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Measurements and Analyses of Control Rod Worths in Large Heterogeneous LMFBR Cores

by

P.J. Collins, S.B. Brumbach and S.G. Carpenter

Argonne National Laboratory
Applied Physics Division
P.O. Box 2528
Idaho Falls, ID 83403-2528

M. Kawashima and S. Suzuki
Power Reactor & Nuclear Fuel Development Corp., Japan

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ABSTRACT

The ZPPR-13 program provides basic physics data for heterogeneous LMFBR cores of 700 MWe size. A number of internal blanket variations were studied and measurements of control rod worths were made in each configuration. The cores are sensitive to asymmetric perturbations and have strong interaction effects between control rods. Calculations with ENDF/B-IV data are within about 5% of experimental values but show systematic variations in accuracy of prediction with location in the core.

INTRODUCTION

The ZPPR-13 program was a joint study by US-DOE and Japan-PNC of radially-heterogeneous LMFBR cores of 700 MWe-size. A principal objective was the study of the effects of changing core/internal-blanket geometry on parameters such as fission distributions and control rod worths. Experience with heterogeneous cores of 350 MWe size,[1,2] led to the anticipation of problems in prediction of spatially varying parameters with current calculation methods and ENDF/B-IV data. Thus, studies of control rod worths, including asymmetric patterns and interaction effects, formed a major part of the program.

Five critical cores in the series had different internal blanket designs. Each core had a large central blanket region, two internal blanket rings and three fuel rings with the same enrichment. The cores were surrounded radially and axially by uranium oxide/sodium/steel blanket zones and by steel reflectors. The cores had a critical mass close to 2500 kg fissile plutonium. Criticality was achieved with each blanket variation by adjusting the fuel enrichment about the nominal value of 0.22. The first four cores followed a sequence from a cylindrical benchmark in 13A, introduction of gaps in blanket rings in 13B/1, addition of discrete blanket sub-assemblies in 13B/3, and addition of control rod positions (CRPs) in 13B/4 to build a more typical LMFBR core. The last core, 13C, returned to unbroken blanket rings but with a marked 60^{o}-symmetry ("snowflake" design). This last core was arranged to have a sensitivity to asymmetric perturbations of the same order as that for a larger, 1300 MWe size, reactor of similar geometry.

MEASUREMENT TECHNIQUES

All measurements of control rod worths in ZPPR-13 were made in subcritical cores using the modified source-multiplication (MSM) technique as described by Carpenter.[3]

DISCLAIMER

A reference core was made subcritical in the range of 10¢ to 20¢ by symmetric removal of fuel. The reactivity of the reference, in cents, was measured by "inverse kinetics analysis" of the power history following a rod drop, with an uncertainty of 0.7%. Control rod worths were measured relative to this reference using the ratios of fission rates taken with a system of 64 in-core fission chambers. Calculated input is provided for the change in "effective source" (in ^{240}Pu) and for "detector efficiency ratios" relative to the reference. The use of sixty-four fission chambers distributed throughout the core ensures that the measured result is insensitive to the accuracy of calculated source ratios and efficiencies for any control rod configuration. Least squares fitting of measured and calculated fission rates, with rejection of detectors in the immediate vicinity of control rods, results in statistical uncertiainties in the range of 0.1% to 0.5% for measurements over a range of -0.3$ to -24$. Small corrections (and uncertainties) are applied due to changes in temperature, ^{241}Pu decay and the interface gap (a feature specific to the ZPR split table machines). The large number of fission chambers proved particularly valuable in ZPPR-13 because of the high sensitivity of the cores to asymmetric perturbations. Use of only a few detectors would lead to additional uncertainties of several percent due to errors in calculated fission distributions.

A further uncertainty component in the measurements arises due to the precise location of all material pieces in the reactor. In ZPPR-13A, repeat measurements of the worths of three control rods were made after an interval of three months during which many other experiments were performed. The repeat measurements differed systematically by up to 0.7% from the initial results, while the relative uncertainty estimates were only 0.2% (1σ).

ZPPR-13B/4 was the only reference core which contained sodium-filled control rod positions (CRPs). In all other cores, the rod worths were measured relative to fuel. Because the ZPPR-13 cores were physics benchmarks and bias factors for a particular design were not sought, measurements relative to CRPs were not required. In addition, measurements relative to fuel were preferable because previous results in ZPPR-9[4] showed C/E biases for worths relative to a few CRPs because of errors in calculated leakages. In several ZPPR-13 cores, additional measurements of the worths of CRPs were made relative to fuel to quantify the calculated errors in the CRP worths.

The mockup control rod design used in ZPPR-13 had four "drawers" completely filled with natural B_4C platelets over the 916 mm height of the core. Axial blanket regions were filled with sodium-containing cans. These rods had a cross sectional area of 122 cm^2. Studies of larger control rods, 183cm^2 in area, were made in ZPPR-13B/1 and ZPPR-13B/4. A series of studies of mockup rods built from 93%-enriched boron carbide pins was made in ZPPR-13B/4. These were similar to rods used in studies in ZPPR-10[4] and ZPPR-11[2]. The measurements studied variations with location in the heterogeneous core design. In order to compare the pin-rod results with results for plate-rods of similar sodium and steel content, measurements were also made using rods built with 50% B_4C plates and 50% sodium plates.

CALCULATION METHODS

The ZPPR-13 data complement ANL studies of control rod worth predictions in conventional and heterogeneos cores of 350 MWe size and in conventional cores of

700-900 MWe size. For consistency, the analysis was made using ENDF/B-IV cross section data with ENDF/B-V delayed neutron data. The processing of the cross sections to account for heterogeneity in the unit cells used a buckling-recycle technique. Group dependent bucklings were obtained from a prior xyz calculation (in 28 groups) and averaged over all occurrences of a given cell type with each reactor zone. This method represents a compromise in dealing with the many individual variations in cell environments that occur in the reactor loadings. The reference calculation method was similar to that used for all control rod worth analysis at ZPPR and to methods employed elsewhere:

- o Diffusion theory in xy geometry
- o Coarse mesh size of 55 mm (one mesh per ZPPR drawer)
- o Eight energy groups
- o Group and energy-dependent axial buckling terms
- o Anisotropic diffusion coefficients generated by the Benoist formulation.

For the principal rod banks in each core, xyz calculations were made in 28 energy groups. These models were used to collapse the data to eight groups and also provided tests of the accuracy of the reference method. A repeat of the xyz calculations in 8 groups provided the axial buckling terms defined to match the leakage at the core/axial blanket interface. Data and bucklings derived for the rod banks were used in all calculations for single-rods. Errors due to groups collapse and buckling treatment in the reference method were between 1% and 2%.

Calculations with a fine mesh spacing and with transport codes are economically feasible in xy geometry with S_4 angular quadrature for complete rod banks to take advantage of the symmetry of the configuration. These calculatons have been made for the principal rod banks in each phase. As is well known, mesh corrections in diffusion theory calculations and transport corrections are of opposite sign and similar magnitude. In the heterogeneous cores these effects compensate to different degrees as a function of location, resulting in changes in spatial predictions.

The calculated worth in dollars is $\Delta k / (k_1 k_2 \beta)$, with k_1 the k_{eff} for the reference core, k_2 the k_{eff} for the core with control rods and β the effective delayed neutron fraction. Although measurements are quite precise, the calculated results have a systematic uncertainty of 5% due to the delayed neutron data.

MEASUREMENTS IN ZPPR-13A

Initial measurements in ZPPR-13 revealed asymmetries in the reactor flux distributions that were not anticipated from previous ZPPR cores. This led to an unusually large number of measurements of fission rates and control rod worths in ZPPR-13A covering all quadrants of the reactor. The worths of each of the 12 rods were measured in the second fuel zone (F2) and in the third zone (F3) as shown in Fig. 1. These provided a sensitive indication of asymmetries in the core (relative uncertainties of about 0.2%). Subsequent investigations showed strong sensitivities to a number of fine details of the loading. Control rod worths were affected by several percent due to:

(i) Local variations in fuel mass, due to piece size distribution and manufacturer, of 0.5% to 1% about the average composition.
(ii) Local variations of up to 0.5% in uranium mass about the average in the internal blankets.
(iii) Changes in uranium content for special blanket drawers used to accommodate the ZPPR safety/shim rods and for the in-core fission chambers.
(iv) A variation in the interface gap of the ZPPR split-table machine. Upon

closure, the two halves of the assembly make contact at the top and leave a very small gap of about 1 mm (over a distance of 4.3 m) at the bottom. This feature produced an increase in rod worths of between 1% and 2% at the top of the core relative to the bottom of the core.

The first three effects were modelled in calculations by using the individual compositions for each drawer in the matrix. (Previous ZPPR analyses used average compositions for each generic drawer loading.) The interface variation was not included in calculations but the measured results were consistent with sensitivity studies for the core. The C/E results for the single control rods are shown in Fig. 1. A variation in prediction of up to 4% is seen between rods in nominally-equivalent positions in the third fuel zone, of which 2% may be attributed to the interface variation.

The analysis of the rod bank worths is given in Table 1. The calculations show a marked discrepancy of 6% between predictions of rod worths in F1 and F3 by diffusion calculation. The discrepancy increases to 8% after transport corrections. It is of interest to find that the mean C/E results for the twelve rods in F2 (1.008) and the twelve rods in F3 (1.038) agree very closely with the results for the rod banks measured at 20$ and 14$ subcritical.

MEASUREMENTS IN ZPPR-13B/1

In ZPPR-13B/1, subassembly-size gaps were created at 60° intervals in the two internal blanket rings. In comparison with 13A, fission rates changed by up to 20% and rod worths changes by up to 40%. The core design is shown in Fig. 2. Measurements in 13B/1 were worths of rod banks and combinations of banks and studies of larger size rods in the center fuel zones and in the blanket ring gaps. Several measurements of single rods were also made.

The results of the principal measurements are given in Table 2. The transport corrected results are available for six cases. Corrections are similar to those shown in Table 1, differing only in detail. We observe:

(i) No difference in accuracy of prediction for the (2x2) and (2x3) size rods in the same location in F2.

(ii) C/Es for rods aligned with blanket gaps are 1% to 2% higher than for rods away from gaps.

(iii) C/E values for rod banks are higher than those in 13A by 2% in F1 and by 1% in F3 (corrected results).

(iv) A radial bias in C/E values of 7% (diffusion) and 6% (transport). The corrected results show a slight improvement over 13A.

(v) C/Es for rods in blanket ring gaps fall between those in adjacent fuel zones.

(vi) Good agreement for the single rods in F3. Rods 22 and 28 indicate a 1.5% bias due to the nonuniform interface gap.

MEASUREMENTS IN ZPPR-13B/3

ZPPR-13B/3 had a similar arrangement to ZPPR-13B/4 with single blanket subassemblies added in the outer fuel ring. No CRPs were in the reference loading and the second blanket ring was thicker than in 13B/4. Measurements in ZPPR-13B/3 were extensive fission distributions and a few single control rod worths. The reactivity due to adding 30 CRPs was measured as the first step in construction of ZPPR-13B/4.

The control rod locations and the C/E results for the single-rod measurements are shown in Fig. 3. The C/E results in the five control rings are 1.00 (R1), 1.00 (R2), 1.01 (R3), 1.03 (R4) and 1.06 (R5). The C/E results are within 1% with those in ZPPR-13B/1 and show a radial bias in prediction of 6%.

MEASUREMENTS IN ZPPR-13B/4

ZPPR-13B/4 modelled a heterogeneous LMFBR design that had been developed by ANL. The core was critical with 30 sodium-filled CRPs inserted. A large number of control rod measurements were made in this core including the worths of single rods, rod banks, banks with missing rods, interaction effects between rod banks and studies of rod-geometry and boron-enrichment effects using pin-type mockup rods. The core configuration is shown in Fig. 4. The control rod locations fall into five rings of six rods each alternately aligned with blanket ring gaps and away from the gaps.

The analysis of the single-rod worths and rod bank worths is given in Table 3. Transport corrected results are available for each of the five complete banks of rods. The interaction data will be discussed separately. The C/E results increase monotonically with radial position. The spread in C/E between Ring 1 and Ring 5 is 6% with diffusion calculations and 8% with tranport calculations. The C/E results for single rods and the rod banks are usually consistent within 1%. The predictions in ZPPR-13B/4 are 1% to 2% lower than results in other cores, where the rods were measured relative to fuel.

Measurements of worths of a pin-type control rods used B_4C with boron of 92% enrichment in ^{10}B. The rod (Fig. 5) was constructed with four ZPPR sodium-filled calandria. The central 32 pins contained enriched B_4C pellets and the outer 32 pins contained stainless-steel rodlets. The worths of the rods were measured in a location in each of the five rings, since similar studies in ZPPR-11[2] showed a variation in prediction with position in the heterogeneous cores. The worth of a larger rod built in six calandria (Fig. 6) was also measured in an extension of CRP15 (denoted CR15E). This rod contained 56 enriched boron carbide pins and 40 steel pins. The worths of plate rods composed of 50% natural B_4C and 50% sodium plates (Fig. 7) were also measured in the pin-rod locations to provide a link to other measurements which used the "solid" B_4C rod.

At this stage, only diffusion theory calculations have been made to derive heterogeneity corrections or "rod bunching factors". The rod worths were calculated first using homogeneous compositions in the rods and then the values were corrected by the ratio of heterogeneous to homogeneous worths. Calculations for the heterogeneous rods used a fine mesh, sixteen points per calandria, modelling each pin region as a square. Five meshes across a drawer were used to model the plate rods. A fine mesh was also used in the surrounding drawers. Quarter-core-plan models were used for economy so that the heterogeneity factors were calculated for two or four rods and assumed to apply to the single rods.

The results are shown in Table 4. The radial variation in C/E is similar to that for the rod banks. Of principal interest is the comparison with the reference plate rod. As shown in the table, the 50/50 plate rods are predicted 1% higher then the reference rods in rings one to three and 2% to 3% higher in rings three and four. The enriched pin rods are predicted between 0.2% and 1.7% higher than the 50/50 plate rods. It is possible that transport calculations for the heterogeneous rods might produce closer agreement. Studies in ZPPR-11 using annular models of pin rods gave bunching factors lower by 1% than those from diffusion theory.[2]

MEASUREMENTS IN ZPPR-13C

Sensitivity calculations made during the design of ZPPR-13C led to anticipation of azimuthal discrepancies in predictions and strong interaction effects. An unusually large number of control rod measurements were made. These included the worths of each individual rod in fuel zones two and three, rod banks and combinations of banks and in the third fuel zone, several combinations of 2, 3, 4, 8, 10, 11 and 12 rods.

The core design and C/E results for the single rods are shown in Fig. 8. The C/E values vary from 0.98 to 1.03 in FR3 and from 0.93 to 0.99 in FR2. Between 1% and 1.5% of this variation is attributed to the ZPPR interface gap.

The results for rod banks including xyz, mesh and transport corrections are shown in Table 5. Two cases of four rods in fuel ring three are included in this series. The first includes CRs (20, 25, 26, 31) disposed about the "x-axis" of the core plan and CRs (22, 23, 28, 29) disposed about the "y-axis". These combinations are not particulatly interesting from the core design viewpoint, but they were chosen to study the azimuthal variation in symmetric patterns amenable to transport calculations. Two observations are of note for the rod banks:

(i) The radial discrepancy in C/E for full rod banks is 9% by the reference diffusion calculations and 10.5% by transport calculations.
(ii) The difference in prediction for rods near the "x-axis" and rods near the "y-axis" of fuel ring three is 8% by diffusion calculations (larger than for the single rods) and is increased to 10% by the transport calculations.

CONTROL ROD INTERACTIONS

Data relating to interaction effects were taken in several ZPPR-13 cores. In ZPPR-13A, the worths of the banks of rods were compared with the sum of the individual rods. The interactions were 43% for 12 rods in the second fuel ring, 44% for 12 rods in the third fuel ring and 50% for six rods in the third fuel ring. For comparison with other cores, the normalized interaction, obtained by dividing by the average single-rod worth in the bank, is more useful. This gives an interaction of 63%/$ for the six rods in fuel ring three compared with values of 30%/$ to 40%/$ in the 350 MWe heterogeneous cores and the 700 MWe conventional cores.[2] These effects are well predicted by the simple diffusion calculations.

Interaction effects between rod banks were measured in ZPPR-13B/1 and ZPPR-13B/4. These varied from -5% for neighboring banks to +25% between the inner ring banks and the outer ring banks and were well predicted.

Table 6 shows another aspect of interaction effects. For each control ring in ZPPR-13B/4, the worths of a single rod are compared, first when adding the rod to the reference core and second when adding the rod when five rods are already inserted in the ring. The latter values are obtained by subtracting the worths of banks of five and six rods. The effective worth of the single rod is increased by 130% in the fourth ring. Calculations slightly underpredict these effects.

SUMMARY

Control rod worths measured in ZPPR-13 cover a wide range, from 30¢ to 1.3$ for single rods, and up to 24$ for banks of twelve rods. The ratios of calculation to experiment are within about 5% of unity but show a marked variation with radial position. The analysis shows similar results for ZPPR-13A and the three phases of ZPPR-13B. Diffusion theory calculations produce a variation in C/E of 5% to 7% between rods in the inner ring and the outer ring. After corrections for modelling and transport effects, the results show a little improvement in consistency between the configurations but the radial discrepancy in C/E values increase to between 7% and 8%. The corrected results for ZPPR-13B/4 are 1% to 2% lower than for the other cores. The difference is attributed to leakage effects in the sodium-filled CRPs which are known to be poorly calculated.

ZPPR-13C was the most "sensitive" core of the series. The separation between the fundamental and the next (azimuthal) harmonic was 1.4%Δk compared with 2.7% (13A) and 3.4% in the other phases. The C/E values for single rods in ZPPR-13C shows a distinct azimuthal variation of about 4%. An even more striking variation of 10% is found between predictions for banks of four rods located near the "x-axis" and near the "y-axis" of the core. Sensitivity studies are being make in an attempt to understand these results.

Calculations for pin-type control rods using boron carbide with boron 92% enriched in ^{10}B gave C/E results up to 1.5% higher than for plate-type rods with 50% volume fraction of natural B_4C and 50 % sodium and steel. The heterogeneity factors calculated for the pin rods by fine-mesh diffusion theory were about 0.89 in all radial positions.

Control rod interactions were, as expected, larger in ZPPR-13 then in the smalle heterogeneous cores or in conventional cores of similar size. These effects were wel predicted by simple diffusion theory methods.

The spatial variations in predictions of control rod worths in ZPPR-13 are correlated with these found in reaction rate distributions and other parameters. Part of the error may be due to cross section processing for the heterogeneous plate cells of the assembly as well as to the ENDF/B-IV data. A calculation for ZPPR-13A is planned using the VIM Monte Carlo code in order to study the cell heterogeneity problems in these cores. These results are seen as an essential step before extrapolations may be made to power reactor designs.

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TABLE I. Worth of Control Rod Banks in ZPPR-13A

	6 CRs in F1	12 CRs in F2	12 CRs in F3
Measured Worth, $	5.73	19.87	13.56
Reference Calculation, $[a]	5.65	20.06	14.16
C/E	0.987	1.010	1.044
Corrections, %			
xyz model	−1.1	−1.1	−1.3
DT mesh	+4.8	+5.7	+4.5
Transport	−4.5	−4.5	−1.9
Corrected C/E	0.980	1.011	1.059

[a]Coarse-mesh diffusion theory in 8 groups, β_{eff} = 0.3294%.

TABLE II. Worth of Control Rods in ZPPR-13B/1

Control Rods[a]	Zone[b]	Measured Worth, $	Reference Calculation[c] Worth, $	Reference Calculation[c] C/E	Corrected C/E
6 CR G (2x3)	F1	7.98	7.92	0.992	1.004
6 CR G (2x3)	B1	13.39	13.41	1.001	1.006
6 CR G (2x2)	F2	13.52	13.78	1.019	---
6 CR G (2x3)	F2	17.78	18.12	1.019	1.033
6 CR A (2x2)	F2	10.58	10.58	1.000	---
12 CR (2x2)	F2	23.46	23.57	1.005	1.011
6 CR G (2x3)	B2	13.44	13.87	1.032	1.045
6 CR A (2x2)	F3	6.52	6.95	1.066	---
6 CR A (2x2)	F3	5.25	5.55	1.056	---
12 CR (2x2)	F3	11.29	11.96	1.059	1.069
CR 22 (2x2)	F3	0.726	0.770	1.060	---
CR 25 (2x2)	F3	0.593	0.623	1.051	---
CR 28 (2x2)	F3	0.738	0.771	1.045	---
CR 31 (2x2)	F3	0.600	0.629	1.049	---

[a]6 CR G means six rods aligned with blanket gaps, 6 CR A means six rods away from gaps. See Fig. 2. (2x2) are reference square rods, (2x3) are larger rods.

[b]F1, F2, F3 refers to fuel zones one, two and three. B1, B2 refer to blanket rings one and two.

[c]Reference calculation 8 groups, coarse-mesh diffusion. Corrected calculations for 28 groups xyz, mesh and S4. β_{eff} = 0.3307.

TABLE III. Worths of Control Rods in ZPPR-13B/4

Control Rods[a]	Rod Ring	Measured Worth, $	Reference Calculation[c] Worth, $	Reference Calculation[c] C/E	Corrected[c] C/E
CR 3 G	R1	1.009	0.981	0.972	---
5 CR G	R1	5.53	5.34	0.965	---
6 CR G	R1	6.52	6.32	0.968	0.986
CR 10 A	R2	1.124	1.096	0.975	---
5 CR A	R2	6.12	5.95	0.973	---
6 CR A	R2	7.86	7.62	0.972	0.996
CR 15 G	R3	0.936	0.927	1.005	---
5 CR G	R3	6.74	6.62	0.982	---
6 CR G	R3	8,67	8.47	0.977	1.007
CR 25 A	R4	0.893	0.908	1.017	---
5 CR A	R4	5.41	5.52	1.019	---
6 CR A	R4	7.47	7.58	1.014	1.042
CR 26 G	R5	0.651	0.670	1.029	---
CR 27 G	R5	0.637	0.658	1.033	---
CR 28 G	R5	0.656	0.675	1.029	---
CR 30 G	R5	0.649	0.658	1.014	---
5 CR G	R5	4.05	4.18	1.032	---
6 CR G	R5	5.15	5.29	1.027	1.063

[a]CR 3 means single roll in position 3. 5 CR G R1 means five control rods in ring 1 aligned with blanket-ring gaps. The single rod measured in each ring is the rod missing in the bank of 5. In ring 5, the missing rod in 5 CR is CR 27.

[b]Reference calculation 8 groups, coarse-mesh diffusion. Corrected calculations for 28 groups; xyz, mesh and S4. β_{eff} = 0.3305%.

TABLE IV. Comparison of Plate and Pin Control Rod Worths in ZPPR-13B/4

Control Rod	Measured Worth (E), $[a]	Calculated Worth, $[b]	Heterogeneity Factor[c]	C/E
Solid B_4C Rods				
CR3	1.010	0.981	1.000	0.971
CR10	1.121	1.103	1.000	0.984
CR15	0.936	0.939	1.000	1.003
CR15E	0.972	0.969	1.000	0.998
CR16	1.054	1.037	1.000	0.984
CR27	0.632	0.657	1.000	1.039
50/50 B_4C/Na Rods				
CR3	0.799	0.790	0.992	0.981
CR10	0.898	0.899	0.993	0.995
CR15	0.748	0.765	0.993	1.061
CR16	0.836	0.854	0.990	1.011
CR27	0.505	0.534	1.002	1.061
Enriched B_4C Pin Rods				
CR3	0.801	0.897	0.890	0.997
CR10	0.902	1.019	0.892	1.008
CR15	0.753	0.864	0.896	1.028
CR15E	0.833	0.963	0.892	1.032
CR16	0.841	0.948	0.889	1.013
CR27	0.518	0.615	0.902	1.071

[a]Relative (statistical) uncertainties are in the range of 0.1% to 0.4%.

[b]Calculations with 8 group xy diffusion theory, 1 mesh per drawer, β = 0.3305%.

[c]Calculated with diffusion theory in xy geometry.

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TABLE V. Worths of Control Rods in ZPPR-13C

	6 CR in F1	12 CR in F2	12 CR in F3	CR (20, 25, 26, 31)[b]	CR (22, 23, 28, 29)[c]
Measured Worth, $	4.65	16.48	16.69	6.94	1.178
Reference Calculation, $[a]	4.42	16.25	17.39	7.40	1.162
C/E	0.951	0.986	1.042	1.065	0.986
Corrections, %					
xyz model	-2.0	-1.7	-0.8	-0.2	-3.9
DT mesh	+5.2	+5.7	+4.2	+4.5	+4.2
Transport S4	-3.4	-3.6	-2.2	-2.5	-1.9
Corrected C/E	0.949	0.990	1.054	1.083	0.970

[a]Coarse-mesh diffusion theory in 8 groups, β_{eff} = 0.3295%.

[b]Four control rods in F3 near the x-axis.

[c]Four control rods in F3 near the y-axis.

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TABLE VI Variation in the Worth of a Single Control Rod in ZPPR-13B/4

	Rods Present in Core	Measured Worth (E), $	Calculated Worth (C), $
Ring 1	5 CRs	1.00	0.98
CR 3	None	1.01	0.98
	Change	-1.1%	-0.1%
Ring 2	5 CRs	1.74	1.67
CR 10	None	1.12	1.10
	Change	+55%	+52%
Ring 3	5 CRs	1.93	1.85
CR 15	None	0.94	0.94
	Change	+106%	+96%
Ring 4	None	2.06	2.07
CR 25	Change	0.89	0.91
		+131%	+127%
Ring 5	5 CRs	1.10	1.11
CR 27	None	0.64	0.66
	Change	+73%	+69%

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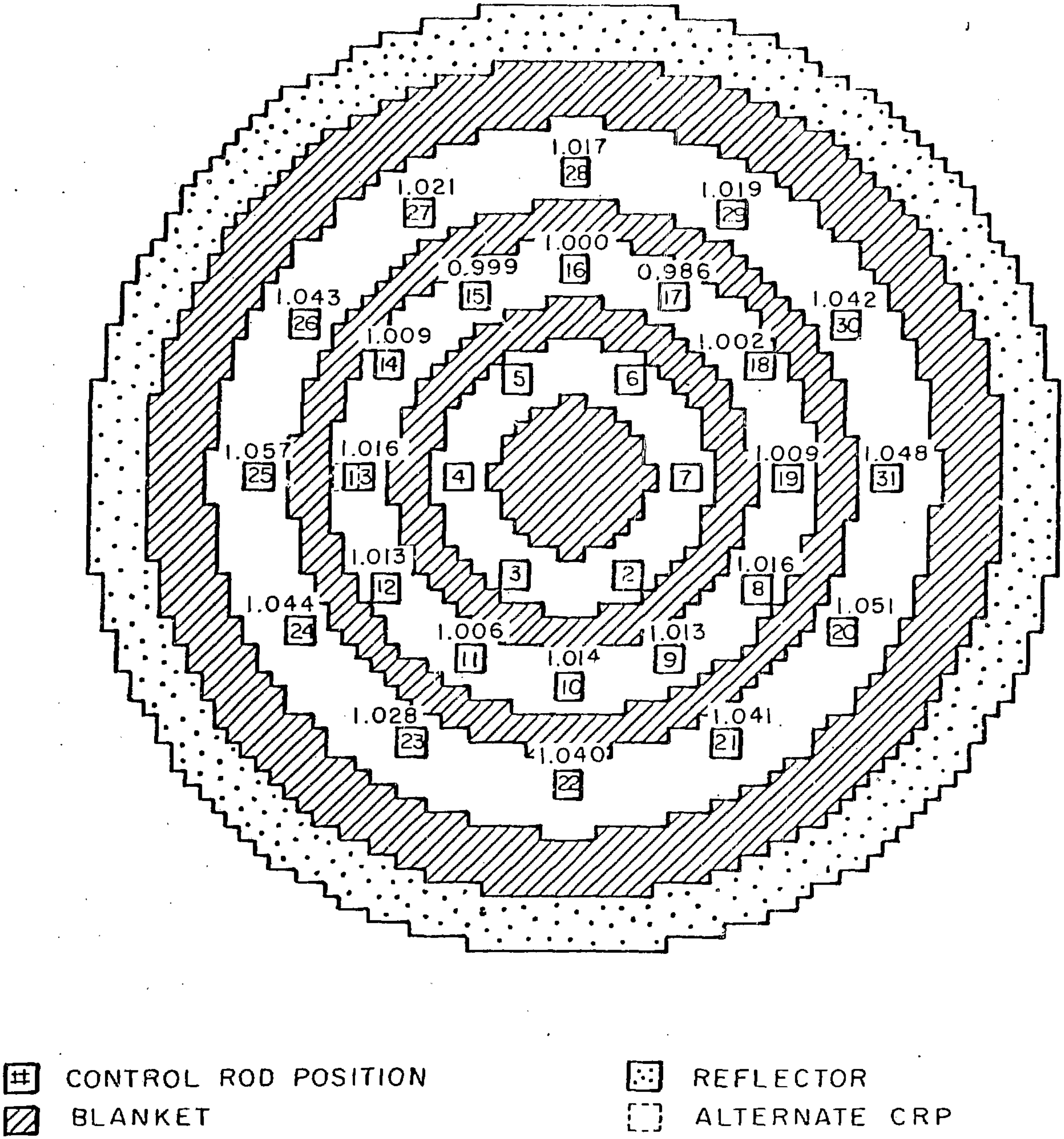

Fig. 1. Core Design, Rod Locations, and C/E Values for the Worths of Individual Rods in ZPPR-13A.

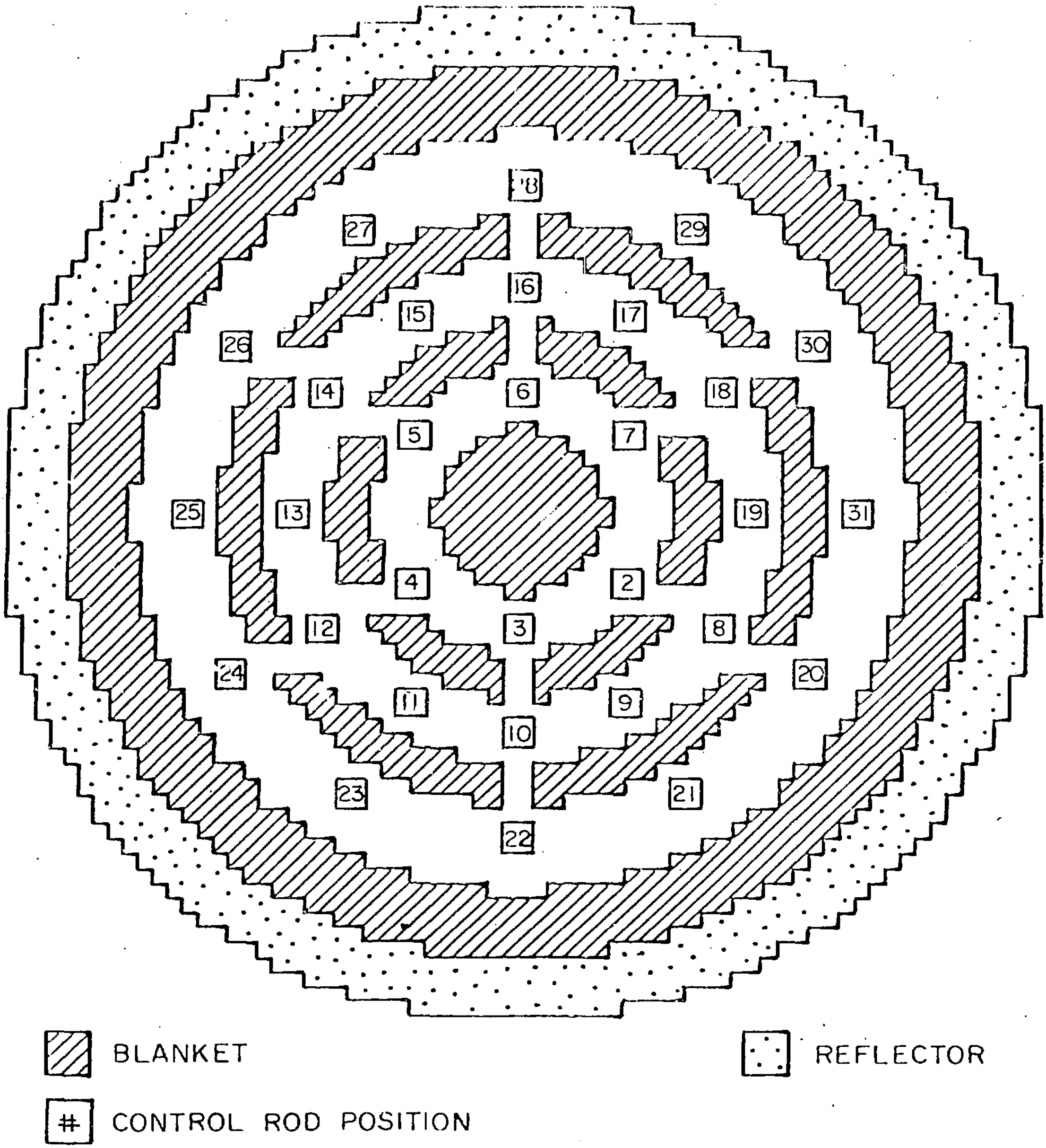

Fig. 2. Core Design and Locations of Two-by-two Control Rods in ZPPR-13B/1.

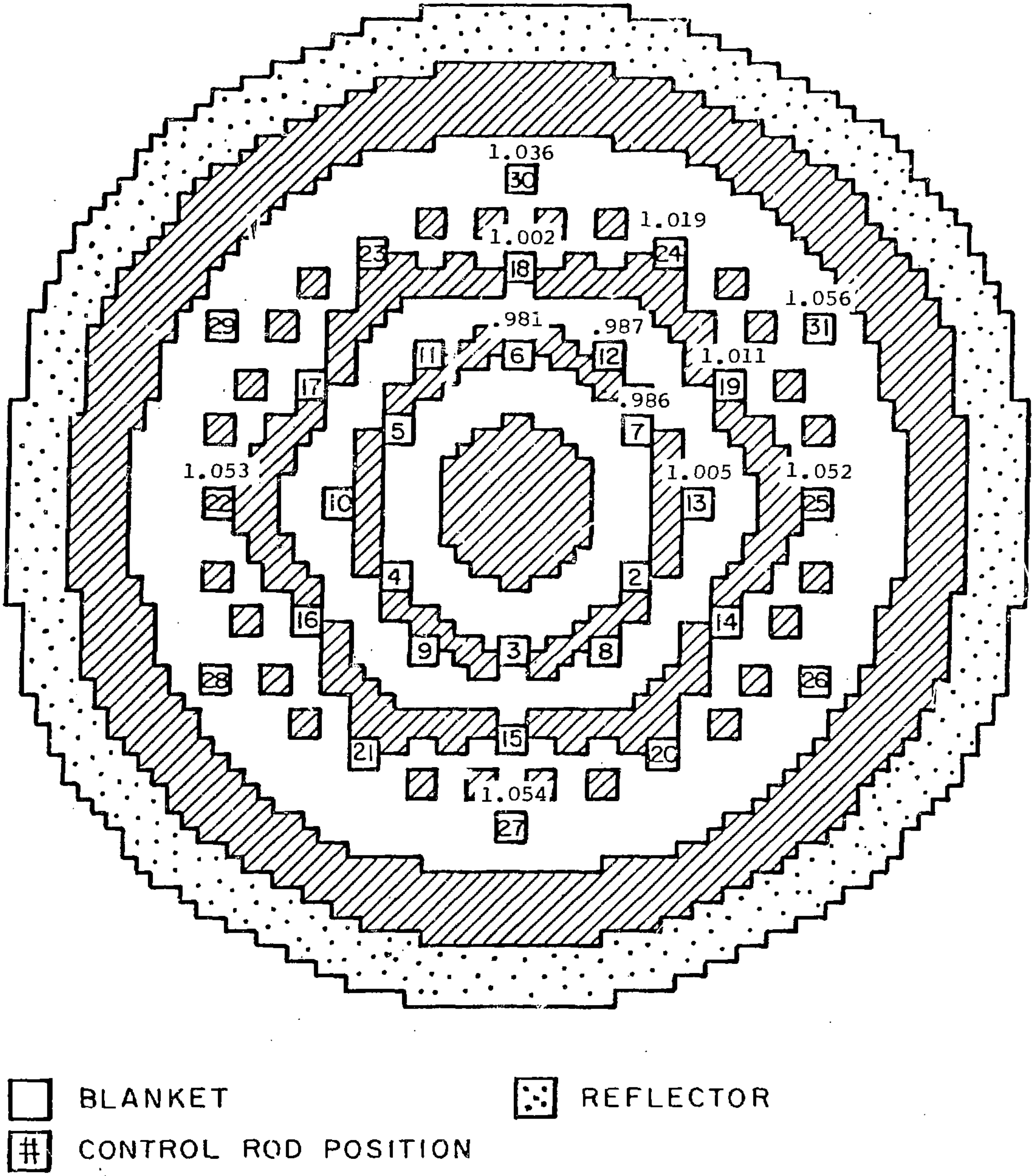

Fig. 3. Core Design, Control Rod Locations, and C/E Values for Single Control Rods in ZPPR-13B/3.

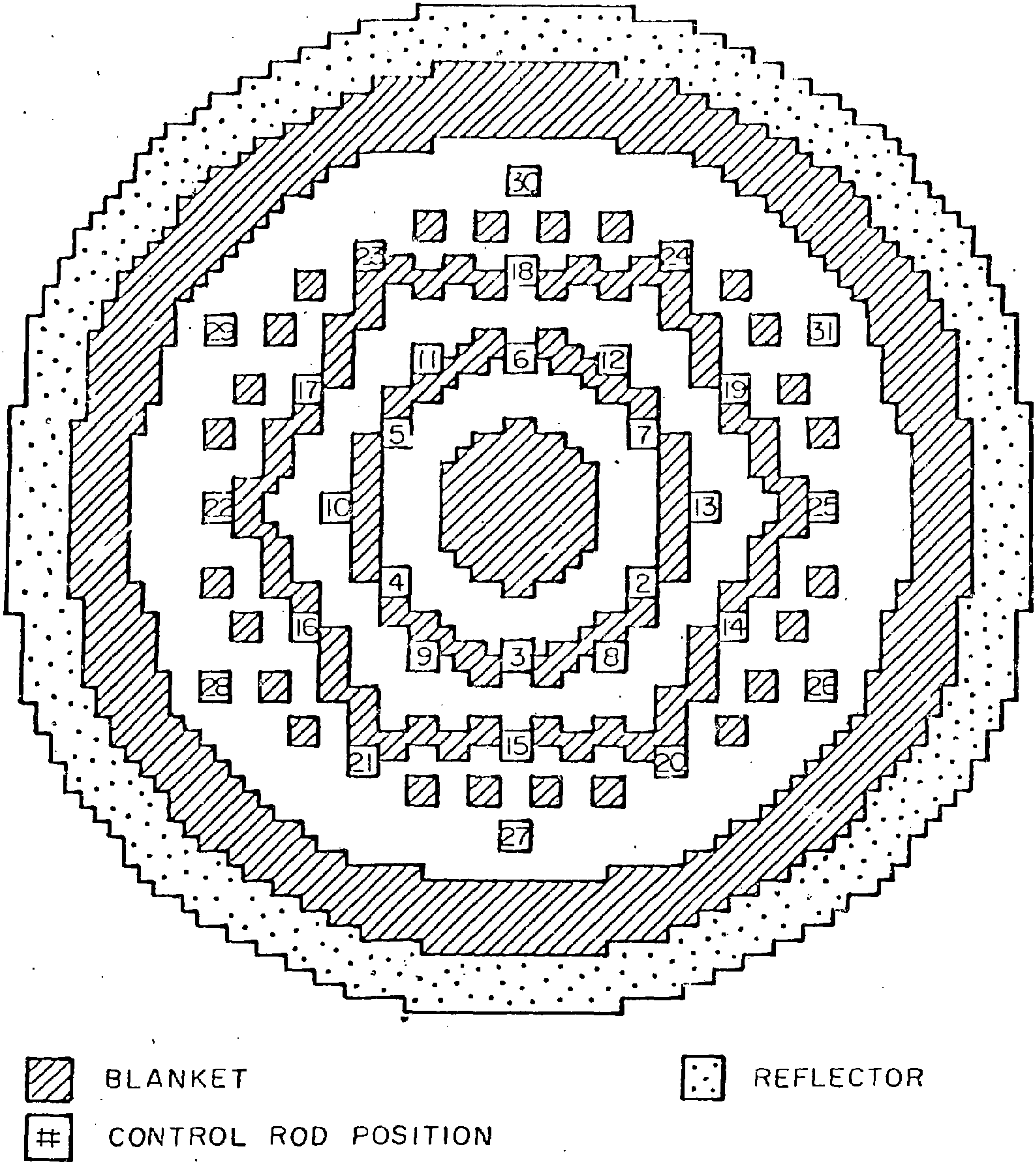

Fig. 4. Core Design and Control Rod Locations in ZPPR-13B/4.

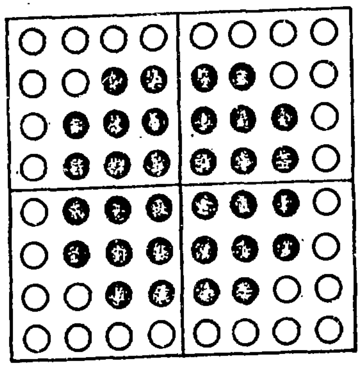

Fig. 5. Loading Pattern for the Thirty-two Pin Control Rod in ZPPR-13B/4. Solid Circles Represent 92%-enriched $^{10}B_4C$, and Open Circles Represent Stainless-steel Pins.

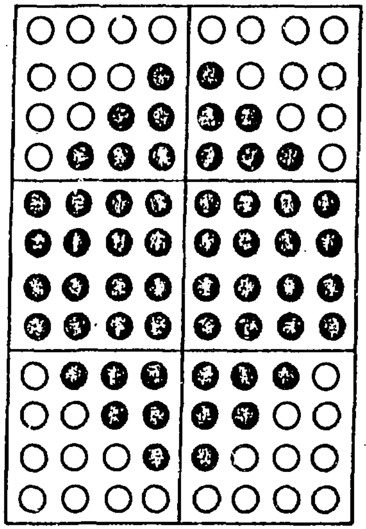

Fig. 6. Loading Pattern for the Fifty-six Pin Control Rod in ZPPR-13B/4. Solid Circles Represent 92%-enriched $^{10}B_4C$, and Open Circles Represent Stainless-steel Pins.

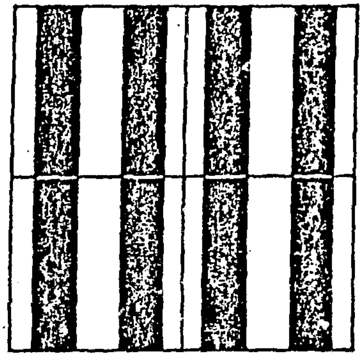

Fig. 7. Loading Pattern for the 50% B_4C, 50% Sodium Plate-type Control Rod in ZPPR-13B/4. Solid Rectangles Represent Natural B_4C Plates and Open Rectangles Represent Sodium Cans.

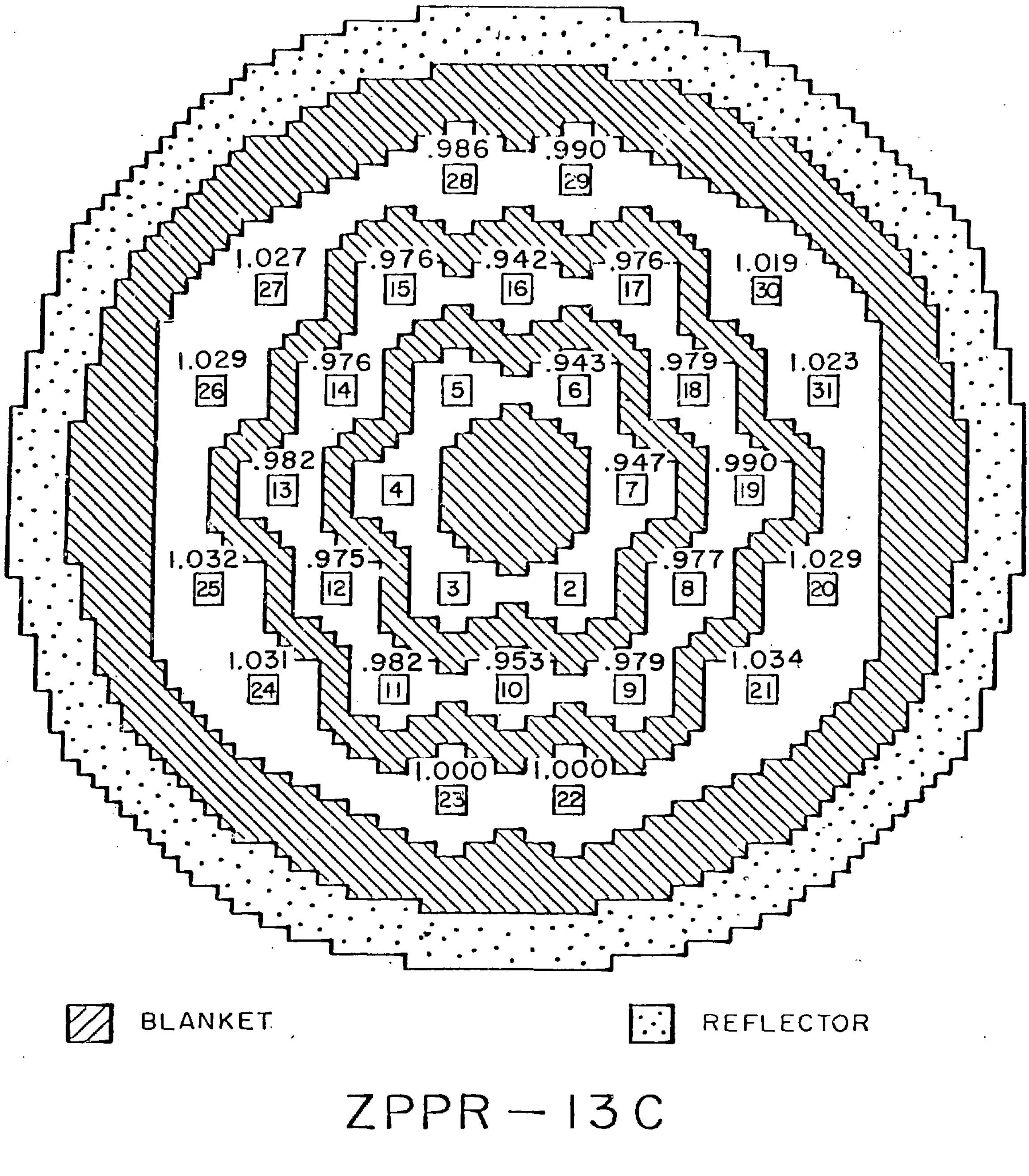

Fig. 8. Core Design, Control Rod Location, and C/E Values for Single Control Rods in ZPPR-13C.