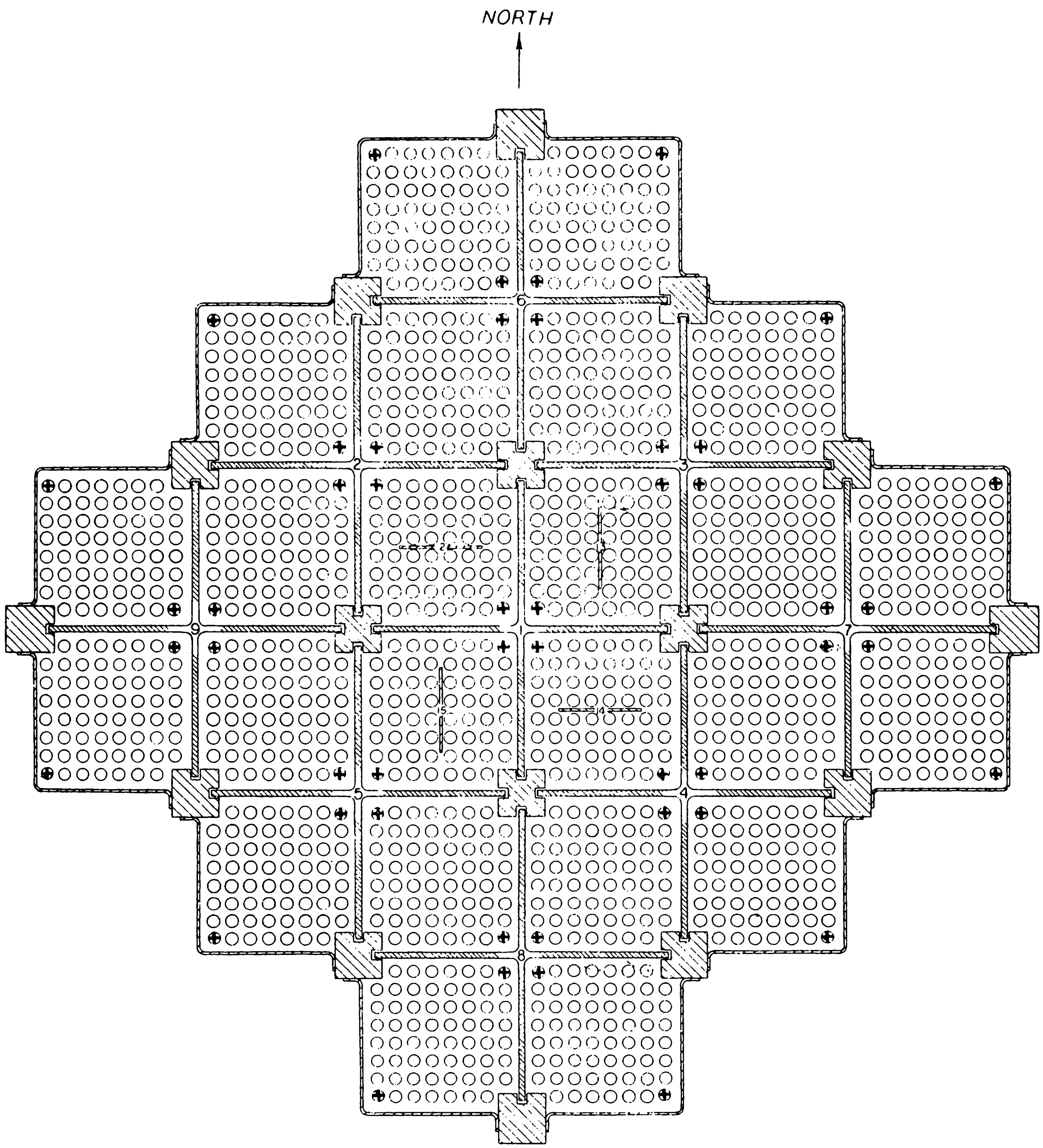
CORE III-A-4. BORON ADJUSTMENT. CRITICAL BANK HEIGHT: 8.67"

O - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

● - 0.0 w/o Boron-Stainless Steel

Figure 16

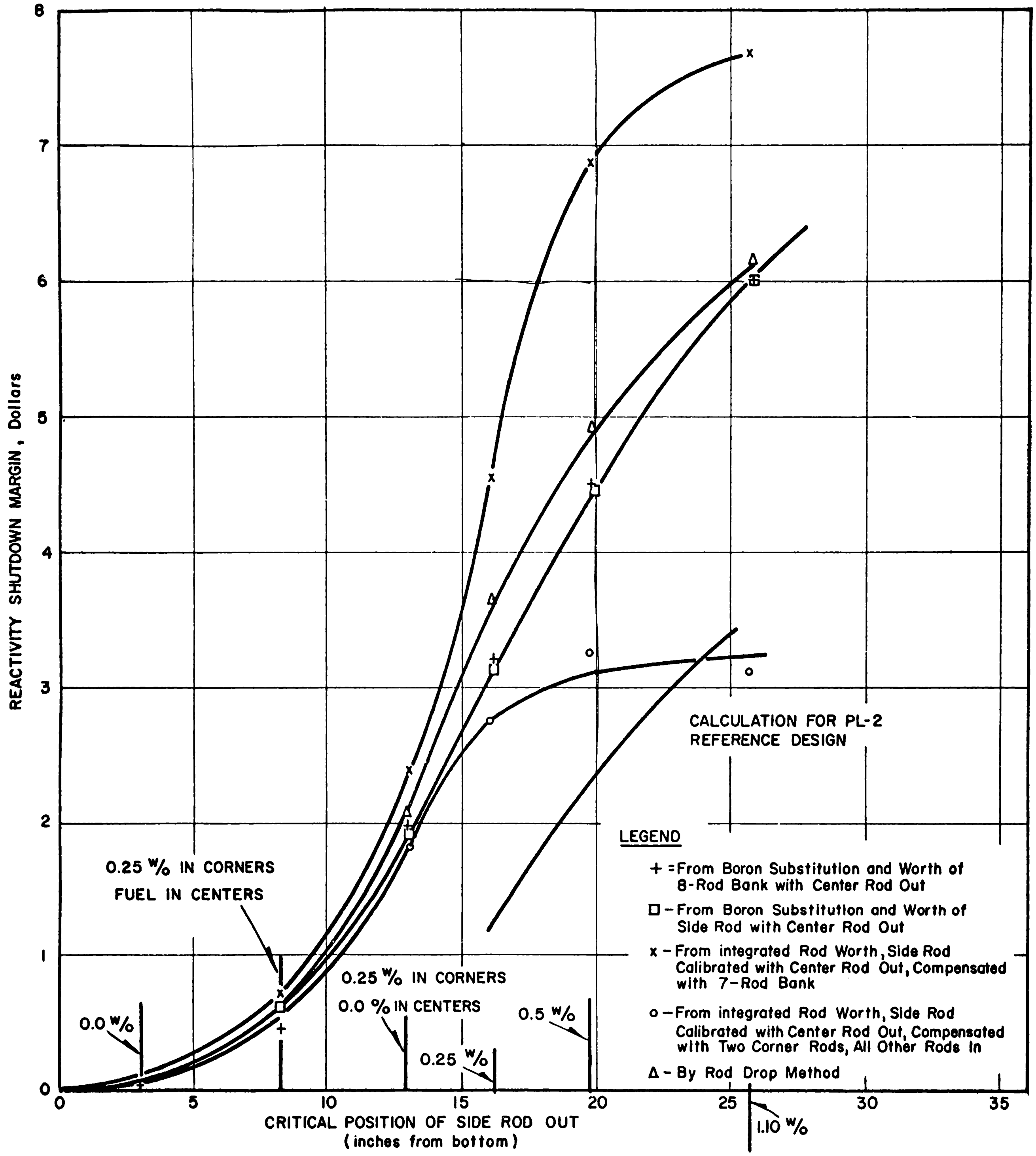


CORE III-A-7. BORON ADJUSTMENT. CRITICAL BANK HEIGHT: 8.26"

○ - Fuel

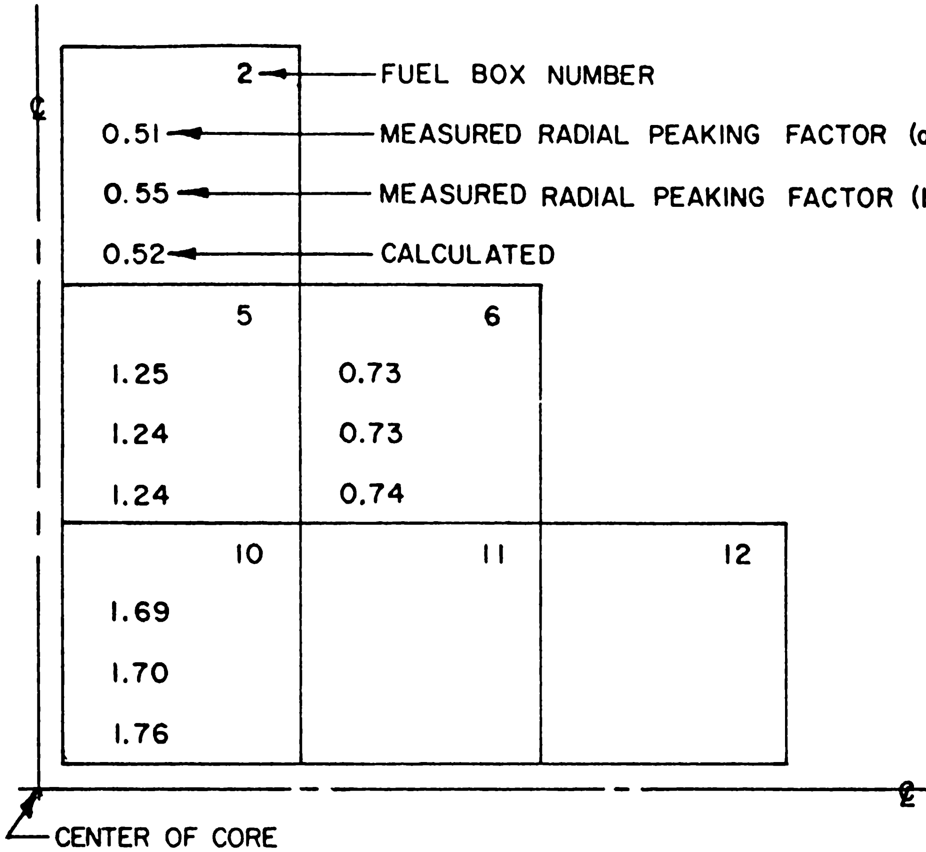
⊕ - 0.25 w/o Boron-Stainless Steel

Figure 17



SHUTDOWN MARGIN WITH CENTER ROD OUT IN COLD MOCK-UP FOR VARIOUS AMOUNTS OF BORON

Figure 18



(a) OBTAINED BY AVERAGING COUNTS AT AXIAL POWER PEAK

(b) OBTAINED BY AVERAGING INTEGRATED COUNTS OVER HEIGHT OF CORE

RADIAL POWER DISTRIBUTION AT AXIAL PEAK AND OVER HEIGHT OF CORE IN COLD MOCK-UP WITH 0.25 w/o BORON-STAINLESS STEEL CONTROL RODS BANKED AT 9.07 INCHES

Figure 19

STANCHION	0.96 0.96	1.07 1.07	1.01 1.09	0.95 1.07	0.97 1.02	0.92 0.97	BORON SS
1.06 1.00	0.90 0.90	0.92 0.92	0.92 0.92	0.88 0.90	0.85 0.87	0.84 0.85	
1.23 1.16	1.01 0.95	0.95 0.92	0.91 0.91	0.90 0.90	0.88 0.88		
1.24 1.22	0.98 0.98	0.97 0.93	0.93 0.91	0.90 0.91			
1.27 1.24	1.00 1.00	0.95 0.94	BORON SS				
1.22 1.23	1.02 0.98	0.94 0.95			0.87 0.92		
1.20 1.21	1.04 1.01						
BORON SS							STANCHION

SMEARED FUEL ELEMENT

℄

CENTER OF CORE

MEASURED — POWER DISTRIBUTION NORMALIZED TO AVERAGE FOR THE FUEL BOX

MEASURED
CALCULATED

PEAKING FACTORS

CALCULATED — AVERAGE SOURCE PER SMEARED FUEL REGION / AVG. SOURCE OVER ENTIRE FUEL BOX

LOCAL POWER DISTRIBUTION AT AXIAL POWER PEAK IN CENTRAL FUEL BOX NO. 10 OF MOCK-UP WITH 0.25 w/o BORON-STAINLESS STEEL POISON ELEMENTS WITH CONTROL RODS BANKED AT 9.07"

Figure 20