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CRITICAL EXPERIMENTS FOR PL-2 AND THEIR ANALYSIS

O. Gailar
R. S. Harding
R. W. Knapp

August 1962

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U. S. ATOMIC ENERGY COMMISSION

NUCLEAR
DIVISION

COMBUSTION ENGINEERING, INC.

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WINDSOR, CONNECTICUT

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I. INTRODUCTION

As part of the Army Boiling Water Reactor Program, an 8.5 MW(t), compact, air-transportable plant has been designed known as the PL-2 plant. It features a low enrichment UO_2 core, light water moderated, containing discrete boron elements for flux suppression and control. It is intended that the core attain a minimum full power life of three years and be capable of shutdown with any one control rod fully withdrawn. To support the design of the PL-2 core, a series of critical experiments was performed and comparisons made with theoretical predictions. Critical experiments started January 16, 1962, and initial criticality was achieved on January 17 in a minimum size core containing 248 fuel rods. By the time the experimental program was concluded on April 18, 1962, approximately 38 distinct fuel and poison combinations and configurations were investigated.

The fuel for the PL-2 consists of UO_2 ceramic pellets, enriched to 4.8 w/o U-235, with a density of 10.5 gm/cm^3 , and clad in stainless steel. The core contains 1416 of these fuel elements arranged in 24 groups, or subassemblies, of 59 elements each with water channels between subassemblies to accommodate cruciform control rods. A subassembly consists of an 8×8 array of fuel elements with two fuel elements at opposite corners replaced by steel stanchions which serve to hold the core together, to define the water channels, and to serve as guides for the control rod tips. The two fuel elements at the remaining two opposite corners - at the intersection of two water channels, are replaced by boron-stainless steel poison rods which serve as flux suppressors and provide shutdown margin. To augment the shutdown margin, a fifth fuel element on the diagonal between the two poison rods is replaced by a third poison rod. These positions for the poison elements will be called the "reference" positions. The core is controlled by nine cruciform control rods made of stainless steel clad Ag-Cd-In. For additional shutdown during critical experimentation with the mockup, four blade rods made of boron-steel could be inserted at the center of the four central subassemblies.

The experiments were carried out for two main reasons. The first was to verify the shutdown margin with the most important control rod out of the core, and if necessary to adjust this margin to be within 1-2% reactivity by suitable changes in the amount of poison contained in the core. The second reason was to verify the calculational methods used during the reactor design, and to supply experimental data against which various calculational schemes could be compared. The major uncertainties in the analytical method were the treatment of the discrete poison elements and the control rods. Small, clean cores were constructed to check these uncertainties systematically. Changes were made step-wise in the amount of

poison (boron) contained in the poison elements, and in the location of these elements. Then with the amount of poison and its location fixed, a control rod was completely inserted in the core and its effects alone on the critical size were measured.

The critical core is an extremely faithful mockup of the design core with the power reactor grade fuel elements used in the critical core. Some of the structural material (stainless steel) in the design core was mocked-up by chrome-plated iron in the critical core. This was the major difference between the mockup and the design and made the mockup about 0.5% more reactive than the design. Because of the accuracy of the mockup, the measured shutdown margin can be applied directly to the cold, beginning of life design core. Similarly, power distribution measurements and critical rod configurations can also be applied to the cold, clean design core.

Results of this work are reported in four main sections: The first is a description of the core; the second covers the experimental results; the third describes the analytical methods; and the fourth presents comparisons of experimental and analytical results.

II. SUMMARY

The more important results of this combined experimental-analysis program are summarized as follows:

- The critical experiments showed that the original specification of 1.0 w/o for the boron concentration could be reduced to 0.25 w/o without reducing the one-rod-out shutdown margin below 2-1/2% reactivity as measured by rod drop experiments. The resulting increase in reactivity lifetime is reported separately.⁽¹⁾
- Good agreement was obtained between calculated and measured eigenvalues for the small, clean cores which were analyzed. In cores with no control rods and containing all fuel, 0.0, 0.25, or 1.1 w/o boron-stainless steel, and with all 0.25 w/o boron-stainless steel and fuel elements surrounded by aluminum-water displacers, the calculated eigenvalues were 0.7 to 1.0% greater than the measured values. In a core with 0.25 w/o boron-stainless steel and with the center control rod fully inserted, the calculated eigenvalue was 1.0% larger than measured. In one case, a core composed entirely of fuel and with the center control rod fully inserted, the calculated eigenvalue was 0.33% Δk smaller than that measured. A summary of these calculated and measured eigenvalues is given in Table I.
- The calculated power distributions compared extremely well with those measured in the fuel assemblies, the difference being less than 6%. Larger differences, up to 14%, were found in atypical regions of the small cores where the analytical model should not be expected to apply, such as single rows of fuel elements with water channels on either side. Of particular interest is the fact that the agreement between measured and calculated power distributions adjacent to boron-stainless steel poison elements was in most cases better than $\pm 5\%$, indicating that the flux in the boron was probably being adequately calculated. Excellent agreement was also obtained between the measured axial power distribution for the cold mockup and that calculated by a three-dimensional synthesis of the core without iterations.
- Shutdown measured by the boron substitution method, where the worth of the boron was measured by calibrating both a single control rod and a bank of rods, was found to give consistent results which in turn agreed to within 0.5% Δk with shutdown measured

TABLE I

COMPARISON OF CALCULATED AND MEASURED EIGENVALUES

Core	Description w/o B-SS Position of B-SS		Size of Core and Notes	Measured Eigenvalue (k)	Calculated Eigenvalue (k)	Calculation Minus Measured (% $\Delta k/k$)
I-A-8	All Fuel	-	16 x 16 less 3 at each corner	1.0017	1.0091	+ 0.74
I-A-9(c)	All Fuel	-	22 x 22 plus 8 centered on each face, and center control rod in	1.0016	.9983	- .33
II-A-8(e)	0.0	Reference	16 x 16 plus 10 centered on each face	1.0043	1.0136	+ .93
II-A-9(d)	0.25	Reference	18 x 18 plus 6 centered on each face	1.0017	1.0082	+ .65
II-A-10(a)	0.25	Boron-Stainless Steel in 4 center fuel box corners exchanged east-west with fuel neighbors	18 x 18 plus 6 centered on each face	1.0050	1.0128	+ .78
II-A-7(c)	0.25	Reference	26 x 26 plus 2 centered on each face, center control rod in	1.0016	1.0119	+ 1.03
II-A-11(c)	0.25	Reference	22 x 22 plus 16 centered on each face; Al displacers around fuel and poison	1.0007	1.0100	+ .93
II-A-3	0.25	Reference	20 x 20 plus 4 centered on each face	1.0059	1.0161	+ 1.02

by the rod drop technique. The rod drop measurements with 1/4 w/o boron gave a shutdown of 2.52% with the central control rod withdrawn. Correcting for the small difference between the mockup and the reference core, the shutdown margin for the PL-2 was 3% $\Delta k/k$. Shutdown measurements obtained by moving a calibrated control rod from all in to its critical position and maintaining criticality by the compensating motion of another rod or rods, were found to give widely differing results depending on the combination of rods used.

- It is recommended that additional analyses be made to further check the validity of the calculational method. The partially rodged core with water displacers partially inserted (Core IV-D-1) should be synthesized to obtain detailed axial power distributions. The almost consistent over-estimate of the eigenvalue from 0.7 to 1.3% indicates that further refinements of the calculations may well be in order. Areas of immediate interest here are the resonance escape probability and the thermal neutron spectrum, both of which together might reduce the calculated eigenvalues by up to 0.4% $\Delta k/k$. Further investigations should be carried out in order to find the cause of the extra rod worth in the core composed entirely of fuel.
- The results of the program suggest several further improvements in design. Measurements in a boron-stainless steel zoned core where the boron-stainless steel poison rods were removed from the outer 12 peripheral subassemblies and replaced with fuel elements, show that the center rod remains the strongest, that the center-rod-stuck-out shutdown margin is reduced very little (-0.28% Δk) from the core containing boron-stainless steel in all subassemblies, and that 1.09% reactivity is gained at beginning of life by removing this boron-stainless steel. This reactivity increase could be used for extending the lifetime of the core. A further increase in lifetime could be obtained by using some material other than stainless steel in the boron-stainless steel poison rods, since when all of the boron is burned out the stainless remains and acts as a poison. For example, boron-zirconium might be investigated.

III. DESCRIPTION OF CORE

A. General

The full size mockup was a low enriched UO_2 core, water moderated, containing 24 fuel assemblies. Each assembly contained 59 fuel rods and three boron-steel rods. Control was provided by nine cruciform rods. The active core was 38.3 inches high and had an effective diameter of 34.9 inches. A complete description of the core is given in CEND-144(2), while the material presented here is of a short descriptive nature.

B. Fuel Elements

The fuel pellets were 4.8 w/o enriched uranium dioxide, $0.420 \pm .0005$ inch in diameter and had a density of 10.5 gm/cm^3 . Fuel pellets (approximately 50) were loaded into Type 348 stainless steel clad tubing of $0.426 \pm .0005$ inch I. D., with a wall thickness of $0.020 \pm .001$ inch. The tubing was 41.035 inches long; the fuel (active) length was $38.30 \pm .15$ inches long. Stainless steel top and bottom plugs were welded to the clad tubing. An expansion spring was placed between the fuel and the top plug and an Al_2O_3 insulator was placed between the fuel and the bottom plug. A chemical analysis of the clad tubing is given in Appendix A.

Assembled fuel elements were covered with a thin, protective layer of pressure-sensitive, hydrocarbon plastic tape, 0.009 inch thick. Each element was rolled into a strip of this tape about 1-1/4 inches wide and 40 inches long. The tape was applied in this manner rather than being spiraled onto the element so that there would be no overlapping and no ridges formed which might have interfered with the free movement of the fuel elements or with certain of the control (blade) rods. A chemical analysis of this tape is given in Appendix A, and a drawing of a completed fuel element is given in Figure 1.

The water used in the critical assemblies was demineralized; and although the experiments were performed at room temperature, the chloride ion content was kept below 0.1 ppm to avoid contaminating the fuel elements with chloride.

C. Poison Elements

Poison elements were made of boron-stainless steel rods, 0.420 inch in diameter and jacketed in the same stainless steel tubing as was used for the fuel cladding. Four boron concentrations were used and were in weight

percent: 1.10, 0.50, 0.25, and 0.00 (stainless steel rods). The bottom plugs had the same shape as those of the fuel elements, allowing complete interchangeability of fuel and poison. The poison elements were color coded; each different concentration was of a different length, the shortest of which was longer than a fuel element, and the top of all poison elements was of a completely different shape than the top of a fuel element. The color coding, different lengths, and tops of the poison elements guarded against the inadvertent interchange of fuel and poison. A drawing of a poison element is included in Figure 1, and the chemical analysis of the four types of poison materials is given in Appendix A.

D. Aluminum Displacers

A set of experiments was carried out in which approximately 20% of the water in the core was replaced by aluminum-water displacers. These displacers were hollow tubes* which fit concentrically around fuel and poison elements. The bottom support grid had recesses cut into it to accept and position these displacers. Thin slots were cut into the bottom of each displacer to insure that the gap between fuel (or poison) elements and the displacers became flooded with water.

E. Grid Tiles and Stanchions

Each fuel assembly contained a top and bottom grid tile for positioning the fuel and poison rods; the bottom grid in addition supported the weight of the rods. These grids were square, 5.9 inches on a side, containing the holes and cut-outs required to accept the core elements. The top grid tiles of the four central assemblies were made of stainless steel and had slits to accommodate the four extra experimental blade control rods. All the remaining grid tiles were of aluminum.

The bottom tiles were bolted directly to an aluminum base plate; the top tiles were supported and positioned by heavy vertical nickel-plated carbon-steel stanchions which were attached rigidly to the base plate. The spaces between tiles, as defined by the stanchions, served as water channels in which cruciform control rods could be moved. These control rods were guided by slots machined in the stanchions.

F. Control Rods

The core contained up to nine cruciform control rods. Each of these rods was made of Ag-Cd-In alloy (80% Ag, 15% In, 5% Cd) contained in a stainless-steel picture frame and clad with stainless steel. The active

* 0.625" O. D., 0.495" I. D.

region was 0.175 inch thick, had a span of 10.578 inches, and was 40.125 inches long. To provide shutdown for more reactive configurations than in the design core, four boron-steel blade rods were added as described above.

G. Fuel Assembly

Each grid tile (which defined a fuel subassembly) could accept 62 fuel or poison rods. The design core calls for 59 fuel and three poison elements; two poison elements were placed in opposite corners next to control rod channels (two per subassembly); and a third was placed in a position along the diagonal joining the two corner poison elements. There are eight positions along this diagonal; the third poison element was placed in the fourth position counting from the center of the core. Poison elements in the positions described above will be known as being in their "reference" positions.

Figure 2 is a cross section of the core at mid-plane, showing the position of fuel subassemblies, poison elements, control rods, and stanchions. Figure 3 is a vertical section through the reactor vessel showing the relative positions of the core, control rods, and support structure. Figure 4 is a perspective of a representative section of the core showing details of the grid-tile construction, placement of fuel and poison elements, control rods, displacers, and stanchions. Volume fractions are given in Appendix B, and homogenized number densities for the core are given in Appendix C.

IV. EXPERIMENTAL RESULTS

A. Description of Experiments

The experimental program can be considered to have been conducted in two major phases. The first phase was the construction of a number of small, clean cores in both square and slab geometry, with low excess reactivity, amenable to simple analysis. In these cores, the fuel and boron-stainless steel elements were interchanged and also the concentration of the boron in the boron-stainless steel was varied. The computing effort for the square cores in particular was minimized by virtue of their symmetry properties. The slab cores permitted experimental determination of the worth of poisons in their typical fuel assembly positions, since in these cores the fuel and poison elements tended to be loaded in full fuel assemblies. The second phase covered the measurements in the full size core which included the determination and adjustment of shutdown margin and measurements of power distribution.

Unless otherwise noted, the blade rods were out of the core and the boron-stainless steel poison elements, if present, were in the "reference" positions as described in Section III. The power distributions which were measured are reported in Section VI.

B. Methods Used to Evaluate Reactivity Changes and Worths of Materials in the Core

1. Excess Reactivity

The excess reactivity is here defined as the reactivity of the core with the control rods at the top of the active fuel and the water well above the core - eight to ten inches above the top of the fuel. For cores with low excess reactivity; i.e., critical with control rods near the top of the core, the excess was evaluated by calibrating a rod or group of symmetric rods from their critical position to the top of the fuel, and integrating their worth over this interval. For these cores, the excess reactivity did not exceed 1/2%, taking β_{eff} as 0.007. In a few cases for cores with very low excess reactivities, the rods could be pulled to the top of the fuel and the resulting period measured.

2. Changes in Reactivity

Reactivity changes from core to core due, for example, to the addition of small amounts of fuel were evaluated 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 critical partial water height was interpreted in the same manner as were the partially inserted control rods. Reactivity changes between two cores were calculated by multiplying the change in the critical water height by the average of the differential worth of water measured at the critical heights in the two cores.

C. Small, Clean Cores

1. Position of Components of the Core

Figure 5 is a drawing of the core showing the positions of fuel subassemblies and control rods and the numbering scheme used to define the various subassemblies, fuel and poison elements, and control rods.

2. Square Cores Containing No Boron Poison Elements (All Fuel)

The first critical core assembled, Core I-A-7, with the center four fuel subassemblies (fuel boxes) filled with fuel rods (a 16 x 16 array), had an excess of 70¢. Three fuel rods were removed from each corner of the core to form Core I-A-8, Figure 6, which had an excess of 24¢. To obtain Core I-A-9(c), Figure 7, the center control rod was fully inserted into Core I-A-8, and the core was built up to a 22 x 22 array of fuel elements with eight extra elements centered on each face. This core had an excess of 23¢. Reactivity calculations for Cores I-A-8 and I-A-9(c) and the power distributions measured in Core I-A-8 are reported in Section VI. Criticality data for Cores I-A-7, I-A-8, and I-A-9(c) are given in Table II.

3. Square Cores With 0.0 w/o Boron-Stainless Steel

Core II-A-8(b) was an 18 x 18 array of fuel and poison elements with an excess of 92¢. In Core II-A-8(d), the loading was reduced to a 16 x 16 array with eight extra fuel rods centered on each face. This core had an excess of 4¢. In order to provide sufficient excess so that the power level for a power distribution measurement could be reached in a short

time, Core II-A-8(e) was built. This was a 16 x 16 array of fuel and poison elements with ten extra fuel elements centered on each face and had an excess of 61¢. The core is shown in Figure 8. The power distribution measured in Core II-A-8(e) is reported in Section VI, and criticality data for Cores II-A-8(b), (d), and (e) are given in Table III.

4. Square Cores With 0.25 w/o Boron-Stainless Steel

Core II-A-9(b), an 18 x 18 array of fuel and poison elements with 12 extra fuel elements centered on each face, had an excess of \$1.20. Core II-A-9(c) was the same core with only eight extra fuel elements centered on each face, reducing the excess to 64¢. Two fuel elements were further removed from each face to form II-A-9(d), an 18 x 18 array with six extra fuel rods centered on each face. This core had an excess of 25¢, and is shown in Figure 9. The power distribution measured in this core is given in Section VI.

In order to check the dependence of the calculational methods upon the position of the poison, the eight 1/4 w/o boron-stainless steel poison elements in the corners of the four central fuel boxes in Core II-A-9(d) were exchanged with their neighboring fuel elements in the east-west direction, forming Core II-A-10(a). This core had an excess of 71¢ and is shown in Figure 10. The power distribution measured in this core is given in Section VI.

To check the calculational method of predicting rod worths, the center rod was fully inserted into Core II-A-9(e), and the core was built up to a 26 x 26 array with two extra fuel elements centered on each face, forming Core II-A-7(c) with a 23¢ excess. This core is shown in Figure 11. Criticality data for cores containing 1/4 w/o boron-stainless steel are given in Table IV.

In order to obtain an experimental value for the sign of the water density coefficient of reactivity, aluminum-water displacers were placed concentrically around fuel and poison elements which reduced the effective water density within a fuel or poison cell or fuel box by 31.3%. Clean core II-A-11(e), a 22 x 22 array with 16 extra fuel elements centered on each face and with an excess of 10¢, was assembled in this manner. This core is shown in Figure 12, and criticality data are given in Table IV.

5. Square Cores With 1.1 w/o Boron-Stainless Steel

Core II-A-3, a 20 x 20 array of fuel and poison elements with four extra fuel elements centered on each face, had an excess reactivity

of 84¢ and is shown in Figure 13. This excess was reduced to 51¢ in Core II-A-4 which was also a 20 x 20 array but with only two extra fuel elements centered on each face.

In order to obtain an experimental estimate of the worth of the 1.1 w/o boron-stainless steel, the four poison elements at the center of Core II-A-4 were removed and replaced with fuel, forming Core II-A-5. This change was worth \$6.00. The four poison elements were put back in place and the four poison elements located in the centers of the four fully filled fuel boxes were removed and replaced with fuel, forming Core II-A-6. The worth of this change relative to Core II-A-4 (with three boron-stainless steel elements in each fully filled fuel box) was about \$3.00. Criticality data for cores with 1.1 w/o boron-stainless steel are given in Table V.

6. Small Slab Cores With Varying Boron-Stainless Steel Loadings and Concentrations

A series of small unrodded slab cores was assembled. 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. The criticality data are given in Table VI.

Core II-B-4, shown in Figure 14, contained boron-stainless rods of 1.1 w/o boron and was 3-1/2 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, also shown in Figure 14, 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 15, was 3-1/4 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 16. For Core II-B-9, also shown in Figure 16, the 0.25 w/o boron-stainless steel rods in Core II-B-8 were replaced with plain stainless steel rods containing no boron.

D. Estimate of Reactivity Worths of Fuel and Boron in Square and Slab Cores

The method described earlier for obtaining reactivity changes from changes in critical control rod positions and water heights was used to estimate the worth of fuel and poison in the various square and slab cores. These worths are summarized in Table VII.

E. 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 17, 18, and 19, and criticality data are presented in Table VIII. Core II-C-3(a) was the first fully loaded core, and differed from the reference design in two minor respects: the stainless steel shroud surrounding the core was removed, and 27 of the 72 stainless steel jackets that contained the boron-stainless steel rods were left out since they were not available; however, they and the shroud were in place for all subsequent measurements.

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

a. Description of Boron Variation

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 surrounded 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 19, 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 19, 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 10. In Core III-A-4, Figure 20, 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, Figure 19, the 0.25 w/o boron-stainless steel in all positions in the core was replaced by 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 and is shown in Figure 21. To form an even more reactive core, 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 22.

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 IX. Table X

contains similar data measured in cores which had various combinations of boron-stainless steel and fuel elements in the design positions.

b. Shutdown Measurements

The reactivity shutdown margin of the PL-2 criticals, with all control rods except one fully inserted, was measured by three techniques: control rod calibration, boron substitution, and rod drop. Each of these techniques has its peculiar disadvantages which are discussed below.

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

In the second configuration the side rod, #2, was 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 was then integrated from fully in to its critical position when rods #7 and #8 were in. The shutdown was this integrated worth. Figure 23 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 are 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 is 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 with all but the center control rod 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 concentrations 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. The disadvantages of this method are twofold: (1) A number of cores were built up by the addition of boron in discrete steps, and the differential rod worth was not known at rod or bank positions other than those obtained for these cores; and (2) the differential rod worth was affected by the boron content possibly being different than the worth in the actual core. 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 23.

The shutdown margin measured by the rod drop and rod calibration methods is given in Table XI and plotted in Figure 23. The uncertainties in the rod drop method arise from a possible change in flux distribution during the rod drop, and an accompanying change in the effective sensitivity of the neutron detectors.

The shutdown curves in Figure 23 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 the 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. They show that the shutdown margin decreases from \$6.10 to \$0.60 as the boron concentration is reduced from 1.1 to 0.0 w/o.

Core III-A-3, with 0.25 w/o boron-stainless steel rods in the reference design positions, contained 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 with the center rod out is shut 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.

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

a. Applicability to Design Core

The critical assembly is an extremely faithful mockup 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 stainless steel ferrules (spacers) between the fuel rods. It is estimated that the critical mockup is about one-half percent more reactive than the design core. This reactivity difference makes the nine-rod bank position in the mockup 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 mockup. In view of this close similarity between the two cores, the extrapolation from one to the other is small and rather simple.

b. Reactivity Measurements

Table XII 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. The motion of these eight rods from 9.07 inches to 11.21 inches, which compensates for the insertion of the center rod from 9.07 inches to fully in, is worth \$4.17 (Table XIII) and, excluding coupling effects, the worth of the eight rods from 9.07 inches to fully out is \$22.64 (Table XIII). The total worth of these eight rods from 11.21 inches to fully out is about \$18.47, so that with the center rod stuck in there would be \$18.47 excess reactivity available. From CEND-135⁽⁴⁾, the total reactivity with all rods out needed for temperature and vapor defects and for fission product poisoning and fuel depletion is about \$21.00. The temperature and vapor defects increase when the control rods are inserted so that with the center rod in somewhat more than \$21.00 would be needed. The \$18.47 excess would probably suffice to allow full power operation for a short time or low power operation for a longer time. The data also show that the core can be shut down with any rod stuck out of the core. Table XIII 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.

c. Void Coefficient of Reactivity

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 inch O.D. and 0.065 inch wall, was placed concentrically around all fuel and poison elements in the center four fuel boxes forming Core IV-B-1, Figure 24. 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. Criticality data for this core are compared to those in other cores containing displacers and to the reference core with no displacers in Table XIV.

d. Power Distributions

(1) Cold Mockup - The power distribution in the cold mockup was measured to test the calculational methods. The rod bank position and axial power distribution were predicted by a zero'th order synthesis (see Section V.F.). The calculated rod bank was one inch lower than the measured position corresponding to a reactivity difference of about $1.8\% \Delta k/k$. The calculated axial power distribution agreed with the measured axial distribution; the predicted axial peak was within one-half inch and its magnitude was within 1%. The bank position, and the measured and calculated axial and radial power distributions are given in Section VI.

(2) Simulated Hot Core - The density of the reactor inlet water at hot operating PL-2 design conditions is 20% less than the density of cold water. Furthermore, calculations for the axial steam or void distribution at full power show that the vapor fraction in the moderator, averaged radially over the core, increases from zero at the bottom of the fuel to 16%, its average axial value, at about 14 inches, from which height it increases more slowly to essentially a constant value of 21% at about 30 inches. Thus, the voids appear and reach more than two-thirds of their maximum value in a region below the rod bank position of 20.6 inches. The density of the hot boiling water averaged over the entire core is 33% less than that of pure cold water.

Because it is practically impossible to simulate a hot, operating core with its xenon content, hardened microscopic cross sections, and vapor and water density distributions, a test core was built in which the overall axial water density (including voids) of the hot operating core was approximated in a simple fashion. The average water density was decreased by placing uniform aluminum-water displacers around all fuel and poison elements starting seven inches above the bottom of the fuel and extending to over the top of the fuel. The resulting rod-bank position was 10.86 inches. In this way, it was possible to introduce the complexity of at least two water densities in the unrodded region of the core. The effective water density was 1.00 below the displacers, and was reduced by 31.3% in fuel assemblies, or 26% over the entire core including water channels, in the axial regions including the displacers. Criticality data for this core, IV-D-1, are given in Table XIV, and the measured power distribution is given in Section VI.

Gas bubbles previously encountered in Core IV-C-1, where the water displacers had been fully inserted and were resting on the bottom grid tiles, were not observed in Core IV-D-1. It is assumed that the chief cause was electrolytic corrosion caused by aluminum-stainless steel junctions at the bottom of the core (clad tubes and grid tiles), and that the displacers trapped the gas and confined it in the small volume between fuel elements and displacers. In Core IV-D-1, with the displacers seven inches from the bottom of the fuel, the displacers passing through the top central four stainless steel grid tiles were insulated from these tiles by a layer of tape, and no bubbles were seen. Criticality data for cores containing displacers are given in Table XIV.

e. Reactivity Dependence on Boron Location

The boron-stainless steel in the corner of each fuel box was exchanged with its nearest fuel neighbor along the diagonal, forming Core IV-A-1, Figure 25. The worth of this change relative to Core III-A-3 was +83¢. A second exchange further in along the diagonal, forming Core IV-A-2, Figure 26, was worth about +6¢, relative to Core IV-A-1. Criticality data for Cores IV-A-1 and IV-A-2 are given in Table XV.

f. 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 together - all fuel boxes next to the reflector. Table XVI gives a summary of the criticality data measured in this sequence, and includes for comparison similar data from the reference core. Figures 27-31 are drawings of these cores.

In Table XVII, the shutdown margin with the center rod out and the reactivity changes relative to the design core are given. The shutdown margin was measured by the rod-drop technique, and by the calibration of a side rod compensated with two opposite corner rods, with all other rods in (the method, as discussed previously, which yields the smallest shutdown value). 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 \$0.40 (from rod calibration), or \$0.60 (from rod-drop measurements). The reactivity with banked rods, however, has increased by \$1.52, as measured by the change in the 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 XVIII. In the table, 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 was 1.57 inches, 2.44 inches, and 3.94 inches respectively, indicating the order of the relative worth of the rods when withdrawn from a bank. In the last three configurations, it is apparent that the core can be made subcritical with any one control rod completely withdrawn. Under these conditions, the center rod is still the more valuable; however, the corner rod appears to be somewhat more valuable than a side rod.

V. ANALYSIS

A. Description of Methods

Two neutron energy groups were used, one fast and one thermal. Fuel boxes were divided into square fuel and boron-stainless steel cells corresponding to the individual fuel and poison elements with their adjoining water; and the materials within a cell were then homogenized. Self-shielding or disadvantage factors were calculated and applied where necessary. Explicit X-Y problems were run in which the structure (stanchions) and shroud were represented explicitly. Individual fuel cells were homogenized over the fuel regions (fuel boxes) and homogenized boron-stainless steel cells were represented explicitly. The axial leakage was applied by input axial bucklings equal to the axial geometric buckling of the core being analyzed.

B. Geometry

Figure 32 presents a cross section of a representative part of the active core, and the equivalent geometry used in the analysis. The figure indicates a fuel (or boron-stainless steel) cell, with the calculational boundary between cells running mid-way between fuel elements. In order to conserve this picture (constant size fuel and poison cells), part of the water channels between fuel boxes had to be included in the fuel box. The offset corner poison elements were treated as though they were not offset but were on the same lattice pitch as the remainder of fuel and poison elements. The boundaries of the stainless steel stanchions were adjusted so that in the analytical model that part of a stanchion protruding into a fuel box occupied the full area of a fuel cell. By further adjustment to the boundary, the volumes of the stanchions were conserved and remained the same as those in the actual core.

C. Fast Cross Sections

Fast macroscopic cross sections were obtained by use of the MUFT code. The fuel and boron cells, water channels, stanchions, and control rods were treated separately; homogenization over the fuel and poison cells was based on a simple area weighting.

There are two input quantities for the MUFT code which are of particular importance: They are the L factor which changes the homogeneous resonance integral assumed by MUFT to the heterogeneous resonance self-shielded value; and the MUFT buckling, which controls the fast leakage and

neutron spectra. The L factor can be calculated if the resonance escape probability for resonance absorbers in the core is known.

1. Resonance Escape Probability

The resonance escape probability for the resolved resonances in U-238 only was calculated using the Bell method for determining average effective rod diameters, and the QUERY code for converting the effective diameter and fuel density to a $(\sigma_a)_{\text{eff}}$. The geometry of a fuel cell cannot be explicitly introduced in the Bell method, but the water-to-metal and water-to-fuel ratios are conserved. To check these calculations, an REP calculation (Monte Carlo) was carried out in which the fuel element was represented explicitly within a square water region. The results of these two types of calculations were the following:

$$P_r^{28} \text{ (Bell-QUERY)} = 0.914$$

$$P_r^{28} \text{ (REP)} = .912$$

The Bell-QUERY value which was first calculated was used in the analysis. The comparison with the REP calculation shows that the difference is small, and that if the REP value were used the reactivity would be decreased by no more than 0.2% $\Delta k/k$.

2. MUFT Buckling

For a given core composition, the group constants (and hence the eigenvalue) calculated by the MUFT code depend in general upon both the number of lethargy groups used and the input "MUFT Buckling."⁽³⁾ For an unrodded core, the particular case in which the eigenvalue is independent of the number of lethargy groups occurs when the MUFT buckling is equal to the geometric buckling and the core is critical. Under these conditions, the MUFT and geometric bucklings are equal to the materials buckling. If the size of the core is increased and the resulting excess reactivity is controlled by inserting the control rods to the critical bank position, it appears appropriate to consider the fast leakage from the unrodded region as unchanged and, therefore, to use the same input MUFT buckling as in the smaller unrodded core. In the following calculations the MUFT buckling was taken to be equal to the materials buckling regardless of core size or position of control rods. The materials buckling, in turn, was taken to be the geometric buckling of the small clean unrodded core with the same composition. A table of the fast macroscopic cross sections used in the analyses of the various cores is given in Appendix D.

D. Thermal Group Cross Sections

Microscopic thermal cross sections were obtained by averaging over a Maxwellian spectrum at room temperature. Self-shielding or disadvantage factors for materials within fuel or poison cells were obtained by a P_3 approximation in cylindrical geometry to the monoenergetic transport equation over these cells using the CEPTR code. The thermal macroscopic cross sections used in the analysis of the various cores are given in Appendix D.

Although spectral hardening and the spatial variation of the thermal neutron spectrum are apparently neglected in this treatment, there is evidence that for these cores the resulting error in eigenvalue is no greater than 0.3%. A set of hardened microscopic cross sections for a fuel cell was obtained using the SOFOCATE code which averages cross sections over a Wigner-Wilkins hardened thermal spectrum. Since the hardening depends upon the effective number of absorbing atoms, it is necessary to self-shield these absorbers. This was done in essentially an iterative manner by obtaining self-shielding factors using the initially hardened cross sections, self-shielding the absorbers and obtaining new hardened cross sections and self-shielding factors. Also, the COGENT code, a 54-group cylindrical diffusion code for thermal neutrons which allows up and down scattering of neutron energies, was used to calculate average, one-group, spatially dependent thermal cross sections within a fuel cell which were then used in the CEPTR code to obtain self-shielding factors. A comparison of the homogenized self-shielded values of ηf in a fuel cell is given in the following table:

Values of ηf for Various Thermal Treatments

<u>Method</u>	<u>ηf</u>
Maxwell-CEPTR	1.6357
SOFOCATE-CEPTR (0 th iteration)	1.6464
SOFOCATE-CEPTR (1st iteration)	1.6455
COGENT-CEPTR	1.6306

The values of ηf in the preceding table differ at most by 0.9%. The Maxwell-CEPTR method gives a value that falls between the other two and which is probably correct to $\pm 0.5\%$. Compared to the COGENT-CEPTR approach which is the most refined, the Maxwell-CEPTR treatment over-estimates the ηf of the fuel cells by about 0.3%. Similarly, one would also expect a compensating over-estimate of the effective absorptions in the poison. The net effect would be an over-estimate of the reactivity by about 0.2%.

E. Control Rods

Control rods were treated separately in the fast and thermal groups in the PDQ code. A black boundary condition was stipulated at the rod surface for the thermal group, and an effective macroscopic absorption cross section for the fast group of 0.15 cm^{-1} was used in the rod region. This fast cross section had been calculated earlier in the ABWR program and is reported in the PL Final Design Report⁽⁴⁾ and in a topical report⁽⁵⁾.

F. Calculation of Rod Bank Positions

A zeroth order three-dimensional synthesis was performed without iteration to obtain the control rod bank position and axial power distribution.* However, this zeroth order solution, although not converged, probably gives reasonably accurate flux distributions and control rod positions. This is because the radial fluxes and flux weighted cross sections are generally insensitive to the axial buckling, and the radial buckling is solved for almost exactly by the explicit PDQ X-Y representation of the core. The axial flux is mostly determined by the radial flux weighted cross sections and the axial buckling.

* A more accurate prediction of the rod bank position and axial power distribution would require a fully converged three-dimensional synthesis of the core. A complete description of the synthesis method is given in Reference 6. In short, the method requires repeated iterations between axial and radial group-dependent bucklings and flux weighted macroscopic cross sections. Generally, at least three iterations must be performed before the scheme converges. Since each iteration requires two radial X-Y (rodded and unrodded section of the core, PDQ) and one axial (WANDA) flux distribution, the process is rather costly.

VI. COMPARISON OF CALCULATION AND EXPERIMENT

A. Comparison of Calculated and Measured Eigenvalues

The eigenvalues of clean, almost square cores with low excess reactivity described in Section III were calculated using the methods described in Section V. Explicit PDQ, X-Y representations of these cores were set up assuming the cores to be completely covered with water and the control rods at the top of the fuel. Axial leakages were calculated from the physical height of the fuel assuming a 7 cm reflector savings at the bottom and 3 cm at the top. The resulting eigenvalues are compared with the measured eigenvalues (equal to 1.000 plus the measured worth of the control rods from their critical position to the top of the fuel). Conversion from dollars to percent reactivity was made assuming a β_{eff} of 0.007. These comparisons are given in Table XX.

1. Dependence of Calculated Eigenvalue on MUFT Buckling

Two calculated eigenvalues are reported for Cores I-A-8 (all fuel) and II-A-3 (with 1.1 w/o boron-stainless steel). The larger values were calculated using the full size core geometric buckling for MUFT input, the smaller values using the geometric buckling of the small clean cores themselves. The difference in eigenvalues caused by the change in MUFT buckling was about 1.1% for Core I-A-8, and 0.5% for Core II-A-3.

2. Rod Bank Position in Cold Mockup

The fast cross sections used in the synthesis of the cold mockup were obtained from MUFT problems in which the MUFT buckling was the full size core geometric buckling. The calculated rod bank position was one inch below the measured rod bank position. The worth of this inch was taken as 1.85% Δk , the average of the calculated bank worth at the calculated critical position (1.88% $\Delta k/\text{inch}$), and the measured bank worth at the measured critical position (1.82% $\Delta k/\text{inch}$). This implies that the calculated core was 1.85% Δk more reactive than the actual core, or that the calculation introduced a bias of +1.85% Δk . Although some of this bias is due to the low order of the synthesis calculation, it would appear that a good part is due to the use of the full size core geometric buckling in the MUFT calculation of fast cross sections rather than the materials buckling.

3. Bias in the Worth of Control Rods

The effectiveness of the treatment of control rods is demonstrated by the eigenvalues obtained for clean, all-fuel Cores I-A-8 and I-A-9(c), and for Cores II-A-9(d) and II-A-7(c), clean with 0.25 w/o boron-stainless steel. There were no control rods in Cores I-A-8 and II-A-9(d), and the center control rod was fully inserted in Cores I-A-9(c) and II-A-7(c). The difference in the biases (calculated eigenvalue minus measured eigenvalue) for similar cores with and without the center control rod inserted should reflect the treatment of the control rod alone. For all-fuel cores, this difference is $+0.74 - (-0.33) = +1.07\% \Delta k/k$, and for the cores with 0.25 w/o boron-stainless steel, is $+0.65 - 1.03 = -0.38\% \Delta k/k$.

Thus, for a core with all fuel the worth of the rod is over-estimated by $1.1\% \Delta k/k$ out of a total worth of about $12.5\% \Delta k/k^*$, whereas for the core with 0.25 w/o boron-stainless steel the worth is under-estimated by $0.4\% \Delta k/k$ out of a total worth of about 9.2% . Although the discrepancies in rod worth are surprisingly small in view of the complex interplay between fuel, water channel, boron-stainless steel, and control rods, they are nevertheless experimentally and theoretically significant.

4. Position of Boron-Stainless Steel

The analytic treatment of the boron-stainless steel poison elements at the corners of the fuel boxes was of concern because of the apparent arbitrariness in the definition of the position and region boundaries of these elements. It was found experimentally, however, in Core II-A-10(a) that the eigenvalue was not very sensitive to an exaggerated motion of poison elements. In this core, the 0.25 w/o boron-stainless steel elements at the corner of the four central fuel boxes in Core II-A-9(d) were exchanged with their fuel neighbors in an east-west direction. This exchange produced a measured reactivity increase of 0.46% compared to a calculated increase of 0.33% . It is therefore apparent that the geometric representation of the poison elements in the calculational model is adequate with respect to eigenvalue.

* Rod worth for these two cores was assumed to be the k_{excess} of the cores without the rods inserted. The k_{eff} was estimated by

$$k_{\text{eff}} = \frac{1 + M^2 B_1^2}{1 + M^2 B_2^2}$$

where $M^2 = 31.6 \text{ cm}^2$ (Table XIX, and Appendix E); B_1^2 is the geometric buckling of the unrodded core; and B_2^2 is the geometric buckling of the rodded core.

5. Boron Concentration

As evident in Table XX, the reactivity biases for cores with varying boron concentrations from all fuel to 0.00 w/o to 0.25 w/o (and 1.1 w/o estimated) are all about the same, varying from +0.65% for 0.25 w/o to 0.93% for 0.00 w/o (stainless steel rods). One can conclude here that the boron pins of all concentrations, in clean unrodded cores, are adequately treated by the present analytical methods.

B. Power Distributions

1. Experimental Method

Power distributions were measured by scanning the activation along the length of fuel rods taken from the core after a power run. The rods moved under a counting head, and the total number of counts over a one-inch motion was recorded. Counting started one-half inch above the bottom of the active fuel and stopped at 37.5 inches, or 0.8 inches below the top of the active fuel. Corrections for dead time, decay, and background were made. To minimize any azimuthal effects the fuel rod was rotated about its major axis three times for every inch it traveled under the counter. A correction for edge effects; i.e., counts received from portions of the rod above and below the one-inch section being measured, was determined and was +13% at the bottom of the fuel, +4 at one-inch, and zero at two inches. Since the counting began one-half inch above the bottom of the fuel and all counts were smeared over one-inch intervals, the correction (+4% at one inch) was negligible and was not applied. The absence of a measured bottom reflector peak can be explained by the lack of data below one inch (average height of lowest measured part of fuel element), and by the smearing of the counts over one-inch intervals.

Table XXI gives a list of the cores in which power distributions were measured, and Figures 33-39 are core maps showing the positions of those fuel rods that were scanned. For the two full size cores, III-A-3 and IV-D-1, the control rods were at their critical bank position and the water was above the top of the core. For the small, clean cores the control rods were at the top of the fuel and criticality was controlled by water height. Eighth-core symmetry was assumed for all but Core II-A-10(a), and one-eighth of all fuel rods were measured. In Core II-A-10(a), a fuel and poison rod interchange destroyed the eighth-core symmetry, and one-quarter of all the fuel rods were measured. Specially selected rods in symmetric positions in the core were also scanned in order to check on core symmetry. The deviation from symmetry is also a measure of the experimental accuracy and

in almost all cases was comparable to the difference between the measured and calculated power distributions. It required three to four successive runs on as many days to fully map out the full size cores, while the small cores required only one day or run each. At the end of the program in order to check reproducibility, the power distribution in the central part of Core II-A-3 was re-measured. The scope of the program limited the number of cores in which power distributions were measured. Further measurements in the two cores with the center control rod fully inserted would be very informative.

Calculated power distributions were obtained from PDQ calculations by integrating the source over each homogenized fuel cell. The PDQ source was proportional to the total number of fissions for all neutron energy groups for all fissionable material.

All radial power distributions for small clean cores were normalized to their average value; that is, the power (counts or integrated source over a fuel cell) at some height z was divided by the average power per fuel element (or fuel cell) for all fuel elements in the core at that height. A slightly different method was used for the two full size cores. Here, the power per fuel element in a particular fuel subassembly was divided by the average power per fuel element in that subassembly, where both the power per fuel element and the average power per fuel element were taken at the same axial positions. Average axial power distributions were obtained by averaging the measured power in all fuel elements at each height (each inch) in the core. It was assumed that the axial power distributions in the small clean cores would essentially follow a cosine distribution, and no axial power distributions were calculated for these cores. Using three-dimensional flux synthesis technique, an axial power distribution was calculated for the cold mockup with banked control rods but none was computed for the simulated hot mockup.

2. Power Distributions in Core With No Poison, Core I-A-8

Figure 40 gives the measured and calculated radial power distribution in a clean core composed of fuel elements only. The measured values were taken at the axial peak. Figure 41 gives the measured axial power distributions for this core normalized to the core average. A chopped cosine distribution was calculated using the same reflector savings (7 cm at the bottom of the fuel and 3 cm at the top of the water) as was assumed in the calculation of geometric bucklings, and is included for comparison in Figure 41. Except for an overall translation of the calculated distribution a few centimeters below the measured distribution, the agreement was

excellent; the calculated position of the axial peak was 1/2 inch below the measured position and was 0.3% smaller. The calculated radial power distribution agreed very well with the measured distribution, the agreement being within 7%. By comparison, the power measured in fuel rods at symmetric positions differed by as much as 5%. Generally, the calculated values were higher at water channel intersections and lower near the steel stanchions. It is to be recalled that in the calculational model the corner element (a fuel rod or more usually boron-steel) was located on pitch, while in the actual core this element was displaced one-eighth inch diagonally away from the corner. This probably leads to a slight overestimate of the power in a fuel rod located in this corner position.

3. Power Distribution in Core With 0.0 w/o Boron, Core II-A-8(e)

Figure 42 shows the calculated and measured radial power distribution; and Figure 43 shows the normalized axial power distribution for Core II-A-8(e) in which the poison elements were boron free stainless steel.

The agreement between the calculated and measured radial power distributions was striking. At the center of the core around the stainless steel rods the calculated value was 1.77, while the measured value was 1.78 (average of eight fuel rods). As in Core I-A-8, the calculated power near the stanchions was somewhat smaller than measured.

The analytical method gave good agreement even in atypical regions of the core; for example, the calculated power distribution in the single row of fuel elements around the outside of the four central fuel subassemblies (essentially a row of elements sitting in the reflector) agreed reasonably well with that measured, with a maximum difference of 14%. The method of calculating the resonance escape probability and especially the thermal self-shielding factors (unit cells in an infinite medium of these cells) should not be expected to apply very well in this region.

4. Power Distributions in Clean Core With 0.25 w/o Boron-Stainless Steel, Core II-A-9(d)

The calculated and measured radial power distributions for Core II-A-9(d) are given in Figure 44. Agreement at the center of the core near the 0.25 w/o boron-stainless steel poison elements was excellent, with an average measured value for eight symmetric fuel elements of 1.53, and a calculated value of 1.55. There was some spread in the measured values for these eight rods, ranging from 1.46 to 1.57, indicating an experimental error of $\pm 4\%$. Near the stanchions, the calculated and measured values

agreed to within 4%. The agreement for fuel rods around the boron-stainless steel elements was within 2%. As in Core II-A-8(e), the difference was larger at the rows of fuel elements around the outside of the four central fuel subassemblies and adjacent to the reflectors where differences as large as 10% were apparent. The average axial power distribution measured in this core is given in Figure 45.

5. Power Distributions in Clean Core With 0.25 w/o Boron- Stainless Steel Moved From Reference Position, Core II-A-10(d)

In this core the eight poison elements situated at the corners of the four central fuel subassemblies were exchanged with their fuel neighbors in such a direction as to keep these poison elements within the four central fuel boxes. The calculated and measured radial power distributions are given in Figure 46. In general, very good agreement was found in the central fuel boxes; and with one exception the difference between calculation and measurement was no greater than 4%. The comparison for the rather isolated corner fuel elements which had been exchanged with boron elements provided a very stringent check on the analysis methods. The difference here was surprisingly no greater than 8%. Comparison of measurements with fuel elements in symmetric core positions indicated an experimental error of $\pm 5\%$.

The agreement between calculation and measurement for fuel elements around poison elements especially in this core and in the preceding one indicated that the analytical treatment of the poison was probably adequate. This was especially significant since the relative neutron flux in the poison element determined the burnup rate of the boron and hence influenced the core lifetime. The average axial power distribution for this core is given in Figure 47.

6. Power Distribution in the Full Size Core With 0.25 w/o Boron- Stainless Steel

a. Cold Mockup, With No Displacers, Core III-A-3

The power distribution was measured in a full octant of the core; because of symmetry, this was sufficient to give a complete mapping of the core. In addition, at the end of the program, the power distribution

in the center of the core was measured again to check symmetry and reproducibility. Three separate runs were required for the full core measurement in which a small axial shift in power was apparent.* Figure 48 shows the measured and calculated radial power distribution in an octant of the core. The calculated factors were taken from an unrodded PDQ. The measured factors were obtained by integrating the power over the total length of the fuel element and, in this manner, the axial shift was cancelled out. The local peaking factors within each box are also given in Figure 48. The measured values were taken at the axial peak and, since all measurements within a box were taken in the same run, no normalization was necessary. The second power distribution measurement over the central part of the core is shown in Figure 49. The normalized average axial distribution for the four fuel boxes obtained during the first measurement is given in Figure 50; and the average axial power distribution from the first measurement for the entire core is given in Figure 51. The average axial distribution for box 10 obtained during the second measurement is given in Figure 52; and the corresponding curve from the first measurement is included for comparison. An axial power shift of about 7% at the peak can be seen in the figure.

* Normalization from run to run was achieved by comparing the total counts from the same monitor fuel rod. Fuel boxes 10 and 6 were measured during the first run; box 5 during the second; and box 2 during the third. Inspection of the data from a number of fuel rods that were in symmetric positions and that had been measured during each run indicated that there was an apparent axial power shift at the center of the core from the first run to the second and third, although the rod bank position remained the same for all three runs. The position of the axial peak did not change, but the magnitude of the peak decreased by about 7%. Further verification was obtained in the last power distribution measurement (carried out at the end of the program in order to check symmetry and reproducibility). The shift was not seen in the local power distributions (power in a fuel cell divided by the average power per fuel cell in a given box), but was seen in the radial power distribution (average power in a box divided by the average power in the core). A comparison of the normalized average axial power distributions measured during the first run and at the end of the program in center fuel box 10 is given in Figure 52.

The agreement between measured and calculated local peaking factors in Figure 48 is excellent, generally from 1-3% near the 0.25 w/o boron-stainless steel poison elements. At a few locations, for example at the water channel between boxes 2 and 5, there is an 8-9% difference. The radial factors in Figure 48 agree to within 8%. The measured average axial power distribution is given in Figure 51. This distribution was also calculated by a zeroth order synthesis of rodded-unrodded core sections and top and bottom reflectors, and is included in Figure 51.

The spread between values at symmetric positions can be seen in Figure 49. The differences appear at first glance to be random, with no evidence of being systematic, to indicate a power tilt. The values of local peaks for fuel rods in box 10 at symmetric positions have been averaged and compared with the calculated values. Figure 53 presents the percent differences obtained from this comparison. From the figure it can be seen that the greatest difference between calculated and measured values is in fuel element #41 (or #85), on a water channel, and mid-way between the stanchions and the boron poison elements. Here the calculation is 6% greater than the measured value. The next largest difference is at the fuel element immediately next to #41 (or #85) on the side away from the water channel where the calculation is 5% less than the measured value. The differences next to boron poison elements and in other parts of the fuel box are random and small, $\pm 4\%$, and within the experimental error.

b. Reference Core With Displacers, Core IV-D-1

A detailed and complete power mapping was made of this core although no analysis has yet been made to compare with predictions. Four separate runs were required and no evidence of a power shift, such as is seen in Core III-A-3, was evident. Figure 54 gives the radial and local power distribution at the axial peak (below the displacers and the rod bank), and at an elevation above the displacers but below the rod bank. Figure 55 shows the power distribution at the axial peak in the fuel rods on either side of the center water channel. In this figure the power in the fuel elements is reported relative to element 71 in fuel box 10. In most cases, the differences among measurements at symmetric positions are 7% or less. The greatest differences are seen in those fuel elements next to the stanchions; however if fuel element 78 in box 15 is neglected (it seems possible that there is some experimental error in the measurement for this rod), the distributions in the remaining seven fuel rods also agree to within 7%. The RMS percent difference between rods in symmetric positions averaged over all 47 fuel rods is 5%.

VII. CONCLUSIONS

A. Shutdown Margin With One Control Rod Withdrawn

It has been demonstrated experimentally that the boron concentration in the boron-stainless steel poison elements can be reduced from the design value of 1.0 w/o to 0.25 w/o with a corresponding decrease in the reactivity shutdown margin with one rod out from about 4.3% to 2.6%. This margin is still quite adequate.

B. Calculation and Measurement of Reactivity

A number of clean cores with varying concentrations of boron in boron-stainless steel poison elements, with a control rod fully in or out, with and without aluminum-water displacers surrounding the fuel and poison, and with the poison in the reference and in adjacent positions, were constructed and analyzed. The calculated eigenvalues for these cores agree with the measured eigenvalues to from -0.33 to +1.03% Δk , with the values of all but one core (all fuel, center control rod fully in) in the range from +0.65 to +1.03% Δk . The analytical method appears to over-estimate the worth of the fully inserted control rod in the all-fuel core by about 1% Δk , out of 12.5%, and under-estimates the worth of the control rod in a core with 0.25 w/o boron-stainless steel by about 0.4% Δk out of 9.2%. This anomaly is not understood at present.

C. Power Distributions

Power distributions in cores with all fuel, with 0.0 w/o and 0.25 w/o boron-stainless steel in the reference positions, and with the 0.25 w/o boron-stainless steel in corners of fuel boxes exchanged with their neighboring fuel rods have been measured; and the calculated local power peaks at the more important fuel elements - such as those at water channel intersections and those adjacent to poison elements - agree to within $\pm 6\%$ with the measured values. Similar agreement for the full size core was obtained.

D. Further Improvements

Measurements in a core with zoned poison, where the poison in the 12 peripheral fuel boxes is replaced with fuel, show a very small decrease in reactivity shutdown margin, from 2.6% to 2.3%, while the overall reactivity increases by about 1% Δk . This increase could be used to increase the core life. The removal of the boron at the periphery of the core would also

tend to increase the power in this region, which would to some extent flatten the radial power distribution.

E. Areas for Improvements in the Analytical Method

The anomalous results in the calculation of the worth of the center rod (in one case the method over-estimates the rod worth, in another case it is under-estimated) should be investigated. The generally positive bias in the reactivity calculations, for 0.65 to 1.03%, should also be investigated for possible improvement.

Some areas which have been investigated indicate that this bias could be reduced possibly by up to 0.4% Δk . A more refined treatment of the resonance escape probability, Section V-C-1, might reduce the reactivity by up to 0.2%. Similarly, a more refined treatment of the thermal neutron spectrum, Section V-D.2, could reduce the reactivity by about 0.2%.

TABLE II

CRITICALITY DATA FOR LOW EXCESS SQUARE CORES WITH NO BORON

Core	Number of Elements		Control Rods		Water Level Control		Excess React.
	Fuel	B-SS	Critical Position ⁽¹⁾ (inches from bottom of core)	Worth Per Rod	Critical Height ⁽²⁾	Worth	
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
I-A-9(c)(3)	500	0	Center In; Others at 34.91"	1.7¢/in. at 36.61"	36.51"	13.2¢/in. at 36.92"	\$0.23

(1) Water level fully up.

(2) All control rods withdrawn, except as noted.

(3) With center control rod fully inserted.

TABLE III
CRITICALITY DATA FOR LOW EXCESS CORES WITH 0.0 w/o BORON-STAINLESS STEEL

Core	Number of Elements		Control Rods Critical Position ⁽¹⁾ (inches from bottom of core)	Worth Per Rod	Water Level Control		Excess React.
	Fuel	B-SS			Critical Height ⁽²⁾	Worth	
II-A-8(b)	284	24	Center Out; Others at 26.97"	4.1¢/in. at 28.52"	31.70"	-	\$0.92
II-A-8(d)	268	12	Center Out; Others at 36.78"	0.63¢/in. ⁽³⁾ at 37.54"	-	-	\$0.04
II-A-8(e)	276	12	Center Out; Others at 29.07"	1.7¢/in. at 33.69"	33.55"	20.5¢/in. at 33.83"	\$0.61

(1) Water level fully up.

(2) Control rods completely withdrawn.

(3) Rod worth measured by complete withdrawal of all four rods.

TABLE IV

CRITICALITY DATA FOR LOW EXCESS CORES WITH 0.25 w/o BORON-STAINLESS STEEL

Core	Number of Elements		Control Rods Critical Positions ⁽¹⁾ (inches from bottom of core)	Worth Per Rod	Water Level Control		Excess React.
	Fuel	B-SS			Critical Height ⁽²⁾	Worth	
II-A-9(b)	332	24	Center Out; Others at 25.43"	5.3¢/in. at 27.01"	-	-	\$1.20
II-A-9(c)	316	24	Center Out; Others at 29.46"	1.8¢/in. at 33.88"	33.60"	19.5¢/in. at 33.93"	\$0.64
II-A-9(d)	308	24	Center Out; Others at 33.35"	1.3¢/in. at 35.83"	36.44"	13.8¢/in. at 36.87"	\$0.25
II-A-10(a) ⁽³⁾	308	24	Center Out; Others at 28.70"	3.4¢/in. at 30.35"	33.07"	20.3¢/in. at 33.29"	\$0.71
II-A-7(c) ⁽⁴⁾	632	36	Center In; Others at 34.96"	1.7¢/in. at 36.63"	36.63"	11.6¢/in. ⁽⁷⁾ at 37.29"	\$0.23
II-A-11(e) ⁽⁵⁾	508	24	Center Out; Others at 36.49"	1.4¢/in. ⁽⁶⁾ at 37.40"	37.95"	Too Small to Measure	\$0.10

(1) Water level fully up.

(2) Control rods completely withdrawn.

(3) Poison elements in corners of center four fuel boxes exchanged with fuel neighbors in east-west direction.

(4) With center control rod fully inserted.

(5) All poison and fuel elements enclosed in aluminum-water displacers.

(6) Rod worth measured by complete withdrawal of all four rods.

(7) Center control rod in, others out.

TABLE V

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

Core	Number of Elements		Control Rods		Water Level Control		Excess React.
	Fuel	B-SS	Critical Position ⁽¹⁾ (inches from bottom of core)	Worth Per Rod	Critical Height ⁽²⁾	Worth	
II-A-3	392	24	5 rods at 30.4" 4 side rods at 28.08"; center out Center at 28.71"; Side rods out	Each side rod 4.34¢/in. at 28.93" Center rod 21.5¢/in. at 28.91"	32.02"	20.57¢/in. at 32.40"	\$0.84
II-A-4	376	24	5 rods at 33.09"; 4 sides at 31.08"; center out	Each side rod 1.75¢/in. at 34.69". Each side rod worth from 31.08" to all out; 12.7¢.	34.61"		\$0.51
II-A-5	380	20	Center at 31.61"; Others out; 5 rods at 18.40" 4 rods with center at 13.31"	55.8¢/in. for four rods at 12.26"			
II-A-6	380	20	4 rods with center out at 19.32"	53.0¢/in. for four rods at 17.97"			

(1) Water level fully up.

(2) Control rods completely withdrawn.

TABLE VI

CRITICALITY DATA FOR SMALL SLAB CORES CONTAINING VARIOUS CONCENTRATIONS OF BORON-STAINLESS STEEL

Core	Number of Elements		Control Rods		Water Level Control		Excess React.
	Fuel	B-SS	Critical Position ⁽¹⁾ (inches from bottom of core)	Worth Per Rod	Critical Height ⁽²⁾	Worth	
II-B-4	422	20, 1.1 w/o	4 rod bank with center out, 33.68"	Two opposite rods to fully 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"	Four rods worth 42.25¢/in. at 19.33"	-	-	-
			5 rod bank, 22.35"				

(1) Water level fully up.

(2) Control rods completely withdrawn.

TABLE VII

REACTIVITY WORTH OF FUEL AND BORON IN SMALL CORES

Change	Cores <u>Initial</u> <u>Final</u>	Total	Reactivity Change		Comments
			Per Fuel Rod	Per Poison Rod	
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, four 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, four pins	II-A-4 II-A-5	\$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 to 0.25 w/o boron-stainless steel	II-B-4	\$2.16	-	-	By rod bank position. Core length changes.
0.25 to 0.00 w/o boron-stainless steel	II-B-8 II-B-9	\$3.37	-	-	By rod bank position. Core cross sections identical.

TABLE VIII

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

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

(1) Water level fully up.

(2) Twenty-seven of the boron-stainless steel rods did not have their stainless steel jackets.

TABLE IX

CRITICAL ROD CONFIGURATIONS AND ROD WORTHS FOR VARIOUS UNIFORM 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
Weight Percent Natural Boron in Boron-Stainless Steel	1.10	1.10	0.50	0.50	0.25	0.00
Figure Number	19	19	19	19	19	19
Shroud Present	No	Yes	No	Yes	Yes	Yes
Rod Positions (inches)						
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, Dollars/Inch						
Side Rod #2(3)	\$0.204	-	-	\$0.330	\$0.382	\$0.044
Seven 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.
- (5) Estimated from eight-rod bank versus center rod calibration curves.

TABLE X

CRITICAL ROD CONFIGURATIONS AND ROD WORTHS FOR VARIOUS BORON AND FUEL COMBINATIONS IN THE REFERENCE POSITION

(All Rod Positions Measured From Bottom of Fuel)

Core	III-A-4	III-A-5	III-A-7
Weight Percent Boron-Stainless Steel	0.25, 0.00	0.25, 0.00	0.25
Figure Number	20	21	22
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 Rods(1) 7 Rods(2) Side Rod #2(3)	8.67 5.84 - 12.99	8.39 4.80 - -	8.26 3.82 4.14 8.29
Rod Worths Near Critical (Dollars/Inches) Side Rod #2(3) Seven Rod Bank(4)	0.380 -	- -	0.178 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.

TABLE XI

REACTIVITY SHUTDOWN MARGIN WITH ONE ROD OUT FOR VARIOUS BORON LOADINGS

	Uniform Boron Concentrations in Design Positions				Combinations of Fuel- Boron-Stainless Steel in Design Positions	
Core	III-A-1	III-A-2	III-A-3	III-A-6	III-A-4	III-A-7
w/o Boron-Stainless Steel	1.10	0.50	0.25	0.00	0.25, 0.00	0.00, fuel
Shutdown in Dollars						
A	3.81	-	-	-	-	-
B	7.67	6.93	4.71	-	-	.72
C	7.95	-	4.66	-	-	-
D	7.03	-	-	-	-	-
E	3.12	3.24	2.82	.034	1.85	.55
Rod Drop						
Schultz(1)	-	-	3.75	-	2.12	.60
GNEC(2)	6.10	4.94	3.67	-	2.05	-

- A. Center rod out, calibrate side rod #2, compensate with rod #4, all others in.
 B. Center rod out, calibrate side rod #2, compensate with seven-rod bank, use bank equivalence factors.
 C. Center rod out, calibrate side rod #2, compensate with seven-rod bank, use rod equivalence factors.
 D. Center rod out, calibrate side rod #2, compensate with rods 6 and 9, all others in.
 E. Center rod out, calibrate side rod #2, compensate with rods 7 and 8, all others in.

(1) Section 5.2-B, Naval Reactor Physics Handbook, Vol. 3.

(2) Comparison of counting rates after rod drop with solution to the kinetics equation for discrete negative step change in reactivity.

TABLE XII

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 ⁽¹⁾	.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
Five Rod Bank With Corner Rod Out	5.17	5.17	38.30	5.17	38.30
Four 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

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

TABLE XIII

CONTROL ROD WORTHS IN REFERENCE CORE WITH 0.25 w/o BORON-STAINLESS STEEL.
ALL VALUES FOR THE NINE 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 Nine 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.

TABLE XIV

CRITICALITY DATA FOR CORES WITH DISPLACERS AND 0.25 w/o BORON-STAINLESS STEEL

Core	III-A-3	IV-B-1	IV-C-1	IV-D-1
Description	Reference Core; No Displacers	Displacers Full Length in Center 4 Fuel Boxes Only	Displacers Full Length Over Entire Core	Displacers 7" Above Bottom of Fuel Over Entire Core
Nine Rod Bank Position	9.08"	10.52"	14.42 - 14.52 ⁽¹⁾	10.86"
Worth of Center Rod at Nine Rod Bank	\$.64/in.	\$.38/in.	\$.34/in.	\$.43/in.
Eight Rod Bank With Center Rod Out	6.83"	9.53"	13.30"	9.69"
Eight Rod Bank With Center Rod In	11.21"	12.53"	20.82 - 20.75 ⁽¹⁾	15.60"
Reactivity Decrease Relative to Reference Design	-	\$.73	\$2.64	\$.96

(1) Formation of gas bubbles caused shift of critical position.

TABLE XV

CRITICALITY DATA FOR CORES WITH 0.25 w/o BORON-STAINLESS STEEL POISON ELEMENTS
EXCHANGED WITH NEIGHBORING FUEL ELEMENTS ON DIAGONAL OF FUEL BOX

Core	III-A-3	IV-A-1	IV-A-2
Description	Reference Core, 0.25 w/o Boron-Stainless Steel in Reference Positions	Boron-Stainless Steel Exchanged With Neighboring Fuel Element on Diagonal	Boron-Stainless Steel Exchanged With Two Neighboring Fuel Elements on Diagonal
Nine Rod Bank	9.08"	8.80"	8.78"
Rod #2 With All Others at 9.08"	9.08"	6.91"	6.72"
Worth of Rod #2 in Above Configuration	\$.32/in.	\$.35/in.	\$.37/in.
Increase of Reactivity Relative to Reference Core	-	\$.71	\$.81

TABLE XVI

CRITICALITY DATA FOR ZONED ARRANGEMENTS OF 0.25 w/o BORON-STAINLESS STEEL POISON ELEMENTS

(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
Figure Number	19	27	28	29	30	31
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
Nine Rod Bank Position, in.	9.07	8.01	8.08	8.80	8.78	8.53
Eight 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 XVII

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⁾	\$2.82	(1)	\$2.04	\$2.56	\$2.52	\$2.43
(b) By Rod Drop	\$3.70	(1)	\$2.56	\$3.37	\$3.29	\$3.11

(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 XVIII

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 #1	Side Rods				Corner Rods			
		#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

TABLE XIX

CRITICAL PARAMETERS FOR CLEAN CORES WITH 1.1 w/o BORON-
STAINLESS STEEL AND WITH ALL FUEL

<u>Core</u>	<u>I-A-8</u> (All Fuel)	<u>II-A-4</u> (1.1 w/o Boron-Stainless Steel)
$k_{\text{eff}} (B_z^2 = 0.0033, \text{PDQ})$	1.2409	1.1639
$k_{\text{oo}} (B_z^2 = 0, \text{PDQ})$	1.3704	-
M^2	31.62 cm ²	31.62 cm ²
$k_{\text{oo}} (\text{from } M^2, k_{\text{eff}}, B_z^2)$	1.3704	1.2654
B_M^2	.0117 cm ⁻²	.0084 cm ⁻²
$B_g^2 (\text{full size core})$	.0029 cm ⁻²	.0029 cm ⁻²
$B_M^2 \left(= B_{g_{\text{expt}}}^2 \right)$	.0104	.0090

TABLE XX
COMPARISON OF CALCULATED AND MEASURED EIGENVALUES

Core	Description w/o B-SS	Position of B-SS	Size of Core and Notes	Measured Eigenvalue (k)	Calculated Eigenvalue (k)	Calculation Minus Measured (% $\Delta k/k$)
I-A-8	All Fuel	-	16 x 16 less 3 at each corner	1.0017	1.0091 1.0203(1)	+ 0.74 + 1.86(1)
I-A-9(c)	All Fuel	-	22 x 22 plus 8 centered on each face, and center control rod in	1.0016	.9983	- .33
II-A-8(e)	0.0	Reference	16 x 16 plus 10 centered on each face	1.0043	1.0136	+ .93
II-A-9(d)	0.25	Reference	18 x 18 plus 6 centered on each face	1.0017	1.0082	+ .65
II-A-10(a)	0.25	Boron-Stainless Steel in 4 Center Fuel Box Corners Exchanged East-West With Fuel Neighbors	18 x 18 plus 6 centered on each face	1.0050	1.0128	+ .78
II-A-7(c)	0.25	Reference	26 x 26 plus 2 centered on each face, center control rod in	1.0016	1.0119	+ 1.03
II-A-11(c)	0.25	Reference	22 x 22 plus 16 centered on each face; Al displacers around fuel and poison	1.0007	1.0100	+ .93
II-A-3	1.1	Reference	20 x 20 plus 4 centered on each face	1.0059	1.0161 1.0209(1)	+ 1.02 + 1.50(1)

(1) MUFT buckling equal to full size core geometric buckling.

TABLE XXI

CORES IN WHICH POWER DISTRIBUTIONS WERE MEASURED

Core	w/o B-SS	Position of B-SS	Size of Core	Notes
III-A-3	0.25	Reference	Full Size	Aluminum-water displacers raised to seven inches above bottom of fuel
IV-D-1	0.25	Reference	Full Size	
I-A-8	All Fuel	-	16 x 16 less 3 fuel elements from each corner	
II-A-8(e)	0.0	Reference	16 x 16 plus 10 fuel elements centered on each face	
II-A-9(d)	0.25	Reference	18 x 18 plus 6 fuel elements centered on each face	
II-A-10(a)	0.25	See Notes	18 x 18 plus 6 fuel elements centered on each face	Boron-stainless steel in corners of center four fuel boxes exchanged with fuel neighbors in east-west direction

APPENDIX A

COMPOSITION OF STAINLESS-STEEL CLAD TUBING, TAPE, AND BORON-STAINLESS STEEL

TABLE A-1

Composition of Stainless Steel Clad Tubing

Percent of Total Clad Tubing	Batch	
	<u>A</u>	<u>B</u>
	10	90
<u>Element</u>	<u>Weight Percent</u>	
Fe	67.147	68.326
Cr	17.870	17.840
Ni	11.940	10.220
Mn	1.590	1.840
B	.001	.001
Ta	.010	.027
Si	.650	.645
Cu	.130	.045
C	.032	.070
Co	.042	.023
Mo	.100	.016
P	.006	.008
S	.002	.006
Cb	.480	.933
Cb + Ta	.580	.960

Density, Measured at Combustion Engineering, Inc., 7.905 gm/cm³.

TABLE A-2

Composition of Tape - Industrial Black, No. 481 - Information
Supplied by Manufacturer, Minnesota Mining and Manufacturing

<u>Element</u>	<u>Weight Percent</u>
C	90.70
H	8.87
O	.285
Zn	.066
P	.032

Density Measured at Combustion Engineering, Inc.: $0.912 \pm .025 \text{ gm/cm}^3$

Thickness Measured at Combustion Engineering, Inc.: $0.00900 \pm .00008 \text{ in.}$

TABLE A-3

Composition of Boron-Stainless Steel, By Weight Percent

Element	Nominal Weight Percent			
	<u>0</u>	<u>1/4</u>	<u>1/2</u>	<u>1</u>
B	.0	.2567	.5017	1.134
C	.051	.03	.04	.05
P	.020	-	-	-
S	.013	.04	-	-
Si	.55	-	.07	.07
Mn	.63	.47	.38	.52
Cr	18.58	19.23	18.72	18.60
Ni	9.39	8.70	9.79	9.70
Fe	Balance	Balance	Balance	Balance

APPENDIX B

VOLUME FRACTIONS OF CORE MATERIALS
AND WATER-TO-METAL RATIOS

TABLE B-1

Volume Fractions Over Individual Fuel and Poison Cells,
and Smeared Over Entire Core

Composition	Individual Cell		Fraction of Core	Total Over Core	
	Without Displacers	With Displacers		Without Displacers	With Displacers
<u>Fuel Cell</u>			0.78440		
UO ₂	0.25844	0.25844		0.20272	0.20272
UO ₂ -Clad Gap ⁽¹⁾	.00744	.00744		.00584	.00584
Clad	.05228	.05228		.04101	.04101
Tape	.02505	.02505		.01965	.01965
Tape-Displacer Gap ⁽²⁾	-	.02307		-	.01810
Displacer	-	.2060		-	.16159
Water	.6568	.4277		.51519	.33549
<u>Poison Cell</u>			.039885		
Boron-Stainless Steel	.25844	.25844		.01031	.01031
Boron-Stainless Steel Clad Gap ⁽¹⁾	.00744	.00744		.00030	.00030
Clad	.05228	.05228		.00209	.00209
Clad-Displacer Gap ⁽²⁾	-	.04812		-	.00192
Displacer	-	.2060		-	.00822
Water	.68185	.4277		.02720	.01706
<u>Shroud</u>			.007698	.00770	.00770
<u>Shroud-Fuel Water⁽³⁾</u>			.013486	.01349	.01349
<u>Rod Absorber and Rod Clad</u>			.055716	.05572	.05572
<u>Rod Water⁽⁴⁾</u>			.046072	.04607	.04607
<u>Stanchions</u>			.052738	.05274	.05274

(1) Fuel-clad and boron-stainless steel clad gaps considered always voided.

(2) Tape-displacer and clad-displacer gaps considered always flooded. These volume fractions are added to other water volume fractions to obtain total water volume fractions.

(3) Water between shroud and fuel boxes.

(4) Water between control rods and fuel boxes.

TABLE B-2

Total Volume Fractions of Core Materials and Water-to-Metal Ratios⁽¹⁾

Material	Without Displacers	With Displacers	
		Gap Between Element and Displacer Flooded	Gap Between Element and Displacer Voided
	Total	Volume Fractions	
Water ⁽¹⁾ , Control Rods Out	0.67732	0.50750	0.48748
Water ⁽¹⁾ , Control Rods In	.62160	.45178	.43176
UO ₂	.20272	.20272	.20272
Boron-Stainless Steel	.01031	.01031	.01031
Voids	.00614	.00614	.02616
Tape	.01965	.01965	.01965
Solids, Excluding Control Rods, UO ₂ , and Tape	.11385	.28366	.28366
Solids, Excluding Control Rods and Tape	.31657	.48638	.48638
Solids, Excluding UO ₂ and Tape	.16957	.33938	.33938
Solids, Excluding Tape	.37229	.54210	.54210
		Volume Ratios	
Water/Solids ⁽¹⁾ , Rods Out	2.139	1.043	1.002
Water/Solids ⁽¹⁾ , Rods In	1.670	.8334	.7965
W/UO ₂ , Rods Out	3.341	2.504	2.405
W/UO ₂ , Rods In	3.066	2.229	2.130
Decrease in Effective Water Density, Relative to Core Without Displacers	Control Rods Out	25%	28%
	Control Rods In	27%	31%

(1) Tape volume added to water volume.

APPENDIX C

NUMBER DENSITIES HOMOGENIZED OVER INDIVIDUAL FUEL AND POISON CELLS

TABLE C-1

Number Densities Homogenized Over Fuel and Poison Cells
All Numbers in Units of $10^{22}/\text{cm}^3$

Element	Pure No. Density	Without Displacers		With Displacers ⁽²⁾	
		Fuel Cell	Poison Cell	Fuel Cell	Poison Cell
U-235	0.11390	0.029436	-	0.029436	-
U-238	2.2300	.57631	-	.57631	-
H ⁽¹⁾	6.6745	4.5035	4.5510	3.1284	3.1759
O ⁽¹⁾	3.3372	3.3739	2.2755	2.6864	1.5880
C	4.1660	.10437	-(3)	.10437	-(3)
Fe	5.9596	.31154	1.8518	.31154	1.8518
Ni	.90145	.047130	.28013	.047130	.28013
Cr	1.6738	.08750	.52012	.08750	.52012
Mn	.17588	.009195	.05465	.009195	.05465
Al ⁽⁴⁾	6.0230	-	-	1.2409	1.2409
B-10 ⁽⁵⁾	.014316	-	.005340	-	.005340

(1) Including protective tape.

(2) With fuel and poison element displacer gaps flooded.

(3) Poison elements were not wrapped in tape, and the carbon in the stainless steel was neglected.

(4) For the calculation of fast cross section, aluminum was treated as low density zirconium, with $N_{\text{Zr}} = 0.365 N_{\text{H}}$.

(5) At 0.25 w/o boron.

APPENDIX D

MACROSCOPIC CROSS SECTIONS USED IN THE ANALYSIS OF THE VARIOUS CORES

TABLE D-1

Macroscopic Cross Sections for PDQ Calculations for All-Fuel Cores

Composition	Cross Section	Fast Group	Thermal Group
Fuel Cell	D	1.217700 1.215870(2)	0.154572
	Σ_a	.009762 .010106(2)	.166673
	Σ_r	.027460 .029366(2)	-
	$\nu\Sigma_f$	.008425 .008699(2)	.272630
Water	D	1.324600 1.351470(2)	.132427
	Σ_a	.000749 .000820(2)	.197140
	Σ_r	.046780 .048238(2)	-
Stanchion	D	.937512 .937512(2)	.295766
	Σ_a	.008422 .008422	.192849
	Σ_r	.000000 .000000(2)	-

- (1) Thermal cross sections include disadvantage factors.
- (2) Fast cross sections computed using MUFT buckling equal to full size core geometric buckling.

TABLE D-2

Macroscopic Cross Sections for PDQ Calculations for Cores Containing
0.0 w/o Boron-Stainless Steel, With No Displacers

Composition	Cross Section	Fast Group	Thermal Group
Fuel ⁽¹⁾	D	1.215530	0.154572
	Σ_a	.009826	.166673
	Σ_r	.027870	-
	$\nu\Sigma_f$	.008474	.272630
Poison ⁽¹⁾	D	1.165230	.159019
	Σ_a	.003589	.079529
	Σ_r	.032099	-
Water	D	1.326550	.132427
	Σ_a	.000757	.019714
	Σ_r	.047140	-
Stanchion	D	.937512	.295766
	Σ_a	.008422	.192849
	Σ_r	.000000	-

(1). Thermal cross sections include disadvantage factors.

TABLE D-3

Macroscopic Cross Sections for PDQ Calculations for Cores Containing
0.25 w/o Boron-Stainless Steel, With No Displacers

Composition	Cross Section	Fast Group	Thermal Group
Fuel ⁽¹⁾	D	1.214350	0.154572
	Σ_a	.009871	.166673
	Σ_r	.028130	-
	$\nu\Sigma_f$	.008509	.272630
Poison ⁽¹⁾	D	1.166080	.144113
	Σ_a	.006345	.192644
	Σ_r	.030110	-
Water	D	1.328100	.132427
	Σ_a	.000763	.019714
	Σ_r	.047400	-
Stanchion	D	.937512	.295766
	Σ_a	.008422	.192849
	Σ_r	.000000	-

(1) Thermal cross sections include disadvantage factors.

TABLE D-4

Macroscopic Cross Sections for PDQ Calculations for Cores
Containing 1.10 w/o Boron-Stainless Steel

Composition	Cross Section	Fast Group ⁽²⁾	Thermal Group
Fuel ⁽¹⁾	D	1.215870	0.154572
	Σ_a	.010106	.166673
	Σ_r	.029366	-
	$\nu\Sigma_f$	.008699	.272630
Poison ⁽¹⁾	D	1.181400	.128441
	Σ_a	.014660	.329575
	Σ_r	.023960	-
Water	D	1.351470	.132427
	Σ_a	.000820	.019714
	Σ_r	.048238	-
Stanchion	D	.937512	.295766
	Σ_a	.008422	.192849
	Σ_r	-	-

(1) Thermal cross sections include disadvantage factors.

(2) Fast constants calculated using MUFT buckling equal to full size core geometric buckling.

TABLE D-5

Macroscopic Cross Sections for PDQ Calculations for Cores Containing
0.25 w/o Boron-Stainless Steel, and With Displacers

Composition	Cross Section	Fast Group	Thermal Group
Fuel ⁽¹⁾	D	1.367100	0.204614
	Σ_a	.009133	.172145
	Σ_r	.018642	-
	$\nu\Sigma_f$	.008288	.285691
Poison ⁽¹⁾	D	1.309250	.187052
	Σ_a	.006106	.200072
	Σ_r	.020250	-
Water	D	1.330820	.132427
	Σ_a	.000772	.019714
	Σ_r	.047730	-
Stanchion	D	.937512	.295766
	Σ_a	.008422	.192849
	Σ_r	.000000	-

(1) Thermal cross sections include disadvantage factors.

TABLE D-6

Stainless Steel and Control Rod Macroscopic Cross Sections

Material	Cross Section	Fast Group	Thermal Group
Stainless Steel; i.e., Shroud, and Control Rod Clad	D	0.937512	0.306228
	Σ_a	.009999	.237083
	Σ_r	.000000	-
Control Rod	D	2.222222	.000000 ⁽¹⁾
	Σ_a	.150000	.495000 ⁽²⁾
	Σ_r	.000000	-

(1) A zero diffusion coefficient is a signal to the PDQ code that a boundary condition is to be applied.

(2) The absorption cross section for a black rod is 0.500; the value of 0.495 indicates that the rod is not completely black (see Reference 5).

APPENDIX E - PRELIMINARY PREDICTIONS OF CRITICAL SIZES

In connection with the planning of the experiments the critical sizes of Cores I-A-8 (all fuel) and II-A-4 (with 1.1 w/o boron-stainless steel) were predicted using a less rigorous method than that described in Section V. Fast and thermal macroscopic cross sections were obtained using the methods described in Section V, with the exception that the full core geometric buckling rather than the materials buckling was used for the calculation of fast constants. Three X-Y, PDQ problems were run, each representing a central fuel subassembly with zero leakage in all except the axial directions. The first two problems represented the core with 1.1 w/o boron-stainless steel; in the third the boron-stainless steel was replaced with fuel. The two problems containing the boron-stainless steel differed only in the axial leakage; one was given an axial leakage that corresponded to the height of the core (geometric axial buckling); the other was given a zero axial leakage. The eigenvalue of the problem with zero axial leakage was the k_{∞} of the subassembly, and the migration area was calculated from this k_{∞} and the k_{eff} given by the first problem. It was assumed that the migration area would not change appreciably when boron-stainless steel was exchanged for fuel. With the migration area and the k_{eff} calculated for the all-fuel subassembly, the k_{∞} for the all-fuel subassembly was determined. Critical sizes based on these values of k_{∞} and M^2 were then predicted assuming a reflector savings of 7 cm at the bottom of the core, 3 cm for the top poisoned reflector, and 6 cm for the radial reflector. The values of M^2 , k_{∞} , and B^2 that were used are given in Table XIX. It is apparent that because of the presence of water channels and core structure outside of the fuel subassembly, this technique is valid for cores containing only integral numbers of fuel subassemblies.

The predicted size of Core I-A-8, clean with no boron-stainless steel, was a 14-1/2 x 14-1/2 array as contrasted with the experimental core, a 16 x 16 array with 12 corner elements removed and with an excess reactivity of 24¢. The predicted size of Core II-A-4 with 1 w/o boron-stainless steel, was an 18 x 18 array as contrasted with the actual core, a 20 x 20 array with four extra fuel elements centered on each face and with a 51¢ excess reactivity. The material bucklings calculated from the values of k_m and M^2 which were used to predict the critical sizes, and the geometric bucklings inferred from the experimental cores are given in Table XIX. For comparison, the full size reference core geometric buckling is included.

As pointed out earlier in Section V.C.2, the geometric buckling inferred from the size of the experimental core was used as input to the MUFT code. These, or very nearly equivalent values, could have been calculated from first principles, as demonstrated in Table XIX. One could consider the preliminary prediction of critical sizes as the first of a one or two-step iteration where the calculated B_m^2 would be used as the MUFT buckling input for a second calculation of fast cross sections and the materials buckling.

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3. H. Kouts, et al, "Physics of H₂O Slightly Enriched Lattices," Session B-18, Vol. 12, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, September 1958.
4. IDO-19030, CEND-135, "PL Final Design Report," Vol. IV of VI, June 30, 1961.
5. ND-SLIP-7, "Treatment of Control Rods in PL Reactor Design Computations," September 1960.
6. SIC-1100-RS-193, "Synthesis Method for the Analysis of a Three-Dimensional Reactor With Partially Inserted Control Rods," A. Schock, June 1958.

SCHEMATIC OF FUEL AND BORON-STEEL
POISON ELEMENTS PL-2 CRITICAL
EXPERIMENTS

Figure 1

Figure 2

Figure 3

FUEL AND POISON ELEMENTS SHOWN WITH AND WITHOUT DISPLACERS FOR ILLUSTRATION ONLY. ACTUAL CORE WILL CONTAIN EITHER ALL DISPLACERS OR NO DISPLACERS

PERSPECTIVE OF REPRESENTATIVE SECTION OF CORE

KEY TO BOX NUMBERING

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

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

● - Fuel Elements

Figure 6

CORE I-A-9(c), ALL FUEL, NO POISON, WITH CENTER ROD FULL IN
CRITICAL WATER HEIGHT: 36.51"

● - Fuel

Figure 7

CORE II-A-8(e), WITH 0.0 w/o BORON-STAINLESS STEEL
CRITICAL WATER HEIGHT: 33.55"

● - Fuel

⊕ - 0.0 w/o Boron-Stainless Steel

Figure 8

CORE II-A-9(d), CLEAN CORE WITH 0.25 w/o BORON-STAINLESS STEEL
CRITICAL WATER HEIGHT: 36.44"

● - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 9

CORE II-A-10(a). 0.25 w/o BORON-STAINLESS STEEL IN CORNERS OF FOUR CENTRAL FUEL BOXES EXCHANGED WITH FUEL NEIGHBORS. CRITICAL WATER HEIGHT: 33.07"

- - Fuel
- ⊕ - 0.25 w/o Boron-Stainless Steel

Figure 10

CORE II-A-7(c). CORE WITH 0.25 w/o BORON-STAINLESS STEEL AND CENTER ROD FULL IN. CRITICAL WATER HEIGHT: 36.63"

● - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 11

CORE II-A-11(e). CORE WITH 0.25 w/o BORON-STAINLESS STEEL AND ALL FUEL AND POISON ELEMENTS SURROUNDED BY ALUMINUM-WATER DISPLACERS. CRITICAL WATER HEIGHT: 37.95"

- - Fuel and Displacer
- ⊕ - 0.25 w/o Boron-Stainless Steel and Displacer

Figure 12

CORE II-A-3. 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

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 14

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

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

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

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

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"
- Fuel

Figure 19

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

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

● - 0.00 w/o Boron-Stainless Steel

CORE III-A-5, WITH A COMBINATION OF
0.25 AND 0.0 w/o BORON-STAINLESS STEEL.
CRITICAL BANK POSITION: 8.39"

- - Fuel
- - 0.0 w/o Boron-Stainless Steel
- ⊕ - 0.25 w/o Boron-Stainless Steel

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

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

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

CORE IV-B-1. CENTRALLY DISPLACED CORE WITH ALL FUEL AND POISON IN CENTRAL FOUR FUEL BOXES ENCLOSED IN ALUMINUM-WATER DISPLACERS. CRITICAL BANK POSITION: 10.52 INCHES

○ - Fuel

⊙ - With Displacers

⊕ - 0.25 w/o Boron-Stainless Steel

⊗ - With Displacers

CORE IV-A-1. POISON ELEMENTS IN CORNERS
OF FUEL BOXES EXCHANGED WITH FUEL
NEIGHBORS ONE POSITION IN ALONG DIAGONAL.
CRITICAL BANK POSITION: 8.80"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 25

CORE IV-A-2. POISON ELEMENTS AT CORNERS OF FUEL
BOXES INTERCHANGED WITH FUEL TWO POSITIONS IN
ALONG DIAGONAL. CRITICAL BANK POSITION: 8.78"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 26

BORON ZONING, CORE IV-A-3. BORON-STAINLESS STEEL
POISON ELEMENTS REMOVED FROM CENTER ZONE,
BOXES 9, 10, 15 AND 16. CRITICAL BANK POSITION: 8.01"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 27

BORON ZONING, CORE IV-A-4. BORON-STAINLESS STEEL
POISON ELEMENTS REMOVED FROM INNER ZONE, BOXES 4, 5,
8, 11, 14, 17, 20 AND 21. CRITICAL BANK POSITION: 8.08"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 28

BORON ZONING, CORE IV-A-5. BORON-STAINLESS STEEL
POISON ELEMENTS REMOVED FROM CORNER ZONE,
BOXES 3, 6, 19, AND 20. CRITICAL BANK POSITION: 8.80"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 29

BORON ZONING, CORE IV-A-6. BORON-STAINLESS STEEL
POISON ELEMENTS REMOVED FROM OUTER ZONE, BOXES 1, 2, 7,
12, 13, 18, 23, AND 24. CRITICAL BANK POSITION: 8.78"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 30

BORON ZONING, CORE IV-A-7. BORON-STAINLESS STEEL REMOVED FROM PERIPHERAL ZONE, BOXES 1, 2, 3, 6, 7, 12, 13, 18, 19, 22, 23, AND 24. CRITICAL BANK POSITION: 8.53"

○ - Fuel

⊕ - 0.25 w/o Boron-Stainless Steel

Figure 31

REPRESENTATIVE SECTION OF CORE SHOWING GEOMETRY
USED IN ANALYTICAL MODEL (PDQ) AND DETAIL OF STANCHION

* Analytical and Actual Dimensions Identical.
All Dimensions, Where Applicable, and if
Not Shown, Were the Same for the Actual
Core and the Analytical Model.

MAP SHOWING FUEL ELEMENTS MEASURED FOR POWER DISTRIBUTION
IN CORE COMPOSED OF ALL FUEL, CORE I-A-8

○ - Fuel Elements Not Measured

● - Fuel Elements Measured

Figure 33

MAP SHOWING FUEL ELEMENTS MEASURED FOR POWER DISTRIBUTION
IN CORE WITH 0.0 w/o BORON-STAINLESS STEEL, CORE II-A-8(e)

- - Fuel Elements Not Measured
- - Fuel Elements Measured
- ⊕ - 0.0 w/o Boron-Stainless Steel

MAP SHOWING FUEL ELEMENTS MEASURED FOR POWER DISTRIBUTION
IN CORE WITH 0.25 w/o BORON-STAINLESS STEEL, CORE II-A-9(d)

- - Fuel Elements Not Measured
- - Fuel Elements Measured
- ⊕ - 0.25 w/o Boron-Stainless Steel

MAP SHOWING FUEL ELEMENTS MEASURED FOR POWER DISTRIBUTION IN CORE WITH 0.25 w/o BORON-STAINLESS STEEL IN CENTRAL FOUR FUEL BOXES EXCHANGED WITH NEIGHBORING FUEL ELEMENTS, CORE II-A-10(a)

- - Fuel Elements Not Measured
- - Fuel Elements Measured
- ⊕ - 0.25 w/o Boron-Stainless Steel

MAP SHOWING FUEL ELEMENTS MEASURED FOR FIRST
POWER DISTRIBUTION IN COLD MOCKUP, CORE III-A-3

⊕ - 0.25 w/o Boron-Stainless Steel

○ - Fuel Elements Not Measured

● Measured, 1st Run ● Measured, 2nd Run ● Measured, 3rd Run

Figure 37

MAP SHOWING FUEL ELEMENTS MEASURED FOR SECOND
POWER DISTRIBUTION IN COLD MOCKUP, CORE III-A-3

⊕ - 0.25 w/o Boron-Stainless Steel

○ - Fuel Elements Not Measured

● - Fuel Elements Measured

Figure 38

MAP SHOWING FUEL ELEMENTS MEASURED
IN CORE WITH DISPLACERS, CORE IV-D-1

⊕ - 0.25 w/o Boron-Stainless Steel

○ - Fuel Elements Not Measured

⊙ - Measured, 1st Run

⊙ - Measured, 3rd Run

⊙ - Measured, 2nd Run

⊙ - Measured, 4th Run

Figure 39

Box 9

- - - - Analysis
. . . - Measurement

RADIAL POWER DISTRIBUTION IN CORE I-A-8, ALL FUEL

Normalized Average Axial Power
Distribution in Clean Core, All Fuel
Core I-A-8

H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O
H ₂ O	H ₂ O	1.10 0.97	0.98 0.86	0.99 0.88	0.98 0.92	0.89 0.80	Fe

H ₂ O	H ₂ O
Fe	

B-SS	0.81 0.79	0.77 0.75	0.80 0.79	0.84 0.82	0.85 0.87	0.77 0.80	Fe
	0.66 0.65	0.69 0.69	0.75 0.76	0.79 0.80	0.82 0.89	0.83 0.86	0.93 1.03
		0.75 0.74	0.82 0.83	0.88 0.88	0.92 0.97	0.96 1.00	1.19 1.31
			0.92 0.90	1.00 1.04	1.03 0.99	1.07 1.12	1.35 1.32
				B-SS	1.13 1.12	1.16 1.17	1.45 1.42
					1.17 1.17	1.22 1.26	1.55 1.58
						1.34 1.35	1.77 1.81
Fe	0.93 0.97	1.19 1.22	1.35 1.34	1.45 1.50	1.55 1.49	1.77 1.72	B-SS

Fe	
1.77 1.83	
B-SS	1.77 1.84

Fe	0.93 0.93	1.19 1.11	1.35	1.45 1.49	1.55 1.42	1.77 1.79	B-SS
							1.77 1.73

B-SS	1.77 1.70
1.77 1.80	

Center of Core

---	Analysis
---	Measurement

RADIAL POWER DISTRIBUTION IN CORE II-A-8(e)
WITH 0.0 w/o BORON-STAINLESS STEEL

Figure 42

Figure 43

Normalized Average Axial Power
Distribution in Clean Core With
0.00 w/o Boron-Stainless Steel
Core II-A-8(e)

H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	0.99 0.95	0.82 0.77	0.81 0.74
B-SS	0.81 0.76	0.94 0.83	1.03 0.93	1.00 0.99	0.88 0.86	0.73 0.74	Fe

Fe	

B-SS	0.69 0.69	0.79 0.82	0.87 0.88	0.93 0.93	0.94 0.96	0.85 0.87	Fe
	0.67 0.68	0.74 0.78	0.81 0.88	0.86 0.92	0.89 0.91	0.90 0.93	1.01 1.05
		0.81 0.78	0.87 0.90	0.93 0.91	0.97 1.01	1.03 1.03	1.28 1.31
			0.94 0.96	0.99 0.99	1.05 1.02	1.12 1.18	1.42 1.42
				B-SS	1.10 1.13	1.19 1.20	1.50 1.53
					1.16 1.17	1.23 1.22	1.54 1.58
						1.28 1.23	1.55 1.49
Fe	1.01 1.04	1.28 1.23	1.42 1.39	1.50 1.53	1.54 1.48	1.55 1.55	B-SS

Fe	
1.55 1.52	
B-SS	1.55 1.52

Fe	1.01 1.04	1.28 1.24	1.42 1.35	1.50 1.41	1.54 1.57	1.55 1.57	B-SS
							1.55 1.53

B-SS	1.55 1.46
1.55 1.57	1.28 1.23

Center of Core

--- Analysis
--- Measurement

RADIAL POWER DISTRIBUTION IN CORE II-A-9(d)
WITH 0.25 w/o BORON-STAINLESS STEEL

H ₂ O	H ₂ O
H ₂ O	B-SS

H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	0.98 0.90	0.81 0.77	0.80 0.80
B-SS	0.80 0.76	0.92 0.88	1.01 1.10	0.98 0.97	0.87 0.86	0.73 0.73	Fe

H ₂ O	B-SS
H ₂ O	0.81 0.78
H ₂ O	0.94 0.87
H ₂ O	1.02 0.95
H ₂ O	0.99 0.98
0.98	0.87
0.88	0.86
0.81	0.73
0.80	0.71
0.80	Fe
0.86	

0.68 0.68	B-SS	0.76 0.77	0.86 0.90	0.91 0.94	0.93 0.95	0.84 0.88	Fe
0.70 0.69	0.65 0.69	0.72 0.72	0.80 0.84	0.85 0.88	0.89 0.89	0.90 0.96	1.01 1.04
0.79 0.78	0.73 0.71	0.79 0.79	0.86 0.90	0.92 0.94	0.97 0.97	1.03 1.02	1.28 1.27
0.87 0.89	0.80 0.85	0.86 0.84	0.93 0.91	0.98 0.96	1.04 1.06	1.13 1.16	1.42 1.34
0.92 0.93	0.85 0.84	0.92 0.94	0.98 1.05	B-SS	1.10 1.11	1.20 1.27	1.52 1.48
0.93 0.88	0.88 0.92	0.97 1.00	1.04 1.02	1.10 1.13	1.16 1.21	1.25 1.24	1.58 1.53
0.84 0.85	0.89 0.90	1.02 0.99	1.12 1.21	1.18 1.23	1.23 1.18	1.30 1.28	1.65 1.64
Fe	1.00 0.97	1.27 1.28	1.41 1.36	1.49 1.48	1.52 1.57	B-SS	1.96 1.82

	Fe

Fe	1.00 1.05	1.27 1.25	1.41 1.49	1.49 1.54	1.52 1.48	B-SS	1.96 1.82

Center of Core

 Analysis

 Measurement

RADIAL POWER DISTRIBUTION IN CORE II-A-10(a), WITH
0.25 w/o BORON-STAINLESS STEEL IN CORNERS OF FOUR
CENTRAL FUEL BOXES EXCHANGED WITH FUEL NEIGHBORS

Figure 46

Figure 47

Normalized Average Axial Power Distribution
in Clean Core With 0.25 w/o Boron-Stainless
Steel. Poison Elements Exchanged With Fuel.
Core II-A-10(a)

Box 2

Fe	0.58	0.66	0.66	0.63	0.58	0.52	B-SS
0.98*	0.59	0.67	0.67	0.64	0.59	0.52	0.72*
0.79	0.69	0.69	0.66	0.62	0.52	0.50	0.54
0.98*							0.72*
1.03	0.82	0.76	0.76	0.75	0.65	0.60	0.70
0.98*							0.72*
1.23	0.95	0.88	0.89	0.82	0.76	0.71	0.85
1.40							0.96
1.44	1.13	0.99	B-SS	0.93	0.89	0.88	0.98
1.55							1.07
1.56	1.24	1.22	1.15	1.07	1.06	0.87	1.08
1.70							0.99
1.72	1.39	1.47	1.40	1.23	1.20	1.09	1.00
B-SS	1.90	1.92	1.90	1.82	1.68	1.37	Fe
	1.84	1.99	1.88	1.69	1.51	1.27	

Box 5

B-SS	0.91	0.91	0.90	0.87	0.81	0.68	Fe
1.02	0.93	0.91	0.91	0.90	0.76	0.63	0.72
1.10	0.88	0.85	0.81	0.78	0.75	0.68	0.68
1.17*							0.93*
1.18	0.94	0.87	0.82	0.82	0.78	0.75	0.80
1.17*			B-SS				0.93*
1.25	1.03	0.95		0.84	0.84	0.81	0.90
1.26							1.06
1.35	1.07	0.99	0.98	0.95	0.87	0.89	0.97
1.34*							1.17*
1.37	1.12	1.08	1.03	1.01	0.98	0.97	1.05
1.34*							1.17*
1.27	1.18	1.18	1.12	1.08	1.05	1.02	1.14
Fe	1.29	1.43	1.45	1.43	1.37	1.46	B-SS
	1.33	1.44	1.44	1.36	1.26	1.29	

Box 10

Fe	0.96	1.07	1.09	1.07	1.02	0.97	B-SS
1.00	0.96	1.07	1.01	0.95	0.99	0.92	
1.06	0.90	0.92	0.92	0.90	0.87	0.85	
1.16	0.95	0.92	0.91	0.90	0.88		
1.23	1.01	0.95	0.91	0.90	0.88		
1.22	0.98	0.93	0.91	0.91			
1.24	0.98	0.97	0.93	0.90			
1.24	1.00	0.94	B-SS				
1.27	1.00	0.95					
1.23	0.98	0.96					
1.22	1.02	0.94					
1.21	1.01						
1.20	1.04						
B-SS							

Center of Core

Local Power Distribution Normalized to Average
in Each Box

* Average over neighboring fuel elements.

Box 6

Fe	0.89*	0.89*	0.83	0.70*	0.70*	0.56	B-SS
1.07	0.53	0.89	0.86	0.72	0.64	0.54	
1.08	0.89	0.84	0.73	0.65	0.60	0.50	
1.42*							
1.31	1.00	0.90	0.79	0.75	0.65		
1.42*							
1.49	1.11	1.03	0.92	B-SS			
1.53			0.99				
1.61	1.25	1.11	0.99				
1.75*	1.31*	1.31*					
1.71	1.32	1.18					
1.75*	1.31*						
1.87	1.43						
B-SS							

0.52	Radial Power Distribution	
0.55		
1.24	0.74	
1.24	0.73	
1.76	1.24	0.52
1.70	1.24	0.55

--- Calculated
--- Measured

POWER DISTRIBUTION AT AXIAL PEAK IN CORE III-A-3
FULL SIZE COLD MOCKUP WITH 0.25 w/o BORON-STAINLESS STEEL

Figure 48

Normalized Average Power Distribution
for Individual Fuel Boxes in Full Size
Core With 0.25 w/o Boron-Stainless Steel
Core III-A-3

Figure 51

Normalized Average Axial Power
Distribution in Full Size Core
With 0.25 w/o Boron-Stainless Steel
Core III-A-3

Figure 52

Normalized Average Axial Power
Distribution in Box 10 at Center of
Core in Full Size Core With 0.25 w/o
Boron-Stainless Steel, Core III-A-3

PERCENT DIFFERENCE BETWEEN CALCULATED
AND AVERAGED MEASURED LOCAL POWER
DISTRIBUTIONS AT AXIAL PEAK IN CENTER FUEL
BOX NO. 10 IN FULL SIZE CORE WITH 0.25 w/o
BORON-STAINLESS STEEL. CORE III-A-3.

Fe	+ 1.1	0.0	0.0	- 0.9	0.0	- 1.0	B-SS
- 1.0	0.0	0.0	- 2.1	+ 2.3	0.0	- 3.4	- 1.0
0.0	+ 1.1	0.0	- 3.2	+ 1.1	+ 2.3	0.0	0.0
+ 6.1	- 4.9	- 1.1	- 2.2	0.0	+ 1.1	+ 2.3	- 0.9
+ 2.5	+ 3.0	+ 3.3	B-SS	- 2.2	- 3.2	- 2.1	0.0
+ 1.7	+ 3.2	- 1.0	+ 3.3	- 1.1	0.0	0.0	0.0
+ 3.4	- 3.8	+ 3.2	+ 3.0	- 4.9	+ 1.1	0.0	+ 1.1
B-SS	+ 3.4	+ 1.7	+ 2.5	+ 6.1	0.0	- 1.0	Fe

Figure 53

Box 2

Fe	0.85	0.96	0.95	0.92	0.84	0.81	B-SS
	0.62	0.69	0.69	0.66	0.58	0.53	
0.97	0.83	0.85	0.83	0.76	0.72	0.69	0.89
0.80	0.71	0.65	0.67	0.60	0.56	0.51	0.59
1.19	1.00	0.93	0.86	0.79	0.75	0.80	1.08
1.05	0.84	0.77	0.73	0.70	0.65	0.59	0.72
1.33	1.12	1.05	0.95	0.92	0.92	0.91	1.16
1.19	0.98	0.87	0.84	0.82	0.77	0.71	0.85
1.15	1.31	1.13	B-SS	1.09	1.02	1.07	1.9
1.35	1.09	1.07		0.92	0.87	0.83	0.96
1.68	1.45	1.35	1.30	1.26	1.16	1.19	1.47
1.50	1.25	1.17	1.15	1.11	1.00	0.92	1.06
1.92	1.65	1.51	1.52	1.49	1.40	1.25	1.36
1.71	1.41	1.37	1.32	1.26	1.16	1.11	1.02
B-SS	2.09	2.13	2.02	2.02	1.87	1.65	Fe
	1.95	1.98	1.80	1.72	1.64	1.37	

Local Power Distribution Normalized to Average in Each Box.

Box 5

B-SS	1.21	1.21	1.15	1.10	1.08	0.94	Fe
	0.95	0.93	0.92	0.94	0.82	0.71	
1.18	1.10	1.05	1.03	1.01	0.96	0.92	0.95
1.00	0.94	0.85	0.82	0.78	0.74	0.72	0.73
1.35	1.17	1.12	1.03	1.03	1.00	0.98	1.09
1.09	0.91	0.90	0.84	0.83	0.78	0.80	0.88
1.39	1.24	1.16	B-SS	1.13	1.08	1.07	1.21
1.15	0.99	0.91		0.87	0.86	0.86	0.96
1.56	1.35	1.25	1.17	1.18	1.13	1.11	1.29
1.24	1.07	0.99	0.97	0.97	0.93	0.92	1.03
1.57	1.37	1.32	1.26	1.22	1.20	1.14	1.37
1.29	1.11	1.05	1.01	1.00	0.95	0.95	1.12
1.50	1.43	1.40	1.38	1.32	1.38	1.31	1.43
1.18	1.13	1.16	1.13	1.07	1.06	1.03	1.14
Fe	1.59	1.65	1.70	1.69	1.63	1.56	B-SS
	1.22	1.38	1.40	1.40	1.32	1.29	

Box 6

Fe	1.11	1.24	1.16	1.06	0.92	0.79	B-SS
	0.74	0.90	0.84	0.75	0.66	0.53	
1.31	1.04	1.00	0.94	0.82	0.72	0.66	
1.07	0.84	0.85	0.73	0.66	0.59	0.49	
1.53	1.17	1.05	0.99	0.83	0.77		
1.36	0.99	0.86	0.80	0.70	0.60		
1.72	1.28	1.15	1.07	B-SS			
1.51	1.11	0.96	0.88				
1.83	1.50	1.26	1.17				
1.60	1.25	1.08	0.98				
1.96	1.54	1.40					
1.66	1.37	1.21			0.85		
1.10	1.62						
1.83	1.42						
B-SS							

Box 10

Fe	1.26	1.38	1.30	1.27	1.27	1.31	B-SS
	0.99	1.09	1.07	1.05	1.01	1.01	
1.21	1.23	1.23	1.11	1.11	1.10	1.07	
1.02	1.00	0.92	0.95	0.90	0.89	0.86	
1.49	1.22	1.23	1.05	1.11	1.13		
1.19	0.98	0.91	0.87	0.86	0.82		
1.46	1.28	1.19	1.02	1.09			
1.25	0.95	0.89	0.87	0.84			
1.44	1.24	1.21	B-SS				
1.19	1.01	0.95					
1.50	1.29	1.22			1.23		
1.19	1.01	0.96			0.93		
1.58	1.32						
1.21	1.05						
B-SS	1.57	1.53	1.49	1.47	1.48	1.32	Fe
	1.25	1.25	1.24	1.21	1.14	1.03	

Center of Core

2	Radial Power Distribution	
0.52		
0.56		
5	6	
1.25	0.73	
1.22	0.76	
10	11	12
1.74	1.25	0.52
1.67	1.22	0.56

--- Above Displacers, Below Control Rods
 --- Below Displacers, Below Rods At Axial Peak

POWER DISTRIBUTION AT THE AXIAL PEAK IN CORE IV-D-1, FULL SIZE CORE
 WITH 0.25 w/o BORON-STAINLESS STEEL WITH ALUMINUM-WATER DISPLACERS
 FROM TOP OF CORE TO SEVEN INCHES ABOVE BOTTOM OF CORE

Figure 54

B-SS							Fe
							0.81
		Box 9			0.75		0.95
							1.03
				B-SS			1.01
							0.95
							1.00
Fe	0.90	0.98	1.03	0.97	1.03	0.97	B-SS

Fe							B-SS
0.84							
0.98		0.75	Box 10			0.68	
1.03							
0.98			B-SS				
0.98						0.77	
1.00							
B-SS	1.03	1.04	1.02	1.00	0.94	0.85	Fe

← Center of Core →

Fe	0.81	0.95	0.99	1.03	1.04	1.04	B-SS
							0.98
		Box 15					1.04
							1.02
				B-SS			1.00
							0.97
		0.74					0.97
B-SS							Fe

B-SS	1.04	1.05	1.03	1.00	0.98	0.82	Fe
1.00							
0.99		Box 16			0.75		
1.04							
0.98							
0.94							
0.88							
Fe							

LOCAL POWER DISTRIBUTION AT
AXIAL PEAK (BELOW WATER
DISPLACERS) AT CENTER OF
CORE IV-D-1, SHOWING MEASURE-
MENTS TAKEN AT SYMMETRIC
POSITIONS NORMALIZED TO FUEL
ELEMENT 71, BOX 10

Figure 55

Figure 56

Normalized Average Axial Power
Distribution for Individual Fuel Boxes
in Full Size Core With Displacers
and 0.25 w/o Boron-Stainless Steel
Core IV-D-1

Normalized Average Axial Power
Distribution in Full Size Core With
Displacers and 0.25 w/o Boron-
Stainless Steel, Core IV-D-1

Figure 57

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