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**THE JUPITER-III
PROGRAM:
ANL ANALYSIS OF
ZPPR-17**

**S. B. Brumbach, P. J. Collins,
G. L. Grasseschi and
R. W. Schaefer**

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S. B. Brumbach, P. J. Collins, G. L. Grasseschi and R. W. Schaefer

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ABSTRACT

The ZPPR-17 assembly was part of the JUPITER-III cooperative program between the U.S. DOE and PNC of Japan. The assembly was designed to study the neutronic behavior of a large, axially heterogeneous, liquid-metal-cooled reactor. The unique feature of the assembly was an internal blanket region in the axial center of the core extending two-thirds of the core radius. Assembly variants with 25 control rod positions and with 13 half-inserted control rods were built. This report describes in detail the results of measurements and analyses of ZPPR-17. The measurements emphasized reaction rate distributions, and gamma dose measurements were included. Additional measurements were control worth, sodium void worth, and reactivity coefficients associated with small material motions in assembly expansion and bowing.

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1. INTRODUCTION

ZPPR-17 was the first of two assemblies in the JUPITER-III Cooperative program between the US DOE and PNC of Japan. The ZPPR-17 assembly was designed to study the neutronic behavior of a large, axially heterogeneous, liquid-metal-cooled reactor (LMR). The ZPPR-17 composition represented mixed plutonium- and depleted uranium-oxide fuel with sodium coolant and stainless steel structural material. The unique feature of the assembly was the presence of an internal blanket region in the axial center of the core extending two-thirds of the core radius.

There were three phases in the ZPPR-17 program, each represented by an assembly configuration, designated A, B, and C. The phase A configuration was a physics benchmark containing neither mockup control rods (CRs) nor control rod positions (CRPs). Phase B contained 25 CRPs. In phase C, 13 of the CRPs contained half-inserted CRs. The core layout, including CRP locations, is given in Fig. 1.1.

This report describes in detail the results of the ANL analyses of the three phases of ZPPR-17. The measurements were conducted between January and July, 1987. Assembly descriptions, measurement results, and many analysis results have been presented in the ZPPR Progress Report series.¹⁻⁵ Other reports describe results from earlier JUPITER programs. JUPITER-I results for conventional cores are in references 6 and 7 and JUPITER-II results for radially heterogeneous cores are in reference 8. This report was compiled primarily for discussions at the JUPITER Analysis Meeting to be held at ANL-West between September 13 and 15, 1988.

The experimental program was designed to emphasize those parameters most sensitive to the presence of the internal blanket. Consequently, power distributions were measured in unusual detail with numerous axial distributions and radial distributions at different axial heights. Detailed gamma dose distributions were also measured. As CRPs and later CRs were added, their effects on power distribution were measured by repeating the foil and TLD irradiations made in ZPPR-17A.

Control rod worths were also an important part of the program. The control rod worth measurements in ZPPR-17A were a series of studies of rods of varying size and boron enrichment and the worth of CRP banks. In 17B, 20 control rod measurements were made including rod banks, combinations of rod banks and banks with missing rods. In 17C, the worths of secondary control rods were measured relative to a core with the primary rods half inserted. Measurements of axial worth profiles of B₄C rods were made in 17B and 17C.

Sodium void worths were measured at several radial locations, with emphasis on the axial worth profile for sodium. In addition to traditional zone voiding methods, a new device called the plate-column oscillator was used in the void-worth experiments.

Additional experiments discussed here concerned reactivity coefficients associated with small material motions in assembly expansion and bowing. New experimental methods and devices were employed.

Calculations were made with ENDF/B-V.2 cross section data. Previous JUPITER analysis has been with ENDF/B-IV. Cross sections were processed for cell heterogeneity with both the commonly used "asymptotic cell" models and with a "buckling recycle" technique. Most reactor calculations were made with xyz-geometry models in either 21 or 6 energy groups with diffusion theory. A number of calculations were also made with transport methods in xyz geometry.

The fundamental to first (azimuthal) eigenvalue separation for ZPPR-17B was calculated to be 4.0% Δk . This is somewhat less than the 5.3% for the similar-size conventional core ZPPR-9, but greater than the 2.7% for the radially heterogeneous ZPPR-13A. Although ZPPR-17 was an axially heterogeneous core, the eigenvalue separation for the first axial harmonic was about 20% Δk . Consistent with these modest eigenvalue separations, kinetics experiments in ZPPR-17 showed only minor decoupling effects similar to those seen earlier in ZPPR-9.

Fig. 1.1 Core Layout of ZPPR-17.

2. DESCRIPTION OF THE ASSEMBLIES

The ZPPR-17 assemblies had distinct regions of internal blanket, core, outer radial blanket, axial blanket and radial and axial reflectors. There were two basic types of core cells; those containing either one or two columns of fuel. Reactivity was adjusted by changing the ratio of single- to double-fuel-column drawers. Both core cell types had versions with and without internal blanket regions. The internal blanket occupied the first 152 mm of the drawer. The radial extent of the internal blanket was about 870 mm. For convenience, that radial portion of the core containing internal blanket is called "inner core" and that portion without internal blanket is called "outer core." The ratio of single to double-fuel-column drawers was essentially constant throughout the core, simulating a single fuel enrichment.

The pattern of single- and double-fuel-column drawers was essentially the same in the inner and outer core regions resulting in a uniform fuel enrichment throughout the core. The single-fuel-column cell without internal blanket is shown in Fig. 2.1 and the double-fuel-column cell is shown in Fig. 2.2. The corresponding cells with internal blanket segments are shown in Figs. 2.3 and 2.4. Only the standard ZPPR Pu-U-Mo alloy fuel was used. The core volume including internal blanket was 5518 liters. The volume of the internal blanket was 741 liters.

Detailed descriptions of ZPPR-17A were reported in reference 1; ZPPR-17B in reference 2 and ZPPR-17C in reference 3. A summary of the salient features of the three assembly variants is given in Table 2.1.

TABLE 2.1 Characteristics of the ZPPR-17 Reference
Critical Configurations

	<u>ZPPR-17A</u>	<u>ZPPR-17B</u>	<u>ZPPR-17C</u>
^{239}Pu Mass, kg	2254	2230	2430
Total Fissile Mass, kg	2300	2274	2478
^{238}U Mass, kg			
Core Region	12,632	12,221	12,787
Internal Blanket	2370	2213	2213
Total Fuel Drawers	3560	3360	3360
Total Drawers with Internal Blanket	1576	1472	1472
CR/CRP Drawers	0	200	200
Enrichment, %	14.9	15.2	15.7
Fraction of Double- Fuel-Column Drawers	0.337	0.400	0.526

Fig. 2.1 Loading Pattern for Single-Fuel-Column Drawers without Internal Blanket.

Fig. 2.2 Loading Pattern for Double-Fuel-Column Drawers without Internal Blanket.

Fig. 2.3. Loading Pattern for Single-Fuel-Column Drawers with Internal Blanket Segment in ZPPR-17.

Fig. 2.4. Loading Pattern for Double-Fuel-Column Drawers with Internal Blanket Segment in ZPPR-17.

3. EXPERIMENTAL TECHNIQUES

Most of the experimental methods used in ZPPR-17 were the same as those described for the JUPITER-II program.⁸ The descriptions provided in reference 8 are applicable for k-effective, reaction rates, control rod worths, sodium void worths and small sample worths using the axial and radial tube oscillators. A minor modification was made to the way uncertainties are evaluated for reactivities produced by the LSFIT path of the McCRUNCH code. This modification was described in reference 4. Also, for the foil reaction rate measurements, the gamma ray counting system was recalibrated in irradiations in ZPPR-17.

Some new experimental techniques were developed at ZPPR since the JUPITER-II program. These new techniques have been aimed at evaluating the reactivity coefficients associated with material movements such as radial and axial expansion and assembly bowing. In addition, a new device called the plate-column oscillator drawer was developed to measure the worth of various core components. These new devices are described below. A brief description of the gamma ray dose measurements is also provided.

3.1. Plate-Column Oscillators

The plate-column oscillator is a new device developed at ZPPR which moves a column of plates axially within a drawer to provide material worth information for reactor constituents. In ZPPR-17, these devices were used to measure worths of fuel, U_3O_8 , Fe_2O_3 and sodium.

The oscillators are made from two normal 920 mm-long drawers welded together at their ends to form a single 1.84 m-long drawer. The front of this drawer can accommodate up to 660 mm of normal core and axial blanket material. The back of the drawer contains a small computer-controlled electric motor, a position encoder, and a coupling to a drive mechanism which is in turn attached to a column of material in the front of the drawer. This system allows the column to be oscillated up to 660 mm axially within the drawer. To assure free movement of the column, one 3.18 mm-wide column of material is normally omitted from the drawer loading

and a tray is introduced as a guide for the moving column. The tray is made from a 0.127 mm-thick, 50 mm wide strip of stainless steel. Plates in the moving column are normally held together with mylar tape. Further details of the plate column oscillators used in ZPPR-17 are provided in reference 3.

3.2. Axial Expansion Oscillator

The axial expansion oscillator is a device which simulates uniform axial expansion by creating a few discrete gaps between segments of a special drawer. The device can fit in almost any matrix tube. In the ZPPR-17 measurements, three 6.35 mm-wide gaps were created in the core region of the drawer. The axial distances from the matrix interface to the points where the drawer segments separate were 152 mm, 305 mm and 457 mm. The width of the gaps was limited by attaching the drawer segments together with mylar tape. The gaps were created by pulling on the back end of the drawer while the front end was anchored. Axial motion was provided by a double-acting air cylinder with a connecting rod that attaches to the back of the last drawer segment. A linear potentiometer measured the total expansion.

Statistical uncertainties of the axial expansion reactivities derived in ZPPR-17 were less than 1%. However, measurements in previous cores indicated an uncertainty of about 3% based on reproducibility in repeat measurements.

3.3. Bowing Oscillator

The bowing oscillator is a new device which simulates fuel assembly bowing by shifting the core section of one drawer about 1.4 mm within the matrix tube. Air driven cams under the four corners of the moveable drawer segment push the drawer up into the cooling air gap. Motion is measured by linear potentiometers in three of the drawer corners. Uncertainties of the bowing reactivity measurements made in ZPPR-17 were 3.5%. More detailed descriptions of the device and the ZPPR-17 experiments are given in reference 3.

3.4 Gamma Ray Dose Measurements

Gamma ray doses were measured in ZPPR-17 as a function of axial and radial location using stainless-steel-encapsulated thermoluminescent dosimeters (TLDs). The LiF TLDs were 1 x 1 x 6 mm and were placed in holes in stainless steel cylinders. The TLDs record neutron capture in the LiF as well as gamma dose in the steel cylinders. Calculation and experiment are compared for this "total dose". Using the calculated fluxes and the neutron sensitivities of the TLDs gives estimates of the neutron contribution to the TLD excitation of 18% in the core and 22% in the blanket.^{19,20}

Measured gamma dose varies significantly with the specific TLD location in a drawer. In-cell variations were calculated in ZPPR-17 and the results used to provide "cell averaging factors" to convert the dose at a specific TLD location to an average dose over the cell. Variations through a cell were dependent upon neighboring cell-types and multi-drawer cell models were used to obtain the most appropriate factors. Cell factors varied between 0.96 and 1.10. Several in-cell measurements were also made which verified the accuracy of the calculated distributions.

Uncertainties in relative dose measurements are about 2% and an additional 2% uncertainty is due to calibration. Calibration of the TLDs in their stainless steel sleeves is made with a ⁶⁰Co source.

4. CALCULATION METHODS

4.1 Introduction

Calculations for ZPPR-17 used ENDF/B-V.2 nuclear data. The cross sections were processed through the MC² and SDX codes, using methods consistent with those used for recent analysis of ZPPR and for benchmark cores, to produce a 21 group cross sections library for reactor calculations.

Two cross section libraries were produced for ZPPR-17. The first used asymptotic cell processing as described in Section 4.2. An improved cross section library used group-dependent bucklings in the cell calculations with a method analogous to that used for analysis of ZPPR-13 (buckling-recycle). This method and comparisons with analysis using asymptotic cell processing are described in Section 4.3.

The improved cross sections were used for analysis of reaction rates, small sample worths and related data. Calculations of control rod worths and sodium void reactivity used the original asymptotic-cell data since the analysis was quite advanced (in a temporal sense) when the newer cross sections became available.

The reference calculation method for ZPPR-17 used an xyz model with nodal diffusion and nodal transport solutions. The models used detailed compositions for each drawer master (with the exception of asymmetric fission chamber and thermocouple drawers) and were set up automatically from the ZPPR database. Calculations were also made using finite-difference diffusion in xyz and rz geometry, using the TWODANT transport code and using the TRITAC xyz transport code from Osaka University. Details of the calculation models are given in Section 4.4.

Because of the large number of control rod measurements and the additional calculations required to obtain detector efficiencies and effective source rates, for ZPPR-17A and -17B these calculations were made in 6 group condensations of the 21 group library. Group collapse was made

using xyz models for each series. Details are given in the control rod sections of this report.

4.2 Multigroup Cross Section Processing

Calculations of the ZPPR cell heterogeneities used a 230 group intermediate library with the SDX code and collapse of the cell-average data to 21 groups was done in a one-dimensional diffusion model. The energy structure of the cross section libraries is shown in Table 4.1.

The 230 group library was collapsed from a single spectrum calculated with the MC²-II code in 2082 groups. This used a homogeneous composition derived for a mixture of single- and double-fuel column drawers in the proportion 65:35, and employed a buckling search to critical ($B^2 = 14.52 \text{ M}^{-2}$). Input parameters chosen were consistent P1 spectrum calculation, "screened" diluent isotopes (Na, Fe, Cr, Ni, Mn, Mo), 20 resolved resonances tested for overlap treatment and thermal group cross sections included from the dataset THERM.

The cell calculations with SDX used standard modelling in one-dimension, preserving mid-cell densities and thicknesses for heavy metal plates. Following treatment of resonance shielding and flux fine structure, the actual homogeneous compositions were used in the final flux calculations for group collapse. The calculations were made for infinite arrays of cells in each case. The following cells were processed:

- (i) Single-column fuel - normal cell (SCFN), voided cell (SCFV)
- (ii) Double-column fuel - normal cell (DCFN), voided cell (DCFV)
- (iii) Internal blanket - normal cell (IBKN), voided cell (IBKV)
- (iv) Axial blanket - normal cell (ABKN), voided cell (ABKV)
- (v) Radial blanket - normal cell (RBKN)
- (vi) Single-column fuel cell with boron blade (PSR)

The PSR cell was used to obtain B_{∞} data averaged over a drawer to model shim rods inserted for reaction rate measurements. The fuel cells were processed with a buckling search to critical and the blanket cells were

processed with a zero buckling. Axial reflectors were treated as homogeneous regions, designated ARI for the 5 in. iron block in the drawers and ARS for the 6 in. steel block loaded in the matrix.

Collapse of the cross sections from 230 groups to 21 groups was done with a slab model of the inner core region shown in Fig. 4.1. The arrangement of cells in the inner core region, SCFN, DCFN, SCFN, was chosen to simplify the collapse procedure within the SEF1D Module of the SDX code. Subsequent reactor calculations used cross sections collapsed in zone 2 for all single-fuel-column drawers and cross sections collapsed in zone 3 for all double-fuel-column drawers. Cross sections for sodium voided cells were collapsed in the same model but with cross sections IBKV, SCFV, etc., used in the internal blanket, core and axial blanket - i.e. in completely voided spectra. Cross sections for the radial blanket and radial reflector were also collapsed in the same model, with these cells replacing the axial blanket and reflector.

Anisotropic diffusion coefficient modifiers were generated by the Benoist method for the cell types listed above, including voided cells for the internal blanket, fuel drawers and the axial blanket. These cell models used plate compositions averaged over the lattice pitch rather than mid-cell compositions.

4.3 Improved Cross Sections for ZPPR-17

The effort to generate a new set of broad group microscopic cross sections for ZPPR-17 was stimulated by disappointing C/E results for a number of experiments. One problem was a shift in reaction rate C/E between core and blanket and even between single-fuel-column (SFC) and double-fuel-column (DFC) drawers within the core. Similarly, there was a mismatch between core and blanket small-sample worth C/Es for some traverses.

Some theoretical considerations suggested that improved cross sections might help remedy the C/E problems. The original cross sections accounted for the close proximity of different cell types only at the stage

of collapsing from 230 to 21 energy groups; in the resonance calculations and the cell homogenization the cells were treated as asymptotic. In the case of blanket cells the zero buckling eigenvalue approach used for the homogenization leads to a substantially distorted in-cell flux distribution. In addition, the particular models used for two blanket cells resulted in excessive ^{238}U resonance self shielding by equivalence theory.

For the new cross sections the buckling recycle approach was used. This is the same method as used for the radially heterogeneous assembly ZPPR-13. (The available alternative, one-dimensional multidrawer cell models, is considerably more difficult to implement and, because of the many combinations of drawer types in multiple dimensions, probably no more accurate.) For each cell type the group-dependent bucklings, averaged over all occurrences of that cell in ZPPR-17A, were extracted from a DIF3D XYZ geometry, 21 group, nodal diffusion theory assembly calculation.

With cell interaction accounted for by bucklings, each cell type was processed separately with the SDX code. The bucklings entered into the SDX calculations of resonance self shielding, cell homogenization and energy collapse from 230 to 21 groups.

Additional steps were taken to improve the cross sections. A 230 group base library was created for the SDX blanket cell calculations. This was done using the internal blanket composition and bucklings in the MC²-2 code. (The original base library was still considered appropriate for the core cells.) Also the blanket cell models were redefined to minimize the equivalence theory resonance self shielding errors. In addition a heterogeneous resonance self shielding treatment was used for sodium in the core and blanket cells. (Originally it was homogeneous.)

Cell average, plate and detector cross sections were saved for each of the cells. The cell average cross sections have the same names as their counterparts in the original set. The first two characters of the name identify the isotope and the next two identify the cell. For example, cell average ^{238}U in the internal blanket is called U8IB. Detector cross section names have H as a fifth character (e.g., U8IBH) and plate cross

section names have a number identifying the plate as a fifth character (e.g., U8IB2). Cell average cross sections are used with homogenized cell models. Plate cross sections are used for sodium and heavy metal isotopes in plate-by-plate cell models. Detector cross sections are used for the remaining isotopes in plate cell models, and also are often the best choice available for small-sample worths and foil reaction rates.

For the ^{239}Pu small sample and activation foils in blanket and reflector regions, detector cross sections are not a good choice. This is because resonance self shielding in the foil and sample are important there, while the Pu detector cross sections have no self shielding there. Accordingly, appropriately shielded cross sections were produced for Pu activation foils (named P9IBR) and for the reactivity sample PU-30. The activation foil cross sections were created using a slab foil, with the correct mean chord length, surrounded with a large region of homogeneous inner blanket and imposing the inner blanket bucklings.

There were two attempts to generate cross sections for PU-30. The first followed the same procedure used for the activation foils, yielding cross sections for ^{239}Pu , ^{240}Pu and ^{241}Pu whose names end in IBW. When used with a broad group sample size correction factor (from the SARCASM code) they gave worths that appear to be overshielded. To overcome this, cross sections were generated that have all the size effects built into them; they are the cell average cross sections from a cell that had PU-30 represented as an infinite cylinder at the center, surrounded by a large annulus of homogeneous blanket and with the inner blanket bucklings imposed (names end in IC).

Boundary region cross sections also were created for some cells near region interfaces. Group-dependent bucklings were extracted for each of the following cases: a SFC cell next to the inner blanket, a DFC cell next to the inner blanket, an inner blanket cell next to the core and an inner blanket cell not near the core. SDX was then rerun for these cells with the boundary bucklings. For these cases characters three through 5 of the cross section name are used to identify the cell. For the cases cited above the characters are SFN, DFF, IBE and IBI, respectively.

The effect of the new cross sections on eigenvalue is shown in Table 4.2 for three models of ZPPR-17A. The first model includes only the central 3x3 array of drawers, with reflective boundary conditions at X and Y boundaries. This is an economical testbed. The other two models use a full assembly representation, one with diffusion theory and the other with transport theory. With all three models it is seen that the new region average cross sections lower the eigenvalue by a little more than 0.1%. When the boundary region cross sections are also included in the first model, the effect is cut in half. The boundary cross sections are cumbersome to use in full assembly models, and their impact does not appear to be large enough to be worth the effort. In any case the cross section effect on eigenvalue is small.

Axial reaction rate traverses were computed for the three cross section options with the first model. The results are given in Table 4.3. Except for ^{239}Pu fission (F9) there are modest changes in the inner blanket and almost no change elsewhere. For F9 there is a large change in the inner blanket, which is due to the resonance shielding treatment discussed earlier. This is illustrated further by Table 4.4, which shows the sensitivity to the reaction cross section type used in the inner blanket.

Using the nodal transport model of the full assembly, reaction rate C/Es were computed with both the old and the new region average cross sections. Generally the C/Es improved with the new cross sections, but not as much as had been hoped. The difference between SFC and DFC C/Es was reduced from 0.9% to 0.2% for F9, reduced from 2.4% to 1.8% for ^{238}U fission and increased from 2.8% to 3.6% for ^{238}U capture. There were similar changes in the C/E difference between the inner blanket and the core.

Small sample worth traverses also were computed with both cross section sets. Generally the worths changed one to two percent. Pu-30 worth in the blankets and reflectors changed much more because the sample cross sections in the new set were used.

In summary, the new cross sections generally have removed only a fraction of the C/E problems. One conjecture as to why the improvements

were not greater has to do with neutron leakage between different cells. Although the region-averaged, group-dependent bucklings should produce a realistic collapsing spectrum and, at least for the blanket, an improved in-cell flux distribution, they do not force preservation of leakage between unlike cells. As currently implemented, the multidrawer cell option in the SDX code does not do this either. This is an area that probably warrants some investigation.

4.4 Reactor Models

The reference calculation model for ZPPR-17 assumes 1/8-core symmetry (one-quarter xy, one-half z). The model follows the reactor loading in detail with the compositions of the principal drawer masters included individually. Loadings of fission chamber and thermocouple drawers were not represented since these were not loaded symmetrically in the reactor. These drawers were assigned compositions of the appropriate standard drawers. The model was constructed automatically from the ZPPR database through the NIPPER code.

Figures 4.2 to 4.4 show the xy planes of the calculation model. The entries in each matrix position are the individual drawer master numbers. Axial composition slices were chosen at 153.16 mm (internal blanket boundary), at 508.76 mm (core/axial blanket interface), at 788.16 mm (axial blanket/reflector interface), at 918.21 mm (iron block reflector to back of drawer), at at 1070.61 mm (stainless steel reflector). The zone boundaries are shown in an rz diagram of ZPPR-17A fig. 4.5.

Average zone compositions, in units of 10^{24} atoms cm^{-3} , are given in Tables 4.5 to 4.7 for the axial slices defined above. These compositions are derived for a weighted average of all the individual drawer masters in a zone (excluding fission chamber and thermocouple drawers). The fuel region above the internal blanket has been labelled inner core, although as can be seen, the compositions are nominally the same as those in the "outer core" region. Compositions for the mixtures of single and double-fuel-column drawers are also included in the table. The compositions are given for the axial slices described above, labelled in inches for simplicity. The

composition data in Tables 4.5 to 4.7 are suitable for use in rz models but, as noted above, the reference xyz models use individual drawer compositions.

Cross sections in 6 groups were collapsed using zone spectra from the 21 group xyz calculations. Benoist diffusion coefficients were also collapsed for the same zones using a $D\phi$ weighting.

TABLE 4.1 Energy Structure of the Cross Section
Sets used for ZPPR-17A Analysis

Energy Boundary ^a	6-Group Number	21-Group Number	230-Group Number ^b	2082-Group Number ^b
14.191 MeV				
1. 6.065		1	36	102
2. 3.679		2	49	162
3. 2.231		3	66	222
4. 1.353	1	4	80	282
5. 820.9 keV		5	93	342
6. 497.9		6	105	402
7. 302.0		7	116	462
8. 183.2		8	128	522
9. 111.1		9	140	582
10. 67.38	2	10	144	642
11. 40.87		11	150	702
12. 24.79		12	157	762
13. 15.03		13	164	822
14. 9.119	3	14	168	882
15. 5.531		15	172	942
16. 3.355		16	178	1002
17. 2.035		17	185	1062
18. 1.234		18	191	1122
19. 748.5 eV			197	1182
20. 454.0	4	19	199	1242
21. 275.4			201	1302
22. 167.0			203	1362
23. 101.3			205	1422
24. 61.44	5	20	207	1482
25. 37.27			209	1542
26. 22.60			211	1602
27. 5.04			217	1782
28. Thermal	6	21	230	2082

^aThe 28 energy boundaries are those of the cross section used in previous JUPITER analysis.

^bThe MC²-II library used 2082 groups with lethargy width of 1/120. The SDX intermediate library had 230 groups with a variable lethargy width tailored to treat the narrow resonances in structural materials.

TABLE 4.2 Effect of New Cross Sections on ZPPR-17A Eigenvalue

	<u>k</u>	
Nodal Diffusion XYZ Model of Central 3 x 3 Drawers		
Old cross sections	0.956980	
		>-.0017
New region avg. cross sections	0.955319	
		>+.0008
New region avg. and boundary cross sections	0.956084	
Nodal Diffusion XYZ Model of Full Assembly, with Benoist, no PSRs		
Old cross sections	0.987060	
		>-.0012
New region avg. cross sections	0.985825	
Nodal Transport XYZ Model of Full Assembly, with Benoist, with PSRs		
Old cross sections	0.990930	
		>-.0012
New region avg. cross sections	0.989749	

TABLE 4.3 Axial Reaction Rate Traverses with Old and New Cross Sections^a

Cross Sections:		Normalized Microscopic Reaction Rates ^b								
		²³⁸ U Fission			²³⁸ U Capture			²³⁹ Pu Fission		
		Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.
Z Mesh	Region	Old	Only	and Bdry.	Old	Only	and Bdry.	Old	Only	and Bdry.
1	IBK	3.00	2.88	2.89	3.00	2.99	2.95	3.00	3.15	3.19
2	IBK	4.88	4.70	4.70	2.92	2.91	2.94	2.97	3.09	3.11
3	SFC	8.25	8.25	8.30	2.86	2.89	2.90	2.81	2.81	2.83
4	SFC	10.66	10.68	10.66	2.75	2.77	2.77	2.89	2.88	2.88
5	SFC	10.07	10.07	10.05	2.51	2.52	2.52	2.67	2.67	2.67
6	SFC	7.13	7.13	7.13	2.22	2.23	2.23	2.24	2.24	2.24
7	ABK	2.84	2.75	2.75	1.84	1.86	1.86			
8	ABK	0.65	0.63	0.63	1.28	1.28	1.28			

^a Traverse in a SFC drawer of the xyz central 3 x 3 drawer model. The indicated cross sections were used for computing both the flux and the reaction rate.

^b Each reaction type is normalized such that the value at Z mesh 1 obtained using the old cross sections is 3.00.

TABLE 4.4 Sensitivity of ^{239}Pu Fission in the Inner Blanket to Cross Section Type

Name	Cross Section used for Reaction Rate ^a		Normalized ²³⁹ Pu(n,f)
	Type		
P9IBR	Activation foil in homogeneous IBKT with avg. B _g ² (most appropriate available)		1.000
P9CO	"Detector" in homogeneous average core (used in earlier reaction rate work)		0.946
P9IBW	Pu-30 equivalent slab in homog. IBKT with avg. B _g ²		0.855
P9IC	Cell avg., cell with Pu-30 cylinder in homog. blanket, with avg. B _g ²		0.876
P9IBH	Detector in het. IBKT with avg. B _g ²		1.070
P9IBIH	Detector in het. IBKT with interior B _g ²		1.079
P9IBEH	Detector in het. IBKT with edge B _g ²		1.052
P9DFH	Detector in het. DFC cell with avg. DFC B _g ²		0.939
P9SFH	Detector in het. SFC cell with avg. SFC B _g ²		0.970
P9SF	SFC cell avg. with avg. SFC B _g ²		0.861
P9SF2	Fuel plate in het. SFC cell with avg. SFC B _g ²		0.898

^aSame flux used for all cases.

Resolved resonance range is 1 to 301 eV
Unresolved resonance range is 301 eV to 25 keV

Contribution to P9IBR f^{**} at $z = 0$ to 7.6 cm

0 eV to 61 eV (GP.21)	4.1%
61 eV to 454 eV (GP.20)	18.9%
454 eV to 24.8 keV (GPS. 13-19)	<u>35.7%</u>

58.7%

TABLE 4.5 ZPPR Assembly 17A: Atom Densities by Zone

Isotope	Central Blanket SFC 0-6	Central Blanket DFC 0-6	Inner Core SFC 6-20	Inner Core DFC 6-20	Axial Blanket 20-31	Reflector Iron Block 31-36
C	0.0000333	0.0000331	0.0000331	0.0022784	0.0000532	0.0005889
O	0.0136987	0.0136964	0.0137650	0.0155776	0.0088214	--
Na	0.0092061	0.0091685	0.0092879	0.0087252	0.0092111	--
Si	0.0001433	0.0001458	0.0001570	0.0001822	0.0001925	0.0001231
Al	0.0000029	0.0000029	0.0000040	0.0000062	0.0000029	--
Mn	0.0002046	0.0002019	0.0002282	0.0002671	0.0003416	0.0006795
Cr	0.0023927	0.0023712	0.0026610	0.0031593	0.0041613	0.0020617
Fe	0.0118901	0.0117862	0.0128337	0.0111569	0.0147819	0.0758126
Ni	0.0010320	0.0010430	0.0011633	0.0014326	0.0017657	0.0008384
Cu	0.0000274	0.0000319	0.0000294	0.0000365	0.0000446	0.0000276
Mo	0.0000129	0.0000150	0.0002395	0.0004633	0.0000348	0.0000138
U5	0.0000178	0.0000178	0.0000127	0.0000182	0.0000179	--
U8	0.0081368	0.0081355	0.0058393	0.0082951	0.0081563	--
P8	--	--	0.0000005	0.0000010	--	--
P9	--	--	0.0008875	0.0017529	--	--
P0	--	--	0.0001175	0.0002314	--	--
P1	--	--	0.0000074	0.0000142	--	--
P2	--	--	0.0000019	0.0000037	--	--
A1	--	--	0.0000109	0.0000210	--	--
P	0.0000053	0.0000047	0.0000053	0.0000047	0.0000101	0.0000236
S	0.0000010	0.0000013	0.0000010	0.0000016	0.0000081	0.0000313
Cl	0.0000003	0.0000003	0.0000003	0.0000060	0.0000003	--
Ca	0.0000021	0.0000021	0.0000021	0.0000010	0.0000021	--
Co	0.0000008	0.0000047	0.0000008	0.0000043	0.0000020	0.0000014

TABLE 4.5 (contd)

Isotope	Reflector Stainless 36-42	Outer Core SFC 0-6	Outer Core DFC 0-6	Outer Core SFC 6-20	Outer Core DFC 6-20	Axial Blanket 20-31
C	0.0002143	0.0000332	0.0022752	0.0000331	0.0022870	0.0000532
O	--	0.0136987	0.0155223	0.0137650	0.0156026	0.0088213
Na	--	0.0092447	0.0087164	0.0092246	0.0087434	0.0091835
Si	0.0008629	0.0001553	0.0001800	0.0001575	0.0001817	0.0001925
Al	--	0.0000038	0.0000057	0.0000041	0.0000062	0.0000029
Mn	0.0015241	0.0002267	0.0002609	0.0002294	0.0002654	0.0003415
Cr	0.0150441	0.0026487	0.0030954	0.0026741	0.0031422	0.0041605
Fe	0.0531084	0.0127704	0.0109304	0.0128793	0.0110970	0.0147790
Ni	0.0066621	0.0011599	0.0014039	0.0011699	0.0014240	0.0017656
Cu	0.0000172	0.0000289	0.0000360	0.0000294	0.0000363	0.0000446
Mo	0.0000083	0.0002402	0.0004697	0.0002398	0.0004685	0.0000349
U5	--	0.0000126	0.0000183	0.0000127	0.0000183	0.0000179
U8	--	0.0057976	0.0083514	0.0058140	0.0083529	0.0081562
P8	--	0.0000003	0.0000010	0.0000004	0.0000010	--
P9	--	0.0008888	0.0017783	0.0008879	0.0017727	--
P0	--	0.0001178	0.0002354	0.0001176	0.0002346	--
P1	--	0.0000064	0.0000145	0.0000066	0.0000145	--
P2	--	0.0000016	0.0000039	0.0000017	0.0000038	--
A1	--	0.0000103	0.0000216	0.0000106	0.0000215	--
P	--	0.0000053	0.0000047	0.0000053	0.0000047	0.0000101
S	--	0.0000010	0.0000016	0.0000010	0.0000016	0.0000081
Cl	--	0.0000003	0.0000060	0.0000003	0.0000061	0.0000003
Ca	--	0.0000021	0.0000010	0.0000021	0.0000010	0.0000021
Co	--	0.0000008	0.0000046	0.0000008	0.0000044	0.0000020

TABLE 4.5 (contd)

Isotope	Reflector Iron Block 31-36	Reflector Stainless 36-42	Radial Blanket 0-6	Radial Blanket 6-20	Axial Blanket 20-31	Reflector Iron Block 31-36
C	0.0005882	0.0002143	0.0000322	0.0000323	0.0000323	0.0005928
O	--	--	0.0223887	0.0225016	0.0224943	--
Na	--	--	0.0042238	0.0042451	0.0042293	--
Si	0.0001244	0.0008629	0.0001388	0.0001397	0.0001397	0.0001164
Al	--	--	0.0000024	0.0000024	0.0000025	--
Mn	0.0006804	0.0015241	0.0001976	0.0001990	0.0001990	0.0006745
Cr	0.0020814	0.0150441	0.0023029	0.0023123	0.0023124	0.0019581
Fe	0.0757474	0.0531084	0.0082260	0.0082639	0.0082641	0.0761486
Ni	0.0008475	0.0066621	0.0009924	0.0009938	0.0009938	0.0007910
Cu	0.0000276	0.0000172	0.0000282	0.0000285	0.0000285	0.0000273
Mo	0.0000139	0.0000083	0.0000133	0.0000132	0.0000132	0.0000137
U5	--	--	0.0000288	0.0000290	0.0000289	--
U8	--	--	0.0132208	0.0132875	0.0132871	--
P8	--	--	--	--	--	--
P9	--	--	--	--	--	--
P0	--	--	--	--	--	--
P1	--	--	--	--	--	--
P2	--	--	--	--	--	--
A1	--	--	--	--	--	--
P	0.0000236	--	0.0000050	0.0000051	0.0000051	0.0000234
S	0.0000313	--	0.0000011	0.0000011	0.0000011	0.0000314
Cl	--	--	0.0000001	0.0000001	0.0000001	--
Ca	--	--	0.0000010	0.0000010	0.0000010	--
Co	0.0000015	--	0.0000018	0.0000017	0.0000017	0.0000012

TABLE 4.5 (contd)

Isotope	Reflector Stainless 36-42	Radial Reflector 0-36	Blanket Central (SFC+DFC) 0-6	Inner Core (SFC+DFC) 6-20	Outer Core (SFC+DFC) 0-6	Outer Core (SFC+DFC) 6-20
C	0.0002143	0.0002510	0.0000332	0.0007739	0.0008016	0.0008056
O	--	--	0.0136981	0.0143632	0.0143237	0.0143948
Na	--	--	0.0091938	0.0091023	0.0090636	0.0090597
Si	0.0008629	0.0008767	0.0001441	0.0001653	0.0001638	0.0001658
Al	--	--	0.0000029	0.0000047	0.0000045	0.0000048
Mn	0.0015241	0.0013973	0.0002037	0.0002410	0.0002384	0.0002417
Cr	0.0150441	0.0153821	0.0023857	0.0028254	0.0028018	0.0028346
Fe	0.0531084	0.0546625	0.0118560	0.0122806	0.0121398	0.0122684
Ni	0.0066621	0.0066801	0.0010357	0.0012522	0.0012436	0.0012570
Cu	0.0000172	0.0000400	0.0000289	0.0000317	0.0000313	0.0000318
Mo	0.0000083	0.0000368	0.0000136	0.0003133	0.0003189	0.0003182
U5	--	--	0.0000178	0.0000145	0.0000146	0.0000146
U8	--	--	0.0081365	0.0066497	0.0066729	0.0066842
P8	--	--	--	0.0000007	0.0000006	0.0000006
P9	--	--	--	0.0011731	0.0011937	0.0011912
P0	--	--	--	0.0001551	0.0001581	0.0001577
P1	--	--	--	0.0000096	0.0000092	0.0000094
P2	--	--	--	0.0000025	0.0000024	0.0000024
A1	--	--	--	0.0000142	0.0000142	0.0000143
P	--	0.0000458	0.0000051	0.0000051	0.0000051	0.0000051
S	--	0.0000352	0.0000011	0.0000012	0.0000012	0.0000012
Cl	--	--	0.0000003	0.0000022	0.0000023	0.0000023
Ca	--	--	0.0000021	0.0000017	0.0000017	0.0000017
Co	--	0.0000009	0.0000021	0.0000020	0.0000021	0.0000020

TABLE 4.5 (contd)

<u>Isotope</u>	<u>Empty Matrix</u>
C	0.0000188
O	--
Na	--
Si	0.0000683
Al	--
Mn	0.0001059
Cr	0.0011891
Fe	0.0042791
Ni	0.0004802
Cu	0.0000172
Mo	0.0000083
U5	--
U8	--
P8	--
P9	--
P0	--
P1	--
P2	--
A1	--
P	0.0000028
S	0.0000007
Cl	--
Ca	--
Co	--

TABLE 4.6 ZPPR Assembly 17B: Atom Densities by Zone

Isotope	Central Blanket SFC 0-6	Central Blanket DFC 0-6	Inner Core SFC 6-20	Inner Core DFC 6-20	Axial Blanket 20-31	Reflector Iron Block 31-36
C	0.0000333	0.0000342	0.0000331	0.0022822	0.0000532	0.0005884
O	0.0136987	0.0136964	0.0137650	0.0155893	0.0088213	- -
Na	0.0091995	0.0091764	0.0092812	0.0087323	0.0092077	- -
Si	0.0001434	0.0001498	0.0001570	0.0001822	0.0001926	0.0001231
Al	0.0000029	0.0000029	0.0000040	0.0000062	0.0000029	- -
Mn	0.0002047	0.0002081	0.0002282	0.0002672	0.0003414	0.0006786
Cr	0.0023943	0.0024413	0.0026606	0.0031600	0.0041603	0.0020566
Fe	0.0118957	0.0120382	0.0128326	0.0111595	0.0147764	0.0757381
Ni	0.0010326	0.0010714	0.0011632	0.0014331	0.0017666	0.0008383
Cu	0.0000274	0.0000329	0.0000294	0.0000365	0.0000448	0.0000277
Mo	0.0000129	0.0000155	0.0002394	0.0004633	0.0000350	0.0000139
U5	0.0000178	0.0000178	0.0000127	0.0000182	0.0000179	- -
U8	0.0081368	0.0081355	0.0058392	0.0082951	0.0081562	- -
P8	- -	- -	0.0000005	0.0000010	- -	- -
P9	- -	- -	0.0008875	0.0017529	- -	- -
P0	- -	- -	0.0001175	0.0002314	- -	- -
P1	- -	- -	0.0000073	0.0000140	- -	- -
P2	- -	- -	0.0000019	0.0000037	- -	- -
A1	- -	- -	0.0000109	0.0000211	- -	- -
P	0.0000053	0.0000049	0.0000053	0.0000047	0.0000101	0.0000235
S	0.0000010	0.0000013	0.0000010	0.0000016	0.0000081	0.0000313
Cl	0.0000003	0.0000003	0.0000003	0.0000060	0.0000003	- -
Ca	0.0000021	0.0000021	0.0000021	0.0000010	0.0000021	- -
Co	0.0000008	0.0000047	0.0000008	0.0000043	0.0000022	0.0000017

TABLE 4.6 (contd)

Isotope	Reflector Stainless 36-42	Outer Core SFC 0-6	Outer Core DFC 0-6	Outer Core SFC 6-20	Outer Core DFC 6-20	Axial Blanket 20-31
C	0.0002143	0.0000343	0.0022792	0.0000331	0.0022898	0.0000532
O	- -	0.0136985	0.0155311	0.0137649	0.0156113	0.0088222
Na	- -	0.0092311	0.0087208	0.0092111	0.0087495	0.0091804
Si	0.0008629	0.0001593	0.0001840	0.0001574	0.0001817	0.0001926
Al	- -	0.0000038	0.0000057	0.0000041	0.0000062	0.0000029
Mn	0.0015241	0.0002328	0.0002673	0.0002294	0.0002654	0.0003414
Cr	0.0150441	0.0027175	0.0031671	0.0026738	0.0031426	0.0041601
Fe	0.0531084	0.0130179	0.0111884	0.0128780	0.0110985	0.0147759
Ni	0.0066621	0.0011875	0.0014329	0.0011697	0.0014240	0.0017666
Cu	0.0000172	0.0000299	0.0000370	0.0000294	0.0000363	0.0000448
Mo	0.0000083	0.0002411	0.0004699	0.0002400	0.0004685	0.0000350
U5	- -	0.0000126	0.0000183	0.0000127	0.0000183	0.0000179
U8	- -	0.0057991	0.0083488	0.0058138	0.0083534	0.0081570
P8	- -	0.0000003	0.0000010	0.0000003	0.0000010	- -
P9	- -	0.0008898	0.0017772	0.0008882	0.0017727	- -
P0	- -	0.0001179	0.0002353	0.0001177	0.0002346	- -
P1	- -	0.0000063	0.0000144	0.0000066	0.0000144	- -
P2	- -	0.0000016	0.0000039	0.0000017	0.0000039	- -
A1	- -	0.0000103	0.0000217	0.0000106	0.0000216	- -
P	- -	0.0000054	0.0000048	0.0000053	0.0000047	0.0000101
S	- -	0.0000010	0.0000016	0.0000010	0.0000016	0.0000081
Cl	- -	0.0000003	0.0000060	0.0000003	0.0000061	0.0000003
Ca	- -	0.0000021	0.0000010	0.0000021	0.0000010	0.0000021
Co	- -	0.0000008	0.0000046	0.0000008	0.0000043	0.0000023

TABLE 4.6 (contd)

Isotope	Reflector Iron Block 31-36	Reflector Stainless 36-42	Radial Blanket 0-6	Radial Blanket 6-20	Axial Blanket 20-31	Reflector Iron Block 31-36
C	0.0005875	0.0002143	0.0000331	0.0000323	0.0000323	0.0005923
O	- -	- -	0.0224198	0.0225016	0.0224943	- -
Na	- -	- -	0.0042298	0.0042451	0.0042293	- -
Si	0.0001234	0.0008629	0.0001420	0.0001397	0.0001397	0.0001148
Al	- -	- -	0.0000024	0.0000024	0.0000025	- -
Mn	0.0006781	0.0015241	0.0002028	0.0001990	0.0001990	0.0006719
Cr	0.0020591	0.0150441	0.0023609	0.0023123	0.0023124	0.0019296
Fe	0.0756250	0.0531084	0.0084347	0.0082639	0.0082641	0.0760459
Ni	0.0008401	0.0066621	0.0010153	0.0009938	0.0009938	0.0007794
Cu	0.0000275	0.0000172	0.0000290	0.0000285	0.0000285	0.0000269
Mo	0.0000138	0.0000083	0.0000137	0.0000132	0.0000132	0.0000135
U5	- -	- -	0.0000288	0.0000290	0.0000289	- -
U8	- -	- -	0.0132393	0.0132875	0.0132871	- -
P8	- -	- -	- -	- -	- -	- -
P9	- -	- -	- -	- -	- -	- -
P0	- -	- -	- -	- -	- -	- -
P1	- -	- -	- -	- -	- -	- -
P2	- -	- -	- -	- -	- -	- -
A1	- -	- -	- -	- -	- -	- -
P	0.0000235	- -	0.0000052	0.0000051	0.0000051	0.0000233
S	0.0000313	- -	0.0000011	0.0000011	0.0000011	0.0000314
Cl	- -	- -	0.0000001	0.0000001	0.0000001	- -
Ca	- -	- -	0.0000010	0.0000010	0.0000010	- -
Co	0.0000017	- -	0.0000017	0.0000017	0.0000017	0.0000012

TABLE 4.6 (contd)

Isotope	Reflector Stainless 36-42	Reflector Reflector 0-36	Central Blanket (SFC+DFC) 0-6	Inner Core (SFC+DFC) 6-20	Outer Core (SFC+DFC) 0-6	Outer Core (SFC+DFC) 6-20
C	0.0002143	0.0002506	0.0000337	0.0009254	0.0009380	0.0009416
O	- -	- -	0.0136978	0.0144887	0.0144375	0.0145095
Na	- -	- -	0.0091902	0.0090633	0.0090264	0.0090259
Si	0.0008629	0.0008751	0.0001459	0.0001670	0.0001693	0.0001672
Al	- -	- -	0.0000029	0.0000049	0.0000046	0.0000049
Mn	0.0015241	0.0013948	0.0002061	0.0002436	0.0002467	0.0002439
Cr	0.0150441	0.0153536	0.0024129	0.0028588	0.0028987	0.0028628
Fe	0.0531084	0.0545599	0.0119522	0.0121688	0.0122826	0.0121628
Ni	0.0066621	0.0066686	0.0010480	0.0012702	0.0012864	0.0012722
Cu	0.0000172	0.0000396	0.0000296	0.0000322	0.0000328	0.0000322
Mo	0.0000083	0.0000366	0.0000139	0.0003282	0.0003333	0.0003320
U5	- -	- -	0.0000178	0.0000149	0.0000149	0.0000149
U8	- -	- -	0.0081363	0.0068136	0.0068261	0.0068368
P8	- -	- -	- -	0.0000007	0.0000006	0.0000006
P9	- -	- -	- -	0.0012308	0.0012471	0.0012444
P0	- -	- -	- -	0.0001627	0.0001652	0.0001648
P1	- -	- -	- -	0.0000100	0.0000096	0.0000097
P2	- -	- -	- -	0.0000026	0.0000025	0.0000026
A1	- -	- -	- -	0.0000149	0.0000149	0.0000151
P	- -	0.0000457	0.0000051	0.0000051	0.0000052	0.0000051
S	- -	0.0000352	0.0000011	0.0000012	0.0000012	0.0000012
Cl	- -	- -	0.0000003	0.0000026	0.0000026	0.0000026
Ca	- -	- -	0.0000021	0.0000017	0.0000016	0.0000016
Co	- -	0.0000009	0.0000024	0.0000022	0.0000023	0.0000022

TABLE 4.6 (contd)

Isotope	Empty Matrix 0-60	Control Position 0-20	Control Position 20-31
C	0.0000188	0.0000314	0.0000369
O	- -	0.0000013	0.0000013
Na	- -	0.0182024	0.0182389
Si	0.0000683	0.0001670	0.0001667
Al	- -	0.0000045	0.0000049
Mn	0.0001059	0.0002460	0.0002462
Cr	0.0011891	0.0029889	0.0029856
Fe	0.0042791	0.0105526	0.0106624
Ni	0.0004802	0.0013379	0.0013366
Cu	0.0000172	0.0000361	0.0000358
Mo	0.0000083	0.0000177	0.0000177
U5	- -	- -	- -
U8	- -	- -	- -
P8	- -	- -	- -
P9	- -	- -	- -
P0	- -	- -	- -
P1	- -	- -	- -
P2	- -	- -	- -
A1	- -	- -	- -
P	0.0000028	0.0000041	0.0000040
S	0.0000007	0.0000013	0.0000012
Cl	- -	0.0000006	0.0000006
Ca	- -	0.0000041	0.0000042
Co	- -	0.0000039	0.0000040

TABLE 4.7 ZPPR Assembly 17C: Atom Densities by Zone

Isotope	Empty Matrix 0-36	Radial Reflector 0-36	Axial Reflector 36-42	Radial Blanket 31-36	Radial Blanket 20-31	Radial Blanket 6-20
B0	--	--	--	--	--	--
B1	--	--	--	--	--	--
C	0.0000188	0.0002440	0.0002143	0.0005923	0.0000323	0.0000323
O	--	--	--	--	0.0224943	0.0225016
Na	--	--	--	--	0.0042293	0.0042451
Si	0.0000683	0.0009017	0.0008629	0.0001148	0.0001397	0.0001397
Al	--	--	--	--	0.0000025	0.0000024
Mn	0.0001059	0.0014353	0.0015241	0.0006719	0.0001990	0.0001990
Cr	0.0011891	0.0157477	0.0150441	0.0019296	0.0023124	0.0023123
Fe	0.0042791	0.0556680	0.0531083	0.0760459	0.0082641	0.0082639
Ni	0.0004802	0.0068483	0.0066621	0.0007794	0.0009938	0.0009938
Cu	0.0000172	0.0000379	0.0000172	0.0000269	0.0000285	0.0000285
Mo	0.0000083	0.0000356	0.0000083	0.0000135	0.0000132	0.0000132
U5	--	--	--	--	0.0000289	0.0000290
U8	--	--	--	--	0.0132871	0.0132875
P8	--	--	--	--	--	--
P9	--	--	--	--	--	--
P0	--	--	--	--	--	--
P1	--	--	--	--	--	--
P2	--	--	--	--	--	--
A1	--	--	--	--	--	--
P	0.0000028	0.0000472	0.0000533	0.0000233	0.0000051	0.0000051
S	0.0000007	0.0000363	0.0000252	0.0000314	0.0000011	0.0000011
Cl	--	--	--	--	0.0000001	0.0000001
Ca	--	--	--	--	0.0000010	0.0000010
Co	--	0.0000007	--	0.0000012	0.0000017	0.0000017

TABLE 4.7 (contd)

Isotope	Radial Blanket 0-6	Axial Refl Outer Core 31-36	Axial Blkt Outer Core 20-31	Outer Core 6-20	Outer Core 0-6	Axial Refl Inner Core 31-36
B0	--	--	--	--	--	--
B1	--	--	--	--	--	--
C	0.0000333	0.0005874	0.0000532	0.0012314	0.0012263	0.0005884
O	0.0223887	--	0.0088214	0.0147521	0.0146783	--
Na	0.0042238	--	0.0091799	0.0089549	0.0089446	--
Si	0.0001428	0.0001236	0.0001928	0.0001703	0.0001724	0.0001232
Al	0.0000024	--	0.0000029	0.0000052	0.0000049	--
Mn	0.0002038	0.0006777	0.0003411	0.0002486	0.0002513	0.0006779
Cr	0.0023727	0.0020570	0.0041582	0.0029237	0.0029578	0.0020511
Fe	0.0084772	0.0756063	0.0147653	0.0119410	0.0120566	0.0757124
Ni	0.0010206	0.0008422	0.0017683	0.0013052	0.0013186	0.0008390
Cu	0.0000292	0.0000281	0.0000454	0.0000331	0.0000337	0.0000283
Mo	0.0000138	0.0000141	0.0000353	0.0003610	0.0003624	0.0000142
U5	0.0000288	--	0.0000179	0.0000156	0.0000156	--
U8	0.0132208	--	0.0081563	0.0071563	0.0071450	--
P8	--	--	--	0.0000007	0.0000007	--
P9	--	--	--	0.0013565	0.0013596	--
P0	--	--	--	0.0001796	0.0001801	--
P1	--	--	--	0.0000108	0.0000106	--
P2	--	--	--	0.0000028	0.0000028	--
A1	--	--	--	0.0000164	0.0000162	--
P	0.0000052	0.0000234	0.0000100	0.0000050	0.0000051	0.0000234
S	0.0000011	0.0000313	0.0000082	0.0000013	0.0000013	0.0000314
Cl	0.0000001	--	0.0000003	0.0000034	0.0000033	--
Ca	0.0000010	--	0.0000021	0.0000015	0.0000015	--
Co	0.0000018	0.0000022	0.0000027	0.0000027	0.0000028	0.0000022

TABLE 4.7 (contd)

Isotope	Axial Blkt Inner Core	Inner Core	Inner Core	Axial Refl Outer Core	Axial Blkt Outer Core	Outer Core
	20-31	6-20	0-6	SCF 31-36	SCF 20-31	SCF 6-20
B0	--	--	--	--	--	--
B1	--	--	--	--	--	--
C	0.0000532	0.0012105	0.0000338	0.0005855	0.0000532	0.0000331
O	0.0088212	0.0147284	0.0136973	--	0.0088213	0.0137650
Na	0.0092079	0.0089966	0.0091901	--	0.0091325	0.0091844
Si	0.0001928	0.0001701	0.0001468	0.0001260	0.0001918	0.0001574
Al	0.0000029	0.0000051	0.0000029	--	0.0000029	0.0000041
Mn	0.0003412	0.0002484	0.0002065	0.0006816	0.0003421	0.0002293
Cr	0.0041587	0.0029197	0.0024191	0.0021181	0.0041628	0.0026730
Fr	0.0147671	0.0119542	0.0119711	0.0754880	0.0147973	0.0128752
Ni	0.0017686	0.0013032	0.0010530	0.0008569	0.0017595	0.0011693
Cu	0.0000454	0.0000331	0.0000303	0.0000256	0.0000432	0.0000294
Mo	0.0000353	0.0003567	0.0000143	0.0000128	0.0000341	0.0002398
U5	0.0000179	0.0000156	0.0000178	--	0.0000179	0.0000127
U8	0.0081561	0.0071223	0.0081361	--	0.0081562	0.0058134
P8	--	0.0000007	--	--	--	0.0000004
P9	--	0.0013416	--	--	--	0.0008879
P0	--	0.0001774	--	--	--	0.0001177
P1	--	0.0000108	--	--	--	0.0000066
P2	--	0.0000028	--	--	--	0.0000017
A1	--	0.0000162	--	--	--	0.0000107
P	0.0000100	0.0000050	0.0000051	0.0000238	0.0000103	0.0000053
S	0.0000082	0.0000013	0.0000012	0.0000312	0.0000080	0.0000010
Cl	0.0000003	0.0000033	0.0000003	--	0.0000003	0.0000003
Ca	0.0000021	0.0000015	0.0000021	--	0.0000021	0.0000021
Co	0.0000027	0.0000027	0.0000029	--	0.0000008	0.0000008

Table 4.7 (contd)

Isotope	Axial Refl		Axial Blkt				Axial Refl	
	Outer Core	Outer Core	Outer Core	Outer Core	Outer Core	Outer Core	Inner Core	
	SCF 0-6	DCF 31-36	DCF 20-31	DCF 6-20	DCF 0-6	DCF 31-36	SCF 31-36	
B0	--	--	--	--	--	--	--	
B1	--	--	--	--	--	--	--	
C	0.0000343	0.0005891	0.0000532	0.0022955	0.0022849	0.0005885		
O	0.0136986	--	0.0088213	0.0156284	0.0155480	--		
Na	0.0092043	--	0.0092218	0.0087510	0.0087138	--		
Si	0.0001592	0.0001216	0.0001937	0.0001818	0.0001842	0.0001232		
Al	0.0000038	--	0.0000029	0.0000063	0.0000058	--		
Mn	0.0002328	0.0006742	0.0003403	0.0002657	0.0002677	0.0006808		
Cr	0.0027171	0.0020027	0.0041540	0.0031463	0.0031715	0.0020771		
Fe	0.0130166	0.0757097	0.0147367	0.0111112	0.0112039	0.0758039		
Ni	0.0011873	0.0008291	0.0017761	0.0014258	0.0014351	0.0008375		
Cr	0.0000299	0.0000303	0.0000473	0.0000363	0.0000370	0.0000260		
Mo	0.0002408	0.0000153	0.0000363	0.0004686	0.0004704	0.0000130		
U5	0.0000126	--	0.0000179	0.0000183	0.0000183	--		
U8	0.0057979	--	0.0081562	0.0083486	0.0083410	--		
P8	0.0000003	--	--	0.0000010	0.0000009	--		
P9	0.0008892	--	--	0.0017726	0.0017773	--		
P0	0.0001178	--	--	0.0002346	0.0002353	--		
P1	0.0000063	--	--	0.0000145	0.0000143	--		
P2	0.0000016	--	--	0.0000038	0.0000038	--		
A1	0.0000103	--	--	0.0000214	0.0000214	--		
P	0.0000054	0.0000230	0.0000098	0.0000047	0.0000048	0.0000238		
S	0.0000010	0.0000315	0.0000083	0.0000016	0.0000016	0.0000312		
Cl	0.0000003	--	0.0000003	0.0000062	0.0000061	--		
Ca	0.0000021	--	0.0000021	0.0000010	0.0000010	--		
Co	0.0000008	0.0000042	0.0000044	0.0000043	0.0000046	--		

TABLE 4.7 (contd)

Isotope	Axial Blkt	Inner Core	Inner Core	Axial Refl	Axial Blkt	Inner Core
	Inner Core	Inner Core	Inner Core	Inner Core	Inner Core	Inner Core
	SCF	SCF	SCF	DCF	DCF	DCF
	20-31	6-20	0-6	31-36	20-31	6-20
B0	--	--	--	--	--	--
B1	--	--	--	--	--	--
C	0.0000532	0.0000331	0.0000333	0.0005882	0.0000532	0.0022897
O	0.0088213	0.0137650	0.0136987	--	0.0088213	0.0156118
Na	0.0092050	0.0092702	0.0091887	--	0.0092107	0.0087458
Si	0.0001919	0.0001569	0.0001434	0.0001232	0.0001937	0.0001821
Al	0.0000029	0.0000040	0.0000029	--	0.0000029	0.0000062
Mn	0.0003422	0.0002281	0.0002047	0.0006753	0.0003402	0.0002669
Cr	0.0041646	0.0026601	0.0023942	0.0020274	0.0041534	0.0031576
Fe	0.0148035	0.0128309	0.0118954	0.0756294	0.0147340	0.0111507
Ni	0.0017604	0.0011629	0.0010325	0.0008404	0.0017760	0.0014319
Cu	0.0000432	0.0000294	0.0000274	0.0000304	0.0000473	0.0000365
Mo	0.0000341	0.0002394	0.0000129	0.0000154	0.0000364	0.0004643
U5	0.0000179	0.0000127	0.0000178	--	0.0000179	0.0000182
U8	0.0081562	0.0058390	0.0081368	--	0.0081562	0.0082988
P8	--	0.0000005	--	--	--	0.0000009
P9	--	0.0008874	--	--	--	0.0017580
P0	--	0.0001175	--	--	--	0.0002323
P1	--	0.0000074	--	--	--	0.0000139
P2	--	0.0000019	--	--	--	0.0000036
A1	--	0.0000109	--	--	--	0.0000210
P	0.0000103	0.0000053	0.0000053	0.0000231	0.0000098	0.0000047
S	0.0000080	0.0000010	0.0000010	0.0000315	0.0000083	0.0000016
Cl	0.0000003	0.0000003	0.0000003	--	0.0000003	0.0000060
Ca	0.0000021	0.0000021	0.0000021	--	0.0000021	0.0000010
Co	0.0000008	0.0000008	0.0000008	0.0000043	0.0000045	0.0000044

TABLE 4.7 (contd)

Isotope	Inner Blkt 0-6	Control Position 31-36	Control Position 20-31	Control Position 6-20	Control Position 0-6	Bank Control Rod 31-36
B0	--	--	--	--	--	--
B1	--	--	--	--	--	--
C	0.0000342	0.0000443	0.0000309	0.0000309	0.0000318	0.0000508
O	0.0136964	0.0000013	0.0000013	0.0000013	0.0000013	0.0000013
Na	0.0091915	0.0179925	0.0184405	0.0183970	0.0180431	0.0180018
Si	0.0001499	0.0001688	0.0001649	0.0001649	0.0001688	0.0001863
Al	0.0000029	0.0000048	0.0000049	0.0000048	0.0000043	0.0000056
Mn	0.0002082	0.0002486	0.0002443	0.0002442	0.0002474	0.0002517
Cr	0.0024420	0.0030099	0.0029657	0.0029644	0.0030089	0.0030170
Fe	0.0120407	0.0108979	0.0104697	0.0104649	0.0106243	0.0109629
Ni	0.0010718	0.0013470	0.0013281	0.0013274	0.0013465	0.0013664
Cu	0.0000329	0.0000365	0.0000353	0.0000353	0.0000367	0.0000364
Mo	0.0000155	0.0000181	0.0000174	0.0000174	0.0000180	0.0000160
U5	0.0000178	--	--	--	--	--
U8	0.0081355	--	--	--	--	--
P8	--	--	--	--	--	--
P9	--	--	--	--	--	--
P0	--	--	--	--	--	--
P1	--	--	--	--	--	--
P2	--	--	--	--	--	--
A1	--	--	--	--	--	--
P	0.0000049	0.0000041	0.0000040	0.0000040	0.0000041	0.0000057
S	0.0000013	0.0000013	0.0000012	0.0000012	0.0000013	0.0000013
Cl	0.0000003	0.0000006	0.0000006	0.0000006	0.0000006	0.0000006
Ca	0.0000021	0.0000041	0.0000042	0.0000042	0.0000041	0.0000041
Co	0.0000048	0.0000043	0.0000037	0.0000037	0.0000040	0.0000059

TABLE 4.7 (contd)

Isotope	Bank Control Rod 20-31	Bank Control Rod 6-20	Bank Control Rod 0-6	Central Control Rod 31-36	Central Control Rod 20-31	Central Control Rod 6-20
B0	0.0160061	0.0151769	0.0158703	- -	0.0160061	0.0157321
B1	0.0649083	0.0615467	0.0643535	- -	0.0649083	0.0637966
C	0.0208421	0.0197666	0.0203715	0.0000508	0.0208421	0.0204374
O	0.0000803	0.0000534	0.0001353	0.0000013	0.0000803	0.0000825
Na	- -	- -	- -	0.0180018	- -	- -
Si	0.0002047	0.0002235	0.0002562	0.0001863	0.0002047	0.0002188
Al	0.0000010	0.0000028	0.0000021	0.0000056	0.0000010	0.0000020
Mn	0.0001928	0.0002204	0.0002066	0.0002517	0.0001928	0.0002028
Cr	0.0022421	0.0026105	0.0024203	0.0030170	0.0022421	0.0023755
Fe	0.0081410	0.0093681	0.0087156	0.0109629	0.0081410	0.0085838
Ni	0.0009734	0.0011621	0.0010609	0.0013664	0.0009734	0.0010417
Cu	0.0000307	0.0000325	0.0000325	0.0000364	0.0000307	0.0000314
Mo	0.0000155	0.0000162	0.0000162	0.0000160	0.0000155	0.0000158
U5	- -	- -	- -	- -	- -	- -
U8	- -	- -	- -	- -	- -	- -
P8	- -	- -	- -	- -	- -	- -
P9	- -	- -	- -	- -	- -	- -
P0	- -	- -	- -	- -	- -	- -
P1	- -	- -	- -	- -	- -	- -
P2	- -	- -	- -	- -	- -	- -
A1	- -	- -	- -	- -	- -	- -
P	0.0000040	0.0000040	0.0000041	0.0000057	0.0000040	0.0000040
S	0.0000012	0.0000012	0.0000013	0.0000013	0.0000012	0.0000012
Cl	- -	- -	- -	0.0000006	- -	- -
Ca	- -	- -	- -	0.0000041	- -	- -
Co	0.0000037	0.0000037	0.0000040	0.0000059	0.0000037	0.0000037

Table 4.7 (contd)

Isotope	Central Control Rod 0-6
B0	0.0158703
B1	0.0643535
C	0.0203715
O	0.0001353
Na	- -
Si	0.0002562
Al	0.0000021
Mn	0.0002066
Cr	0.0024203
Fe	0.0087156
Ni	0.0010609
Cu	0.0000325
Mo	0.0000162
U5	- -
U8	- -
P8	- -
P9	- -
P0	- -
P1	- -
P2	- -
A1	- -
P	0.0000041
S	0.0000013
Cl	- -
Ca	- -
Co	0.0000040

Fig. 4.1 Slab Model used to Collapse
Cross Sections for ZPPR-17A

Axial Height, cm	Zone	Cell Cross Sections
0		
	1. Internal Blanket	IBKN
15.31		
	2. Inner Core Single Column	SCFN
27.16		
	3. Inner Core Double Column	DCFN
39.01		
	4. Inner Core Single Column	SCFN
50.86		
	5. Axial Blanket	ABKN
78.82		
	6. Iron Axial Reflector	ARI
91.09		
	7. Steel Axial Reflector	ARS
106.33		

R/C	-50	-51	-52	-53	-54	-55	-56	-57	-58	-59	-60	-61	-62	-63	-64	-65	-66	-67	-68	-69	-70	-71	-72	-73	-74	-75	-76	-77	-78	-79	-80	-81	
117-	402	402	402	402	402	402	402	402	402	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
118-	402	402	402	402	402	402	402	402	402	402	402	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
119-	402	402	402	402	402	402	402	402	402	402	402	402	403	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
120-	502	502	502	502	502	502	402	402	402	402	402	402	403	403	403	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
121-	501	501	501	501	502	502	502	502	502	502	402	402	403	403	403	403	404	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
122-	501	501	501	501	501	501	501	501	502	502	502	502	403	403	403	403	404	404	404	.	.	.	.	.	.	.	.	.	.	.	.	.	
123-	501	501	501	501	501	501	501	501	501	501	501	501	502	502	502	403	403	403	404	404	404	.	.	.	.	.	.	.	.	.	.	.	
124-	501	501	501	501	501	501	501	501	501	501	501	501	501	502	502	502	403	404	404	404	405	.	.	.	.	.	.	.	.	.	.	.	
125-	105	103	203	106	501	501	501	501	501	501	501	501	501	501	501	501	502	502	404	404	404	405	405	.	.	.	.	.	.	.	.	.	
126-	203	101	102	202	103	106	203	501	501	501	501	501	501	501	501	501	502	502	404	404	405	405	405	.	.	.	.	.	.	.	.	.	
127-	102	207	103	102	203	102	104	203	105	102	501	501	501	501	501	501	501	502	502	404	405	405	405	405	.	.	.	.	.	.	.	.	
128-	104	102	203	101	104	202	105	102	202	104	106	202	501	501	501	501	501	501	502	502	405	405	405	405	405	.	.	.	.	.	.	.	
129-	207	101	105	207	106	102	203	103	101	203	102	103	203	106	501	501	501	501	501	502	502	404	404	404	404	404	.	.	.	.	.	.	.
130-	106	203	102	101	207	103	101	202	106	102	202	104	101	203	101	501	501	501	501	501	502	502	404	404	404	404	404	.	.	.	.	.	.
131-	103	102	207	104	102	203	102	105	203	101	103	203	106	102	202	101	501	501	501	501	501	502	502	404	404	404	404	.	.	.	.	.	.
132-	202	105	101	203	106	101	207	101	104	207	102	101	207	103	104	203	101	501	501	501	501	501	502	502	403	403	404	404	.	.	.	.	.
133-	107	205	107	102	207	103	104	203	102	105	203	106	101	203	106	101	203	101	501	501	501	501	501	502	502	403	403	403	.	.	.	.	.
134-	107	107	803	107	107	205	105	103	207	102	103	202	105	805	203	106	104	202	101	501	501	501	501	501	502	403	403	403	403	.	.	.	.
135-	205	107	107	205	107	107	205	108	106	203	102	104	207	103	102	203	103	102	203	106	501	501	501	501	502	502	403	403	403	.	.	.	.
136-	107	205	107	107	205	107	107	205	107	107	207	106	207	207	105	101	207	106	101	203	501	501	501	501	501	502	403	403	403	403	.	.	.
137-	107	107	205	107	107	205	107	107	205	107	107	203	106	104	202	106	101	203	104	103	202	501	501	501	501	502	502	402	402	402	.	.	.
138-	205	107	107	205	107	107	205	107	107	205	107	107	207	102	103	203	102	103	202	102	106	501	501	501	501	501	502	402	402	402	402	.	.
139-	107	205	107	107	205	107	107	205	107	107	205	107	107	203	102	105	207	101	102	203	104	102	501	501	501	501	502	502	402	402	402	.	.
140-	107	107	205	107	107	205	107	107	205	107	107	205	107	106	207	102	104	203	106	101	202	105	501	501	501	501	502	502	402	402	402	402	.
141-	205	107	107	205	107	107	205	107	107	205	107	107	205	108	103	203	101	105	202	103	102	203	501	501	501	501	501	502	402	402	402	402	.
142-	107	205	107	107	205	107	107	205	107	107	205	107	107	205	105	104	207	102	101	203	105	104	203	501	501	501	501	502	402	402	402	402	.
143-	107	107	205	107	107	205	107	107	205	107	107	205	107	107	205	103	101	203	103	102	202	102	106	501	501	501	501	502	502	402	402	402	.
144-	205	107	107	205	107	107	205	107	107	205	107	107	205	801	107	207	106	805	808	112	104	203	103	501	501	501	501	502	502	402	402	402	.
145-	107	205	107	107	205	107	107	205	107	107	205	107	107	205	107	102	203	104	101	207	101	102	202	106	501	501	501	501	502	402	402	402	.
146-	107	107	205	107	107	205	107	107	205	107	107	205	107	107	205	107	107	102	105	203	103	102	203	501	501	501	501	502	402	402	402	.	
147-	205	107	107	205	107	107	205	107	107	205	107	107	205	107	107	205	105	102	203	101	102	207	101	103	501	501	501	501	502	402	402	402	.
148-	107	205	107	107	205	107	107	205	107	107	205	107	107	205	107	107	202	103	106	207	104	102	203	105	501	501	501	501	502	402	402	402	.

	-51	-52	-53	-54	-55	-56	-57	-58	-59	-60	-61	-62	-63	-64	-65	-66	-67	-68	-69	-70	-71	-72	-73	-74	-75	-76	-77	-78	-79	-80	-81	
117	402	402	402	402	402	402	402	402	402	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
118	402	402	402	402	402	402	402	402	402	402	402	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
119	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
120	502	502	502	502	502	502	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
121	501	501	501	501	502	502	502	502	502	502	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
122	501	501	501	501	501	501	501	501	501	502	502	502	502	502	403	403	403	403	403	403	403	403	403	403	403	403	403	403	403	403	403	
123	501	501	501	501	501	501	501	501	501	501	501	501	501	501	502	502	502	403	403	403	403	403	403	403	403	403	403	403	403	403	403	
124	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	502	502	502	403	404	404	404	404	404	404	404	404	404	404	404	404	
125	105	103	203	106	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
126	203	101	102	202	103	106	203	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
127	102	207	103	102	203	102	104	203	105	102	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
128	104	226	203	101	104	202	105	102	202	104	106	202	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
129	207	101	105	207	106	102	203	103	207	203	102	103	203	106	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
130	104	203	102	101	207	103	226	202	106	102	202	104	101	203	101	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
131	103	102	207	104	102	203	102	105	203	101	103	203	106	102	202	101	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
132	202	105	203	601	601	101	207	101	104	207	102	101	207	103	104	203	101	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
133	107	205	107	601	601	103	104	203	226	105	203	106	226	203	106	207	203	101	501	501	501	501	501	501	501	501	501	501	501	501	501	
134	107	107	803	107	205	205	105	103	207	102	103	202	105	815	203	106	104	202	101	501	501	501	501	501	501	501	501	501	501	501	501	
135	205	107	107	205	107	107	205	108	106	203	102	226	207	103	102	203	103	102	203	106	501	501	501	501	501	501	501	501	501	501	501	
136	601	205	107	107	205	107	107	205	107	107	207	601	601	207	105	207	207	106	101	203	501	501	501	501	501	501	501	501	501	501	501	
137	601	205	205	107	107	205	205	107	205	107	107	601	601	104	202	106	101	203	104	103	202	501	501	501	501	501	501	501	501	501	501	
138	205	107	107	205	107	107	205	107	107	205	107	107	207	102	103	203	102	103	202	102	106	501	501	501	501	501	501	501	501	501	501	
139	107	205	107	107	205	107	107	205	107	205	205	107	107	203	102	105	207	203	102	203	104	102	501	501	501	501	501	501	501	501	501	
140	107	107	205	205	107	205	107	107	205	107	107	205	107	106	207	226	104	203	106	101	202	105	501	501	501	501	501	501	501	501	501	
141	205	107	107	601	601	107	205	107	107	205	107	107	205	108	103	203	101	105	202	103	102	203	501	501	501	501	501	501	501	501	501	
142	107	205	107	601	601	107	107	205	107	601	601	205	107	205	105	104	207	102	226	203	105	104	203	501	501	501	501	501	501	501	501	
143	107	107	205	205	107	205	107	107	205	601	601	205	107	205	205	103	101	203	103	102	202	102	106	501	501	501	501	501	501	501	501	
144	205	107	107	205	107	107	205	107	107	205	107	107	205	801	107	601	601	805	808	112	104	203	103	501	501	501	501	501	501	501	501	
145	107	205	107	107	205	205	107	205	205	107	205	107	107	205	107	601	601	104	101	207	203	102	202	106	501	501	501	501	501	501	501	
146	107	107	205	107	107	205	107	107	205	107	107	205	107	107	205	107	226	202	102	105	203	103	226	203	501	501	501	501	501	501	501	
147	205	107	205	205	107	107	205	107	107	205	107	205	205	107	107	205	105	227	203	101	102	207	101	103	501	501	501	501	501	501	501	
148	601	205	107	107	205	107	601	601	107	205	107	107	205	107	107	202	103	106	207	104	102	203	105	501	501	501	501	501	501	501	501	

Fig. 4.3 The xyz Calculational Model for ZPPR-17B.

-50	-51	-52	-53	-54	-55	-56	-57	-58	-59	-60	-61	-62	-63	-64	-65	-66	-67	-68	-69	-70	-71	-72	-73	-74	-75	-76	-77	-78	-79	-80	-81
117-	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
118-	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
119-	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	402	
120-	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502	
121-	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
122-	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
123-	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
124-	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
125-	236	103	203	106	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
126-	203	101	235	202	103	106	203	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
127-	102	207	103	102	203	102	230	203	105	102	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
128-	104	226	203	101	230	202	105	231	202	104	235	202	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
129-	207	101	105	207	106	102	203	103	207	203	102	103	203	106	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
130-	106	203	235	101	207	103	226	202	106	102	202	233	101	203	101	501	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
131-	232	102	207	104	230	203	102	105	203	227	103	203	106	235	202	101	501	501	501	501	501	501	501	501	501	501	501	501	501	501	
132-	202	105	203	601	601	101	207	101	104	207	102	101	207	103	104	203	101	501	501	501	501	501	501	501	501	501	501	501	501	501	
133-	107	205	107	601	601	226	104	203	226	105	203	106	226	203	106	207	203	101	501	501	501	501	501	501	501	501	501	501	501	501	
134-	107	229	803	107	205	205	105	103	207	102	236	202	105	805	203	106	104	202	101	501	501	501	501	501	501	501	501	501	501	501	
135-	205	107	107	205	107	205	108	106	203	102	226	207	103	236	203	103	235	203	106	501	501	501	501	501	501	501	501	501	501	501	
136-	601	205	107	228	205	107	205	107	205	107	228	207	601	601	207	105	207	207	106	101	203	501	501	501	501	501	501	501	501	501	
137-	601	205	205	107	205	205	107	205	107	205	107	228	601	601	230	202	106	101	203	233	103	202	501	501	501	501	501	501	501	501	
138-	205	107	107	205	234	107	205	107	228	205	107	107	207	102	237	203	102	103	202	102	235	501	501	501	501	501	501	501	501	501	
139-	107	205	107	205	107	205	107	205	107	205	205	107	228	203	102	105	207	203	102	203	104	102	501	501	501	501	501	501	501	501	
140-	205	107	205	205	107	205	234	107	205	107	228	205	107	106	207	226	104	203	106	235	202	105	501	501	501	501	501	501	501	501	
141-	205	107	228	601	601	107	205	107	205	107	205	107	205	106	103	203	101	105	202	103	102	203	501	501	501	501	501	501	501	501	
142-	107	205	107	601	601	229	107	205	234	107	205	234	601	601	205	107	205	226	104	207	102	226	203	105	227	203	501	501	501	501	
143-	229	107	205	205	107	205	107	205	107	205	601	601	205	107	205	205	103	236	203	103	235	202	102	235	501	501	501	501	501	501	
144-	205	107	205	107	205	107	205	234	107	205	107	228	205	801	107	601	601	805	808	112	104	203	103	501	501	501	501	501	501	501	
145-	107	205	107	205	205	107	205	205	107	205	107	205	107	205	107	205	107	226	202	102	226	203	103	226	203	501	501	501	501	501	
146-	107	229	205	107	205	228	107	205	107	205	107	234	205	107	205	205	107	226	202	102	226	203	103	226	203	501	501	501	501	501	
147-	205	107	205	107	205	107	205	107	228	205	107	205	107	205	107	205	105	102	203	101	102	207	101	103	501	501	501	501	501	501	
148-	601	205	107	107	205	229	107	601	601	107	205	107	205	229	107	202	232	106	207	230	102	203	236	501	501	501	501	501	501	501	

Fig. 4.4 The xyz Calculational Model for ZPPR-17C (half one).

Dimensions in cm

Fig. 4.5 rz Diagram of ZPPR-17A.

5. CALCULATED EIGENVALUES AND EFFECTIVE DELAYED NEUTRON FRACTIONS

5.1 Experimental Reactivities and Nodal Diffusion Results

Both critical and subcritical references were established for each phase of ZPPR-17. The excess reactivities with operating shim rods withdrawn were measured for the critical reference by the positive period technique and for the subcritical reference by inverse kinetics analysis of a rod drop. Cross sections for ZPPR analysis are conventionally processed for a temperature of 293 K. Experimental excess reactivities are adjusted to this temperature using measured temperature coefficients and converted to Δk units using the calculated β -effective values. No adjustment is made for the absolute interface gap, but adjustment to a reference half-separation and ^{241}Pu decay date is made for comparison of reactivities. Tables 5.1 to 5.3 show the experimental k -effective values for the critical and subcritical references of ZPPR-17A, 17B, and 17C and a comparison with the nodal diffusion calculations using xyz geometry and 21 group ENDF/B-V.2 data.

The uncertainties shown in the tables result only from the statistics of the kinetics analysis and reactivity coefficients. The total uncertainty is much larger. For ZPPR-17, this will be close to that evaluated for ZPPR-13, since the principal source of uncertainty is the knowledge of the fuel masses. This total uncertainty on the experimental k -effective values is close to 0.00050 (1σ).

For ZPPR-17A, the difference between critical and subcritical reference reactivities is due to replacement of a double-fuel-column drawer in location 136-62 and the seven symmetric matrix positions (total 4.35 kg ^{239}Pu). This reactivity difference is $0.001099 \Delta k \pm 0.000039 \Delta k$ assuming that all uncertainties, other than those in Table 5.1, are closely correlated. The calculated difference is 0.001187 giving a C/E value of 1.080. This result is consistent with that obtained for analysis of fuel worths.

The nodal diffusion k -effective for 17B is 0.2% lower than that for 17A. This result is attributed to overestimation of leakage in CRPs by

diffusion theory and is consistent with results for several other ZPPR cores.

5.2 Results for Other Calculation Models

Several calculations, in addition to the reference nodal diffusion model (NDT), were made for different analyses. A nodal transport (NTT) calculation with shim rods (WSH) inserted was made for reaction rate analysis. A finite-difference diffusion (FDDT) calculation was made for β -effective. Six group (6G) xyz calculations were made for control rod studies and rz calculations were made for initial analysis of reactivity coefficients. The k-effective values from these models used a 55 mm mesh in xyz geometry and a similar mesh in rz geometry. The nodal diffusion models used coarse z nodes of 70 to 150 mm (and a 55 mm node spacing in the xy-plane in order to represent the ZPPR geometry). These calculations have a very small truncation error. Results based on the different models are given in Tables 5.4 to 5.6. The effects of several modelling approximations for 17A are shown in Table 5.7. Modelling effects for ZPPR-17B are similar to those found for ZPPR-17A. The worth of the operating shim rods inserted to the core/blanket interface is $+0.0415\% \Delta k$. The error due to the use of coarse mesh (about 55 mm) in finite difference diffusion calculations is $+0.206\% \Delta k$ in 21 groups and $+0.221\% \Delta$ in 6 groups. The nodal transport correction to the nodal diffusion k-effective for ZPPR-17B is $+0.497\%$. the increased transport correction compared with that for ZPPR-17A ($+0.406\%$) is attributed to the overestimate of leakage in the CRP banks by diffusion calculations.

The modelling effects derivable from the present calculations for ZPPR-17C are only approximate due to differences in core models. The transport correction to the nodal diffusion k-effective is $+0.57\% \Delta k$ taking into account a correction of $+0.04\% \Delta k$ for difference in the shim rod positions (calculated for ZPPR-17B). This compares with a transport correction of $+0.50\% \Delta k$ calculated for ZPPR-17B.² The error due to coarse mesh size in FDDT appears to be $+0.58\% \Delta k$. However, differences of one or two tenths of a percent may arise from use of generic master compositions in

FDDT models. Modelling effects that are somewhat different to those for ZPPR-17B are to be expected due to the presence of the control rods.

For ZPPR-17A, a noteworthy discrepancy exists between diffusion to transport corrections calculated by the nodal codes in xyz geometry and by the finite difference codes in rz geometry. The nodal transport calculation predicts a transport effect of +0.41% while the rz models predict +0.60%. A similar difference was found for ZPPR-17B from a comparison of an S_4 calculation made in xyz geometry with the TRITAC code¹² with the nodal transport result.

5.3 Summary of Eigenvalue Analysis

Fuel and ^{238}U loadings for ZPPR-17 are shown in Table 5.8. The fuel enrichment increased from 14.9% in 17A to 15.7% in 17C which was critical with 13 control rods half inserted. The calculated k_{eff} s were obtained from xyz geometry models with 21 group cross sections. Nodal diffusion results were relatively low, 0.987 for the simple core 17A, 0.984 in 17B (due to an overestimate of leakage in the CRPs) and 0.985 in 17C. Nodal transport results were 0.4% to 0.6% higher. The S_4 transport calculations were made for 17A using the TWODANT code in rz geometry and for 17B using the TRITAC code in xyz geometry.^{11,12} These showed significantly larger transport corrections; 0.6% in 17A and 0.8% in 17B, than the nodal transport values. For 17C, the S_4 transport correction was estimated from six-group calculations for the subcritical core with control rods inserted.

The nodal transport results for ZPPR-17 appear to be somewhat less accurate than in other homogeneous and radially heterogeneous cores. Previous tests of the code for ZPPR-13 showed that over 80% of the diffusion theory error was eliminated.¹³ The S_4 results, with a bias of 0.993, are consistent with other results for LMR cores.¹⁴

5.4 Delayed Neutron Fractions

Delayed neutron parameters were calculated with the 21 group xyz models. The finite-difference solutions were used since at the start of the

analysis the editing of the nodal solutions in the VARI3D code has not been fully tested. Results are given in Tables 5.9 to 5.11. The calculated β_{eff} s decrease slightly as the enrichment increases from 17A to 17C.

TABLE 5.1 Experimental and Calculated k-effective Results for ZPPR-17A

	<u>Critical Reference</u>	<u>Subcritical Reference</u>
Date	02/23/87	02/26/87
Reactor Run Number	22	25
Temperature, K	300.3	300.47
Interface Gap, GIU ^a	-44.2	-44.3
Measured Excess Reactivity, ϕ	$+7.1 \pm 0.1$	-25.86 ± 0.21
Adjustment to 293K, ϕ ^b	$+7.88 \pm 0.80$	$+8.07 \pm 0.82$
Adjustment to 44.2 GIU ^c , ϕ	---	$+0.34 \pm 0.04$
Adjustment to 02/23/87, ϕ	---	$+0.072 \pm 0.007$
Adjusted Reactivity, ϕ	$+15.0 \pm 0.8$	-17.38 ± 0.85
Experimental K-effective (E) ^d	1.000508 ± 0.000027	0.999412 ± 0.000029
Calculation, 21G XYZ NDT (C)	0.987075	0.985888
C/E for k-effective	0.986574	0.986468

^aGIU = Gap interface unit (approximately 1 mil) on a scale with arbitrary zero.

^bUsing measured temperature coefficient $-1.08 \pm 0.11 \phi \text{ K}^{-1}$.

^cUsing measured gap coefficient $-0.18 \pm 0.02 \phi \text{ GIU}^{-1}$.

^dUsing calculated ^{241}Pu decay coefficient $-0.02386 \phi \text{ day}^{-1}$.

^eUsing calculated β -effective 0.003385.

TABLE 5.2 Experimental and Calculated k-effective Results for ZPPR-17B

	<u>Critical Reference</u>	<u>Subcritical Reference</u>
Date	5/8/87	5/07/87
Reactor Run Number	96	95
Temperature, K	300.1	300.2
Interface Gap, mil ^a	42.1	42.0
Measured Excess Reactivity, ϕ	$+11.7 \pm 0.1$	-22.45 ± 0.18
Adjustment to 293K, ϕ ^b	$+7.67 \pm 0.78$	$+7.78 \pm 0.79$
Adjustment to 42.1 mil ^c , ϕ	---	-0.02 ± 0.00
Adjustment to 5/8/87, ϕ ^d	---	-0.02 ± 0.00
Adjusted Reactivity, ϕ	$+19.4 \pm 0.8\phi$	-14.71 ± 0.81
Experimental K-effective (E) ^e	1.000655 ± 0.000027	0.999504 ± 0.000029
Calculation, 21G XYZ NDT (C)	0.984989	---
C/E for k-effective	0.984344	---

^aOn a scale with arbitrary zero.

^bUsing measured temperature coefficient $-1.08 \pm 0.11\phi \text{ K}^{-1}$.

^cUsing measured gap coefficient $-0.18 \pm 0.02\phi \text{ mil}^{-1}$.

^dUsing calculated ^{241}Pu decay coefficient $-0.02386\phi \text{ day}^{-1}$.

^eUsing calculated β -effective 0.003374.

TABLE 5.3 Experimental and Calculated k-effective Results for ZPPR-17C

	<u>Critical Reference</u>	<u>Subcritical Reference</u>
Date	6/16/87	6/12/87
Reactor Run Number	152	150
Temperature, K	298.93	300.4
Interface Gap, mil ^a	40.1	42.3
Measured Excess Reactivity, ϕ	$+6.7 \pm 0.1$	-25.2 ± 0.2
Adjustment to 293K, ϕ ^b	$+6.40 \pm 0.6$	$+7.99 \pm 0.8$
Adjustment to 40.1 mil ^c , ϕ	---	$+0.40 \pm 0.04$
Adjustment to 6/16/87, ϕ ^d	---	-0.10 ± 0.01
Adjusted Reactivity, ϕ	$+13.1 \pm 0.7$	-16.9 ± 0.8
Experimental K-effective (E) ^e	1.000440 ± 0.000023	0.999432 ± 0.000027
Calculation, 21G XYZ NDT (C)	0.984640	---
C/E for k-effective	0.984207	---

^aOn a scale with arbitrary zero.

^bUsing temperature coefficient $-1.08 \pm 0.11 \phi \text{ K}^{-1}$, measured in ZPPR-17A.

^cUsing gap coefficient $-0.18 \pm 0.02 \phi \text{ mil}^{-1}$, measured in ZPPR-17A.

^dUsing ^{241}Pu decay coefficient $-0.02386 \phi \text{ day}^{-1}$, calculated for ZPPR-17A.

^eUsing calculated β -effective 0.003357.

TABLE 5.4 k-effective Calculations for Several Models of ZPPR-17A

	Reactor Loading ^a	Number of Groups	Geometry	Mesh	Calculation Method ^b	Streaming	Shim Rods ^c	k-effective ^d
1	C	21	xyz	32 x 32 x 9	NDT	Yes	No	0.987075
2	S	21	xyz	"	NDT	Yes	No	0.985888
3	C	21	xyz	"	NDT	Yes	Yes	0.986869
4	C	21	xyz	"	NTT	Yes	Yes	0.990930
5	C	21	xyz	32 x 32 x 20	FDDT	Yes	No	0.989820
6	C	6	xyz	32 x 32 x 9	NDT	Yes	No	0.987662
7	S	6	xyz	"	NDT	Yes	No	0.986489
8	C	21	rz	40 x 20	FDDT	Yes	No	0.988684
9	C	21	rz	40 x 20	FDDT	No	No	0.992676
10	C	21	rz	64 x 40	FDDT	No	No	0.991398
11	C	21	rz ^e	∞	FDDT	No	No	0.990946
12	C	21	rz	40 x 20	S4	No	No	0.996979
13	C	6	rz	40 x 20	FDDT	No	No	0.992986
14	C	21	xyz	32 x 32 x 9	NDT	No	No	0.990657

^aC = critical reference, S = subcritical reference.

^bNDT = nodal diffusion, NTT = nodal transport, FDDT = finite difference diffusion, S4 = transport, S4 quadrature, TWODANT code.

^cShim rods at core/axial blanket interface for foil irradiations.

^dNot C/E values.

^eExtrapolated to infinite mesh by $1/n^2$ variation.

TABLE 5.5 k-effective Calculations for Several Models of ZPPR-17B

	Reactor Loading ^a	Number of Groups	Geometry	Mesh	Calculation Method ^b	Streaming	Shim Rods ^c	k-effective ^d
1	C	21	xyz	32 x 32 x 9	NDT	Yes	No	0.984989
2	C	21	xyz	"	NDT	Yes	Yes	0.984574
3	C	21	xyz	"	NTT	Yes	Yes	0.989548
4	C	21	xyz	32 x 32 x 20	FDDT	Yes	No	0.987051
5	C	6	xyz	"	FDDT	Yes	No	0.986379
6	S	6	xyz	32 x 32 x 9	NDT	Yes	No	0.984174
7	S	6	xyz	32 x 32 x 20	FDDT	Yes	No	0.985234
8	C	21	rz	50 x 20	FDDT	Yes	No	0.984383
9	C	6	rz	50 x 20	FDDT	Yes	No	0.984196

^aC = critical reference, S = subcritical reference.

^bNDT = nodal diffusion, NTT = nodal transport, FDDT = finite difference diffusion,
S₄ = transport, S₄ quadrature, TWODANT code.

^cShim rods at core/axial blanket interface for foil irradiations.

^dNot C/E values.

TABLE 5.6 k-effective Calculations for Several Models of ZPPR-17C

	Reactor Loading ^a	Number of Groups	Geometry	Mesh	Calculation Method ^b	Streaming	Shim Rods ^c	k-effective ^d
1	C	21	xyz	32 x 32 x 18	NDT	Yes	No	0.984640
2	C	21	xyz	32 x 32 x 18	NTT	Yes	Yes	0.989924
3	C	21	xyz	32 x 32 x 40	FDDT	Yes	No	0.990465
4	C	6	xyz	32 x 32 x 40	FDDT	Yes	No	0.988263
5	C	21	rz	50 x 40	FDDT	Yes	No	0.980588

^aC = critical reference.

^bNDT = nodal diffusion, NTT = nodal transport, FDDT = finite difference diffusion.

^cShim rods at core/axial blanket interface for foil irradiations.

^dNot C/E values.

TABLE 5.7 Modelling Effects Calculated
for ZPPR-17A

Correction		Table 5.4 Cases	Δk Value
rz $\rightarrow$ xy Geometry 6 Groups $\rightarrow$ 21 Groups		8 $\rightarrow$ 5	+0.001136 ^a
	xyz	6 $\rightarrow$ 1	-0.000587
	xyz	7 $\rightarrow$ 2	-0.000601
	rz	13 $\rightarrow$ 9	-0.000310 ^a
Mesh in FDDT	xyz	5 $\rightarrow$ 1	-0.002745 ^b
	rz	9 $\rightarrow$ 11	-0.001730
Streaming	xyz	14 $\rightarrow$ 1	-0.003582
	rz	9 $\rightarrow$ 8	-0.003992 ^a
Shim Rod Worth	xyz	1 $\rightarrow$ 3	-0.000206 ^c
Diffusion $\rightarrow$ Transport	xyz	3 $\rightarrow$ 4	+0.004061
	rz	11 $\rightarrow$ 12	+0.006033

^aThis result includes a small mesh inconsistency between 40 radial points and 32 xy points.

^bAssuming nodal diffusion solution has a negligible mesh error.

^cCalculated reactivity for 8 shim rods inserted to core/axial blanket interface relative to the fully withdrawn position, model used for calculations of reaction rate distributions.

TABLE 5.8 ZPPR-17 Fuel Loadings and
Criticality Predictions

	<u>17A</u>	<u>17B</u>	<u>17C</u>
Fissile Pu, kg	2272	2247	2450
²³⁸ U, kg			
Core	12659	12248	12815
Internal Blanket	2375	2218	2218
Fuel Enrichment, %	14.9	15.2	15.7
<u>Calculated k_{eff}</u>			
Nodal Diffusion	0.9866	0.9843	0.9846
Nodal Transport	0.9906	0.9893	0.9903
S ₄ Transport	0.9926	0.9924	0.9934

TABLE 5.9 Delayed Neutron
Parameters for ZPPR-17A

Family	a_i	λ_i, s^{-1}	$\beta_i, \%$
1	0.02420	0.01298	0.00819
2	0.20807	0.03144	0.07043
3	0.18628	0.13560	0.06306
4	0.36059	0.34601	0.12206
5	0.16632	1.3679	0.05630
6	0.05455	3.7597	0.01846

 β -effective 0.3385%Prompt neutron lifetime $4.660 \times 10^{-7}s$ TABLE 5.10 Delayed Neutron
Parameters for ZPPR-17B

Family	a_i	λ_i, s^{-1}	$\beta_i, \%$
1	0.02433	0.01298	0.00821
2	0.20868	0.03144	0.07040
3	0.18655	0.13557	0.06293
4	0.36032	0.34589	0.12216
5	0.16576	1.3673	0.05592
6	0.05436	3.7561	0.01834

 β -effective 0.3374%Prompt neutron lifetime $4.895 \times 10^{-7}s$ TABLE 5.11 Delayed Neutron
Parameters for ZPPR-17C

Family	a_i	λ_i, s^{-1}	$\beta_i, \%$
1	0.02428	0.01298	0.00815
2	0.20858	0.03144	0.07003
3	0.18651	0.13562	0.06262
4	0.36028	0.34589	0.12096
5	0.16592	1.3673	0.05570
6	0.05443	3.7570	0.01828

 β -effective 0.3357%Prompt neutron lifetime $4.235 \times 10^{-7}s$

6. ANALYSIS OF REACTION RATE MEASUREMENTS

Detailed measurements of fission rates in ^{239}Pu , ^{235}U and ^{238}U and capture in ^{238}U were made in the three critical ZPPR-17 reference configurations. The standard ZPPR foil techniques were used.¹⁵ However, the gamma counting system was recalibrated using the latest reference data.¹⁶ This section presents the cell-average experimental results and comparisons with analysis. More detailed results were reported in references 3 and 5.

The number of experimental reaction rate values is quite overwhelming: 623 cell-average values in 17A, 536 in 17B and 1078 in 17C. (Several hundred foil measurements were made in addition to obtain cell-average/foil factors in different cells.) The results in this section are selected to give a summary of the analysis. Full details of the data are available in the references.

6.1 Description of the Measurements

Foil locations were chosen to emphasize the axial characteristics of the ZPPR-17 assemblies. Comparisons with calculations are provided for the cases of no CRPs or CRs (17A), of 25 CRPs (17B) and of 13 half-inserted CRs (17C). The measurements fell into three basic categories:

(i) Radial distributions along the x-axis at $z = 5$ cm (through the internal blanket), at $z = 18$ cm (just above the internal blanket), and at $z = 28$ cm from the midplane. In 17C, measurements were made at these axial displacements in both halves.

(ii) Radial distributions at 45° to the axis, using ^{235}U foils, for the same three axial elevations. In 17A, these measurements were made at $z = 5$ cm only. In 17C, measurements were made at the three axial displacements in both halves.

(iii) Axial distributions. In ZPPR-17A, these were in 148-50 (core center), 148-66 (peak flux region just outside the radial edge

of the internal blanket) and in 148-70 (half way between internal and radial blankets). In ZPPR-17B, these were in 148-51 (adjacent to the central CRP), in 148-62 (adjacent to an outer-ring CRP) and in 148-70. In ZPPR-17C, the 17B measurements were repeated, but included both half-one and half-two.

The foil placement in ZPPR-17A in the xy plane is shown in Fig. 6.1 and in an rz sense in Fig. 6.2. Placements for 17B and 17C are shown in Fig. 6.3.

The statistical uncertainties on the measured reaction rates are in the range 0.5% to 0.7% for fission in ^{235}U and ^{239}Pu and for capture in ^{238}U , within the core and internal blanket regions, increasing to 0.9% in the axial blanket. For fission in ^{238}U , statistical uncertainties are about 1.5% in the fuel regions, 4% in the internal blanket and 4% (near core boundary) to 15% in the axial blanket.

ZPPR-17A

Fig. 6.1. Foil Locations in ZPPR-17A in the xy Plane.

Fig. 6.2. Foil Locations in ZPPR-17A in the xz Plane.

Fig. 6.3 Foil Locations in ZPPR-17B and 17C in the xy Plane

6.2 Calculations

Calculations were made with ENDF/B-V.2 cross sections in 21 groups using an xyz model and the nodal transport path of the DIF3D code. The microscopic data were processed for cell heterogeneity using a buckling-recycle technique (section 4.3). These cross sections were prepared for ZPPR-17A and used in 17B and 17C without reprocessing. The nodal transport calculations for ZPPR-17A and 17B used a quartic polynomial approximation for the fluxes. However, since ZPPR-17C required a full-z model, a cubic polynomial approximation was used because of computer storage limitations.

The models for reaction rate analysis included the ZPPR operating shim rods at or close to their average insertion during the irradiations. The measurements used eight symmetrically inserted rods specifically for convenience in the analysis. Cross sections for the shim rods were self-shielded for the boron blade and averaged over a matrix area with a special model using the SDX code. Measured shim rod reactivities were 6¢ in 17A, 11¢ in 17B and 2¢ in 17C. These reactivities were reproduced by calculation within 2¢ which is adequate in view of the small overall perturbations to core fission rates of less than 1% except in the immediate vicinity of the control drawers.

Calculated reaction rates were interpolated to the foil locations using the nodal polynomial coefficients for each mesh region and energy group. It is recognized that this procedure is somewhat flawed since the coefficients are calculated to give the average flux in a node and internal values are only approximate. An alternative method using quadratic interpolation on the node-average fluxes gave less satisfactory results in ZPPR-17 due to the coarse axial node spacings in the z-dimension which were typically 10 cm to 15 cm.

The appropriate cell-average cross sections were used for calculations of reaction rates. For plutonium fission in blanket regions, cross sections self-shielded for the foil thicknesses were calculated in a special SDX model. Previous tests showed that foil shielding effects for ^{235}U were small in core regions. This may not be the case for ^{235}U fission

in the softer spectra of the depleted uranium blanket regions. The present analysis uses cell average cross sections for ^{235}U which are close to infinite dilution.

For comparison with experiment, the calculated data (C) have been normalized to experiment (E) to give an average C/E of unity for all results available for plutonium fission in the core regions. In ZPPR-17A, 74 results for plutonium fission were available and the distributions covered most of the core region (Fig. 6.1). However, in 17B and 17C, fewer plutonium fission measurements were possible because of foil inventory limitations. In the latter two cores, plutonium fission measurements were made axially adjacent to the central CRP or CRP/CR and in a few radial positions near the core center. Consequently, the normalizations differ among the three cores because of the spatial mispredictions of reaction rates. The C/E results for 17B and 17C are about 3% higher than those in 17A.

The experimental results are normalized to a reactor power of approximately 1 watt using countrates on two boron-trifluoride chambers (EXP1 and EXP2 in the ZPPR jargon) positioned outside the core. Although the relative normalization between the results in the three cores is only approximate the experimental reaction shapes can be compared. All experimental reaction rates in the following tables are given in units of 10^{-18} reactions per atom per second at a power of 1 watt.

6.3 Reaction Rate Distributions in ZPPR-17A

Experimental reaction rates and C/E results for distributions along the x-axis at about 5 cm from the axial midplane are shown in Table 6.1. Similar tables for distributions at 18 cm and 28 cm from the midplane plus results for ^{235}U fission along the y-axis and at 45° to the axes are given in reference 3. The results for fission in plutonium at $z = 5$ and $z = 28$ cm are plotted in Fig. 6.4. Results for fission in ^{238}U at $z = 5$ and 28 cm are plotted in Fig. 6.5.

The results in Table 6.1 are generally typical of those throughout ZPPR-17 analysis:

(i) The C/E results increase with distance from the core center for all reactions.

(ii) The C/E results for ^{238}U capture and fission vary systematically by 2% to 3% between single- and double-fuel-column drawers.

(iii) ^{238}U fission rates are inconsistently predicted by 5% to 10% across the boundaries of fuel and blanket zones.

(iv) ^{235}U fission and ^{238}U capture are predicted consistently through the radial blanket up to the last drawer, while C/E results for ^{239}Pu fission decrease by several percent with penetration. The C/E results for ^{238}U fission decrease with distance into the radial blanket by 25% but the statistical uncertainties are comparable at these penetrations.

(v) ^{235}U fission is markedly overpredicted at the last position in the blanket and the first position in the steel reflector. Note that the results in the outer part of the reflector are meaningless because of the boundary condition in the calculations.

The radial reaction rate analysis is summarized in Table 6.2. The C/E results have been averaged for groups of four successive matrix

positions along each traverse. This has the advantage of reducing the statistical fluctuations and shows clearly the monotonic increase in C/E with distance from the center for all traverses and all reactions.

Since the axial reaction rate distributions are of major interest, these results are given in detail in Tables 6.3 for the core center, in Table 6.4 for matrix 148-66 in the outer core adjacent to the internal blanket and in Table 6.5 for the center of the outer core. Plots of the axial distributions of ^{239}Pu and ^{238}U fission at the three locations are given in Figs. 6.6 and 6.7.

Axial reaction rate distributions are well predicted through the internal blanket and core regions. Within a given zone, fluctuations of individual C/Es from the mean are not significant in comparison with experimental statistics. Calculations of ^{238}U fission through the internal blanket and the core (Table 6.3 and Fig. 6.7) are remarkably good in view of the variation in fission rates of a factor of four.

Results in the axial blanket are similar to those from the radial blanket but more definitive due to the increased thickness. The C/Es for ^{235}U fission and ^{238}U capture are consistent up to the last position (74 cm from the core midplane) while C/Es for ^{239}Pu fission and ^{238}U fission decrease with distance into the blanket. Predictions of ^{235}U fission in the steel axial reflector are high by about 10% (Table 6.3).

TABLE 6.1 ZPPR-17A: Radial Reaction Rate Distributions along the X-axis at $z = 5$ cm

Matrix	Zone	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IB	6.983	0.962	8.016	0.993	0.9636	1.019	0.0538	0.899
148 51	IB	7.045	0.959	8.109	0.997	0.9790	1.011	0.0428	1.003
148 52	IB	7.079	0.960	8.156	0.997	0.9766	1.020	0.0457	0.935
148 53	IB	7.090	0.967	8.168	1.004	0.9844	1.021	0.0439	0.982
148 54	IB	7.116	0.975	8.256	1.005	1.0020	1.015	0.0460	0.952
148 55	IB	7.211	0.976	8.329	1.011	1.0090	1.023	0.0456	0.967
148 56	IB	7.408	0.967	8.495	1.009	1.0230	1.028	0.0468	0.962
148 57	IB	7.492	0.976	8.650	1.011	1.0480	1.025	0.0437	1.058
148 58	IB	7.633	0.980	8.865	1.009	1.0700	1.028	0.0456	1.037
148 59	IB	7.813	0.982	9.022	1.015	1.0940	1.032	0.0472	1.041
148 60	IB	7.991	0.987	9.220	1.018	1.1320	1.026	0.0518	1.005
148 61	IB	8.115	0.998	9.379	1.024	1.1460	1.042	0.0580	0.955
148 62	IB	8.295	1.002	9.517	1.028	1.1750	1.042	0.0614	0.998
148 63	IB	8.467	1.003	9.582	1.033	1.1890	1.048	0.0704	1.007
148 64	IB	8.522	1.009	9.509	1.037	1.2030	1.043	0.0799	1.081
148 65	IB	8.368	1.024	9.241	1.037	1.1910	1.036	0.1119	1.059
148 66	OC D	7.925	1.013	8.680	1.022	1.1250	1.068	0.1997	1.004
148 67	OC S	7.846	1.030	8.454	1.024	1.1210	1.058	0.2060	1.033
148 68	OC S	7.763	1.023	8.201	1.018	1.0850	1.053	0.2130	1.030
148 69	OC D	7.393	1.024	7.767	1.014	0.9775	1.085	0.2233	1.019
148 70	OC S	6.895	1.012	7.134	1.024	0.9483	1.051	0.1881	1.042
148 71	OC S	6.132	1.026	6.461	1.019	0.8512	1.060	0.1663	1.056
148 72	OC D	5.333	1.024	5.615	1.023	0.7102	1.098	0.1539	1.028
148 73	OC S	4.407	1.011	4.869	1.005	0.6319	1.074	0.1115	0.957
148 74	RB	3.747	0.996	4.123	1.014	0.5204	1.048	0.0482	1.060
148 75	RB	2.871	0.999	3.260	1.023	0.3970	1.084	0.0269	0.978
148 76	RB	2.253	0.961	2.575	1.009	0.3097	1.057	0.0142	1.008
148 77	RB	1.759	0.939	2.022	1.007	0.2309	1.060	0.0103	0.768
148 78	RB	1.464	0.925	1.659	1.041	0.1878	0.999	0.0058	0.766
148 79	RR	--	--	1.665	1.079	--	--	--	--
148 80	RR	--	--	1.350	1.026	--	--	--	--
148 81	RR	--	--	0.828	0.734	--	--	--	--

TABLE 6.2 ZPPR-17A: Summary of Radial Reaction Rate Distribution C/E Values^a

Reaction	Distribution	Inner Zone	ICA	ICB	ICC	ICD	OCE	OCF	RBG
$^{239}\text{Pu}(n,f)$	X-axis Z=5 cm	IB	0.962	0.974	0.987	1.010	1.023	1.018	0.974
	X-axis Z=18 cm	IC	0.963	0.965	0.976	1.005	1.025	1.025	0.974
	X-axis Z=28 cm	IC	0.978	0.978	0.985	1.007	1.023	1.017	0.975
$^{235}\text{U}(n,f)$	X-axis Z=4 cm	IB	0.998	1.009	1.017	1.034	1.020	1.018	1.013
	45-Deg. Z=4 cm	IB	1.006	1.011	1.015	1.026	1.007	1.013	1.026
	Y-axis Z=4 cm	IB	0.997	1.004	1.015	1.024	1.007	1.004	1.017
	X-axis Z=18 cm	IC	0.978	0.983	0.994	1.005	1.018	1.012	1.016
	X-axis Z=28 cm	IC	0.971	0.974	0.987	1.003	1.016	1.013	1.015
$^{238}\text{U}(n,\gamma)$	X-axis Z=5 cm	IB	1.018	1.023	1.032	1.042	1.066	1.071	1.062
	Y-axis Z=5 cm	IB	1.026	1.029	1.037	1.038	1.054	1.065	1.058
	X-axis Z=18 cm	IC	1.025	1.024	1.037	1.070	1.073	1.069	1.063
	X-axis Z=28 cm	IC	1.013	1.029	1.032	1.055	1.071	1.066	1.080
$^{238}\text{U}(n,f)$	X-axis Z=5 cm	IB	0.955	0.985	1.010	1.036	1.021	1.030	0.954
	Y-axis Z=5 cm	IB	0.941	1.008	1.013	1.069	1.004	0.990	0.972
	X-axis Z=18 cm	IC	0.969	0.956	0.973	1.002	1.026	1.031	0.979
	X-axis Z=28 cm	IC	0.979	0.975	1.008	1.008	1.034	0.990	0.955

^aResults shown are the mean C/E values for four successive matrix positions along the traverse.

TABLE 6.3 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-50 (Core Center)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
IB	26.2	7.049	0.958	8.060	1.006	0.9777	1.013	0.0434	0.906
IB	49.6	7.115	0.947	8.055	1.001	0.9742	1.013	0.0417	1.015
IB	77.0	6.983	0.962	8.016	0.993	0.9636	1.019	0.0538	0.899
IB	100.4	6.912	0.966	7.889	0.994	0.9624	1.011	0.0600	0.953
IB	127.8	6.813	0.971	7.669	0.996	0.9414	1.018	0.0719	0.998

Zone Average C/E			0.961			1.015		0.954	
Standard Deviation			0.009			0.003		0.052	
IC S	178.6	6.274	0.965	7.154	0.980	0.9323	1.027	0.1337	0.975
IC S	229.4	6.399	0.960	6.947	0.974	0.8978	1.032	0.1576	1.000
IC S	280.2	6.317	0.976	6.784	0.974	0.8933	1.012	0.1702	0.999
IC S	331.0	6.188	0.979	6.574	0.979	0.8623	1.020	0.1691	0.997
IC S	381.8	5.827	0.989	6.286	0.976	0.8267	1.015	0.1595	0.996
IC S	432.6	5.460	0.970	5.826	0.981	0.7715	1.014	0.1410	0.991
IC S	483.4	4.901	0.960	5.405	0.970	0.7189	1.001	0.1183	0.925

Zone Average C/E			0.971			1.017		0.983	
Standard Deviation			0.011			0.010		0.027	
AB	534.2	4.604	0.954	5.115	0.970	0.6556	1.008	0.0611	0.924
AB	585.0	4.153	0.934	4.637	0.978	0.5819	1.020	0.0364	0.871
AB	635.8	3.675	0.922	4.221	0.965	0.5176	1.007	0.0241	0.730
AB	686.6	3.291	0.901	3.756	0.972	0.4435	1.016	0.0162	0.739
AB	737.4	3.070	0.884	3.450	0.997	0.4033	0.985	0.0105	0.714

Zone Average C/E			0.919			1.007		0.796	
Standard Deviation			0.027			0.014		0.095	
AR	839.0	--	--	3.741	1.126	--	--	--	--
AR	889.8	--	--	3.713	1.064	--	--	--	--
AR	946.9	--	--	2.641	1.119	--	--	--	--
AR	997.7	--	--	1.937	0.988	--	--	--	--

TABLE 6.4 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-66 (Outer Core)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
OC D	51.6	7.925	1.013	8.680	1.022	1.1250	1.068	0.1997	1.004
OC D	102.4	7.950	1.006	8.496	1.031	1.0900	1.087	0.2119	0.971
OC D	178.6	7.716	1.022	8.260	1.019	1.0350	1.098	0.2217	0.997
OC D	229.4	7.586	1.013	7.993	1.014	0.9971	1.096	0.2185	1.033
OC D	280.2	7.267	1.013	7.637	1.009	0.9568	1.084	0.2205	1.002
OC D	331.0	6.870	1.005	7.206	1.003	0.9086	1.071	0.2027	1.018
OC D	381.8	6.244	1.012	6.580	1.009	0.8377	1.068	0.1781	1.048
OC D	432.6	5.539	1.014	5.936	1.007	0.7507	1.076	0.1539	1.039
OC D	483.4	4.795	1.005	5.264	1.007	0.6661	1.078	0.1202	1.008
			-----			-----			
Zone Average C/E			1.011			1.080			
Standard Deviation			0.005			0.012			
AB	534.2	4.410	0.987	4.825	1.015	0.6114	1.072	0.0614	0.891
AB	585.0	3.865	0.973	4.356	1.002	0.5305	1.082	0.0365	0.927
AB	635.8	3.341	0.959	3.781	1.008	0.4655	1.055	0.0230	0.913
AB	686.6	2.937	0.933	3.307	1.011	0.3939	1.059	0.0155	0.801
AB	737.4	2.632	0.931	2.954	1.044	0.3356	1.073	0.0114	0.643
			-----			-----			
Zone Average C/E			0.957			1.068			
Standard Deviation			0.025			0.011			
AR	839.0	--	--	3.043	1.188	--	--	--	--
AR	889.8	--	--	2.883	1.162	--	--	--	--

TABLE 6.5 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-70 (Outer Core)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
OC S	51.6	6.895	1.012	7.134	1.024	0.9483	1.051	0.1881	1.042
OC S	102.4	6.740	1.021	7.054	1.020	0.9360	1.049	0.1895	1.020
OC S	178.6	6.427	1.025	6.765	1.019	0.8865	1.060	0.1764	1.050
OC S	229.4	6.163	1.021	6.483	1.016	0.8607	1.043	0.1711	1.033
OC S	280.2	5.758	1.026	6.121	1.012	0.8056	1.048	0.1621	1.022
OC S	331.0	5.305	1.027	5.624	1.018	0.7441	1.050	0.1448	1.048
OC S	381.8	4.809	1.020	5.089	1.021	0.6757	1.051	0.1317	1.019
OC S	432.6	4.266	1.009	4.539	1.020	0.6011	1.056	0.1086	1.037
OC S	483.4	3.734	0.985	4.069	1.005	0.5412	1.038	0.0875	0.974
Zone Average C/E		1.016		1.017		1.050		1.027	
Standard Deviation		0.013		0.006		0.006		0.023	
AB	534.2	3.344	0.989	3.710	1.002	0.4778	1.041	0.0479	0.907
AB	585.0	2.865	0.986	3.277	1.001	0.4054	1.066	0.0270	0.902
AB	635.8	2.488	0.961	2.863	0.997	0.3521	1.046	0.0158	0.855
AB	686.6	2.174	0.936	2.448	1.015	0.2931	1.057	0.0106	0.840
AB	737.4	1.953	0.928	2.189	1.042	0.2471	1.077	0.0097	0.571
Zone Average C/E		0.960		1.011		1.057		0.815	
Standard Deviation		0.028		0.018		0.015		0.139

Fig. 6.4 Measured and Calculated Fission Rates in ^{239}Pu Along the x-axis of ZPPR-17A.

Fig. 6.5 Measured and Calculated Fission Rates in ^{238}U Along the x-axis of ZPPR-17A.

Fig. 6.6. Measured and calculated axial distributions for ^{239}Pu fission in ZPPR-17A.

Fig. 6.7. Measured and calculated axial distributions for ^{238}U fission in ZPPR-17A.

6.4 Reaction Rate Distributions in ZPPR-17B

Reaction rate measurements in ZPPR-17B were made in similar positions to those in 17A except that no measurements along the y-axis or in symmetric locations were included. Additional traverses for ^{235}U fission at 45° to the axis, through a control position, were made at 18 cm and 28 cm in anticipation of comparisons with ZPPR-17C where a control rod was one-half inserted. For the same reason, one axial traverse was moved to matrix 138-62 (Fig. 6.3) adjacent to the CRP. The axial traverse near the center was moved to matrix 148-51 to be adjacent to the central CRP. Fewer plutonium foils were available for 17B and these were used in the axial traverse near to the central CRP and in a number of positions around the center to obtain reaction rate ratio data. Previous analyses have shown that essentially the same information on the accuracy of prediction of fission distributions in the core regions is obtained from ^{235}U foils instead of ^{239}Pu foils. This may be verified by examination of the results for ZPPR-17A. Differences between the analysis of ^{235}U and ^{239}Pu are found in the softer spectra of the blanket regions.

The detailed results for ZPPR-17B are found in Reference 5. We show here only the summary of radial reaction analysis in Table 6.6 and the detailed axial distributions in Tables 6.7 to 6.9.

TABLE 6.6 ZPPR-17B: Summary of Radial Reaction Rate Distribution Analyses

Reaction	Distribution ^a	Inner Zone	ICA	ICB	ICC	ICD	OCE	OCF	RBG
$^{239}\text{Pu}(n,f)$	X-axis Z=5 cm	IB	1.017	1.028	--	--	--	--	--
	X-axis Z=18 cm	IC	0.996	0.995	--	--	--	--	--
	X-axis Z=28 cm	IC	0.998	1.016	--	--	--	--	--
$^{235}\text{U}(n,f)$	X-axis Z=5 cm	IB	1.039	1.048	1.053	1.074	1.061	1.068	1.066
	45-Deg. Z=5 cm	IB	1.040	1.056	1.049	1.066	1.042	1.047	1.070
	X-axis Z=18 cm	IC	1.011	1.017	1.025	1.049	1.063	1.061	1.061
	45-Deg Z=18 cm	IC	1.006	1.023	1.028	1.043	1.051	1.052	1.072
	X-axis Z=28 cm	IC	1.011	1.025	1.028	1.039	1.059	1.060	1.065
	45-Deg Z=28 cm	IC	1.010	1.008	1.023	1.035	1.054	1.046	1.065
$^{238}\text{U}(n,\gamma)$	X-axis Z=5 cm	IB	1.066	1.076	1.088	1.093	1.109	1.119	1.105
	X-axis Z=18 cm	IC	1.048	1.049	1.062	1.107	1.118	1.114	1.110
	X-axis Z=28 cm	IC	1.043	1.054	1.069	1.096	1.110	1.110	1.107
$^{238}\text{U}(n,f)$	X-axis Z=5 cm	IB	1.032	1.048	1.088	1.142	1.051	1.066	0.983
	X-axis Z=18 cm	IC	0.980	0.996	1.008	1.052	1.062	1.067	1.028
	X-axis Z=28 cm	IC	1.016	1.006	1.024	1.052	1.064	1.055	1.007

^aResults shown are the mean C/E values for groups of successive matrix positions along the traverse.

TABLE 6.7 ZPPR-17B: Axial Reaction Rate Distributions in Matrix 148-51 (Near Core Center)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
IB	26.2	7.078	1.018	8.280	1.026	0.9673	1.052	0.0435	0.969
IB	49.6	7.082	1.014	8.227	1.026	0.9658	1.050	0.0491	0.918
IB	77.0	7.023	1.014	8.109	1.027	0.9523	1.057	0.0511	1.006
IB	100.4	6.909	1.020	7.814	1.046	0.9382	1.061	0.0560	1.075
IB	127.8	6.800	1.017	7.751	1.021	0.9319	1.048	0.0722	1.029
		-----		-----		-----		-----	
Zone Average C/E		1.017		1.029		1.054		0.999	
Standard Deviation		0.003		0.010		0.005		0.060	
IC D	178.6	6.063	0.995	7.049	0.995	0.8894	1.034	0.1434	0.962
IC D	229.4	6.060	1.003	--	--	0.8573	1.043	0.1613	0.984
IC D	280.2	6.160	0.985	6.582	1.008	0.8414	1.041	0.1693	0.984
IC D	331.0	5.919	1.001	6.276	1.020	0.7954	1.064	0.1733	0.962
IC D	432.6	5.235	0.992	5.652	1.003	0.7253	1.034	0.1431	0.985
IC D	483.4	4.725	0.981	5.270	0.995	0.6647	1.040	0.1136	0.967
		-----		-----		-----		-----	
Zone Average C/E		0.993		1.004		1.043		0.974	
Standard Deviation		0.009		0.010		0.011		0.011	
AB	534.2	4.594	0.994	5.100	1.009	0.6141	1.073	0.0536	0.981
AB	585.0	4.171	0.995	4.777	1.001	0.5723	1.045	0.0332	1.030
AB	635.8	3.878	0.961	4.336	1.009	0.4972	1.069	0.0219	1.018
AB	686.6	3.573	0.945	3.997	1.007	0.4422	1.061	0.0147	0.913
AB	737.4	3.423	0.927	3.808	1.008	0.3937	1.066	0.0111	0.740
		-----		-----		-----		-----	
Zone Average C/E		0.964		1.007		1.063		0.936	
Standard Deviation		0.030		0.003		0.011		0.119	
AR	825.2	--	--	4.008	1.129	--	--	--	--
AR	876.0	--	--	3.771	1.171	--	--	--	--
AR	933.1	--	--	3.008	1.152	--	--	--	--
AR	983.9	--	--	2.168	1.106	--	--	--	--
AR	1034.7	--	--	1.383	0.864	--	--	--	--

TABLE 6.8 ZPPR-17B: Axial Reaction Rate Distributions
in Matrix 138-62 (next to CRP)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC S	51.6	8.954	1.040	1.1320	1.083	0.1856	0.971
OC S	102.4	8.808	1.041	1.1000	1.098	0.1967	0.944
OC S	178.6	8.452	1.038	1.0500	1.099	0.2032	0.999
OC S	229.4	8.016	1.047	1.0150	1.090	0.2089	1.002
OC S	280.2	7.677	1.037	0.9642	1.087	0.2025	1.017
OC S	331.0	7.178	1.037	0.9180	1.070	0.1905	1.006
OC S	381.8	6.595	1.040	0.8487	1.065	0.1745	0.994
OC S	432.6	5.986	1.037	0.7622	1.073	0.1529	0.976
OC S	483.4	5.338	1.040	0.6829	1.069	0.1167	0.976
		-----		-----		-----	
Zone Average C/E		1.040		1.082		0.987	
Standard Deviation		0.003		0.013		0.022	
AB	534.2	5.041	1.038	0.6090	1.101	0.0572	0.938
AB	585.0	4.523	1.041	0.5327	1.108	0.0354	1.001
AB	635.8	4.008	1.042	0.4566	1.115	0.0227	1.034
AB	686.6	3.526	1.061	0.3869	1.133	0.0142	0.960
AB	737.4	3.211	1.085	0.3471	1.103	0.0102	0.798
		-----		-----		-----	
Zone Average C/E		1.053		1.112		0.946	
Standard Deviation		0.020		0.013		0.091	
AR	825.2	3.227	1.182	--	--	--	--
AR	876.0	2.957	1.227	--	--	--	--

TABLE 6.9 ZPPR-17B: Axial Reaction Rate Distributions
in Matrix 148-70 (Outer Core)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC S	51.6	7.390	1.062	0.9561	1.108	0.1951	1.094
OC S	102.4	7.036	1.098	0.9415	1.108	0.1949	1.079
OC S	178.6	6.935	1.066	0.9064	1.100	0.1812	1.114
OC S	229.4	6.658	1.059	0.8677	1.097	0.1759	1.096
OC S	280.2	6.246	1.061	0.8137	1.099	0.1691	1.067
OC S	331.0	5.767	1.062	0.7514	1.100	0.1514	1.092
OC S	381.8	5.207	1.066	0.6885	1.091	0.1321	1.105
OC S	432.6	4.703	1.052	0.6153	1.090	0.1127	1.086
OC S	483.4	4.155	1.052	0.5563	1.066	0.0897	1.032
		-----		-----		-----	
Zone Average C/E		1.064		1.095		1.083	
Standard Deviation		0.014		0.013		0.025	
AB	534.2	3.814	1.039	0.4753	1.092	0.0475	1.019
AB	585.0	3.304	1.061	0.4129	1.091	0.0306	0.883
AB	635.8	2.917	1.050	0.3560	1.080	0.0178	0.845
AB	686.6	2.549	1.050	0.2976	1.090	0.0119	0.836
AB	737.4	2.275	1.084	0.2597	1.076	0.0088	0.702
		-----		-----		-----	
Zone Average C/E		1.057		1.086		0.857	
Standard Deviation		0.017		0.007		0.114	

6.5 Reaction Rate Distributions in ZPPR-17C

Measurements in ZPPR-17C were made in the same locations as in 17B but duplicated in both halves of the reactor. The intent was to compare measured values and the accuracy of calculations both for the axial shapes adjacent to the half-inserted control rods and the perturbations in the radial distributions. The plutonium fission rates adjacent to the central control position were measured in both halves of the core.

As for ZPPR-17B, we show here only a summary of the analysis of radial distributions in Table 6.10. Detailed axial distributions are given in Tables 6.11 to 6.16. The control rods were inserted in reactor half two.

The measured axial ^{235}U fission distributions adjacent to the central control position in both ZPPR-17B and 17C are shown in Fig. 6.8. The measured distributions in the two cores adjacent to an outer control position are shown in Fig. 6.9.

Measured ^{235}U fission radial distributions at the six axial heights along the x-axis of ZPPR-17C are shown in Fig. 6.10.

Reaction rate results for ZPPR-17C are given in greater detail in Reference 5.

TABLE 6.10 ZPPR-17C: Summary of Radial Reaction Rate Distribution Analysis

Reaction	Distribution ^a	Inner Zone	ICA	ICB	ICC	ICD	OCE	OCF	RBG
$^{239}\text{Pu}(n,f)$	X-axis Z=+5 cm	IB	1.003	1.016	--	--	--	--	--
	X-axis Z=-5 cm	IB	0.999	1.005	--	--	--	--	--
	X-axis Z=+18 cm	IC	1.007	1.000	--	--	--	--	--
	X-axis Z=-18 cm	IC	1.011	0.991	--	--	--	--	--
	X-axis Z=-28 cm	IC	1.016	1.007	--	--	--	--	--
$^{235}\text{U}(n,f)$	X-axis Z=+5 cm	IB	1.031	1.041	1.048	1.084	1.074	1.077	1.100
	X-axis Z=-5 cm	IB	1.018	1.047	1.058	1.082	1.079	1.085	1.102
	45-Deg. Z=+5 cm	IB	1.036	1.054	1.055	1.070	1.067	1.070	1.089
	45-Deg. Z=-5 cm	IB	1.017	1.053	1.068	1.078	1.076	1.075	1.098
	X-axis Z=+18 cm	IC	1.016	1.015	1.030	1.054	1.072	1.068	1.084
	X-axis Z=-18 cm	IC	1.013	1.016	1.033	1.067	1.066	1.078	1.094
	45-Deg. Z=+18 cm	IC	1.016	1.033	1.035	1.053	1.062	1.071	1.079
	45-Deg. Z=-18 cm	IC	1.007	1.022	1.037	1.046	1.076	1.069	1.094
	X-axis Z=+28 cm	IC	1.012	1.023	1.029	1.044	1.061	1.059	1.095
	X-axis Z=-28 cm	IC	1.009	1.020	1.031	1.054	1.075	1.078	1.097
	45-Deg. Z=+28 cm	IC	1.017	1.025	1.025	1.042	1.055	1.060	1.074
	45-Deg. Z=-28 cm	IC	1.013	1.023	1.030	1.043	1.075	1.071	1.088
	All Z=+-5 cm	IB	1.025	1.049	1.057	1.078	1.074	1.077	1.097
	All Fuel Reg.	IC	1.013	1.022	1.031	1.050	1.068	1.069	1.087
$^{238}\text{U}(n,\gamma)$	X-axis Z=+5 cm	IB	1.060	1.077	1.095	1.110	1.149	1.157	1.137
	X-axis Z=-5 cm	IB	1.058	1.070	1.096	1.095	1.150	1.163	1.150
	X-axis Z=+18 cm	IC	1.075	1.071	1.087	1.140	1.148	1.133	1.143
	X-axis Z=-18 cm	IC	1.073	1.064	1.089	1.133	1.162	1.144	1.140
	X-axis Z=+28 cm	IC	1.061	1.069	1.073	1.116	1.134	1.145	1.136
	X-axis Z=-28 cm	IC	1.072	1.073	1.077	1.120	1.159	1.151	1.152
	All Z=+-5 cm	IB	1.059	1.073	1.095	1.103	1.149	1.160	1.144
	All Fuel Reg.	IC	1.070	1.069	1.081	1.127	1.151	1.143	1.143
$^{238}\text{U}(n,f)$	X-axis Z=+5 cm	IB	1.016	1.036	1.076	1.153	1.084	1.085	1.040
	X-axis Z=-5 cm	IB	1.002	1.025	1.048	1.120	1.097	1.097	1.060
	X-axis Z=+18 cm	IC	0.999	0.995	1.020	1.047	1.091	1.108	1.011
	X-axis Z=-18 cm	IC	1.006	0.995	0.998	1.052	1.090	1.120	1.040
	X-axis Z=+28 cm	IC	1.029	0.989	1.026	1.039	1.091	1.094	1.091
	X-axis Z=-28 cm	IC	1.026	1.005	1.018	1.074	1.080	1.096	0.995
	All Z = ± 5 cm	IB	1.009	1.030	1.062	1.136	1.090	1.091	1.050
	All Fuel Reg.	IC	1.015	0.996	1.015	1.053	1.088	1.104	1.034

^aResults shown are the mean C/E values for groups of successive matrix positions along the traverse.

TABLE 6.11 ZPPR-17C: Axial Reaction Rate Distributions in Matrix 148-51 (near Core Center)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
IB	26.2	5.625	0.995	6.648	1.008	0.8000	1.046	0.0390	1.013
IB	49.6	5.924	1.005	6.990	1.018	0.8319	1.062	0.0444	0.996
IB	77.0	6.267	1.011	7.211	1.032	0.8680	1.069	0.0534	0.986
IB	100.4	6.482	1.001	7.371	1.022	0.8921	1.058	0.0604	1.051
IB	127.8	6.596	1.005	7.428	1.020	0.8985	1.064	0.0775	1.033
		-----		-----		-----		-----	
Zone Average C/E		1.003		1.020		1.059		1.016	
Standard Deviation		0.006		0.009		0.009		0.027	
IC D	178.6	6.332	1.009	7.171	1.013	0.9163	1.063	0.1574	0.967
IC D	229.4	6.609	1.010	7.106	1.030	0.9108	1.075	0.1865	0.993
IC D	280.2	6.846	1.001	7.232	1.022	0.9209	1.073	0.1978	0.979
IC D	331.0	6.725	1.029	7.026	1.045	0.9013	1.091	0.2028	0.988
IC D	381.8	6.494	1.010	6.758	1.039	0.8855	1.059	0.1876	1.003
IC D	432.6	6.064	1.001	6.458	1.018	0.8302	1.058	0.1684	1.015
IC D	483.4	5.555	0.987	6.029	1.017	0.7786	1.054	0.1386	0.960
		-----		-----		-----		-----	
Zone Average C/E		1.007		1.026		1.068		0.983	
Standard Deviation		0.013		0.012		0.013		0.021	
AB	534.2	--	--	5.832	1.027	0.7209	1.091	0.0639	1.051
AB	585.0	--	--	5.405	1.044	0.6618	1.093	0.0414	0.960
AB	635.8	--	--	5.008	1.045	0.5845	1.115	0.0279	0.962
AB	686.6	--	--	4.577	1.077	0.5135	1.140	0.0190	0.838
AB	737.4	--	--	4.222	1.120	0.4592	1.146	0.0107	0.945
		-----		-----		-----		-----	
Zone Average C/E		--		1.063		1.117		0.951	
Standard Deviation		--		0.037		0.026		0.076	
AR	825.2	--	--	4.668	1.099	--	--	--	--
AR	876.0	--	--	4.350	1.155	--	--	--	--
AR	933.1	--	--	3.453	1.251	--	--	--	--
AR	983.9	--	--	2.550	1.120	--	--	--	--
AR	1034.7	--	--	1.597	0.861	--	--	--	--

TABLE 6.12 ZPPR-17C: Axial Reaction Rate Distributions in Matrix 248-51 (near Core Center)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
AR	1034.7	--	--	0.900	0.779	--	--	--	--
AR	983.9	--	--	1.356	1.063	--	--	--	--
AR	933.1	--	--	1.787	1.206	--	--	--	--
AR	876.0	--	--	2.043	1.152	--	--	--	--
AR	825.2	--	--	2.022	1.052	--	--	--	--
AB	737.4	1.306	0.964	1.474	1.140	0.1871	1.061	0.0055	0.851
AB	686.6	1.415	0.964	1.642	1.060	0.2062	1.071	0.0096	0.806
AB	635.8	1.594	0.984	1.885	1.022	0.2448	1.037	0.0121	1.108
AB	585.0	1.860	1.015	2.138	1.053	0.2827	1.059	0.0194	1.069
AB	534.2	2.161	1.032	2.463	1.041	0.3226	1.062	0.0331	1.081
Zone Average C/E			0.992	1.063		1.058		0.983	
Standard Deviation			0.031	0.045		0.013		0.143	
IC D	483.4	2.491	1.007	2.717	1.024	0.3494	1.065	0.0709	0.986
IC D	432.6	2.879	1.008	3.034	1.029	0.3929	1.055	0.0907	1.014
IC D	381.8	3.193	1.012	3.386	1.016	0.4341	1.049	0.1032	1.009
IC D	331.0	3.414	1.025	3.631	1.019	0.4585	1.069	0.1103	1.030
IC D	280.2	3.491	1.020	3.770	1.021	0.4827	1.057	0.1117	1.003
IC D	229.4	3.552	1.004	3.863	1.019	0.4949	1.059	0.1088	1.004
IC D	178.6	3.525	1.000	4.107	0.989	0.5175	1.053	0.0908	1.013
Zone Average C/E			1.011	1.017		1.058		1.006	
Standard Deviation			0.009	0.013		0.007		0.020	
IB	127.8	3.909	1.002	4.592	1.015	0.5681	1.047	0.0500	1.041
IB	100.4	4.020	1.000	4.833	1.010	0.5946	1.041	0.0421	1.022
IB	77.0	4.170	0.988	5.025	1.009	0.6173	1.037	0.0364	1.034
IB	49.6	4.375	1.006	5.314	1.016	0.6497	1.048	0.0349	0.998
IB	26.2	4.735	0.992	5.671	1.024	0.6850	1.058	0.0334	1.032
Zone Average C/E			0.998	1.015		1.046		1.025	
Standard Deviation			0.007	0.006		0.007		0.017	

TABLE 6.13 ZPPR-17C: Axial Reaction Rate Distributions
in Matrix 138-62 (next to CRP)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC D	51.6	7.370	1.045	0.9295	1.144	0.1691	1.018
OC D	102.4	7.904	1.051	0.9882	1.138	0.1873	1.013
OC D	178.6	8.130	1.054	1.0170	1.129	0.2159	1.021
OC D	229.4	8.099	1.044	1.0200	1.108	0.2271	1.031
OC D	280.2	7.933	1.042	1.0070	1.095	0.2322	1.029
OC D	331.0	7.596	1.053	0.9661	1.106	0.2160	1.082
OC D	381.8	7.094	1.049	0.9153	1.084	0.2050	1.009
OC D	432.6	6.516	1.039	0.8277	1.091	0.1760	1.027
OC D	483.4	5.912	1.034	0.7510	1.087	0.1365	1.005
			-----			-----	-----
Zone Average C/E			1.046			1.109	1.026
Standard Deviation			0.007			0.023	0.023
AB	534.2	5.514	1.041	0.6643	1.139	0.0648	1.050
AB	585.0	5.005	1.050	0.5954	1.139	0.0371	1.090
AB	635.8	4.453	1.065	0.5171	1.150	0.0256	1.062
AB	686.6	3.984	1.092	0.4474	1.168	0.0172	0.918
AB	737.4	3.602	1.130	0.3864	1.190	0.0123	0.803
			-----			-----	-----
Zone Average C/E			1.076			1.157	0.984
Standard Deviation			0.036			0.022	0.122
AR	825.1	3.601	1.152	--	--	--	--
AR	875.9	3.378	1.174	--	--	--	--

TABLE 6.14 ZPPR-17C: Axial Reaction Rate Distributions
in Matrix 238-62 (next to CR)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
AR	875.9	1.290	1.093	--	--	--	--
AR	825.1	1.232	1.073	--	--	--	--
AB	737.4	1.058	1.088	0.1546	1.067	0.0064	0.685
AB	686.6	1.193	1.059	0.1707	1.111	0.0108	0.687
AB	635.8	1.410	1.040	0.2090	1.074	0.0144	0.912
AB	585.0	1.690	1.055	0.2522	1.081	0.0198	1.026
AB	534.2	2.034	1.038	0.2969	1.079	0.0326	1.075
Zone Average C/E			1.056		1.082		0.877
Standard Deviation			0.020		0.017		0.184
OC D	483.4	2.337	1.057	0.3290	1.115	0.0681	1.032
OC D	432.6	2.760	1.055	0.3844	1.110	0.0945	1.013
OC D	381.8	3.146	1.063	0.4335	1.124	0.1109	1.026
OC D	331.0	3.471	1.078	0.4829	1.125	0.1241	1.072
OC D	280.2	3.771	1.080	0.5294	1.117	0.1308	1.076
OC D	229.4	4.067	1.076	0.5637	1.133	0.1401	1.020
OC D	178.6	4.349	1.074	0.6072	1.132	0.1379	1.021
OC D	102.4	4.869	1.058	0.6789	1.132	0.1333	1.017
OC D	51.6	5.356	1.073	0.7486	1.126	0.1411	0.992
Zone Average C/E			1.068		1.124		1.030
Standard Deviation			0.010		0.008		0.027

TABLE 6.15 ZPPR-17C: Axial Reaction Rate Distributions
in Matrix 148-70 (Outer Core)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC D	51.6	7.074	1.088	0.8810	1.163	0.2270	1.085
OC D	102.4	7.166	1.090	0.8865	1.172	0.2301	1.087
OC D	178.6	7.193	1.075	0.8889	1.157	0.2229	1.113
OC D	229.4	6.971	1.074	0.8701	1.144	0.2184	1.102
OC D	280.2	6.717	1.068	0.8365	1.141	0.2101	1.096
OC D	331.0	6.236	1.091	0.7828	1.158	0.1957	1.105
OC D	381.8	5.700	1.088	0.7155	1.155	0.1796	1.061
OC D	432.6	5.113	1.082	0.6444	1.147	0.1482	1.099
OC D	483.4	4.531	1.077	0.5715	1.146	0.1087	1.107
Zone Average C/E			1.081		1.154		1.095
Standard Deviation			0.008		0.010		0.016
AB	534.2	4.150	1.046	0.5286	1.105	0.0573	1.066
AB	585.0	3.704	1.048	0.4601	1.121	0.0315	1.091
AB	635.8	3.245	1.052	0.4029	1.102	0.0221	0.986
AB	686.6	2.828	1.085	0.3418	1.124	0.0117	1.072
AB	737.4	2.549	1.109	0.2933	1.135	0.0098	0.783
Zone Average C/E			1.068		1.117		1.000
Standard Deviation			0.028		0.014		0.128

TABLE 6.16 ZPPR-17C: Axial Reaction Rate Distributions
in Matrix 248-70 (Outer Core)

Zone	z(mm)	$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
AB	737.4	1.406	1.100	0.1657	1.118	0.0078	0.619
AB	686.6	1.597	1.077	0.1905	1.149	0.0084	0.953
AB	635.8	1.876	1.050	0.2342	1.108	0.0137	1.017
AB	585.0	2.169	1.068	0.2739	1.133	0.0211	1.051
AB	534.2	2.535	1.054	0.3199	1.129	0.0370	1.072
		-----		-----		-----	
Zone Average C/E		1.070		1.127		0.942	
Standard Deviation		0.020		0.016		0.186	
OC D	483.4	2.881	1.080	0.3696	1.133	0.0738	1.070
OC D	432.6	3.361	1.091	0.4244	1.157	0.0993	1.104
OC D	381.8	3.897	1.089	0.4935	1.148	0.1213	1.087
OC D	331.0	4.384	1.095	0.5559	1.152	0.1393	1.104
OC D	280.2	4.912	1.082	0.6138	1.153	0.1499	1.141
OC D	229.4	5.294	1.097	0.6732	1.148	0.1684	1.110
OC D	178.6	5.759	1.090	0.7150	1.169	0.1855	1.089
OC D	102.4	6.230	1.105	0.7849	1.167	0.2016	1.095
OC D	51.6	6.636	1.088	0.8245	1.166	0.2083	1.110
		-----		-----		-----	
Zone Average C/E		1.091		1.155		1.097	
Standard Deviation		0.008		0.012		0.024

Fig. 6.8. Measured axial distributions for fission in ^{235}U adjacent to the central control position in ZPPR-17B and in ZPPR-17C.

Fig. 6.9. Measured axial distributions for fission in ^{235}U adjacent to an outer control position in ZPPR-17B and in ZPPR-17C.

Fig. 6.10. Measured ^{235}U fission distributions at six axial heights along the x-axis in ZPPR-17C.

6.6. Reaction Rate Ratios

Experimental reaction rate ratios relative to ^{239}Pu fission were formed simply by using the cell-average values derived at each foil position. These ratios are not quite the same as those that would be obtained if all reaction rates were measured at the same xyz position. However, since the calculated values are obtained the same way, it is assumed that the effect on the C/E ratios would be very small. The measured values quoted are accurate to within a few percent and suffice to indicate the effects of changing spectrum throughout the reactor.

The number of ratio results varies from about 40 in 17B, 70 in 17C to 90 in 17A. For the ^{238}U reactions more extensive data, covering a wider spectrum range, could be obtained by taking ratios relative to ^{235}U fission rather than to plutonium fission.

The detailed reaction rate ratio data on the point by point basis are given in References 3 and 5. Tables 6.17 to 6.19 show a summary of the reaction rate ratio analyses for the three phases of ZPPR-17, first giving data by traverse and by region and then giving average values for all measurements in the internal blankets and in the fuel regions.

The standard deviations of the C/E distributions for all results in the internal blanket or fuel regions are similar those of the foil statistics (about 1% for the non-threshold reactions). This is a consequence of each reaction having a similar trend of spatial mispredictions as noted in the previous sections. Reaction rate ratio C/Es in the radial and axial blanket regions have standard deviations significantly larger than experimental statistics due to the differing predictions as a function of distance into the blankets.

Table 6.20 compares the C/E values for reaction rate ratios in the three assemblies.

TABLE 6.17 ZPPR-17A: Summary of Reaction Rate Ratio Analysis

Distribution	Zone	$^{235}\text{U}(n,f)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,f)/^{239}\text{Pu}(n,f)$		
		No.	C/E	S.D.	No.	C/E	S.D.	No.	C/E	S.D.
X-Axis Z=5 cm	IB	16	1.032	0.007	16	1.047	0.013	16	1.013	0.043
	OC	8	0.998	0.006	8	1.047	0.017	8	1.001	0.026
	RB	5	1.058	0.043	5	1.089	0.025	5	0.948	0.118
X-Axis Z=18 cm	IC	11	1.012	0.012	11	1.063	0.007	11	0.997	0.019
	OC	8	0.990	0.007	8	1.044	0.016	8	1.003	0.030
	RB	5	1.062	0.052	5	1.017	0.024	5	0.963	0.146
X-Axis Z=28 cm	IC	16	0.996	0.006	16	1.045	0.012	16	1.007	0.019
	OC	8	0.995	0.006	8	1.020	0.020	8	0.992	0.028
	RB	5	1.060	0.046	5	1.107	0.029	5	0.980	0.133
Axial 148-50	IB	5	1.039	0.014	5	1.056	0.009	5	0.994	0.057
	IC S	7	1.005	0.011	7	1.047	0.017	7	1.012	0.024
	AB	5	1.064	0.042	5	1.096	0.026	5	0.864	0.081
Axial 148-66	OC D	9	1.002	0.010	9	1.068	0.010	9	1.002	0.024
	AB	5	1.063	0.040	5	1.117	0.027	5	0.872	0.109
Axial 148-70	OC S	9	1.001	0.011	9	1.033	0.012	9	1.009	0.020
	AB	5	1.054	0.048	5	1.102	0.043	5	0.847	0.130
<hr/>										
All Internal Blanket		21	1.034	0.009	20	1.049	1.012	20	1.012	0.044
All Fuel Region		76	1.000	0.011	70	1.050	0.017	70	1.004	0.023
All Single Col. Fuel		49	1.001	0.012	46	1.043	0.015	46	1.008	0.024
All Double Col. Fuel		25	0.999	0.008	24	1.063	0.009	24	0.995	0.019

TABLE 6.18 ZPPR-17B: Summary of Reaction Rate Ratio Analysis

Distribution	Zone	$^{235}\text{U}(n,f)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,f)/^{239}\text{Pu}(n,f)$		
		No.	C/E	S.D.	No.	C/E	S.D.	No.	C/E	S.D.
X-axis Z=5 cm	IB	10	1.021	0.007	10	1.047	0.007	10	1.017	0.036
X-axis Z=18 cm	IC	10	1.019	0.009	10	1.054	0.009	10	0.994	0.016
X-axis Z=28 cm	IC	10	1.011	0.013	10	1.041	0.010	10	1.004	0.025
Axial 148-51	IB	5	1.012	0.008	5	1.036	0.005	5	0.983	0.057
	IC S	5	1.013	0.009	6	1.050	0.011	6	0.981	0.015
	AB	5	1.045	0.034	5	1.103	0.039	5	0.969	0.103

All Internal Blanket		15	1.018	0.008	15	1.043	0.009	15	1.006	0.045
All Fuel Region		24	1.015	0.011	25	1.049	0.013	25	0.996	0.021
All Single Col. Fuel		12	1.013	0.009	12	1.046	0.013	12	1.010	0.019
All Double Col. Fuel		12	1.017	0.012	13	1.053	0.012	13	0.983	0.012

TABLE 6.19 ZPPR-17C: Summary of Reaction Rate Ratio Analysis

Distribution	Zone	$^{235}\text{U}(n,f)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)$			$^{238}\text{U}(n,f)/^{239}\text{Pu}(n,f)$		
		No.	C/E	S.D.	No.	C/E	S.D.	No.	C/E	S.D.
X-axis Z=+5 cm	IB	10	1.026	0.007	10	1.059	0.011	10	1.016	0.021
X-axis Z=-5 cm	IB	10	1.031	0.022	10	1.060	0.009	10	1.011	0.026
X-axis Z=+18 cm	IC	10	1.012	0.009	10	1.069	0.009	10	0.994	0.016
X-axis Z=-18 cm	IC	10	1.014	0.020	10	1.070	0.014	10	1.000	0.025
X-axis Z=-28 cm	IC	10	1.005	0.018	10	1.062	0.013	10	1.006	0.023
Axial 148-51	IB	5	1.017	0.004	5	1.056	0.003	5	1.012	0.029
	IC D	7	1.020	0.009	7	1.061	0.008	7	0.980	0.020
Axial 248-51	IB	5	1.017	0.009	5	1.049	0.011	5	1.026	0.022
	IC D	7	1.006	0.012	7	1.047	0.009	6	0.998	0.012
	AB	5	1.074	0.070	5	1.068	0.036	5	0.989	0.123

All Internal Blanket		30	1.025		30	1.057		30	1.015	
All Fuel Region		44	1.011		44	1.063		44	0.997	

TABLE 6.20 Reaction Rate Ratio C/E Results for ZPPR-17A, 17B and 17C

<u>Phase</u>	<u>Zone</u>	<u>Number of Data</u>	<u>C/E for F25/F49</u>	<u>C/E for C28/F49</u>	<u>C/E for F28/F49</u>
17A	Internal Blanket	20	1.034	1.049	1.012
	Fuel Regions	76	1.000	1.050	1.004
17B	Internal Blanket	15	1.018	1.043	1.006
	Fuel Regions	24	1.015	1.049	0.996
17C	Internal Blanket	30	1.025	1.057	1.015
	Fuel Regions	44	1.011	1.063	0.997

6.7 Comparison of Fission Rate Analysis in ZPPR-17A, 17B, and 17C

The preceding reaction rate analysis gave results which were normalised to a mean C/E for ^{239}Pu fission in each core. Fewer plutonium foils were available in ZPPR-17B and 17C than in ZPPR-17A and were positioned around the core center. Because of the strong radial dependence of the C/Es, the results in the preceding sections must be renormalised in order to make comparisons among the three cores.

The normalisation chosen was to ^{235}U fission for common distributions in the fuel zones. These were at the x-axis and at 45° for $z = 5$ cm (outer core only), at the x-axis for $z = 18$ cm and $z = 28$ cm and for axial traverses at the center, at the inner/outer core boundary, and in the outer core. Results for ZPPR-17C included both halves of the assembly. The normalising factors, relative to those used for the previous results were 1.002 for 17A (89 foils), 1.054 for 17B (96 foils), and 1.063 for 17C (192 foils).

A summary of radial distribution analyses for ^{235}U fission is given in Table 6.21. All results show a trend of increasing C/E with radius, as indicated by the ratio of the outer core average C/E to that for the central region (ICA) shown in the last column.

The results for $z = 5$ cm pass through the internal blanket and show quite a wide spread among the results, principally for the center region ICA which is near to the half-inserted control rod in ZPPR-17C. The radial discrepancies at 45° are less than along the x-axis, possibly due to approximations in the nodal transport solution or in the interpolation procedure.

The distributions at 18 cm and 28 cm for the midplane show a monotonic increase in C/E from the central region to the outer core. The ratios of outer core to inner (ICA) results are 1.04 (17A), 1.05 (17B), and 1.06 (17C).

The analyses of axial distributions for the three cores are given in Tables 6.22 to 6.25. Measurements near the core center and near the edge

of the internal blanket are adjacent to a CRP in 17B and adjacent to a half-inserted control rod in 17C. Near the core center, distributions were measured both for fission in ^{239}Pu (Table 6.22) and for fission in ^{235}U (Table 6.23). Results in the outer core, matrix 1,248-70, in Table 6.25 are about 25 cm removed from a control position.

The results in the fuel regions are of most interest. Fluctuations in the C/E results at different distances from the midplane are consistent with experimental statistics as shown by the standard deviations of the distributions. The mean C/E results adjacent to CRPs are systematically lower than those in the fuel regions of 17A by 1% to 3%. No clear trend is apparent for calculation of fission rates adjacent to a control rod compared with those adjacent to a CRP. The relative results vary by 1% at the central position for ^{239}Pu and ^{235}U fission (Tables 6.23 and 6.24) and by 2% near the outer control position (Table 6.24).

We conclude that the fission rates adjacent to a CRP or adjacent to a control rod can be calculated with a confidence of 2-3% relative to those in neighboring fuel regions using the nodal transport method.

TABLE 6.21. Comparison of Radial ^{235}U Fission Rate C/E Values in ZPPR-17A, 17B, and 17C

Distribution ^a	Core	ICA	ICB	ICC	ICD	OCE	OCF	RBG	OC/ICA
X-axis Z=+5 cm	17A	0.996	1.007	1.015	1.032	1.018	1.016	1.011	1.021
	17B	0.986	0.994	0.999	1.019	1.007	1.013	1.011	1.024
	17C	0.970	0.979	0.986	1.020	1.010	1.013	1.034	1.043
	Z=-5 cm 17C	0.958	0.985	0.995	1.018	1.015	1.021	1.037	1.063
45-Deg. Z=+5 cm	17A	1.004	1.009	1.013	1.024	1.005	1.011	1.024	1.004
	17B	0.987	1.002	0.995	1.012	0.989	0.993	1.015	1.004
	17C	0.975	0.992	0.992	1.007	1.004	1.007	1.024	1.031
	Z=-5 cm 17C	0.957	0.991	1.005	1.014	1.012	1.011	1.033	1.057

All Z=5 cm data	17A	1.000	1.008	1.014	1.028	1.011	1.013	1.017	1.012
	17B	0.986	0.998	0.997	1.015	0.998	1.003	1.013	1.015
	17C	0.965	0.987	0.994	1.015	1.010	1.013	1.032	1.048

X-axis Z=+18 cm	17A	0.976	0.981	0.992	1.003	1.016	1.010	1.014	1.038
	17B	0.959	0.965	0.972	0.995	1.009	1.007	1.007	1.051
	17C	0.956	0.955	0.969	0.992	1.009	1.005	1.020	1.053
	Z=-18 cm 17C	0.953	0.956	0.972	1.004	1.003	1.014	1.029	1.058
X-axis Z=+28 cm	17A	0.969	0.972	0.985	1.001	1.014	1.011	1.013	1.045
	17B	0.959	0.972	0.975	0.986	1.005	1.006	1.010	1.048
	17C	0.952	0.962	0.968	0.982	0.998	0.996	1.030	1.047
	Z=-28 cm 17C	0.949	0.959	0.970	0.992	1.011	1.014	1.032	1.067

All Z=18 cm and Z=28 cm data	17A	0.972	0.976	0.988	1.002	1.015	1.010	1.013	1.042
	17B	0.959	0.968	0.973	0.990	1.007	1.006	1.008	1.050
	17C	0.952	0.973	0.970	0.992	1.005	1.007	1.028	1.057

^aResults shown for negative z for ZPPR-17C are in half-2 which contains inserted control rods.

TABLE 6.22. Comparison of C/E Values for ^{239}Pu Fission Axial Traverses Near the Center of ZPPR-17A, 17B, and 17C

Zone	Z(mm)	ZPPR-17A	ZPPR-17B	ZPPR-17C	
		Fuel ^a	Adj. CRP	Adj. CRP	Adj. CR
IB	26.2	0.956	0.966	0.936	0.933
IB	49.6	0.945	0.962	0.945	0.946
IB	77.0	0.960	0.962	0.951	0.929
IB	100.4	0.964	0.968	0.942	0.941
IB	127.8	0.969	0.965	0.945	0.943
Zone Average C/E		0.959	0.965	0.944	0.939
Standard Deviation		0.009	0.003	0.006	0.007
IC	178.6	0.963	0.944	0.949	0.941
IC	229.4	0.958	0.952	0.950	0.944
IC	280.2	0.974	0.935	0.942	0.960
IC	331.0	0.977	0.950	0.968	0.964
IC	381.8	0.987	--	0.950	0.952
IC	432.6	0.968	0.941	0.940	0.948
IC	483.4	0.958	0.931	0.929	0.947
Zone Average C/E		0.969	0.942	0.947	0.951
Standard Deviation		0.011	0.009	0.013	0.009
AB	534.2	0.952	0.943	--	0.971
AB	585.0	0.932	0.944	--	0.955
AB	635.8	0.920	0.912	--	0.926
AB	686.6	0.989	0.897	--	0.907
AB	737.4	0.882	0.880	--	0.907
Zone Average C/E		0.917	0.915		0.933
Standard Deviation		0.027	0.030		0.031

^aIn 17A the measurements were made in a single-fuel-column drawer, in 17B and 17C they were in double-fuel-column drawers.

TABLE 6.23. Comparison of C/E Values for ^{235}U Fission Axial Traverses Near the Center of ZPPR-17A, 17B, and 17C

Zone	Z(mm)	ZPPR-17A	ZPPR-17B	ZPPR-17C	
		Fuel ^a	Adj. CRP	Adj. CRP	Adj. CR
IB	26.2	1.004	0.973	0.949	0.963
IB	49.6	0.999	0.973	0.958	0.955
IB	77.0	0.991	0.974	0.971	0.949
IB	100.4	0.992	0.992	0.961	0.950
IB	127.8	0.994	0.969	0.960	0.955
		-----	-----	-----	-----
	Zone Average C/E	0.986	0.976	0.960	0.955
	Standard Deviation	0.005	0.010	0.009	0.006
IC	178.6	0.978	0.944	0.961	0.930
IC	229.4	0.972	--	0.969	0.959
IC	280.2	0.972	0.956	0.961	0.960
IC	331.0	0.977	0.969	0.983	0.959
IC	381.8	0.974	--	0.977	0.956
IC	432.6	0.979	0.952	0.958	0.968
IC	483.4	0.968	0.944	0.957	0.963
		-----	-----	-----	-----
	Zone Average C/E	0.974	0.953	0.965	0.957
	Standard Deviation	0.004	0.010	0.012	0.013
AB	534.2	0.968	0.957	0.966	0.979
AB	585.0	0.976	0.950	0.982	0.991
AB	635.8	0.963	0.957	0.983	0.961
AB	686.6	0.970	0.955	1.013	0.992
AB	737.4	0.995	0.956	1.054	1.072
		-----	-----	-----	-----
	Zone Average C/E	0.974	0.955	1.000	1.000
	Standard Deviation	0.012	0.003	0.037	0.045

^aIn 17A the measurements were made in a single-fuel-column drawer, in 17B and 17C they were in double-fuel-column drawers.

TABLE 6.24. Comparison of C/E Values for ^{235}U Fission Axial Traverses Near the Edge of the Inner Blanket in ZPPR-17A, 17B, and 17C

Zone ^a	Z(mm)	ZPPR-17A	ZPPR-17B	ZPPR-17C	
		Fuel	Adj. CRP	Adj. CRP	Adj. CR
OC	51.6	1.020	0.987	0.983	1.009
OC	102.4	1.029	0.988	0.989	0.995
OC	178.6	1.017	0.985	0.992	1.010
OC	229.4	1.012	0.993	0.982	1.012
OC	280.2	1.007	0.984	0.980	1.016
OC	331.0	1.001	0.984	0.990	1.014
OC	381.8	1.007	0.987	0.987	1.000
OC	432.6	1.005	0.984	0.977	0.992
OC	483.4	1.005	0.987	0.973	0.994
		-----	-----	-----	-----
Zone Average		1.011	0.987	0.984	1.005
Standard Deviation		0.009	0.003	0.007	0.010
AB	534.2	1.013	0.985	0.979	0.976
AB	585.0	1.000	0.988	0.988	0.992
AB	635.8	1.006	0.989	1.002	0.978
AB	686.6	1.009	1.007	1.027	0.996
AB	737.4	1.042	1.029	1.063	1.024
		-----	-----	-----	-----
Zone Average		1.014	0.999	1.012	0.993
Standard Deviation		0.016	0.020	0.036	0.020

^aMeasurements were made in 148-66 (DCF) for 17A, 138-62 (SCF) for 17B and in 138/238-62 (DCF) for 17C.

TABLE 6.25. Comparison of C/E Values for ^{235}U Fission Axial Traverses in 1,248-70 (Outer Core) in ZPPR-17A, 17B and 17C

Zone ^a	Z(mm)	ZPPR-17A	ZPPR-17B	ZPPR-17C	
		Fuel	Fuel	Half-1	Half-2
OC	51.6	1.022	1.008	1.024	1.024
OC	102.4	1.018	1.042	1.025	1.040
OC	178.6	1.017	1.011	1.011	1.025
OC	229.4	1.014	1.005	1.010	1.032
OC	280.2	1.010	1.007	1.005	1.018
OC	331.0	1.016	1.008	1.026	1.030
OC	381.8	1.019	1.011	1.024	1.024
OC	432.6	1.018	0.998	1.018	1.026
OC	483.4	1.003	0.998	1.013	1.016
		-----	-----	-----	-----
Zone Average		1.015	1.009	1.017	1.026
Standard Deviation		0.006	0.014	0.008	0.008
AB	534.2	1.000	0.986	0.984	0.992
AB	585.0	0.999	1.007	0.986	1.005
AB	635.8	0.995	0.996	0.990	0.988
AB	686.6	1.013	0.996	1.021	1.013
AB	737.4	1.040	1.028	1.043	1.035
		-----	-----	-----	-----
Zone Average		1.009	1.003	1.005	1.007
Standard Deviation		0.018	0.017	0.028	0.020

^aSingle-fuel-column drawer (SCF) in 17A and 17B, double-fuel-column drawer (DCF) in 17C.

7. ANALYSIS OF GAMMA HEATING MEASUREMENTS IN ZPPR-17A

Gamma dose measurements using thermoluminescent dosimeters (TLDs) were made in the three phases of ZPPR-17.⁵ Analysis has been completed only for ZPPR-17A. This work was done by H. Unesaki and is reported in detail in reference 10. This section summarizes the results of the analysis.

The analysis used the system recently developed by the Applied Physics Division in ANL-E for use in LMR design. The starting point is a base production library for MC² with 230 neutron and 94 gamma groups which was generated from the ENDF/B-5.2 data using the NJOY code. The calculation procedure for ZPPR-17 involved several steps as follows:

- (i) Cell-averaging and group collapse using the SDX code, producing

- 21 group neutron library

- 21 group gamma interaction library

- 21-neutron/21-gamma group coupled library (PMATRX).

For calculations of heating distributions within the ZPPR cells, in-plate cross sections for the Pu and U isotopes were generated in addition to cell-average data.

- (ii) A 21 group neutron flux calculation using the nodal transport method with an xyz model. Calculation of a gamma source file by mesh and group using the GAMSOR-2 code with the PMATRX library.

- (iii) A 21 group gamma flux calculation in the xyz nodal transport model using the gamma source file as input and the gamma interaction library.

- (iv) Edit of the gamma dose in steel using a code written at ZPPR called TOTDOSE. The inputs to the code are neutron and gamma flux files, neutron and gamma response functions for the TLDs and mass-energy absorption coefficients for steel.

The measured dose distributions give values in a sodium plate within each drawer. For comparison with calculated cell-average doses, factors relating dose rates in the position of the measurement to the cell average are calculated by

(v) Calculations for the cell using the TWODANT code following steps (ii) to (iv) above. TLD/cell average factors are calculated with the TOTDOSE code. The cell calculations were made with $S_{16}P_0$ (transport corrected) for neutron fluxes and $S_{16}P_3$ for the gamma fluxes, using the double P_N approximation. Three mesh intervals in diluent plates and five mesh intervals in Pu and U regions were used.

The positions of the gamma dose measurements in ZPPR-17A are shown in Fig. 7.1. Several in-cell measurements were also made to test calculated distributions. In these, the TLDs were placed in small indentations in sodium-plate clads or in special uranium plates. Results for a double-fuel-column cell are shown in Fig. 7.2. Measured distributions in the single-fuel-column cell were rather uninteresting since it was not possible to position a TLD near the fuel plate.¹⁰ Several multiple-cell calculations were made, since the cell factors for a given cell varied with its environment. The results are shown in Table 7.1. The most appropriate factors were used for each cell occurring in the reactor distributions.

The quantities calculated in the TOTDOSE code are as follows:

$$\text{Neutron} = D_n = \int_E \phi_n(E) \cdot S(E),$$

$$\text{gamma} = D_\gamma = \int_E \phi_\gamma(E) \cdot \left(\frac{\mu}{\rho}\right)_{ss}(E) \cdot f(E) \cdot \bar{E}(E) \quad ,$$

where $\phi_n(E)$: neutron flux for group E
 $S(E)$: neutron sensitivity of TLD for group E
 $\phi_\gamma(E)$: Gamma Flux for group E

$\left(\frac{\mu}{\rho}\right)_{ss}(E)$: Mass energy absorption coefficient of
 stainless steel for group E

$f(E)$: Dose in LiF to Dose in SS Conversion factor
for group E

$E(E)$: Average photon energy for group E.

The energy structures of the neutron and gamma libraries are given in Table 7.2. Sensitivity factors are given in Table 7.3 and mass energy absorption coefficients for steel are in Table 7.4.

The calculated and measured dose rates are compared on an absolute basis by normalizing to ^{239}Pu fission rates. The measurements were normalized to fission rates from a foil irradiation using the ex-core monitors. Calculations were normalized using the mean C/E obtained from 62 measurements of fission in ^{239}Pu in ZPPR-17A.

Calculated and experimental dose rates are compared for x-axis distributions in Tables 7.5 and 7.6 and for three axial distributions in Tables 7.7 to 7.9. The results are also plotted in Figs. 7.3 and 7.4.

The mean C/E for dose in the fuel regions relative to ^{239}Pu fission is 0.95. However, a systematic difference is obtained between results in the single-fuel-column cells (mean C/E = 0.99) and the double-column fuel cells (mean C/E = 0.90). This difference may be due to inadequacies in calculations of the variations of gamma dose through the unit cells. The problem is similar to that found for ^{238}U fission rates and may have a common source. The dose distributions in the core are mispredicted by 5% as a function of radius, as would be expected from the analysis of fission rates. The results for the internal blanket are very good with a mean C/E = 1.00. Only six results are available in the axial blanket but these are well calculated (mean C/E = 0.98). Five results in the radial blanket have a mean C/E of 0.90.

TABLE 7.1 Summary of Cell Averaging Factors

<u>Cell Type</u>	<u>Environment</u>	<u>Cell Factor (Total Dose)</u>
SCF	Asymptotic	1.0220
"	$\underline{S} + S + D$	1.0049
"	$\underline{S} + \underline{S} + D$	1.0368
"	$\underline{S} + RB$	0.9845
DCF	Asymptotic	1.0392
"	$S + S + \underline{D}$	1.0444
"	$IB + \underline{D}$	1.1050
IBK	Asymptotic	0.9993
"	$\underline{IB} + D$	1.0915
RBK	Asymptotic	0.9960
"	$S + \underline{RB}$	0.9657

TABLE 7.2 Broad Group Structures for Neutron
and Gamma Cross Section Library

Broad Group Number	Upper Bound, eV	
	Neutron	Gamma
1	1.41907 + 7	2.00000 + 7
2	6.06531 + 6	1.00000 + 7
3	3.67879 + 6	8.00000 + 6
4	2.23130 + 6	7.00000 + 6
5	1.35335 + 6	6.00000 + 6
6	8.20850 + 5	5.00000 + 6
7	4.97871 + 5	4.00000 + 6
8	3.01974 + 5	3.00000 + 6
9	1.83156 + 5	2.50000 + 6
10	1.11090 + 5	2.00000 + 6
11	6.73795 + 4	1.50000 + 6
12	4.08677 + 4	1.00000 + 6
13	2.47875 + 4	7.00000 + 5
14	1.50344 + 4	4.50000 + 5
15	9.11883 + 3	3.00000 + 5
16	5.53085 + 3	1.50000 + 5
17	3.35463 + 3	1.00000 + 5
18	2.03469 + 3	2.50000 + 4
19	1.23410 + 3	4.50000 + 4
20	4.54000 + 2	3.00000 + 4
21	6.14423 + 1	2.00000 + 4

TABLE 7.3 Neutron and Gamma Response Functions
for TLDs

<u>Group</u>	<u>Neutron S(E)</u>	<u>Gamma f(E)</u>
1	3.20027E-10	1.06001
2	1.85294E-10	1.05745
3	1.05852E-10	1.05828
4	6.19877E-11	1.06023
5	3.91033E-11	1.06297
6	2.35668E-11	1.06685
7	2.36631E-11	1.07483
8	1.84305E-11	1.08027
9	5.73654E-12	1.08257
10	3.28982E-12	1.07968
11	4.73238E-12	1.06549
12	2.80550E-12	1.04134
13	9.61333E-13	1.00073
14	5.93583E-13	0.91057
15	4.35426E-13	0.62258
16	3.16693E-13	0.21927
17	2.10752E-13	0.08248
18	1.44300E-13	0.04020
19	7.29792E-14	0.02764
20	2.87526E-14	0.02843
21	4.54593E-14	0.03775

TABLE 7.4 Mass Absorption Coefficients for
Stainless Steel

Gamma Group	E (eV)	$\left(\frac{\mu}{\rho}\right)_{ss}^a$
1	1.5 + 7	0.0224
2	9.0 + 6	0.0210
3	7.5 + 6	0.0206
4	6.5 + 6	0.0203
5	5.5 + 6	0.0200
6	4.5 + 6	0.0199
7	3.5 + 6	0.0202
8	2.75 + 6	0.0209
9	2.25 + 6	0.0217
10	1.75 + 6	0.0230
11	1.25 + 6	0.0250
12	8.5 + 5	0.0269
13	5.75 + 5	0.0287
14	3.75 + 5	0.0311
15	2.25 + 5	0.0440
16	1.25 + 5	0.1458
17	8.75 + 4	0.3320
18	6.0 + 4	0.9382
19	3.75 + 4	4.1026
20	2.50 + 4	14.7236
21	1.25 + 4	92.2460

^aStainless steel composition is 18% Cr, 2% Mn,
70% Fe and 10% Ni.

TABLE 7.5 Measured and Calculated Dose Rates along
the X-axis at 3 in. from the Midplane

Location	Drawer Type ^a	Exp. ^b	Cell Factor	Corrected Exp.	Calc. ^c	C/E
149-50	SF	0.1601	0.9993	0.1600	0.85903E-03	0.9514
149-51	DF	0.1625	0.9993	0.1624	0.86263E-03	0.9412
149-52	SF	0.1612	0.9993	0.1611	0.86386E-03	0.9502
149-53	SF	0.1600	0.9993	0.1599	0.87177E-03	0.9661
149-54	DF	0.1622	0.9993	0.1621	0.88390E-03	0.9662
149-55	SF	0.1636	0.9993	0.1635	0.89344E-03	0.9683
149-56	SF	0.1655	0.9993	0.1654	0.91013E-03	0.9751
149-57	DF	0.1663	0.9993	0.1662	0.93169E-03	0.9934
149-58	SF	0.1667	0.9993	0.1666	0.95112E-03	1.0117
149-59	SF	0.1789	0.9993	0.1788	0.97890E-03	0.9702
149-60	DF	0.1781	0.9993	0.1780	0.10129E-02	1.0084
149-61	SF	0.1866	0.9993	0.1865	0.10462E-02	0.9941
149-62	SF	0.1896	0.9993	0.1895	0.10920E-02	1.0212
149-63	DF	0.2002	0.9993	0.2001	0.11538E-02	1.0219
149-64	SF	0.2136	0.9993	0.2135	0.12480E-02	1.0360
149-65	SF	0.2489	1.0915	0.2717	0.15602E-02	1.0176
149-66	DF	0.4885	1.1050	0.5398	0.27325E-02	0.8969
149-67	SF	0.4698	1.0049	0.4721	0.26702E-02	1.0021
149-68	SF	0.4434	1.0368	0.4597	0.26691E-02	1.0287
149-69	DF	0.5065	1.0444	0.5290	0.27598E-02	0.9244
149-70	SF	0.4204	1.0049	0.4225	0.23253E-02	0.9752
149-71	SF	0.3573	1.0368	0.3704	0.21000E-02	1.0044
149-72	DF	0.3642	1.0444	0.3804	0.19379E-02	0.9027
149-73	SF	0.2510	0.9845	0.2471	0.13487E-02	0.9671
149-74	B	0.1330	0.9657	0.1284	0.64630E-03	0.8916
149-75	B	0.0814	0.9960	0.0811	0.39647E-03	0.8665
149-76	B	0.0555	0.9960	0.0553	0.27384E-03	0.8778
149-77	B	0.0377	0.9960	0.0375	0.19310E-03	0.9112
149-78	B	0.0258	0.9960	0.0257	0.13518E-03	0.9321
149-79	R	0.0171	1.0000	0.0171	0.71451E-04	0.7404
149-80	R	0.0127	1.0000	0.0127	0.39789E-04	0.5551
149-81	R	0.0076	1.0000	0.0076	0.17826E-04	0.4156

^aSF is single fuel column DF is double fuel column, B is blanket and R is reflector.

^bMeasured total dose rate (gamma and neutron) in mrd/s at an estimated reactor power of 1 watt. Statistical uncertainties 2%.

^cNodal transport calculation in xyz geometry with fluxes normalized to 8 watts, calculated doses in rads. For comparison with measurement the calculated doses are normalized by the mean C/E for ²³⁹Pu fission from 62 foil measurements in the core region.

TABLE 7.6 Measured and Calculated Dose Rates along
the X-Axis at 9 in. from the Midplane

Location	Drawer Type ^a	Exp. ^b	Cell Factor	Corrected Exp.	Calc. ^c	C/E
149-50	SF	0.3573	1.0368	0.3704	0.19986E-02	0.9559
149-51	DF	0.4248	1.0444	0.4437	0.21643E-02	0.8644
149-52	SF	0.3640	1.0049	0.3658	0.19721E-02	0.9553
149-53	SF	0.3523	1.0368	0.3653	0.20115E-02	0.9758
149-54	DF	0.4359	1.0444	0.4553	0.22078E-02	0.8593
149-55	SF	0.3776	1.0049	0.3795	0.20282E-02	0.9471
149-56	SF	0.3607	1.0368	0.3740	0.20845E-02	0.9876
149-57	DF	0.4477	1.0444	0.4676	0.23047E-02	0.8733
149-58	SF	0.3897	1.0049	0.3916	0.21311E-02	0.9642
149-59	SF	0.3786	1.0368	0.3925	0.22033E-02	0.9945
149-60	DF	0.4592	1.0444	0.4796	0.24484E-02	0.9046
149-61	SF	0.4176	1.0049	0.4196	0.22709E-02	0.9588
149-62	SF	0.4161	1.0368	0.4314	0.23510E-02	0.9656
149-63	DF	0.4879	1.0444	0.5096	0.26099E-02	0.9075
149-64	SF	0.4294	1.0049	0.4315	0.24135E-02	0.9911
149-65	SF	0.4358	1.0368	0.4518	0.24997E-02	0.9802
149-66	DF	0.5010	1.0444	0.5232	0.27825E-02	0.9422
149-67	SF	0.4372	1.0049	0.4393	0.25154E-02	1.0145
149-68	SF	0.4129	1.0368	0.4281	0.24575E-02	1.0172
149-69	DF	0.4598	1.0444	0.4802	0.25035E-02	0.9237
149-70	SF	0.3374	1.0049	0.3391	0.20904E-02	1.0924
149-71	SF	0.3167	1.0368	0.3284	0.18772E-02	1.0130
149-72	DF	0.3291	1.0444	0.3437	0.17229E-02	0.8882
149-73	SF	0.2259	0.9845	0.2224	0.11928E-02	0.9503

^aSF is single fuel column, DF is double fuel column, B is blanket and R is reflector.

^bMeasured total dose rate (gamma and neutron) in mrd/s at an estimated reactor power of 1 watt. Statistical uncertainties 2%.

^cNodal transport calculation in xyz geometry with fluxes normalized to 8 watts, calculated doses in rads. For comparison with measurement the calculated doses are normalized by the mean C/E for ²³⁹Pu fission from 62 foil measurements in the core region.

TABLE 7.7 Measured and Calculated Dose Rates in the
Axial Direction in Matrix 149-53

Axial Displacement (mm)	Exp. ^a	Cell Factor	Corrected Exp.	Calc. ^b	C/E
76.2	0.1600	0.9993	0.1599	0.87177E-03	0.9661
127.0	0.1965	0.9993	0.1964	0.11017E-02	0.9941
228.6	0.3523	1.0368	0.3653	0.20115E-02	0.9758
330.2	0.3400	1.0368	0.3525	0.20730E-02	1.0420
431.8	0.3051	1.0368	0.3163	0.17344E-02	0.9715
584.2	0.1005	1.0000	0.1005	0.54986E-03	0.9694
685.8	0.0638	1.0000	0.0638	0.34260E-03	0.9515

^aMeasured total dose rate (gamma and neutron) in mrd/s at an estimated reactor power of 1 watt. Statistical uncertainties 2%.

^bNodal transport calculation in xyz geometry with fluxes normalized to 8 watts, calculated doses in rads. For comparison with measurement the calculated doses are normalized by the mean C/E for ²³⁹Pu fission from 62 foil measurements in the core region.

TABLE 7.8 Measured and Calculated Dose Rates in the
Axial Direction in Matrix 149-60

Axial Displacement (mm)	Exp. ^a	Cell Factor	Corrected Exp.	Calc. ^b	C/E
76.2	0.1781	0.9993	0.1780	0.10129E-02	1.0084
127.0	0.2257	0.9993	0.2255	0.12830E-02	1.0079
228.6	0.4592	1.0444	0.4796	0.24484E-02	0.9046
330.2	0.4544	1.0444	0.4746	0.24471E-02	0.9137
431.8	0.3823	1.0444	0.3993	0.20229E-02	0.8977
584.2	0.1016	1.0000	0.1016	0.57995E-03	1.0114
685.8	0.0640	1.0000	1.0640	0.35406E-03	0.9802

^aMeasured total dose rate (gamma and neutron) in mrd/s at an estimated reactor power of 1 watt. Statistical uncertainties 2%.

^bNodal transport calculation in xyz geometry with fluxes normalized to 8 watts, calculated doses in rads. For comparison with measurement the calculated doses are normalized by the mean C/E for ²³⁹Pu fission from 62 foil measurements in the core region.

TABLE 7.9 Measured and Calculated Dose Rates in
the Axial Direction in Matrix 149-70

Axial Displacement (mm)	Exp. ^a	Cell Factor	Corrected Exp.	Calc. ^b	C/E
76.2	1.0049	1.0049	0.4225	0.23253E-02	0.9753
127.0	0.3889	1.0049	0.3908	0.22681E-02	1.0283
228.6	0.3374	1.0049	0.3391	0.20904E-02	1.0924
330.2	0.3112	1.0049	0.3127	0.18131E-02	1.0273
431.8	0.2407	1.0049	0.2419	0.13880E-02	1.0168
584.2	0.0744	1.0000	0.0744	0.40232E-03	0.9581
685.8	0.0423	1.0000	0.0423	0.23585E-03	0.9879

^aMeasured total dose rate (gamma and neutron) in mrd/s at an estimated reactor power of 1 watt. Statistical uncertainties 2%.

^bNodal transport calculation in xyz geometry with fluxes normalized to 8 watts, calculated doses in rads. For comparison with measurement the calculated doses are normalized by the mean C/E for ²³⁹Pu fission from 62 foil measurements in the core region.

Figure 7.1 RZ Plot of ZPPR-17 and TLD Locations

Figure 7.2 Measured and Calculated Doses in a Double-Fuel-Column Cell

Fig. 7.3 Measured and Calculated Total Dose Rates Along the x-axis of ZPPR-17A.

Fig. 7.4 Measured and Calculated Axial Distributions of Total Dose Rates in ZPPR-17A.

8. CONTROL ROD ANALYSIS

Control rod measurements in ZPPR-17 were selected to cover different design options for the axially heterogeneous core. Measurements in ZPPR-17A, which did not contain CRPs in its reference configurations, focused on the worth of a single, central rod as a function of rod size, geometry and composition. Worths of CRP banks and one special four-rod bank were also measured. All measurements in ZPPR-17A were made with respect to fuel.

Worth of control rod banks, combinations of banks and banks with missing rods were measured in ZPPR-17B and 17C. All these measurements were with respect to CRPs.

All data processing was done with the McCRUNCH code and all results presented in this section used the LSFIT option in McCRUNCH. The reference control rod positions and the locations of the special bank measured in 17A are shown in Fig. 8.1.

Calculations of detector efficiencies and effective source ratios required for processing experimental data may usually be made to sufficient accuracy by two-dimensional xy models. However, the internal blanket of ZPPR-17 caused strong variations in the axial buckling as a function of radius, especially around the edge of the internal blanket. To avoid complication of the model, all calculations were made with a three-dimensional xyz model with the cross sections collapsed to six energy groups. The data were collapsed from a 21-group xyz model. Six-group cross sections were obtained for the internal blanket, for single- and double-fuel-column drawers in the inner core and in the outer core, for the radial blanket, radial reflector, axial blanket and axial reflector. Source-driven calculations for the real flux were made for cases with reactivity below one dollar subcritical. Cases with reactivity closer to critical used a homogeneous flux solution.

8.1 Results for ZPPR-17A

The ZPPR-17A measurements included both plate- and pin-type rods using both natural and enriched B₄C. Rod size was mostly two-by-two drawers, but rods two-by-three and three-by-three drawers in size were measured. The additional drawers in the two-by-three rod were 1,248-48 and 1,249-48. Added to these for the three-by-three rod were 1,250-48, 1,250-49 and 1,250-50.

Some pin-type rods used pin calandria and some had the B₄C pellets tightly packed in drawers. The loading pattern of the tightly packed rod is given in Fig. 8.2. Measured results and C/E values from ZPPR-17A were reported in reference 2. Atom densities for the various rod types are given in Table 7.2 of reference 1.

Six-group cross sections for control rods and CRPs were generated for a model with one of the ZPPR-17B rod patterns: center and inner ring control rods, middle ring CRPs, odd-numbered control rods (15-25) and even numbered CRPs (14-24) in the outer ring. For all central rods, data processing was performed using detector efficiencies and source ratios calculated for the 100% natural B₄C rod. These values were used in the McCRUNCH code to process worths for all central and near-central rod variations. All central and near-central CRPs used calculated values for the central two-by-two CRP. Because of these approximations, C/E values are only produced for the central CR and the central CRP. Table 8.1 gives the analysis results for the central CR and CRP, the special bank of CRs and CRPs and reference CRP banks.

8.2 Results for ZPPR-17B

In ZPPR-17B, a series of 20 control worth measurements was made. These included each of the rod banks, the inner and outer banks half-inserted, 8 different combinations of rod banks and 6 configurations with a rod missing from one of the banks representing stuck rod or rod run-out events. Generally, the central rod plus either the 12 outer-ring rods (numbers 14 to 25) or 6 outer ring rods (15 to 25 odd-numbered) were

designated as operating (regulating) rods. The inner ring were startup rods and the middle ring or the middle ring plus the even-numbered rods in the outer ring were the secondary (shutdown) rods.

As in the case for ZPPR-17A, the 17B six-group cross sections were obtained for the internal blanket, for single- and double-fuel-column drawers in the inner core and in the outer core, for the radial blanket, radial reflector, axial blanket and axial reflector. Cross sections for CRPs were also obtained with this model. A second calculation with the center rod and 12 outer rods inserted was used to collapse data for the control rods.

The calculations were made in xyz geometry with full-xy/half-z, quarter-xy/half-z, and quarter xy/full-z symmetry as required to represent the geometry of the rod patterns. For the subcritical states, both an adjoint flux for the homogeneous problem and a source-driven real flux were required to calculate detector efficiencies and effective source ratios. All calculations were made with the finite-difference solution of DIF3D.

The measured values and C/E results are given in Tables 8.2, 8.3 and 8.4, grouped into rod banks, rod bank combinations and banks with missing rods. A shorthand notation (a,b,c,d) is used to describe the number of control rods in the center position, the inner ring, the middle ring and the outer ring. Where necessary, the letter H is used to indicate rods half inserted and 0 is used to indicate odd-numbered rods. Worths are given as positive numbers for simplicity.

Greater detail of the measurements and data processing are given in reference 4.

The C/E results are in the range of 0.95 (center rod) to 1.00 (outer ring half-inserted). No clear trend in C/E as a function of radius emerges from the present analysis. The center rod is predicted 2-3% lower than the inner ring (C/E = 0.98) the middle ring C/E is 0.97 and the outer ring C/E is 0.99.

Predictions for rod banks combinations and banks with missing rods are consistent with those for the individual banks with C/E values in the range 0.97 to 1.00.

The ratios of worths for rod banks half-inserted to the worths of the fully inserted banks are quite interesting:

inner ring	measured	0.545
	calculated	0.542
outer ring	measured	0.478
	calculated	0.482

Thus, the rods half-inserted in the internal blanket are worth 9% more than half of the worth when fully-inserted while at the periphery of the blanket they are worth 4% less than half of the worth when fully-inserted. Experiment and calculation agree closely for these ratios.

Some rod interaction effects are shown in Table 8.5 which compares the worth of the center rod and of different banks of rods when inserted alone or with other rod banks inserted in the core. These worths were obtained by subtraction of the worths in the previous tables, hence the statistical uncertainties increase. The worth of the center rod, 1\$ when inserted alone, varies from 0.22\$ with the inner and middle rings inserted to 2.14\$ with the outer ring inserted.

The worths of withdrawal of single rods from a bank in different situations are compared in Table 8.6. Since the single rod worths were not measured, the average worth of the rods in the appropriate banks are given for comparison. The worths of the withdrawn rods vary considerably: the worth of CR2 in the inner bank is 0.46\$ when the center and middle banks are inserted and 0.94\$ when the center and 6 outer bank rods are inserted compared with the mean worth in the bank of 0.97 \$. The worth of CR14 in the outer bank (with center rod also inserted) is 4.1\$ compared with the mean worth in the outer bank of 1.9\$. These interaction effects are calculated within 10% by diffusion theory.

Calculations for the symmetric rod banks have been made by nodal diffusion (NDT) and nodal transport (NTT) models. The results are compared with the finite difference diffusion (FDDT) values, using a 55 mm mesh size, in Table 8.7. Mesh and transport effects are quite different to those found in conventional and radially-heterogeneous cores. Mesh corrections are relatively large -- from +8% to +12% -- while the transport correction is near zero for the central rod increasing with radius to -5% for the outer rod bank. The calculated worths are notably higher (6% to 9%) by nodal transport calculation than the original finite difference diffusion.

The nodal transport C/E results show no clear trend with radius but the center rod and the middle bank have C/Es about 1% lower than those for the inner bank and the outer bank. The C/E results for bank combinations fall between those for the individual banks. The spread in C/E values (1.041 to 1.057) is less than half of the spread with the finite difference diffusion calculations.

8.3 Results for ZPPR-17C

The ZPPR-17C reference core simulated a beginning-of-cycle loading with primary control rods -- center and 12 outer ring -- half inserted. The control rod worth measurements provide data on the worths of full insertion of secondary control banks in this loading. The secondary rod locations were the six inner ring (IR) positions and the six middle ring (MR) positions. The basic rod banks were six inner ring (6IR), six middle ring (6MR), 3IR, 3MR and a combination 3IR + 3MR. The three-rod patterns were measured both for the rods symmetrically disposed around the hexagonal bank and for the three rods in adjacent locations. Several cases of banks with missing rods were also measured, 5IR, 5MR, 3IR + 2MR and 2IR + 2IR + 3MR.

Three of the rod patterns, 6IR, 6MR and 5MR, were also measured in ZPPR-17B, the end-of-cycle simulation with all rods withdrawn. These cases provide a comparison of the interaction effects and of the accuracy of calculation of rod worths in an operating condition rather than in a reference core with no rods inserted.

The six-group data used the microscopic cross sections produced for 17B and were not separately collapsed for 17C. Only two of the control configurations permitted quarter-xy symmetry to be used, six cases required full-xy representation while two cases were symmetric about the y-axis and one was symmetric about the x-axis. All configurations were calculated with the full-xy model to avoid proliferation of models.

Since the control rod worths were measured with the rods fully inserted, the model used half-z symmetry. Shielding factors for the half-inserted rods in the reference core, 0.292 for the CRs and 0.708 for the CRPs, were used to adjust the k-effective in this model to 0.9888. The k-effective for the reference core using a quarter-xy full-z model was 0.989323. The two control patterns with quarter-xy symmetry (6 inner ring and 6 middle ring) were also calculated with the full-z model to check the results from the approximate models.

Calculations of detector efficiencies and effective source worths were made with the finite-difference diffusion path of DIF3D. Calculated worths for the two symmetric rod banks were also obtained with the nodal diffusion and nodal transport solutions.

Additional details of the measurements and data processing are given in reference 4.

Measured worths and C/E values are given in Table 8.8. Statistical and correlated uncertainty components are given to three figures to facilitate derivation of uncertainties when subtracting configuration worths. The calculated worths in Table 8.8 are obtained from the half-z model.

The C/E results vary by only 3% over the range of the configurations. The highest values are for the three adjacent rods in the inner and middle ring. In both bases, these are predicted 2% higher than their counterparts which have three rods symmetrically disposed around the ring. Apart from these two cases, the C/E values are in the range 0.949 to 0.963.

Rod interaction effects are shown in Table 8.9 in terms of the worth per rod (WPR) in banks of 6, 5, 3 and 2 rods. The inner ring rods show a negative interaction (WPR for the 3 symmetric rods is 15% higher than for the bank of 6 rods or 3 adjacent rods). The wider-spaced rods in the middle ring show a more neutral interaction (WPR for the 3 symmetric rods is the same as that for the bank of 6 rods, but 25% greater than for 3 adjacent rods). The worth of either bank of 3 rods is suppressed by 20% when the other bank is also present. These latter effects are predicted with a C/E bias similar to that for the individual banks.

Improved calculations have been made for the complete inner and middle banks of rods which were symmetric in the xy-plane. These calculations used full-z representation to model the half-inserted rods in the reference loading. Calculations were made with finite-difference diffusion (FDDT), with nodal diffusion (NDT) which has a small mesh-size error and with nodal transport (NTT). The calculated rod bank worths are compared in Table 8.10.

The effects on k-effective due to using the half-z model vary a little between the reference and the control bank cases and result in changes in rod worths of 0.5% and 0.7%. Corrections to rod worths for diffusion theory mesh size are +10% and +11% while transport corrections are -0.6% and -2%. The mesh corrections are considerably larger than found in other cores. Similar mesh and transport corrections were found for ZPPR-17B. Thus the effects are due to the internal blanket rather than the rods which were half-inserted in the core.

The worths of the inner bank, the middle bank and five rods in the middle bank were measured both in ZPPR-17B and in ZPPR-17C. The experimental worths and predictions are compared in Table 8.11. The worth of the inner bank is similar in either core but the worth of the middle bank is depressed by 8% in 17C due to the half-inserted outer bank. The C/E results are consistent between 17B and 17C within the (total) uncertainties of the experiments of about 0.9%.

8.4 Axial Worth Profiles for B₄C

The worth profile for a central control rod was measured in both ZPPR-17B and 17C. In 17B, the profile was measured for a 1.02 m-long, two-by-two-drawer B₄C column inserted in 102 mm steps by rearranging the contents of the control rod drawers. There was a separate reactor run for each step. Worths for the various steps were calculated with nodal xyz diffusion methods using the six-group cross section data. The axial node spacings in the model were adjusted so that the leading edge of the control rod corresponded to a node. Calculated and measured worths are shown in Fig. 8.3. The calculated values are normalized to the average C/E value and reproduce the measured profile within 1% except for the initial, small insertion.

In addition to these static measurements, the worth profile in 17B was measured for a 1.02 m-long B₄C segment using the long drawer technique. Reactivity values were derived for various axial positions as the B₄C column was driven from 102 mm above the core/axial blanket interface until the column exactly filled the core region. Values were obtained for several in-out cycles. The long drawer segments were in 149-49 and 249-49 and the other three drawers in the central control position contained their standard sodium-filled drawers.

A third measure of the axial worth profile of boron was obtained using the axial tube small sample oscillator technique. This measurement was made in ZPPR-17A in location 159-49, in the region containing internal blanket but well away from the core center. The enriched boron sample was a cylinder 55 mm long and 10.2 mm in diameter with a ¹⁰B mass of 3.65 g. In order to compare with the other techniques, the small sample reactivities were integrated over the core height.

Results from the three profile measurements are shown in Fig. 8.4. Note that rod position zero corresponds to full insertion. The reactivity values are those from the long-drawer measurement. Reactivities from the other measurements were normalized to the long-drawer value at full

insertion to allow the worth profiles to be compared. As Fig. 8.4 shows, the three methods give essentially the same shape, even with ^{10}B sample mass variation from 3.65 g in the small sample experiment to 735.6 g in the static experiment. This implies that the axial flux tilt caused by the boron is not large. These results also show that calculated worth profiles can be verified by comparing with any of the three measured profiles.

Details of the 17B axial boron measurements are given in reference 2.

The long-drawer measurement was repeated in two locations in ZPPR-17C. In the first location, 149-49 and 249-49, the central, half-inserted control rod was removed and replaced with the long-drawer (1.02 m-long B_4C column) and CRP drawers elsewhere. The 12 half-inserted, outer-ring rods were in place. The second location was in 1,265-49, an outermost location with internal blanket. In this second case, all 13 half-inserted rods were in place. The results for these two measured profiles are given in Figs. 8.5 and 8.6. Again, rod position zero corresponds to full insertion. The difference in axial profiles can be seen with a smaller slope in the internal blanket for the core-center measurement. The axial asymmetry of the core is seen for both locations in the smaller slope in the axial portion with the inserted control rods (higher values of rod position).

Details of the 17C axial boron measurements are given in reference 5.

8.5 Additional Calculations for ZPPR-17B

The reference calculations for ZPPR-17 used finite difference diffusion since this model was used to provide detector efficiencies and source ratios for experimental data processing. More refined calculations for a number of cases using nodal diffusion and nodal transport methods are shown for 17B in Table 8.7 and for 17C in Table 8.10. Additional calculations were made for the principal rod bank worths in ZPPR-17B.

The effects of group collapse were estimated by calculating the bank worths by nodal diffusion with 21 group cross sections. The results are compared with those from the six group calculations in Table 8.12. Group condensation effects were larger than expected from results in other cores and varied with position from -7% for the central rod to -4% for the outer rod bank. These corrections increase the radial discrepancy in C/E by 3 to 4%.

The rod worths were also calculated using the TRITAC code in xzy geometry and S4 quadrature. The results are given in Table 8.13. Corrections for anisotropic transport, not treated in the TRITAC code, were calculated using the nodal transport code. These varied from -1.8% for the central control rod to +0.5% for the outer bank. The TRITAC worths, after adjustment for streaming, were lower than the nodal transport worths. The difference varied with radius from -4% for the central rod to -0.6% for the outer bank.

Table 8.14 compares the rod bank worth C/Es for ZPPR-17B by different calculation methods, after the group condensation corrections have been supplied. The radial variation in C/E is about 10% and twice that found in the analysis of radial fission rates.

TABLE 8.1 Recommended Control and CRP Worths in ZPPR-17A and Comparison with Calculation

Case	Experimental Worth, \$	Total 1 σ Uncertainty, %	Calculated k_{eff}^a	Calculated Worth, \$ ^b	C/E
Central CR	1.073	0.88	0.984803	1.044	0.973
4 CRs	3.347	0.87	0.977174	3.386	1.012
4 CRPs	0.588	0.92	0.986100	0.650	1.105
Central CRP	0.0837	1.45	0.987935	0.0932	1.114
Central 6 Inner CRPs	1.054	0.89	0.984374	1.175	1.115
Central 6 Inner 6 Middle CRPs	1.776	0.88	0.981545	2.040	1.150
All 25 CRPs	6.649	0.87	0.963450	7.693	1.157

^aFinite-difference diffusion calculation, 6 energy groups, xyz geometry, 5 cm mesh; Reference $k_{eff} = 0.988243$.

^bUsing $\beta = 0.3385\%$.

TABLE 8.2 Worths of Control Rod Banks in ZPPR-17B

Step ^a	Control Rods ^b	Experimental Worth, \$	Statistical 1 σ , %	Correlated 1 σ , %	Calculated k-eff ^c	Calculated Worth, \$ ^d	C/E
1	Central CR (1,0,0,0)	1.001	0.087	0.811	0.982117	0.955	0.954
3	IR (0,6,0,0)	5.822	0.116	0.866	0.966887	5.708	0.980
2	IR Half Inserted (0,6H,0,0)	3.171	0.123	0.865	0.975199	3.095	0.976
10	MR (0,0,6,0)	8.318	0.121	0.859	0.959562	8.048	0.968
18	OR (0,0,0,12)	22.477	0.120	0.855	0.917563	22.186	0.987
17	OR Half Inserted (0,0,0,12H)	10.731	0.146	0.859	0.951408	10.695	0.997

^aRefer to Table 2.2.

^bIR = inner ring, MR = middle ring, OR = outer ring, H = half-inserted.

^cFinite difference diffusion, xyz geometry, 6 energy groups, reference k-effective 0.985234.

^dk-effective = 0.3374%.

TABLE 8.3 Worths of Rod Bank Combinations in ZPPR-17B

Step ^a	Control Rods ^b	Experimental Worth, \$	Statistical 1 σ , %	Correlated 1 σ , %	Calculated k-eff ^c	Calculated Worth, \$ ^d	C/E
4	Center + IR (1,6,0,0)	6.137	0.117	0.869	0.965778	6.060	0.987
9	Center + MR (1,0,6,0)	9.017	0.126	0.861	0.957436	8.734	0.968
19	Center + OR (1,0,0,12)	24.589	0.118	0.852	0.912298	24.050	0.978
6	IR + MR (0,6,6,0)	11.952	0.163	0.870	0.948020	11.809	0.988
13	IR + OR odd (0,6,0,6 $\emptyset$)	17.856	0.147	0.858	0.931124	17.482	0.979
5	Center + IR + MR (1,6,6,0)	12.169	0.158	0.874	0.947343	12.032	0.989
14	Center + IR + OR odd (1,6,0,6 $\emptyset$)	18.279	0.137	0.861	0.929798	17.936	0.981
16	Center + MR + OR odd (1,0,6,6 $\emptyset$)	20.490	0.113	0.857	0.923764	20.018	0.977

^aRefer to Table 2.2.

^bIR = inner ring, MR = middle ring, OR = outer ring, $\emptyset$ = odd numbered rods.

^cFinite difference diffusion, xyz geometry, 6 energy groups, reference k-effective 0.985234.

^d β -effective = 0.3374%.

TABLE 8.4 Worths of Rod Banks with Missing Rods in ZPPR-17B

Step ^a	Control Rods ^b	Experimental Worth, \$	Statistical 1 σ , %	Correlated 1 σ , %	Calculated k-eff ^c	Calculated Worth, \$ ^d	C/E
11	MR-CR8 (0,0,5,0)	6.537	0.134	0.863	0.964752	6.387	0.977
8	Center, IR-CR2, MR (1,5,6,0)	11.718	0.161	0.872	0.948817	11.546	0.985
12	Center, IR-CR2, OR odd (1,5,0,6 $\emptyset$)	17.321	0.131	0.860	0.932462	17.025	0.983
7	Center, IR, MR-CR8 (1,6,5,0)	10.804	0.180	0.880	0.951187	10.768	0.997
15	Center, MR-CR8, OR odd (1,0,5,6 $\emptyset$)	18.625	0.161	0.860	0.928746	18.297	0.982
20	Center, OR-CR14 (1,0,0,11)	20.435	0.170	0.862	0.922999	20.284	0.993

^aRefer to Table 2.2.

^bIR = inner ring, MR = middle ring, OR = outer ring, $\emptyset$ = odd numbered rods.

^cFinite difference, xyz geometry, 6 energy groups, reference k-effective 0.985234.

^d β effective = 0.3374%.

TABLE 8.5 Control Rod Interaction Effects in ZPPR-17B

Control Rods	From Steps	Rods Inserted in Core	Experimental Worth, \$	Statistical Uncertainty, %	Calculated Worth, \$	C/E
CR	1	None	1.001	0.1	0.955	0.954
	6,5	IR + MR	0.217	12.6	0.223	1.028
	4,3	IR	0.315	3.1	0.352	1.117
	14,13	IR + 6OR odd	0.423	8.6	0.454	1.073
	9,10	MR	0.699	2.2	0.686	0.981
	19,18	OR	2.112	1.7	1.864	0.883
IR	3	None	5.823	0.1	5.708	0.980
	6,10	MR	3.634	0.6	3.761	1.035
MR	10	None	8.318	0.1	8.048	0.968
	6,3	IR	6.130	0.3	6.101	0.995
6 OR odd	13,3	IR	12.034	0.2	11.774	0.978
	14,4	Center + IR	12.142	0.2	11.876	0.978
	16,9	Center + MR	11.475	0.2	11.284	0.983

TABLE 8.6 Worth of Single Rods Withdrawn from Rod Banks in ZPPR-17B

Control Rods	From Steps	Rods Inserted in Core	Experimental Worth, \$	Statistical Uncertainty, %	Calculated Worth, \$	C/E
CR2	5,8	Center + 6IR + 6MR	0.451	6.0	0.486	1.078
	14,12	Center + 6IR + 6OR odd	0.958	3.5	0.911	0.970
Mean Worth in Bank	3	6IR	0.970	0.1	0.951	0.980
CR8	10,11	6MR	1.781	0.7	1.661	0.933
	5,7	Center + 6IR + 6MR	1.365	2.0	1.264	0.926
	16,15	Center + 6MR + 6OR odd	1.865	2.0	1.721	0.923
Mean Worth in Bank	10	6MR	1.386	0.1	1.341	0.968
CR14	19,20	Center + 12OR	4.154	1.1	3.766	0.907
Mean Worth in Bank	18	12OR	1.873	0.1	1.849	0.987

TABLE 8.7 Calculated Control Rod Worths in ZPPR-17B using Nodal
Diffusion and Nodal Transport Models

Control Rods	FDDT Worth, \$	NDT Worth, \$	Mesh Correction, %	NTT Worth, \$	Transport Correction, \$	C/E
CR1	0.955	1.044	+9.3	1.042	-0.2	1.041
IR	5.708	6.211	+8.8	6.136	-1.2	1.054
MR	8.048	8.918	+10.8	8.694	-2.5	1.045
ØR	22.186	24.776	+11.7	23.643	-4.8	1.052
CR1 + IR	6.060	6.555	+8.2	6.488	-1.0	1.057
CR1 + MR	8.734	9.635	+10.3	9.420	-2.2	1.045
CR1 + ØR	24.050	26.966	+12.1	25.796	-4.3	1.049
IR + MR	11.809	12.805	+8.4	12.582	-1.8	1.053
CR1 + IR + MR	12.032	13.011	+8.1	12.797	-1.7	1.052

TABLE 8.8 Control Rod Worths in ZPPR-17C

Step ^a	Control Rods ^a	Experimental Worth, \$	Statistical 1 σ , %	Correlated 1 σ , %	Calculated k_{eff} ^b	Calculated Worth, \$ ^c	C/E
7	6IR	5.869	0.132	0.870	0.970615	5.651	0.963
6	5IR	5.039	0.187	0.869	0.973270	4.814	0.955
1	3IR symmetric	3.390	0.111	0.868	0.978374	3.217	0.949
5	3IR adjacent	2.850	0.138	0.872	0.979829	2.765	0.970
11	6MR	7.682	0.114	0.862	0.965254	7.356	0.958
10	5MR	6.045	0.190	0.868	0.970106	5.812	0.963
9	3MR symmetric	3.827	0.099	0.866	0.976877	3.684	0.963
8	3MR adjacent	3.052	0.123	0.873	0.979077	2.999	0.983
3	3IR + 3MR	6.613	0.187	0.865	0.968448	6.338	0.958
2	3IR + 2MR	5.370	0.168	0.868	0.972151	5.166	0.962
4	2IR + 3MR	5.636	0.192	0.866	0.971377	5.411	0.960

^aRefer to Table 3.1. 6IR refers to 6 inner ring control rods etc.

^bCalculations 6 group xyz with half-z model, finite difference diffusion, reference $k_{effective} = 0.988823$.

^cUsing $\beta_{effective} = 0.3357\%$.

TABLE 8.9 Control Rod Interaction Effects in ZPPR-17C

Rod Bank	Worth Per Rod			
	Measured, \$	σ_s , %	Calculated, \$	C/E
6IR	0.978	0.13	0.942	0.963
5IR	1.008	0.19	0.963	0.955
3IR adjacent	0.950	0.14	0.922	0.970
3IR symmetric	1.130	0.11	1.072	0.949
3IR symmetric with 3MR inserted	0.929	0.46	0.885	0.953
2IR with 3MR inserted	0.905	0.62	0.864	0.955
6MR	1.280	0.11	1.226	0.958
5MR	1.209	0.19	1.162	0.962
3MR adjacent	1.017	0.12	1.000	0.983
3MR symmetric	1.276	0.10	1.228	0.963
3MR symmetric with 3IR inserted	1.074	0.40	1.040	0.969
2MR with 3IR inserted	0.990	0.49	0.974	0.984

TABLE 8.10 Comparison of Control Rod Worths in ZPPR-17C using Different Calculation Models

Rod Bank	Calculation ^a Method	k-effective	Worth, \$	C/E	Corrections ^b	
					(1) Model	(2) DT mesh (3) Transport
					k-eff, %	Worth, %
Reference	FDDT-half z	0.988823	---	---	---	---
	FDDT-full z	0.989323	---	---	(1) + 0.050	---
	NDT-full z	0.983503	---	---	(2) - 0.582	---
	NTT-full z	0.990016	---	---	(3) + 0.651	---
6IR	FDDT-half z	0.970615	5.651	0.963	---	---
	FDDT-full z	0.971002	5.681	0.968	(1) + 0.039	+0.5
	NDT-full z	0.963580	6.262	1.067	(2) - 0.742	+10.2
	NTT-full z	0.969960	6.222	1.060	(3) + 0.638	-0.6
6MR	FDDT-half z	0.965254	7.356	0.958	---	---
	FDDT-full z	0.965558	7.411	0.965	(1) + 0.030	+0.7
	NDT-full z	0.957433	8.247	1.074	(2) - 0.813	+11.3
	NTT-full z	0.964102	8.088	1.053	(3) + 0.667	-2.0

^aFDDT = finite difference diffusion, NDT = nodal diffusion, NTT = nodal transport.

^b(1) Model correction half-z to full-z, (2) FDDT mesh 55 mm to effective fine mesh in NDT, (3) fine-mesh diffusion (NDT) to transport (NTT).

TABLE 8.11 Comparison of Control Rod Worths in
ZPPR-17B and ZPPR-17C

<u>Control Rods</u>	<u>Core</u>	<u>Measured Worth, \$</u>	<u>Total Uncertainty, %</u>	<u>FDDT C/E</u>	<u>NTT C/E</u>
6IR	17B	5.822	0.87	0.954	1.054
	17C	5.869	0.88	0.968	1.060
6MR	17B	8.318	0.87	0.968	1.045
	17C	7.682	0.87	0.965	1.053
5MR	17B	6.537	0.87	0.977	---
	17C	6.045	0.89	0.969 ^a	---

^aAssuming +0.7% modelling correction for 6MR (Table 8.10).

TABLE 8.12 Calculations of Control Rod Worths in ZPPR-17B Using 21 Group Data

<u>Case</u>		<u>k-effective^a</u>	<u>Worth \$</u>	<u>Group Correction %</u>
Reference	6G	0.982957	--	(+0.00039Δk)
	21G	0.983351	--	
CR1	6G	0.979565	1.044	-7.4
	21G	0.980200	0.969	
6IR	6G	0.963118	6.211	-5.9
	21G	0.964591	5.862	
6MR	6G	0.954720	8.918	-4.0
	21G	0.956123	8.583	
120R	6G	0.908321	24.776	-3.7
	21G	0.911074	23.911	

^aNodal diffusion calculations

TABLE 8.13 Calculations of Control Rod Worths in ZPPR-17B with the TRITAC Code

<u>Case</u>	<u>k-effective^a</u>	<u>Control Rod Worth, \$</u>	<u>Streaming^b Correction, \$</u>
Subcritical Reference	0.989229	---	(-0.00236Δk)
CR1	0.985801	1.010	-0.018
6 Inner Ring	0.969377	5.927	+0.026
6 Middle Ring	0.961333	8.694	+0.006
12 Outer Ring	0.916876	23.643	+0.115

^aCalculations 6 group, xyz, S4, 5 cm. mesh size with average compositions for each cell-type.

^bNot included in TRITAC results.

TABLE 8.14 Calculations of Control Rod Banks in ZPPR-17B by Different Methods

<u>Rods</u>	<u>Applied Group Correction, %</u>	<u>F.D. Diffusion C/E^a</u>	<u>Nodal Diffusion C/E</u>	<u>Nodal Transport C/E</u>	<u>TRITAC S₄ C/E</u>
CR1	-7.2	0.885	0.968	0.966	0.920
6 Inner Ring	-5.6	0.925	1.007	0.995	0.965
6 Middle Ring	-3.8	0.931	1.031	1.005	0.981
12 Outer Ring	-3.5	0.953	1.064	1.015	1.009

^aFinite difference, 50 mm mesh size.

n CRP location

S Special measurements of four control rods and CRPs

Fig. 8.1 Control Positions used in ZPPR-17A Measurements.

Fig. 8.2 Loading Pattern for Close-packed Pin Control Rod.

Fig. 8.3 Worth Profile for Mockup Central Control Rod in ZPPR-17B.

Fig. 8.4 Comparison of Axial Worth Profiles of B_4C in ZPPR-17B.

Fig. 8.5 Measured Axial Worth Profile for B_4C in 149-49/249-49 in ZPPR-17C.

Fig. 8.6 Measured Axial Worth Profile for B_4C in 165-49/265-49 in ZPPR-17C.

9. SODIUM VOID WORTHS

Sodium void worths were measured only in ZPPR-17A. Two different techniques were used. In one technique, a subcritical reactivity difference was measured after substituting empty cans for sodium-filled cans in two different zones of the assembly. Void-can substitution was done in a series of axial steps. The second technique used the new plate column oscillator devices described in section 2 to move a single column of sodium or void cans axially through one assembly half. Oscillator measurements were made at ten different radii.

9.1 Plate Substitution Results

The reference configuration for the plate substitution measurements was the ZPPR-17A subcritical reference. Two zones were voided. The first zone was just outside the region with the internal blanket and contained 36 drawers per assembly half. The second zone was at the core center and contained 52 drawers per assembly half. The zones are shown in Fig. 9.1. The sodium carbonate in double-fuel-column drawers was not included in the voiding. Reactivity changes were measured using the modified source multiplication method. Both zones were voided in a series of cumulative axial steps which corresponded to the lengths of the sodium cans. In the outer zone, the steps were ± 203 mm, ± 406 mm, ± 508 mm and ± 787 mm. In the inner core, the fuel region was voided first (± 152 mm to ± 330 mm, ± 152 mm to ± 508 mm) then the internal blanket (0 to 152 mm) and finally the external axial blanket to ± 787 mm. Step reactivity worths are given in Table 9.1. Further details of the measurements were given in reference 1. The uncertainties are dominated by a 0.2 cent contribution from reproducibility of the reactivity of the subcritical reference before and after the voiding. Other, smaller, components from reactivity scale calibration (0.7%) and statistical uncertainties (0.04¢) are included. In the measurements, the steel mass changed slightly with each step due to mass differences between sodium filled cans and empty cans. Reactivity effects of these steel mass changes were estimated by calculations to be small; 0.06¢ for the 0.34 kg case in the inner core. Because the steel corrections

are small compared to the uncertainties, no reactivity corrections were made to the step worths in Table 9.1.

Calculations were made for the central zone voiding. Calculated results were obtained by diffusion theory in rz geometry. Exact perturbation theory (voided adjoint) was used to show the non-leakage and leakage components for each step. Values of C-E are given for the various steps in Table 9.2. Calculated values are within 7 to 15% of experiment for the core and internal blanket voiding. However, the present calculated values are lower than the measured values in the steps of small leakage fraction, in contrast to other results with ENDF/B-V.2 data where calculation is a few percent higher. It is concluded that further studies of cross section processing for void cells in different environments and transport calculations will be necessary to refine these results. Analysis of the outer-core measurements is not complete.

9.2 Oscillator Results

Sodium worth oscillator measurements were made in ten locations which are shown in Fig. 9.1. Five locations (148-49, 148-43, 147-39, 148-35, 148-34) contained single-fuel-column drawers with internal blanket, three (147-33, 148-32, 147-27) contained single-fuel-column drawers with no internal blanket and two (148-25 and 148-23) contained radial blanket drawers.

Reactivity was derived as a function of column position by inverse kinetics analysis of power history recorded by ex-core BF_3 chambers. Three full oscillation cycles were used. Two measurements were made in each location; one with sodium-filled cans and one with empty cans and the sodium effect obtained by difference. The mass of sodium in one column was about 358 gm and the mass of steel about 264 gm.

Results for six representative locations are given in Fig. 9.2. Values in the figure are integrated reactivities for the front of the sodium column at various distances from the front of the drawer. Zero position corresponds to the sodium column against the front of the drawer. The zero

of reactivity is somewhat arbitrarily set to correspond to the fully withdrawn sodium column. The shapes of the curves are qualitatively similar for all core locations except 147-27. In these three core locations, the sodium worth is small and positive in the axial blanket, reaches a maximum positive value between 254 mm and 508 mm from the interface and is negative near the interface. At 147-27, the outermost portion of the core, the worth is essentially always positive and increases monotonically toward the interface. The innermost blanket result, 148-25, is similar to the outer core result. Deeper into the blanket, in 148-23, the sodium worth is very small with only a small axial variation.

Statistical uncertainty of the oscillator results was about 0.0015\$ at 25 mm displacement intervals, or about 2% of the maximum reactivity values. Detailed results for the oscillator measurements were given in reference 1.

Of perhaps greater interest in axially heterogeneous cores, is the differential sodium void worth. Figure 9.3 shows both calculated and measured differential worth results for the core center (148-49). The measured values are averages for three oscillations to reduce statistical fluctuations on the differences between successive steps. The void reactivities are commonly analyzed in terms of the leakage component, which varies with position approximately as the square of the flux gradient, and the non-leakage component which varies approximately as the square of the total flux. These two calculated components (by first-order perturbation) and their sum are also shown in Fig. 9.3. The leakage component has two minima, produced by inward leakage to the internal blanket and outward leakage to the axial blanket with a zero component below the axial center of the fuel. The calculated total worth reproduces the measured shape quite well.

TABLE 9.1 Step Reactivity Worths for Sodium Voiding in ZPPR-17A

<u>Step^a</u>	<u>Mass Sodium Voided, kg</u>	<u>Mass Steel Added, kg</u>	<u>Measured Reactivity Change, ϕ</u>	<u>Total Uncertainty 1σ, ϕ</u>	<u>Specific Reactivity $\phi/\text{kg (Na)}$</u>
<u>Outer Core</u>					
0 - 203 mm	12.625	0.111	+6.82	0.21	+0.540
203 - 406 mm	12.624	0.111	+1.68	0.30	+0.133
406 - 508 mm	6.160	0.065	-2.09	0.30	-0.339
508 - 787 mm	21.097	0.071	-3.87	0.30	-0.183
<u>Inner Core</u>					
152 - 330 mm	15.472	0.341	+4.92	0.21	+0.318
330 - 508 mm	15.472	0.340	+1.35	0.30	+0.087
0 - 152 mm	16.821	0.020	+7.98	0.31	+0.474
508 - 787 mm	30.741	0.101	-4.52	0.30	-0.147

^aVoided symmetrically in each half.

\ Void Zones
 ■ Oscillator Measurement

Fig. 9.1 Locations of Sodium Void Worth Measurements in ZPPR-17A.

Fig. 9.2 Reactivity versus Sodium Column Displacement for Various Locations in ZPPR-17A.

Fig. 9.3 Calculated and Measured Sodium Void Worths as a Function of Axial Position in ZPPR-17A.

10. CALCULATIONS OF BOWING, EXPANSION AND SMALL-SAMPLE WORTH EXPERIMENTS IN ZPPR-17A

10.1. Introduction

The purpose of these experiments was to test the accuracy of reactivity feedback calculations in reactor safety analyses. The inherent safety phenomena addressed by the experiments are bowing, radial expansion, axial expansion and sodium density change. Reactivity feedbacks related to core disruption were addressed by measuring the worth of fuel, structure, control and coolant samples at various locations.

The measurements are described thoroughly in Section 10 of Ref. 3. There was one static experiment (plate shifting) and a large number of material oscillation experiments. Table 10.1 and Figure 10.1 give an overview of the oscillator experiments that were done.

The methods used to calculate these experiments generally are consistent with methods used by reactor designers. In some cases, however, extra calculational effort was required to account for phenomena that are more important in the critical experiments.

XYZ geometry and nodal diffusion theory were used in calculating each of the experiments. Models of the exact reactor loadings were used to analyze the plate shifting experiment. For all other experiments a model of the critical reference configuration with all operational control rods fully withdrawn was used. Except for the radial tube oscillator (RTO) experiments, the true reactor configurations for the oscillator experiments were essentially the same as the critical reference and the control rods were withdrawn into the axial blanket. Use of the reference configuration for the RTO calculations is justified by the fact that the configuration differences affected the fission rate near the oscillator by less than 1%, according to the 64 fission chamber data.

The 21 group cross sections based on ENDF/B Version 5.2 data and produced by the buckling recycle method were always used (see Section 4).

Calculated reactivities were converted from $\Delta k/k$ to cents using a beta-effective value of 0.003409. This value is based on ENDF/B Version 5 delayed neutron data. It includes an adjoint correction factor of 1.0087 that accounts for the error in the standard adjoint flux caused by using forward-flux weighting in the cross section homogenization¹⁷.

In each of the remaining subsections a class of experiments is discussed. The analysis techniques are described, representative C/E results are presented and some observations about the results are made. In all cases the quoted uncertainties for the C/Es include only experimental sources, not calculated ones. C/Es are not displayed when the uncertainty exceeds 20%. A complete description of the calculations and C/Es is given in Ref. 18 and many of them are included in Ref. 19. The C/Es quoted in Ref. 19 for the ZPPR-17 axial expansion oscillator and sodium plate column oscillator experiments are 1.7% larger than those appearing here because an error was found after Ref. 19 was submitted.

10.2 RTO and ATO Small-Sample Worth Experiments

Worths of 4 or 5 sample materials were measured using both the radial tube oscillator (RTO) and axial tube oscillator (ATO) techniques. The locations of the radial traverse and the 3 axial traverses - ATO-1, ATO-2 and ATO-3 - are indicated in Fig. 10.1.

The basic method for computing the sample worths was first-order perturbation theory (FOP) within a nodal diffusion theory framework. These nodal perturbation calculations used the fission emission spectrum of the sample material when it was fissionable. They yielded the node-average worths of infinitesimal, cell-spanning samples. A computer program interpolated the node-average worths and applied a number of correction factors, yielding the worths of the true finite samples at their exact reactor locations.

In most cases "detector" cross sections were used to compute the worths. These cross sections are homogeneously self-shielded using the cell-average composition. For PU-30 outside the core and for DU-6

everywhere detector cross sections provide an inadequate resonance shielding representation. For DU-6 the ^{238}U cross sections of a ZPPR fuel plate (in a double-fuel-column drawer) was used everywhere because the mean chord length of ^{238}U in the fuel plate is only 5% different (smaller) than in DU-6. For PU-30 in locations outside the core we generated cross sections that have the resonance shielding and broad group effects of the finite sample size built into them.

Correction factors to account for self multiplication and broad group-type self shielding in the samples were computed with the SARCASM code²⁰.

Adjoint heterogeneity corrections were computed for the $\Delta k/k$ values of sample worths in addition to the adjoint correction of beta-effective. The prescription of Ref. 17 was followed.

For the ATO traverses, corrections were computed to get from cell-spanning worth to worth at the sample location within the cell. These correction factors were obtained using broad group, transport perturbation theory FOP worth calculations. No in-cell position corrections were computed for the RTO experiments because there the samples always spanned the unit cells.

Global transport corrections were computed for all the worth traverses. These correction factors were obtained by comparing sample worths from fine mesh, S_4 transport theory and fine mesh finite-difference diffusion theory calculations.

Global axial position corrections were computed for the RTO traverses. These corrections are essentially factors that interpolate to the tube location within the first axial node of the XYZ ZPPR-17A model. This is necessary because the axial node spacing is large (spacings in X and Y are not) and the traverse processing code interpolated only along the direction of traverse.

The experimental, calculated and C/E results for some of the RTO

and ATO worth traverses that included the internal blanket are shown in Tables 10.2 through 10.6 and Figures 10.2 through 10.6. For the radial traverses the position # is the matrix column, and for the axial traverses it is simply the stop-point number starting from the innermost position. The position X or Z is the distance from the center of the assembly to the center of the sample. The initial C/E is the result without correction factors; it uses the interpolated nodal FOP calculated value and includes only special cross section effects (for PU-30 outside the core, and for DU-6). The size factor is from the SARCASM code. The position factor is the global axial factor for the radial traverses and is the in-cell factor for the axial traverses.

Self shielding and other sample size effects for PU-30 outside the core have not been dealt with very successfully. A symptom of these size effect problems is the C/E discontinuity that occurs at every core/blanket interface in all the PU-30 traverses. Two alternative treatments for PU-30 outside the core were tried but results from them were also poor.

The radial traverses all have C/Es that are less than unity in the internal blanket, and for all of these traverses the C/Es increase substantially with increasing radius through the internal blanket and core. This trend with radius has been observed in ZPPR-17A radial reaction rate traverses and in similar experiments in other large LMR critical assemblies. However, the C/E increase for the ZPPR-17A radial worth traverses is larger than seen previously. The C/Es from the axial traverses generally look better than those from the radial traverses. The C/Es are within a few percent of unity and nearly constant axially in most cases.

There seems to be some inconsistency between the radial and axial traverses. The two kinds of traverses never sampled the same reactor location but, assuming radial symmetry, they did sample similar locations. The difference between RTO and ATO C/Es from the similar locations are shown in Table 10.7. In some cases there is no discrepancy but C/E differences as large as 8% can be seen. The cause of this has not been identified.

Region-average C/Es have been computed to summarize the radial

and axial traverse results. They are shown in Table 10.8. Only values with uncertainties of 10% or less have been used to obtain the averages. In the core region, most of the C/Es are within 5% of unity and all are within about 10%. The C/E discrepancies generally are larger in the blankets, but most C/Es are within 12% of unity. The problem of increasing C/E with increasing core radius is evident from comparing the core region ATO C/Es for B-1 and for U-6, but the trend is not clear from the PU-30 ATO traverses.

10.3 Neutron Importance Traverse

The radial profile of the neutron importance was inferred from ^{252}Cf traverses with the RTO. The ^{252}Cf neutron source importance was calculated consistently with the RTO small-sample worth calculations.

The experimental and calculated results are shown in Table 10.9 and Fig. 10.7. The experimental importance at the full-out position (not shown) was taken to be identically zero, and the uncertainty at that position was added in quadrature to the uncertainties at each of the other positions. The experimental importance was normalized to have a peak value of unity. The transport correction was normalized such that its average value in the core is unity. Then the corrected calculated values were normalized such that the average C/E in the core is unity.

It can be seen that the error in the calculated importance has the same trend as for small-sample worths from the RTO; the C/E increases substantially with increasing radius through the internal blanket and core. Both of the correction factors aggravate this problem, but it is qualitatively the same with or without the corrections. One might expect that the error in the adjoint flux profile would be the same as the error in the forward flux profile, but that does not seem to be the case. The radial reaction rate traverses, which depend on the forward flux but not the adjoint, have C/E tilts that are much smaller than the importance C/E tilt. Furthermore the magnitudes of the tilts in the PU-30 and B-1 RTO C/Es, which depend on both the forward and adjoint fluxes, are about the same as the magnitude of the importance C/E tilt. Thus it appears that the sample worth

C/E tilts are due more to an adjoint profile error than to a forward flux profile error.

10.4 Plate Column Oscillator Experiments

Plate column oscillators were used to measure the worth of removing Pu-U fuel, U_3O_8 , Fe_2O_3 , sodium and void can (stainless steel) columns. The experiments are referred to as PCO-1 through PCO-10. All the measurements except PCO-5 were made at SFC matrix positions.

The moving plate column sometimes consisted of a mix of materials. In PCO-1 and PCO-3 it was stainless steel-clad Pu-U (standard ZPPR fuel) for the first 50.80 cm and stainless steel plates from there to the end of the column (66.04 cm). According to calculations the clad and steel plate contributions are each about 2% of the column worth and are of opposite sign, so the net steel contribution is less than 1%. In PCO-5 and PCO-6 the entire moving column was clad Pu-U; the presence of the clad reduces the calculated worth by about 2%. The experimental worth of the void can column (PCO-9) was subtracted from the experimental worth of the clad sodium column (PCO-8) to get the net worth of sodium (PCO-8-9), which is the quantity for which calculations are presented.

Calculations of these experiments were done using first order perturbation theory, even though the perturbations are not believed to be first order. The perturbations were too small to cause significant global flux changes (with the possible exceptions of PCO-1,3 and 6), but the disruption of the intracell flux was probably significant. No corrections were applied other than the adjoint correction to beta-effective. Accordingly the calculated results presented here are considered preliminary.

Actually an attempt to compute accurate worths was made in the case of sodium (PCO-8-9). Special attention was given to this experiment because it is the only one in the ZPPR-17 program that attempted to measure a coolant density feedback coefficient. To account for the disruptions to the standard SFC cell, cell average cross sections were computed for the PCO-8 and PCO-9 drawer loadings (with the moving columns inserted). Both of

these cross section calculations used group- and region-dependent bucklings from the reference eigenvalue solution to account for the fact that the experiment was surrounded by a normal core. Comparing the sodium worths based on the standard and special cross sections yielded cell correction factors, which range from 0.94 to 0.96. In addition, an adjoint correction factor for the $\Delta k/k$ values was computed, as described in Section 10.2; this factor is 0.83, an unusually large adjustment.

The basic FOP calculations were done in same way as those for the radial and axial tube experiments. Nodal perturbation theory and the integral interpolation scheme were used. Core cell average cross sections were used to compute the worths because, of the standard types available, they probably best represent the plate columns in the unit cell.

Worth traverse results for the two traverses that included the internal blanket are shown in Tables 10.10 and 10.11. The cumulative worths are for withdrawing the plate column the distance indicated from the full-in position. The incremental worths are for the change from the previous withdrawal position to the current one. There is a definite pattern of increasing C/E with increasing withdrawal from the internal blanket, and C/Es are higher in the core than in the internal blanket. This is similar to the RTO C/E behavior, but not like the ATO-1 PU-30 C/E behavior.

The experimental uncertainties used here are larger than those tabulated in Section 10 of Ref. 3. The increase is due to incorporating the estimated uncertainty in the withdrawal position. It is estimated that the withdrawal from full in is uncertain by about 0.04 cm, but the distance between other positions is known to about 0.004 cm. This has a significant effect only on small withdrawals; for example this uncertainty is 11% for 0.38 cm withdrawal but less than 1% for 5 cm withdrawal.

A comparison between PCO experiment C/Es and radial and axial tube experiment C/Es is shown in Table 10.12. There is only a rough correspondence between the PCO and tube experiments; the sample compositions generally were quite different, the cell types where the measurements were done were often different, and the measurement positions were only roughly

comparable. In addition, the preliminary nature of the PCO calculations should be born in mind. Overall the PCO C/Es are larger than those from the RTO and ATO experiments but the C/E differences seem reasonable.

To summarize the PCO results, representative core region C/Es from each experiment are given in Table 10.13. The sodium (PCO-8-9) results indicate that accounting for local flux distortions and the adjoint heterogeneity error can greatly improve at least the scattering worth C/Es. Considering that the calculations are preliminary, the C/Es, although large, are not disturbing.

10.5 Axial Expansion Oscillator Experiments

Three measurements were made with the axial expansion oscillator, which are referred to as AEO-1, AEO-2 and AEO-3. All of the locations (see Fig. 10.1) had DFC core cells.

The expansion worths were computed by FOP with nodal diffusion theory. Cell average cross sections were used since the worth of unit cell motion was being computed. For each material that moved - core, axial blanket and reflector - the material worth in each axial node at the oscillator matrix position was calculated. A utility program fit the cumulative integral of a material's worth along this traverse to a cubic spline and then interpolated to get the integrals over the axial intervals where that material changed. (This is the same interpolation scheme that was used for the RTO, ATO and PCO calculations.)

The results are shown in Table 10.14. The expansion worth is about half as large for AEO-1 even though the material motion was the same in all three experiments. This because the internal blanket at this location flattens the flux gradients. Another effect of the internal blanket is that motion of core material did not dominate the net calculated worth as much as in the other cases. The calculations appear to handle the internal blanket effects well, since all the C/Es are near unity and agree with each other to within the experimental uncertainty (3%).

10.6 Bowing Oscillator Experiment

The bowing oscillator (BO) shifted the core segment of a drawer radially a distance typical of power reactor bowing motion. The displacement was essentially uniform over the axial extent of the core segment; the effective average displacement, which was used here, was 0.133 cm. The motion occurred in a steep radial flux gradient - one drawer from the radial blanket on the Y axis (see Fig. 10.1). The experimental worth is -0.01392% and has a total uncertainty of 3.5%.

C/Es were obtained by several methods. All of them used FOP, which should be valid for such a small perturbation. First a basic calculated worth was obtained by nodal diffusion theory with the XYZ geometry critical reference model. The resulting C/E is 1.33. Then YZ geometry models were used to calculate a number of improvements to the basic C/E. The YZ models represented matrix column 49 of the reactor explicitly and used group- and region-dependent DB^2 values from the XYZ solutions to represent the X dimension. Because the shifted material was quite similar to a normal DFC cell, standard DFC cell average microscopic cross sections were used in all the calculations.

The adjustments to the basic C/E are shown in Table 10.15. Since the bowing drawer composition matched the standard DFC cell composition reasonably well, there was little improvement from using the exact composition in the flux and adjoint computations. There is also little effect on the drawer-average flux and adjoint from halving the Y-direction node spacing. Replacing diffusion perturbation theory with S_4 transport perturbation theory calculations made the C/E larger by 3.2%.

Since there was material motion within a Y node interval and only node average (or node integrated) worths are known, the worth variation within a node must be inferred to get the bowing motion worth. Several schemes to do this were tried, and in each of them it was assumed that the known average worth equals the worth at the Y-center of the node. The scheme used for the basic C/E, called full-cell linear interpolation, was to linearly interpolate between mesh centers. The full cell designation refers

to the Y-interval from which the average is taken being one cell (drawer) wide. Half-cell linear interpolation is the same as the basic method except that there are 2 nodes per drawer in Y. Half-cell linear extrapolation is the new ANL design method due to Finck²¹. It differs by extrapolating the linear variation between mesh centers to the edges of the cell in which the bowing occurs. The last alternative shown in Table 10.15 assumes the worth is constant within the half-cell wide node interval. It is the old design method, and gives an unreasonably low C/E.

The final C/E for the bowing oscillator experiment uses the first three adjustments of Table 10.15 and the current design interpolation scheme (half-cell linear extrapolation). The resulting C/E is 1.26.

10.7 All-Plate Shifting Experiment

In this experiment plate columns of a cell were rearranged such that most of the cell moved radially a small distance. To achieve this it was necessary to move a narrow, low worth section of the cell a much larger distance in the opposite direction. To make the shift look as much as possible like bowing, the only material moving counter to the rest of the cell was a 0.64 cm-wide clad sodium column. The shifting occurred in a zone of cells that spanned much of the radial extent of the outer core (see Fig. 10.1). The zone had the normal mix of SFC and DFC cells, but the cells were modified to have 0.64 cm-wide sodium columns at the cell edges. The experimental worth is -6.02 cents and is uncertain by 3.1%. As in the bowing oscillator analysis a basic solution was obtained and then some refinements were made. For these calculations the exact reactor configuration used in the experiment was modeled to get the flux and adjoint. Anticipating the use of the various interpolation schemes described in Section 10.6, the XYZ geometry model had a half-drawer node spacing in the X direction over the range of the shifting zone. The worths were computed by FOP in nodal diffusion theory. In the basic calculation the standard SFC and DFC microscopic cross sections were used to compute the material worths. The basic calculation used half-cell linear interpolation and yielded a C/E of 1.17.

The main calculational refinement was to account for the change in the within-cell flux distribution that occurred when the plate columns were rearranged. This was done by computing cell average cross sections for each of the pre-shift and post-shift cell types. Group-dependent bucklings for that drawer type in the zone, obtained from the XYZ geometry nodal diffusion flux calculation, were used in this cross section processing. The reactivity effect due to changing from pre-shift to post-shift microscopic cross sections was calculated to be +1.01 cents. This reduces the C/E from 1.17 to 1.00.

The last adjustment was to use the new design method interpolation scheme, half-cell linear extrapolation. This changed the calculated worth by only 1%, yielding a final C/E of 1.01.

This C/E is considerably lower than the final C/E from the bowing oscillator experiment, even though the bowing oscillator was at a radius encompassed by the plate shifting zone. This C/E variation is believed to be due partly to the difficulty of calculating gradients induced by the mix of SFC and DFC cells, which occurs in ZPPR assemblies but not power reactors. Another factor contributing to the C/E difference is the difference in the combination of diluent and fuel motion that occurred in the two kinds of experiments. Also, 3% of the difference is attributable to using a transport correction for only the bowing oscillator calculation.

TABLE 10.1 Description of ZPPR-17A Oscillator Measurements

Name	Oscillator	Sample	Matrix Position ^a
ATO-1	Axial Tube	PU-30 DU-6 B-1 D-14 SS-1 U-6	159-49 (D)
ATO-2	Axial Tube	PU-30 DU-6 B-1 D-14 SS-1 U-6	163-41 (E)
ATO-3	Axial Tube	SS-1 DU-6 D-14 PU-30 B-1	171-49 (G)
RTO	Radial Tube	PU-30 DU-6 B-1 D-14 SS-1 Cf @ 3 W Cf @ 80 W	1,248 (.)
AEO-1	Axial Expan.	I.C. DFC	138-49 (D)
AEO-2	Axial Expan.	O.C. DFC	163-41 (E)
AEO-3	Axial Expan.	O.C. DFC	166-55 (F)
BO	Bowing	O.C. DFC repeat	126-49 (G)
PCO-1	Plate Column	Pu-U + SS	147-33 (B)
PCO-2	Plate Column	U O	147-33 (B)
PCO-3	Plate Column	Pu- ³ _U + SS	149-40 (A)
PCO-4	Plate Column	U O	149-40 (A)
PCO-5	Plate Column	Pu- ³ _U	163-41 (E)
PCO-6	Plate Column	Pu-U	148-31 (C)
PCO-7	Plate Column	U ₃ O ₈	148-31 (C)
PCO-8-9	Plate Column	Na	148-68 (C)
PCO-9	Plate Column	Void Cans	148-68 (C)
PCO-10	Plate Column	Fe ₂ O ₃	148-31 (C)

^aLocation symbol for Figure 10.1 is in parentheses.

TABLE 10.2 PU-30, RTO Worth Traverse

Position			Experimental Worth ^a (cents)	Initial C/E ^b	Calculation Correction Factors				Final Results		
#	Regn	X (cm)			Size	Transp	Position	Adj Het	C (cents)	C-E	C/E ^b
49	IBKT	2.77	0.2195 ± 0.0020 (± 0.9%)	0.99	1.000	0.942	1.005	0.997	0.2060	-0.0135	0.938 ± 0.008
48	IBKT	8.29	0.2210 ± 0.0018 (± 0.8%)	0.99	1.000	0.943	1.005	0.997	0.2074	-0.0136	0.938 ± 0.008
47	IBKT	13.82	0.2259 ± 0.0018 (± 0.8%)	0.98	1.000	0.943	1.005	0.997	0.2098	-0.0161	0.929 ± 0.007
46	IBKT	19.34	0.2263 ± 0.0022 (± 1.0%)	1.00	1.000	0.943	1.005	0.997	0.2136	-0.0127	0.944 ± 0.009
45	IBKT	24.86	0.2330 ± 0.0021 (± 0.9%)	0.99	1.000	0.942	1.005	0.997	0.2189	-0.0141	0.940 ± 0.008
44	IBKT	30.39	0.2386 ± 0.0021 (± 0.9%)	1.00	1.000	0.941	1.005	0.997	0.2258	-0.0128	0.946 ± 0.009
43	IBKT	35.91	0.2512 ± 0.0022 (± 0.9%)	0.99	1.000	0.940	1.006	0.997	0.2345	-0.0167	0.934 ± 0.008
42	IBKT	41.44	0.2541 ± 0.0021 (± 0.8%)	1.02	1.000	0.939	1.006	0.997	0.2454	-0.0086	0.966 ± 0.008
41	IBKT	46.96	0.2716 ± 0.0019 (± 0.7%)	1.01	1.000	0.938	1.007	0.997	0.2586	-0.0129	0.952 ± 0.007
40	IBKT	52.49	0.2871 ± 0.0021 (± 0.7%)	1.02	1.000	0.937	1.007	0.997	0.2748	-0.0123	0.957 ± 0.007
39	IBKT	58.01	0.3007 ± 0.0017 (± 0.6%)	1.04	1.000	0.937	1.008	0.997	0.2942	-0.0065	0.978 ± 0.006
38	IBKT	63.53	0.3186 ± 0.0020 (± 0.6%)	1.06	1.000	0.936	1.009	0.997	0.3173	-0.0013	0.996 ± 0.006
37	IBKT	69.05	0.3319 ± 0.0021 (± 0.6%)	1.10	1.000	0.935	1.008	0.997	0.3442	0.0122	1.037 ± 0.007
36	IBKT	74.59	0.3527 ± 0.0019 (± 0.5%)	1.13	1.000	0.934	1.008	0.997	0.3754	0.0227	1.064 ± 0.006
35	IBKT	80.11	0.3728 ± 0.0021 (± 0.6%)	1.18	1.000	0.933	1.006	0.997	0.4119	0.0391	1.105 ± 0.006
34	IBKT	85.63	0.3914 ± 0.0022 (± 0.6%)	1.25	1.000	0.946	1.003	0.997	0.4641	0.0727	1.186 ± 0.007
33	DFC	91.15	0.4067 ± 0.0017 (± 0.4%)	1.10	1.046	0.976	1.002	0.972	0.4444	0.0377	1.093 ± 0.005
32	SFC	96.68	0.4090 ± 0.0024 (± 0.6%)	1.11	1.051	0.986	1.003	0.959	0.4522	0.0432	1.106 ± 0.006
31	SFC	102.21	0.3974 ± 0.0021 (± 0.5%)	1.11	1.055	0.987	1.005	0.959	0.4410	0.0436	1.110 ± 0.006
30	DFC	107.73	0.3666 ± 0.0020 (± 0.5%)	1.09	1.059	0.988	1.006	0.972	0.4101	0.0436	1.119 ± 0.006
29	SFC	113.26	0.3089 ± 0.0024 (± 0.8%)	1.11	1.056	0.989	1.007	0.959	0.3461	0.0372	1.120 ± 0.009
28	SFC	118.78	0.2526 ± 0.0026 (± 1.0%)	1.11	1.055	0.989	1.008	0.959	0.2814	0.0288	1.114 ± 0.012
27	DFC	124.30	0.1903 ± 0.0022 (± 1.2%)	1.09	1.055	0.986	1.009	0.972	0.2123	0.0221	1.116 ± 0.013
26	SFC	129.83	0.1370 ± 0.0020 (± 1.5%)	1.07	1.041	0.969	1.009	0.959	0.1430	0.0060	1.044 ± 0.015
25	RBKT	135.35	0.0875 ± 0.0020 (± 2.3%)	1.24	1.000	0.940	1.009	1.000	0.1030	0.0155	1.177 ± 0.027
24	RBKT	140.88	0.0559 ± 0.0022 (± 4.0%)	1.03	1.000	0.929	1.010	1.000	0.0538	-0.0021	0.962 ± 0.038
23	RBKT	146.40	0.0312 ± 0.0021 (± 6.8%)	0.94	1.000	0.930	1.010	1.000	0.0274	-0.0038	0.878 ± 0.060
22	RBKT	151.92	0.0178 ± 0.0023 (± 12.8%)	0.82	1.000	0.935	1.010	1.000	0.0137	-0.0041	0.771 ± 0.099
21	RBKT	157.45	0.0072 ± 0.0020 (± 28.1%)	-	1.000	0.942	1.010	1.000	0.0070	-0.0001	-
20	RREF	162.97	0.0071 ± 0.0021 (± 29.8%)	-	1.000	0.937	1.010	1.000	0.0036	-0.0036	-

^aUncertainty of full-out reactivity, which is included in all the uncertainties, is 0.0013 cents.

^bC/E is not shown when the experimental uncertainty exceeds 20%.

TABLE 10.3 DU-6, RTO Worth Traverse

Position			Experimental Worth ^a (cents)	Initial C/E ^b	Calculation Correction Factors				Final Results		
#	Regn	X (cm)			Size	Transp	Position	Adj Het	C (cents)	C-E	C/E ^b
49	IBKT	2.76	-0.0121 ± 0.0009 (± 7.6%)	0.84	0.992	0.981	0.966	0.999	-0.0096	0.0025	0.793 ± 0.060
48	IBKT	8.30	-0.0107 ± 0.0010 (± 9.5%)	0.96	0.992	0.982	0.966	0.999	-0.0096	0.0010	0.902 ± 0.086
47	IBKT	13.82	-0.0128 ± 0.0012 (± 9.2%)	0.81	0.992	0.981	0.966	0.999	-0.0098	0.0030	0.763 ± 0.070
46	IBKT	19.34	-0.0122 ± 0.0009 (± 7.4%)	0.87	0.992	0.981	0.966	0.999	-0.0099	0.0023	0.812 ± 0.060
45	IBKT	24.86	-0.0107 ± 0.0011 (± 9.9%)	1.01	0.992	0.980	0.966	0.999	-0.0101	0.0006	0.947 ± 0.094
44	IBKT	30.39	-0.0114 ± 0.0010 (± 8.9%)	0.98	0.992	0.978	0.966	0.999	-0.0105	0.0009	0.920 ± 0.082
43	IBKT	35.91	-0.0128 ± 0.0010 (± 8.1%)	0.91	0.992	0.977	0.966	0.999	-0.0108	0.0019	0.850 ± 0.068
42	IBKT	41.44	-0.0140 ± 0.0009 (± 6.5%)	0.86	0.992	0.975	0.966	0.999	-0.0113	0.0027	0.807 ± 0.052
41	IBKT	46.96	-0.0142 ± 0.0011 (± 7.5%)	0.90	0.993	0.973	0.967	0.999	-0.0119	0.0023	0.841 ± 0.063
40	IBKT	52.48	-0.0120 ± 0.0010 (± 8.5%)	1.13	0.993	0.971	0.967	0.999	-0.0127	-0.0007	1.055 ± 0.090
39	IBKT	58.01	-0.0154 ± 0.0010 (± 6.8%)	0.95	0.993	0.968	0.967	0.999	-0.0136	0.0018	0.884 ± 0.060
38	IBKT	63.54	-0.0167 ± 0.0010 (± 6.3%)	0.96	0.993	0.966	0.968	0.999	-0.0148	0.0018	0.890 ± 0.056
37	IBKT	69.06	-0.0174 ± 0.0011 (± 6.4%)	1.02	0.993	0.964	0.972	0.999	-0.0164	0.0010	0.944 ± 0.060
36	IBKT	74.59	-0.0202 ± 0.0010 (± 4.9%)	0.98	0.994	0.964	0.977	0.999	-0.0184	0.0018	0.912 ± 0.045
35	IBKT	80.11	-0.0203 ± 0.0010 (± 5.0%)	1.09	0.994	0.970	0.983	0.999	-0.0210	-0.0007	1.033 ± 0.052
34	IBKT	85.63	-0.0229 ± 0.0011 (± 4.9%)	1.08	0.996	0.981	0.990	0.999	-0.0240	-0.0010	1.045 ± 0.051
33	DFC	91.15	-0.0257 ± 0.0010 (± 3.7%)	1.06	0.999	0.996	0.998	0.947	-0.0256	0.0001	0.997 ± 0.037
32	SFC	96.68	-0.0270 ± 0.0010 (± 3.8%)	1.04	1.001	1.006	1.004	0.972	-0.0276	-0.0006	1.022 ± 0.038
31	SFC	102.20	-0.0257 ± 0.0011 (± 4.4%)	1.04	1.003	1.011	1.007	0.972	-0.0265	-0.0008	1.032 ± 0.046
30	DFC	107.73	-0.0213 ± 0.0010 (± 4.6%)	1.07	1.004	1.014	1.009	0.947	-0.0223	-0.0010	1.045 ± 0.048
29	SFC	113.26	-0.0169 ± 0.0011 (± 6.5%)	1.07	1.003	1.017	1.011	0.972	-0.0181	-0.0012	1.072 ± 0.069
28	SFC	118.78	-0.0086 ± 0.0011 (± 12.3%)	1.56	1.003	1.019	1.011	0.972	-0.0135	-0.0049	1.565 ± 0.192
27	DFC	124.30	-0.0058 ± 0.0010 (± 17.2%)	1.34	1.002	1.021	1.012	0.947	-0.0076	-0.0018	1.310 ± 0.225
26	SFC	129.83	0.0015 ± 0.0010 (± 63.0%)	-	0.999	1.041	1.014	0.972	-0.0030	-0.0045	-
25	RBKT	135.35	0.0026 ± 0.0010 (± 39.7%)	-	0.996	1.229	1.016	1.000	-0.0009	-0.0035	-
24	RBKT	140.88	0.0027 ± 0.0010 (± 37.9%)	-	0.994	1.332	1.017	1.000	-0.0004	-0.0031	-
23	RBKT	146.40	0.0006 ± 0.0009 (±168.2%)	-	0.993	1.356	1.017	1.000	-0.0001	-0.0007	-
22	RBKT	151.92	-0.0016 ± 0.0011 (± 67.8%)	-	0.992	1.253	1.018	1.000	-0.0001	0.0015	-
21	RBKT	157.45	-0.0019 ± 0.0011 (± 57.2%)	-	0.991	1.074	1.014	1.000	0.0000	0.0019	-
20	RREF	162.98	0.0006 ± 0.0011 (±167.3%)	-	0.991	0.992	1.012	1.000	0.0000	-0.0007	-

^aUncertainty of full-out reactivity, which is included in all the uncertainties, is 0.0006 cents.

^bC/E is not shown when the experimental uncertainty exceeds 20%.

TABLE 10.4 PU-30, ATO-1 Worth Traverse

Position			Initial C/E	Calculation Correction Factors				Final Results		
#	Regn	X (cm)	Experimental Worth ^a (cents)	Size	Transp	Position	Adj Het	C (cents)	C-E	C/E
1	IBKT	3.99	0.2864 ± 0.0023 (± 0.8%)	1.07	1.000	0.937	0.997	0.2866	0.0002	1.001 ± 0.008
2	IBKT	7.62	0.2872 ± 0.0024 (± 0.8%)	1.12	0.996	0.939	0.997	0.2993	0.0122	1.042 ± 0.009
3	IBKT	12.70	0.2966 ± 0.0025 (± 0.9%)	1.13	1.003	0.952	0.997	0.3171	0.0205	1.069 ± 0.009
4	DFC	17.78	0.3146 ± 0.0025 (± 0.8%)	1.04	1.029	0.979	0.999	0.3241	0.0095	1.030 ± 0.008
5	DFC	22.87	0.3246 ± 0.0024 (± 0.8%)	0.98	1.051	1.000	1.001	0.3242	-0.0004	0.999 ± 0.008
6	DFC	27.95	0.3277 ± 0.0025 (± 0.8%)	0.94	1.059	1.008	1.001	0.3187	-0.0090	0.972 ± 0.007
7	DFC	33.02	0.3088 ± 0.0026 (± 0.9%)	0.96	1.058	1.006	1.001	0.3053	-0.0035	0.989 ± 0.008
8	DFC	38.10	0.2726 ± 0.0024 (± 0.9%)	0.99	1.055	1.002	1.000	0.2763	0.0037	1.013 ± 0.009
9	DFC	43.18	0.2295 ± 0.0024 (± 1.1%)	0.98	1.052	0.996	1.000	0.2297	0.0002	1.001 ± 0.011
10	DFC	48.26	0.1782 ± 0.0029 (± 1.6%)	0.98	1.043	0.984	1.000	0.1745	-0.0037	0.979 ± 0.016
11	ABKT	53.34	0.1286 ± 0.0022 (± 1.7%)	1.07	1.014	0.958	1.000	0.1331	0.0045	1.035 ± 0.018
12	ABKT	58.42	0.0977 ± 0.0027 (± 2.8%)	1.08	0.994	0.940	1.000	0.0989	0.0012	1.012 ± 0.028
13	ABKT	63.50	0.0664 ± 0.0026 (± 4.0%)	1.12	0.991	0.937	1.000	0.0688	0.0024	1.036 ± 0.041
14	ABKT	68.58	0.0423 ± 0.0025 (± 5.9%)	1.11	0.998	0.944	1.000	0.0441	0.0018	1.043 ± 0.061
15	ABKT	73.66	0.0346 ± 0.0023 (± 6.8%)	0.82	1.002	0.949	1.000	0.0272	-0.0074	0.785 ± 0.053
16	ABKT	78.75	0.0216 ± 0.0027 (± 12.7%)	0.86	1.002	0.951	1.000	0.0181	-0.0035	0.837 ± 0.106
17	AREF	83.82	0.0149 ± 0.0023 (± 15.4%)	0.94	1.000	0.953	1.000	0.0134	-0.0015	0.900 ± 0.139

^aUncertainty of full-out reactivity, which is included in all the uncertainties, is 0.0015 cents.

TABLE 10.5 B-1, ATO-1 Worth Traverse

Position			Experimental Worth ^a (cents)	Initial C/E ^b	Calculation Correction Factors				Final Results		
#	Regn	X (cm)			Size	Transp	Position	Adj Het	C (cents)	C-E	C/E ^b
1	IBKT	3.99	-0.2486 ± 0.0024 (± 1.0%)	1.42	0.703	0.969	1.003	1.000	-0.2407	0.0079	0.968 ± 0.009
2	IBKT	7.62	-0.2718 ± 0.0026 (± 1.0%)	1.43	0.696	0.972	1.004	1.000	-0.2631	0.0087	0.968 ± 0.009
3	IBKT	12.70	-0.3213 ± 0.0028 (± 0.9%)	1.39	0.705	0.980	1.003	1.000	-0.3095	0.0118	0.963 ± 0.008
4	DFC	17.78	-0.3810 ± 0.0026 (± 0.7%)	1.28	0.745	0.990	0.997	0.998	-0.3596	0.0215	0.944 ± 0.007
5	DFC	22.86	-0.3971 ± 0.0027 (± 0.7%)	1.27	0.780	0.998	0.992	0.997	-0.3880	0.0091	0.977 ± 0.007
6	DFC	27.94	-0.3954 ± 0.0027 (± 0.7%)	1.24	0.798	1.003	0.991	0.997	-0.3878	0.0076	0.981 ± 0.007
7	DFC	33.02	-0.3720 ± 0.0028 (± 0.8%)	1.22	0.802	1.005	0.993	0.997	-0.3618	0.0103	0.972 ± 0.007
8	DFC	38.10	-0.3301 ± 0.0027 (± 0.8%)	1.21	0.800	1.004	0.994	0.997	-0.3191	0.0110	0.967 ± 0.008
9	DFC	43.18	-0.2653 ± 0.0028 (± 1.1%)	1.25	0.793	1.001	0.994	0.997	-0.2618	0.0035	0.987 ± 0.010
10	DFC	48.26	-0.2023 ± 0.0029 (± 1.4%)	1.25	0.775	0.995	0.994	0.997	-0.1935	0.0088	0.957 ± 0.014
11	ABKT	53.34	-0.1281 ± 0.0024 (± 1.9%)	1.36	0.739	0.987	0.998	0.999	-0.1268	0.0013	0.990 ± 0.019
12	ABKT	58.42	-0.0762 ± 0.0029 (± 3.8%)	1.44	0.712	0.980	1.001	1.000	-0.0757	0.0005	0.993 ± 0.037
13	ABKT	63.50	-0.0407 ± 0.0027 (± 6.5%)	1.62	0.703	0.973	1.001	1.001	-0.0434	-0.0027	1.065 ± 0.070
14	ABKT	68.58	-0.0272 ± 0.0027 (± 10.1%)	1.44	0.698	0.969	1.000	1.000	-0.0258	0.0014	0.948 ± 0.095
15	ABKT	73.67	-0.0123 ± 0.0027 (± 21.8%)	-	0.672	0.966	1.000	1.000	-0.0145	-0.0022	-
16	ABKT	78.74	-0.0079 ± 0.0030 (± 37.7%)	-	0.623	0.967	1.000	1.000	-0.0084	-0.0005	-
17	AREF	83.82	-0.0031 ± 0.0025 (± 81.8%)	-	0.578	0.968	1.000	1.000	-0.0053	-0.0022	-

^aUncertainty of full-out reactivity, which is included in all the uncertainties, is 0.0017 cents.

^bC/E is not shown when the experimental uncertainty exceeds 20%.

TABLE 10.6 U-6, ATO-1 Worth Traverse

Position			Initial C/E	Calculation Correction Factors				Final Results			
#	Regn	X (cm)		Experimental Worth ^a (cents)	Size	Transp	Position	Adj Het	C (cents)	C-E	C/E
1	IBKT	3.99	0.3138 ± 0.0024 (± 0.8%)	1.30	0.849	0.947	0.999	0.997	0.3255	0.0117	1.037 ± 0.008
2	IBKT	7.62	0.3108 ± 0.0023 (± 0.7%)	1.27	0.860	0.949	0.999	1.000	0.3226	0.0119	1.038 ± 0.008
3	IBKT	12.71	0.3025 ± 0.0024 (± 0.8%)	1.22	0.892	0.960	0.998	0.996	0.3153	0.0128	1.042 ± 0.008
4	DFC	17.78	0.2920 ± 0.0026 (± 0.9%)	1.16	0.940	0.984	0.996	0.978	0.3045	0.0125	1.043 ± 0.009
5	DFC	22.86	0.2860 ± 0.0026 (± 0.9%)	1.09	0.975	1.003	0.994	0.966	0.2928	0.0067	1.024 ± 0.009
6	DFC	27.94	0.2813 ± 0.0027 (± 0.9%)	1.04	0.991	1.011	0.994	0.963	0.2808	-0.0005	0.998 ± 0.009
7	DFC	33.02	0.2670 ± 0.0027 (± 1.0%)	1.04	0.990	1.011	0.994	0.968	0.2662	-0.0008	0.997 ± 0.010
8	DFC	38.10	0.2335 ± 0.0026 (± 1.1%)	1.08	0.985	1.007	0.995	0.970	0.2411	0.0077	1.033 ± 0.011
9	DFC	43.18	0.2031 ± 0.0027 (± 1.3%)	1.06	0.979	1.002	0.994	0.968	0.2038	0.0006	1.003 ± 0.013
10	DFC	48.26	0.1617 ± 0.0028 (± 1.7%)	1.08	0.962	0.991	0.994	0.969	0.1603	-0.0015	0.991 ± 0.017
11	ABKT	53.34	0.1298 ± 0.0023 (± 1.8%)	1.11	0.917	0.967	0.998	0.989	0.1261	-0.0036	0.972 ± 0.017
12	ABKT	58.42	0.1010 ± 0.0026 (± 2.6%)	1.16	0.873	0.951	1.001	1.004	0.0974	-0.0035	0.965 ± 0.025
13	ABKT	63.50	0.0739 ± 0.0026 (± 3.5%)	1.23	0.840	0.948	1.001	1.007	0.0722	-0.0017	0.977 ± 0.034
14	ABKT	68.58	0.0491 ± 0.0027 (± 5.4%)	1.37	0.807	0.953	1.000	1.002	0.0511	0.0020	1.041 ± 0.056
15	ABKT	73.66	0.0366 ± 0.0023 (± 6.2%)	1.37	0.752	0.957	1.000	0.998	0.0358	-0.0008	0.977 ± 0.061
16	ABKT	78.75	0.0258 ± 0.0027 (± 10.6%)	1.59	0.672	0.958	1.000	0.998	0.0262	0.0004	1.016 ± 0.108
17	AREF	83.82	0.0149 ± 0.0026 (± 17.4%)	2.35	0.594	0.959	1.000	1.000	0.0200	0.0051	1.342 ± 0.234

^aUncertainty of full-out reactivity, which is included in all the uncertainties, is 0.0015 cents.

TABLE 10.7 Difference Between RTO and
ATO C/Es at Similar Positions

RTO Position # ATO Traverse ^a	39 ATO-1	33 ATO-2	27 ATO-3
<u>Sample</u>	<u>C/E Difference</u>		
PU-30	-0.023 ± 0.010	0.043 ± 0.007	0.068 ± 0.015
DU-6	-	-0.009 ± 0.082	-
B-1	-0.076 ± 0.012	0.006 ± 0.006	0.000 ± 0.012

^aAt axial position #1.

TABLE 10.8 Region-Average C/Es From ZPPR-17A RTO
and ATO Traverses

Sample	Traverse	Region-Average C/E		
		Internal Blanket	Core	Outer Blanket
PU-30	RTO	0.988	1.103	1.006
PU-30	ATO-1	1.037	0.998	0.982
PU-30	ATO-2	-	1.049	1.188
PU-30	ATO-3	-	1.043	1.109
DU-6	RTO	0.900	1.033	-
DU-6	ATO-2	-	1.023	-
B-1	RTO	0.890	1.026	1.085
B-1	ATO-1	0.967	0.969	1.016
B-1	ATO-2	-	1.004	0.902
B-1	ATO-3	-	1.037	1.099
U-6	ATO-1	1.039	1.013	0.986
U-6	ATO-2	-	1.065	1.117

C/Es with uncertainties exceeding 10% did not contribute to the averages.

TABLE 10.9 Neutron Importance Radial Traverse^a

#	Position		Experimental Importance ^b	Transp. Corr.	Position Corr.	Final C	C/E
	Regn	X (cm)					
49	IBKT	2.77	0.631 ± 0.030 (± 4.8%)	0.978	0.985	0.528	0.838 ± 0.040
48	IBKT	8.29	0.652 ± 0.033 (± 5.1%)	0.978	0.985	0.530	0.814 ± 0.042
47	IBKT	13.82	0.610 ± 0.033 (± 5.5%)	0.978	0.985	0.533	0.874 ± 0.048
46	IBKT	19.34	0.611 ± 0.033 (± 5.5%)	0.978	0.985	0.538	0.880 ± 0.048
45	IBKT	24.86	0.633 ± 0.033 (± 5.3%)	0.978	0.985	0.545	0.861 ± 0.045
44	IBKT	30.39	0.623 ± 0.033 (± 5.4%)	0.977	0.985	0.553	0.888 ± 0.048
43	IBKT	35.91	0.645 ± 0.033 (± 5.2%)	0.977	0.985	0.564	0.874 ± 0.045
42	IBKT	41.44	0.653 ± 0.033 (± 5.1%)	0.976	0.986	0.577	0.884 ± 0.045
41	IBKT	46.96	0.688 ± 0.033 (± 4.8%)	0.975	0.986	0.593	0.862 ± 0.042
40	IBKT	52.48	0.675 ± 0.033 (± 4.9%)	0.975	0.987	0.612	0.907 ± 0.045
39	IBKT	58.01	0.759 ± 0.033 (± 4.4%)	0.974	0.988	0.636	0.837 ± 0.037
38	IBKT	63.54	0.761 ± 0.033 (± 4.4%)	0.974	0.989	0.664	0.871 ± 0.038
37	IBKT	69.06	0.772 ± 0.033 (± 4.3%)	0.974	0.990	0.697	0.902 ± 0.039
36	IBKT	74.59	0.824 ± 0.033 (± 4.0%)	0.973	0.992	0.737	0.894 ± 0.036
35	IBKT	80.11	0.866 ± 0.033 (± 3.8%)	0.974	0.994	0.785	0.906 ± 0.035
34	IBKT	85.63	0.892 ± 0.035 (± 3.9%)	0.983	0.997	0.851	0.954 ± 0.037
33	DFC	91.15	0.969 ± 0.033 (± 3.4%)	0.996	0.999	0.931	0.961 ± 0.033
32	SFC	96.68	0.997 ± 0.033 (± 3.3%)	1.001	1.001	0.963	0.965 ± 0.032
31	SFC	102.21	1.000 ± 0.033 (± 3.3%)	1.002	1.002	0.959	0.959 ± 0.032
30	DFC	107.73	0.963 ± 0.033 (± 3.5%)	1.002	1.003	0.924	0.960 ± 0.033
29	SFC	113.26	0.839 ± 0.033 (± 4.0%)	1.002	1.004	0.850	1.012 ± 0.040
28	SFC	118.78	0.742 ± 0.033 (± 4.5%)	1.002	1.004	0.763	1.029 ± 0.046
27	DFC	124.30	0.656 ± 0.033 (± 5.1%)	1.001	1.004	0.653	0.995 ± 0.051
26	SFC	129.83	0.469 ± 0.033 (± 7.1%)	0.994	1.005	0.524	1.117 ± 0.080
25	RBKT	135.35	0.424 ± 0.033 (± 7.9%)	0.980	1.005	0.394	0.930 ± 0.073
24	RBKT	140.88	0.263 ± 0.033 (±12.7%)	0.973	1.005	0.280	1.066 ± 0.135
23	RBKT	146.40	0.203 ± 0.033 (±16.4%)	0.972	1.005	0.196	0.965 ± 0.159
22	RBKT	151.92	0.081 ± 0.033 (±41.1%)	0.973	1.005	0.134	-
21	RBKT	157.45	0.117 ± 0.033 (±28.5%)	0.975	1.005	0.090	-
20	RREF	162.98	0.085 ± 0.033 (±39.0%)	0.984	1.005	0.056	-

^aE normalized to a maximum value of 1.0 and then C normalized such that the average C/E in the core is 1.0.

^bUncertainty of full-out importance, which is included in all the uncertainties, is 0.019.

TABLE 10.10 Clad Pu-U + SS Column Worth Traverse, PCO-3

Withdrawal (cm)	Incremental Worth		Cumulative Worth	
	E (ϕ)	C/E	E (ϕ)	C/E
2.540	-0.10088 $\pm$ 3.3%	0.917 $\pm$ 0.030	-0.10088 $\pm$ 3.3%	0.917 $\pm$ 0.030
12.699	-0.49258 $\pm$ 0.6%	0.996 $\pm$ 0.006	-0.59346 $\pm$ 0.6%	0.983 $\pm$ 0.006
15.240	-0.14388 $\pm$ 2.4%	1.028 $\pm$ 0.025	-0.73734 $\pm$ 0.5%	0.992 $\pm$ 0.005
17.780	-0.14565 $\pm$ 2.4%	1.078 $\pm$ 0.026	-0.88299 $\pm$ 0.4%	1.006 $\pm$ 0.004
48.260	-1.83794 $\pm$ 0.2%	1.064 $\pm$ 0.002	-2.72093 $\pm$ 0.1%	1.045 $\pm$ 0.001
65.412	-0.51668 $\pm$ 0.6%	1.013 $\pm$ 0.006	-3.23761 $\pm$ 0.1%	1.040 $\pm$ 0.001

TABLE 10.11 U_3O_8 Column Worth Traverse, PCO-4

Withdrawal (cm)	Incremental Worth		Cumulative Worth	
	E (ϕ)	C/E	E (ϕ)	C/E
2.550	0.02710 $\pm$ 2.3%	0.859 $\pm$ 0.020	0.02710 $\pm$ 2.3%	0.859 $\pm$ 0.020
12.710	0.10003 $\pm$ 0.5%	0.934 $\pm$ 0.004	0.12713 $\pm$ 0.5%	0.918 $\pm$ 0.005
15.250	0.02474 $\pm$ 2.1%	0.991 $\pm$ 0.021	0.15187 $\pm$ 0.4%	0.930 $\pm$ 0.004
17.790	0.02408 $\pm$ 2.3%	1.064 $\pm$ 0.025	0.17595 $\pm$ 0.4%	0.948 $\pm$ 0.004
30.490	0.13263 $\pm$ 0.4%	1.005 $\pm$ 0.004	0.30859 $\pm$ 0.2%	0.973 $\pm$ 0.002

TABLE 10.12 Comparison of C/Es From PCO vs.
RTO and ATO Experiments

<u>Plutonium Sample</u>		<u>Depleted Uranium Sample</u>	
	<u>C/E</u>		<u>C/E</u>
PCO-1		PCO-2	
PCO-1, 2.54 cm	1.20	PCO-2, 2.54 cm	1.05
RTO, pos. # 33	1.09	RTO, pos. # 33	1.00
PCO-1, core	1.14	PCO-2, core	1.09
ATO-2, core	1.05	ATO-2, core	1.02
PCO-1, ax. bkt.	1.08		
ATO-2, ax. bkt.	1.19	PCO-4	
		PCO-4, 2.55 cm	0.86
PCO-3		RTO, pos. # 39,41	0.86
PCO-3, 2.54 cm	0.92		
RTO, pos. # 40	0.96	PCO-7	
PCO-3, in. bkt.	0.99	PCO-7, 1.28 cm	1.09
ATO-1, in. bkt.	1.04	RTO, pos. # 31	1.03
PCO-3, core	1.07		
ATO-1, core	1.00	<u>Stainless Steel Sample</u>	
PCO-3, ax. bkt.	1.01		<u>C/E</u>
ATO-1, ax. bkt.	0.98	PCO-9, 5.08 cm	1.50
		RTO, pos. # 31	1.21
PCO-5			
PCO-5, core	1.07		
ATO-2, core	1.05		
PCO-6			
PCO-6, 1.02 cm	1.15		
RTO, pos. # 31	1.11		

TABLE 10.13 Representative Core Region C/Es From PCO Experiments

Traverse	Sample	C/E
PCO-1	50.8 cm-long Clad Pu-U + 15.2 cm-long SS	1.15
PCO-2	66.0 cm-long UO_3	1.08
PCO-3	50.8 cm-long Clad Pu-U + 15.2 cm-long SS	1.06
PCO-4	101.6 cm-long UO_3	1.01
PCO-5	Last 66.0 cm of 101.6 cm-long Clad Pu-U	1.07
PCO-6	101.6 cm-long Clad Pu-U	1.16
PCO-7	101.6 cm-long UO_3	1.09
PCO-8-9	101.6 cm-long Na_2O	1.08 ^a
PCO-9	101.6 cm-long Void Cans (SS)	1.36
PCO-10	101.6 cm-long Fe_2O_3	1.35

^aC/E is 1.37 without corrections

TABLE 10.14. Axial Expansion Oscillator Results

	<u>AEO-1</u>	<u>AEO-2</u>	<u>AEO-3</u>
Experimental Worth ^a (ϕ)	-0.0498	-0.1044	-0.1106
% Contribution to C			
Core	121.8	101.0	98.2
Ax. Bkt.	-21.6	-1.1	1.7
Ax. Ref.	-0.2	0.1	0.1
C/E	1.008	1.041	1.011

^aExperimental uncertainty is about 3%.

TABLE 10.15 Bowing Oscillator C/E Adjustments
From YZ Model Calculations

	<u>Adjustment</u>
Exact composition of BO in ϕ, ϕ^* calculations	-0.7%
Half-drawer Y-node spacing in ϕ, ϕ^* calculations	-0.9%
S ₁ transport theory	+3.2%
Interpolation Schemes ^a	
half-cell linear interpolation	-2.6%
half-cell linear extrapolation	-6.6%
half-cell piecewise constant	-49.5%

^aRelative to full-cell linear interpolation

[A] PCO-3, PCO-4

[B] PCO-1, PCO-2

[C] PCO-6 --- PCO-10

[D] ATO-1, AEO-1

[E] ATO-2, AEO-2, PCO-5

[F] AEO-3

[G] ATO-3, BO

[■] PLATE SHIFTING ZONE

[□] RTO-1, RTO-2

Fig. 10.1 Locations of Plate Shifting Zone and Oscillators in ZPPR-17A

PU-30, Radial Traverse

Fig. 10.2 Radial Traverse for PU-30 Sample in ZPPR-17A.

DU-6, Radial Traverse

Fig. 10.3 Radial Traverse for DU-6 Sample in ZPPR-17A.

PU-30, First Axial Traverse (159-49)

Fig. 10.4 First Axial Traverse (ATO-1) for PU-30 Sample in ZPPR-17A.

B-1, First Axial Traverse (159-49)

Fig. 10.5 First Axial Traverse (ATO-1) for B-1 Sample in ZPPR-17A.

U-6, First Axial Traverse (159-49)

Fig. 10.6 First Axial Traverse (ATO-1) for U-6 Sample in ZPPR-17A.

Neutron Importance Radial Traverse

Fig. 10.7 Neutron Importance Radial Traverse in ZPPR-17A.

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