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ZPPR PROGRESS REPORT: APRIL 1987 THROUGH JULY 1987

edited by

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1. JUPITER-III PROGRAM STATUS (S. B. Brumbach and P. J. Collins)

This report describes the progress through July 1987 in the JUPITER-III program, a cooperative study between the USDOE and PNC of Japan. The status of other programs at ZPPR will be given in a subsequent report.

Experiments have been completed in ZPPR-17, the first assembly in the JUPITER-III program. The ZPPR-17 assembly was an axially heterogeneous benchmark of about 700 MWe size. The initial configuration, ZPPR-17A, was a physics benchmark with no control rods or control rod positions. The most extensive set of measurements was made in this configuration. Reaction rate and gamma ray dose distributions were measured in foil and TLD irradiations. Because of the interesting axial variations in composition, reaction rate measurements emphasized axial distributions and radial distributions at various axial heights. Sodium void coefficients were measured by both the plate substitution and self-contained oscillator techniques. Reactivity coefficients associated with axial and radial expansion were also measured. A new device called the bowing oscillator was used to raise and lower the contents of a drawer within a matrix tube to simulate a bowing motion. Radial expansion effects were measured with a static method in which the contents of a zone were rearranged. The segmented oscillator drawer was used to measure axial expansion effects. The worths of various cell components were measured using the self-contained oscillator drawers as well as the traditional radial and axial tube oscillators. Additional ZPPR-17A experiments measured kinetic parameters and worths of a single, central control rod as a function of size, composition and geometry.

The second ZPPR-17 configuration, designated ZPPR-17B, had 25 control rod positions. Measurements were limited to reaction rate distributions and control rod worth measurements (banks and partial banks). The axial worth profile of $B_{\infty}C$ at the assembly center was measured statically in a series of steps with progressively greater rod insertion and dynamically using the long-drawer technique.

The third configuration, ZPPR-17C, had thirteen half-inserted control rods and twelve CRP channels. Measurements were again limited to reaction rate distributions, control rod bank worths, and axial worth profiles for B₄C.

During July, the annual containment tests of the ZPPR facility were performed. Following these tests, fuel drawer unloading began for drawers which will not be used in ZPPR-18.

Analysis of ZPPR-17 is being made with ENDF/B-V.2 data. Initial calculations have used asymptotic-cell processing to treat ZPPR plate heterogeneity followed by a spatial collapse to produce 21 group and 6 group cross section libraries. It is recognized that use of multi-cell processing will be desirable for final analysis, particularly for cells at the core/blanket interfaces.

Calculation models for ZPPR-17A, 17B and 17C have been set up automatically from the ZPPR data base using the NIPPER code. The models treat detailed variations of the assembly compositions by drawer master type. Asymmetrically-loaded drawers, principally the fission chambers, are not treated in the present models. The effect of not treating these asymmetric drawers is very small and there would be a penalty of a factor of eight in computer charges if they were included.

The calculations completed for ZPPR-17 have been aimed primarily at providing analysis necessary for processing of experimental data. Analysis of criticality by a number of different models is described in this report. Analysis of fission rates in ^{235}U and ^{239}Pu in ZPPR-17A has been made by nodal transport calculations in xyz geometry. Reporting of the reaction rate data awaits the final calibration of ^{238}U foil measurements which required further irradiations in ZPPR-17C. Detector efficiencies and source ratios have been produced for control rod banks and control positions in ZPPR-17A and processing of experimental reactivities is completed.

Initial analysis of sodium void reactivity in central zones and for axial small sample traverses (self-contained oscillator) was made in an rz-geometry model. In the last two months, a nodal-diffusion perturbation code has been made operational by cooperative work between AP-Idaho and AP-Illinois. This code will permit perturbation calculations to be made in xyz geometry using the nodal solutions and will be used for the off-center sodium void zones and for perturbation worths in general.

The new gamma-ray heating calculation system developed by AP-Illinois is presently being used for analysis of ZPPR-15 and it is intended that analysis of TLD measurements in ZPPR-17 will start in the near future.

2. REFERENCE CONFIGURATIONS FOR THE ZPPR-17A AXIALLY HETEROGENEOUS BENCHMARK ASSEMBLY (S. B. Brumbach)

2.1 Introduction

ZPPR-17 is the first of two assemblies in the JUPITER-III cooperative program between the USDOE and PNC of Japan. The purpose of the ZPPR-17 assembly is to study the neutronic behavior of a large, axially heterogeneous, liquid-metal-cooled reactor. The ZPPR-17 composition represents mixed plutonium-oxide and depleted-uranium-oxide fuel with sodium coolant and stainless steel structure. The unique feature of the assembly is the presence of an internal blanket region in the axial center of the core. This blanket extends radially outward from the core center about two thirds of the distance to the core edge. The first phase of the ZPPR-17 program is represented by a configuration designated ZPPR-17A, a physics benchmark containing neither mockup control rods nor control rod positions.

2.2 Description of the Assembly

The ZPPR-17A assembly has distinct regions of internal blanket, core, radial blanket, axial blankets and radial and axial reflectors. There are two basic types of core cells; containing either one or two columns of fuel. The two drawer types have versions with and without internal blanket regions. The internal blanket occupies the front 152 mm (6 inches) of the drawer. The single-fuel-column cell without axial blanket is shown in Fig. 2.1 and the double-fuel-column cell is shown in Fig. 2.2. The corresponding drawers with internal blanket segments are shown in Figs. 2.3 and 2.4.

Standard ZPPR Pu-U-Mo alloy fuel is used throughout. Drawers with one fuel column contain oxygen in U_3O_8 and Fe_2O_3 . Drawers with two fuel columns contain oxygen in U_3O_8 and Na_2CO_3 . The axial blankets are somewhat deficient in oxygen because of limitations in the Fe_2O_3 inventory. The radial blanket drawer loading pattern is shown in Fig. 2.5.

The core half-height is 509 mm (20 inches) and the height of the axial blanket is 279 mm (11 inches). The axial half-height of the radial blanket is 787 mm (31 inches). The remaining 127 mm (5 inches) in each core and radial blanket drawer contains a mild steel block. Behind each core and radial blanket drawer is a 152 mm (6 inch) long stainless steel block. Radial reflector drawers contain stainless steel blocks over their full 914 mm (36 inch) length. There are no blocks behind the radial reflector drawers. The various assembly regions and their dimensions are shown in an rz diagram in Fig. 2.6. The core volume, including internal blanket is 5518 liters. The volume of the fuel-bearing core is 4777 liters.

An interface diagram of ZPPR-17A is shown in Fig. 2.7. Zone outlines, the pattern of single- and double-fuel-column drawers and the locations of the operating rods are shown. As Fig. 2.7 indicates, the ratio of single- to double-fuel-column drawers is the same throughout the core.

The operating rods used for power regulation in a critical configuration are in 134-36 and the seven equivalent locations. Dual-blade poison safety rods are in locations 144-30 and 31, 153-30 and 31, 144-67 and 68, and 153-67 and 68 and the corresponding half two locations. These dual-blade locations are not all symmetrically equivalent. In order to maintain symmetry, special drawers which look like narrow drawers adjacent to PSRs are used in matrix locations 144-32, 144-69, 153-32 and 153-69 and the corresponding half two locations.

Sixty-nine fission chambers are distributed through the core, blanket and reflector zones. In the core region (including the internal blanket) fission chambers are only in single-fuel-column drawers. The normal 12.7 mm-wide fission chambers are all centered 77 mm from the assembly interface. Smaller chambers, 6.4 mm wide, are centered 230 mm and 382 mm back from the interface in location 156-39 (which also has a standard chamber in the front of the drawer). In location 256-39 there are three 6.4 mm-wide chambers; centered 77 mm, 230 mm and 382 mm from the interface. Detector locations are given in Table 2.1.

2.3 The ZPPR-17A Critical Reference Configuration

The ZPPR-17A critical reference was established on February 23, 1987, in loading number 26, reactor run number 22. The excess reactivity, determined in a positive period measurement, was $7.1 \pm 0.1\%$ at an average core temperature of 27.3°C . The interface diagram is given in Fig. 2.7 with the matrix locations marked with an "X" containing double-fuel-column drawers. A drawer loading summary is given in Table 2.2 and mass summaries for various regions are given in Table 2.3. For convenience, the term "inner core" is applied to that region of the core which contains the internal blanket.

2.4 The ZPPR-17A Subcritical Reference Configuration

The ZPPR-17A subcritical reference was established on February 26, 1987, in loading number 27, reactor run number 25. The reactivity was $-25.86 \pm 0.1\%$ determined by inverse kinetics analysis of a rod-drop. The interface diagram is given in Fig. 2.7 with the matrix locations marked with an "X" containing single-fuel-column drawers. The total fissile mass was 4.418 kg less in the subcritical reference than in the critical reference.

TABLE 2.1. Fission Chamber Locations in ZPPR-17A

<u>Matrix Location^a</u>	<u>Region^b</u>	<u>Matrix Location^a</u>	<u>Region^b</u>
120-57	RR	226-39	RB
126-57	RB	232-33	C
132-51	C	232-44	C
132-63	C	238-27	RB
138-57	IB	238-39	IB
138-69	C	244-32	C
144-64	IB	244-45	IB
144-75	RB	250-27	C
126-45	C	226-51	C
132-27	RB	226-64	RB
132-39	C	232-57	C
138-33	C	232-69	RB
139-46	IB	232-51	IB
144-27	C	238-63	C
144-39	IB	244-58	IB
144-51	IB	244-69	C
150-33	C	250-51	IB
150-45	IB	250-63	IB
156-27	RB	250-75	RB
156-39	IB	256-39 ^e	IB
156-39 ^c	C	256-39 ^c	C
156-39 ^d	C	256-39 ^d	C
156-51	IB	256-57	IB
162-33	C	256-69	C
162-45	IB	262-51	IB
168-39	C	262-63	C
150-57	IB	268-57	C
150-69	C	250-39	IB
156-63	IB	256-33	C
162-57	IB	256-45	IB
162-69	C	262-27	RB
168-51	C	262-39	C
168-63	C	268-33	RB
174-63	RB	268-45	C
		274-51	RB

^aChambers centered ± 77 mm from midplane.

^bRR is radial reflector, RB is radial blanket, C is core, IB is internal blanket.

^cNarrow chamber centered 230 mm from miplane.

^dNarrow chamber centered 382 mm from midplane.

^eNarrow chamber centered 77 mm from midplane.

TABLE 2.2. Drawer Loading Summary for the
ZPPR-17A Critical Reference

Inner Core - Drawers with Internal Blanket

Drawers with one column of fuel (Includes 23 drawers with fission chambers and 8 narrow drawers adjacent to PSRs)	1056
---	------

Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	520
---	-----

Outer Core

Drawers with one column of fuel (Includes 28 drawers with fission chambers, two drawers with thermocouples, and 16 narrow drawers adjacent to PSRs)	1304
---	------

Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	680
---	-----

Radial Blanket

Radial blanket drawers (Includes 13 drawers with fission chambers)	1752
--	------

Radial Reflector

Stainless-steel-filled reflector drawers (Includes one drawer with fission chamber)	1272
---	------

TABLE 2.3. Mass Summary for Various Regions in the
ZPPR-17A Critical Reference

Material	Mass, kg ^b				
	Inner Core	Outer Core	Internal Blanket	Radial Blanket	Axial Blanket
Total Pu	911.090	1666.738	---	---	---
Fissile Pu	803.161	1469.219	---	---	---
Total Fissile	812.846	1486.758	5.112	47.500	21.260
²³⁸ Pu	0.449	0.713	---	---	---
²³⁹ Pu	796.474	1457.609	---	---	---
²⁴⁰ Pu	105.733	193.817	---	---	---
²⁴¹ Pu ^a	6.687	11.610	---	---	---
²⁴² Pu	1.747	2.988	---	---	---
Americium ^a	9.619	17.464	---	---	---
²³⁵ U	9.684	17.539	5.112	47.500	21.260
²³⁸ U	4495.945	8135.879	2369.604	22109.920	9787.461
Total Heavy Metal	5426.336	9837.617	2374.716	22157.420	9808.723
O	652.692	1176.432	268.122	2515.876	711.462
Na	591.425	1060.325	256.722	678.242	1061.658
Mo	85.398	156.285	1.595	8.932	16.913
Steel ^c	2619.347	4698.207	1049.908	4557.519	5883.968

^aMasses for all isotopes decayed to the date 2/25/87.

^bMasses are based on the average masses for plate types.

^cSteel mass is the sum of masses of elements Cr, Mn, Fe and Ni.

Fig. 2.1. Loading Pattern for Single-Fuel-Column Drawers in ZPPR-17.

Fig. 2.2. Loading Pattern for Double-Fuel-Column Drawers in ZPPR-17.

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.

Fig. 2.5. Loading Pattern for Radial Blanket Drawers in ZPPR-17.

RZ PLOT OF ZPPR-17

(Dimensions in cm)

Fig. 2.6. RZ Diagram of ZPPR-17.

Fig. 2.7. Interface Diagram for the ZPPR-17A Reference Configurations.

3. MULTIGROUP CROSS SECTION DATA AND CALCULATION MODELS FOR ZPPR-17A
(G. L. Grasseschi and P. J. Collins)

3.1 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 section library for reactor calculations. Details of the cross section processing are given in Section 3.2.

The reference calculation method for ZPPR-17 was a nodal diffusion model using individual drawer compositions and Benoist diffusion coefficients. Additional calculations were made with the nodal transport path of DIF3D and also in rz geometry using diffusion (DIF3D) and transport methods (TWO-DANT). For economy, a 6 group condensation of the 21 group data was used for processing control rod reactivity measurements. Details of the calculation model are given in Section 3.3 and the calculated k-effective results are given in Section 4.

3.2 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 3.1.

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, treatment of resonance shielding and flux fine structure, and the actual homogeneous compositions 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. 3.1. 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.

The cross sections processed for asymptotic cell models will be used for initial analysis of ZPPR-17 and for calculations required to process experimental data. Previous analyses of heterogeneous cores showed that the use of more refined cell processing methods is desirable. These methods would treat effects of mixed cells, e.g. SCFN/DCFN or SCFN/IBKN either by imposing group dependent leakages in the SDX calculations or by multiple cell models.

3.3 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 (ANL-ZPR-473, p. 100).

Figure 3.2 shows an xy map of the model; the entries are individual drawer master numbers. A description of each drawer master and its zone assignment is given in Table 3.2. See Section 2 for a description of the cells. 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), and at 1070.61 mm (stainless steel reflector). The zone boundaries are shown in an rz plot in Fig. 2.6.

Average zone compositions are given in Table 3.3 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 Table 3.3 are suitable for use in an rz model of ZPPR-17A but, as noted above, the reference xyz model uses individual drawer compositions.

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

TABLE 3.1. 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 3.2. Drawer Masters in ZPPR-17A

Zone	Master	Description ^a
Core Without Internal Blanket (Outer Core)	101	Fuel-SC
	102	Fuel-SC
	103	Fuel-SC
	104	Fuel-SC
	105	Fuel-SC
	106	Fuel-SC
	109	Fuel-SC-Symmetry retaining
	110	Fuel-SC-Symmetry retaining
	111	Fuel-SC-Symmetry retaining
	112	Fuel-SC-Symmetry retaining
	202	Fuel-DC
	203	Fuel-DC
	207	Fuel-DC
	701	Fuel-SC-FC
	702	Fuel-SC-FC
	703	Fuel-SC-FC
	705	Fuel-SC-FC
	706	Fuel-SC-FC
	711	Fuel-SC-Thermocouple
	714	Fuel-SC-FC-Symmetry retaining
	715	Fuel-SC-FC-Symmetry retaining
	805	Fuel-SC-PSR
	806	Fuel-SC-PSR
	807	Fuel-DC-PSR
	808	Fuel-DC-PSR
	809	Fuel-SC-PSR
	810	Fuel-SC-PSR

TABLE 3.2. (contd)

Zone	Master	Description ^a
Core With Internal Blanket (Inner Core)	107	Fuel-SC
	108	Fuel-SC
	205	Fuel-DC
	707	Fuel-SC-FC
	708	Fuel-SC-FC
	712	Fuel-SC-Axially distributed FC
	713	Fuel-SC-Axially distributed FC
	801	Fuel-SC-PSR
	802	Fuel-SC-PSR
	803	Fuel-DC-PSR
	804	Fuel-DC-PSR
Radial Blanket	501	DU
	502	DU
	709	DU-FC
Radial Reflector	402	Stainless Steel
	403	Stainless Steel
	404	Stainless Steel
	405	Stainless Steel
	710	Stainless Steel

^aSC is single fuel column, DC is double fuel column, FC is fission chamber, PSR is adjacent to poison safety rod, DU is depleted uranium.

TABLE 3.3. 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 3.3. (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 3.3. (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 3.3. (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 3.3. (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	--

Fig. 3.1. Slab Model used to Collapse
Cross Sections for ZPPR-17A

<u>Axial Height, cm</u>	<u>Zone</u>	<u>Cell Cross Sections</u>
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	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	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	101	207	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	202	103	106	207	104	102	203	105	501	501	501	501	502	402	402	402	.	.	

Fig. 3.2. The xyz Calculation Model for ZPPR-17A.

4. K-EFFECTIVE, DELAYED NEUTRON PARAMETERS AND ^{241}Pu DECAY COEFFICIENT FOR ZPPR-17A (G. L. Grasseschi and P. J. Collins)

4.1 Experimental and Calculated k-effectives

The reference configurations for ZPPR-17A are described in Section 2 of this report. 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. Table 4.1 shows the experimental k-effective values for the critical and subcritical references of ZPPR-17A and a comparison with the nodal diffusion calculations using xyz geometry and 21 group ENDF/B-V.2 data (Section 3).

The uncertainties shown in Table 4.1 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).

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 Pu^{239} , see Section 2). This reactivity difference is $0.001099 \Delta k \pm 0.000039 \Delta k$ assuming that all uncertainties, other than those in Table 4.1, are closely correlated. The calculated difference is 0.001187 giving a C/E value of 1.080.

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 90 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 Table 4.2. The effects of several modelling approximations derived from these results are shown in Table 4.3.

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%.

The C/E values for the k-effective of ZPPR-17A are 0.9906 from nodal transport xyz and 0.9926 from nodal diffusion xyz with rz corrections to S⁴. Both of these results are a few tenths of a percent lower than the value expected with ENDF/B-V.2 data, for example, 0.9943 for ZPPR-13C. The lower value may be due in part to use of asymptotic cell processing. Use of reactor cell bucklings for ZPPR-11 cell processing was found to increase the k-effective by 0.2% (ZPR-TM-424, Table IV.9, p. 107).

4.2 Calculated β -effective for ZPPR-17A

Delayed neutron parameters for ZPPR-17A were calculated with the finite-difference diffusion model in xyz geometry. The kinetics parameters for the six delayed neutron families are given in Table 4.4. The effective delayed neutron fraction is 0.3385%. An earlier calculation using rz geometry gave a similar value of 0.3406%.

4.3 Calculated ^{241}Pu Decay Coefficient for ZPPR-17A

The ^{241}Pu decay coefficient for ZPPR-17A was calculated from the first order perturbation worth of ^{241}Pu in an rz model. For a uniform

increase of 10% in ^{241}Pu density over the whole core, the eigenvalue change was $6.1239 \times 10^{-4} \Delta\lambda$. Using the ^{241}Pu half life of 14.4 years (decay constant $1.319 \times 10^{-4} \text{ day}^{-1}$), and the calculated β -effective of 0.3385% (Section 4.2), the decay coefficient for ZPPR-17A was calculated to be $-0.0002386 \text{ day}^{-1}$. The (1σ) uncertainty on this value is estimated to be 10%.

TABLE 4.1. 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	$+15.0 \pm 0.8\phi$	-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 4.2. 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 4.3. Modelling Effects Calculated
for ZPPR-17A

Correction		Table 4.2 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 4.4. Delayed Neutron
Parameter 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 $4.660 \times 10^{-7}s$

5. ZPPR-17A OPERATIONAL MEASUREMENTS (R. W. Goin)

5.1. Critical Reference Excess Reactivity

In loading 26, the critical reference was achieved and the excess reactivity was measured in reactor run no. 22, using a positive period method. The average reactor temperature using the 15 thermocouples (see section 4 below) was 27.3°C . The excess reactivity was $7.1 \pm 0.1\phi$. This is recorded as file 8 of DATAZ17A.Z01 on the Perkin-Elmer system.

5.2. Subcritical Reference Reactivity

The subcritical reference configuration is obtained by replacing double-fuel-column drawers with single-fuel-column drawers in locations 1,236-37, 1,236-62, 1,261-37 and 1,261-62. The reactivity of this subcritical reference has been measured several times in the experimental sequence, and two reactivities are recorded in Table 5.1. All data are recorded in DATAZ17A.Z01, and the reactivities were obtained from rod drops.

5.3. Gap Worth

The gap worth was measured by recording the power history while driving the halves apart on slow speed for 10 s. This resulted in a table movement of 58.5×10^{-3} inches as determined from the four corner closure indicator readings before and after the table movement. The resulting reactivity history indicates a gap worth of $-0.18 \pm 0.02 \phi/\text{mil}$ (1 mil = 0.001 inch). This measurement was done in reactor run no. 24 and is recorded as file 21 on DATAZ17A.Z01.

5.4. Temperature Coefficient

The temperature coefficient was determined by recording the power history and the output from 16 thermocouples for about 4-1/2 hours, starting shortly after the reactor halves were closed. This measurement was done in reactor run no. 24 and is recorded as file 16 in

DATAZ17A.Z01. After analyzing the data, the best correlation of temperature to reactivity results from using 15 thermocouples: 4, 5, 6, 9, 21, 49, 50, 51, 52, 58, 59, 72, 93, 94 and 95. The temperature coefficient of reactivity using the mean readout of these 15 thermocouples is $-1.08 \pm 0.11 \text{ } \phi/\text{ }^{\circ}\text{C}$.

5.5. Rod Pair Worths

The worths of the rod pairs in one quadrant of ZPPR-17A were determined using the rod-drop technique. These measurements were done in reactor runs 23 and 24, and the data are recorded in files 13, 14, 17 and 18 in DATAZ17A.Z01. The measured worths are given in Table 5.2. The ratio of detector efficiency before and after the rod drop, which is also obtained from the inverse kinetics solution of the power history, is given for the two ex-core power monitors (designated EXP 1 and EXP 2). These compare very well with the detector efficiency ratios obtained from the 64 fission chamber data.

5.6. Shim Rod Calibration

All eight rods which are used as shim rods in ZPPR-17A were calibrated in reactor run 23. The rods were calibrated by driving them through their full range of travel, for three full cycles, then fitting the resulting reactivity listing to a fourth-order polynomial in rod position and third-order in time. The resulting calibration coefficients are given in Table 5.3. The data are recorded as files 11 and 12 of DATAZ17A.Z01. To account for the change in detector efficiency caused by moving a particular rod, the inverse kinetics solution used combinations of the two ex-core power monitors based upon results of the detector efficiency ratios obtained from rod drops and from the 64-fission detector measurements.

5.7. Delayed Neutron Parameters

The delayed neutron fractions for ZPPR-17A were obtained from a rod drop measurement with the reactor power leveled at 0.5×10^{-5} on EXP 1.

The resulting power history was analyzed using an iterative inverse kinetics solution which solves for the delayed neutron fractions, the reactivity after the drop, the effective source term, and the detector efficiency ratio. The resulting parameters are given in Table 5.4. The decay constants, λ_i , were obtained from an RZ calculation. This measurement was done in reactor run 24 and is recorded as file 19 on DATAZ17A.Z01.

5.8. Source Term Measurement

The effective source term for the two ex-core power monitors was measured in reactor run 22 and the data recorded as file 9 on DATAZ17A.Z01. The measurement was done starting at 0.9×10^{-7} on EXP 1 and dropping group 2 rods, which perturb the detector efficiency ratio least. The resulting source terms are $157.34 \pm 0.06 \Delta k/k$ counts s^{-1} for EXP 1 and $133.27 \pm 0.06 \Delta k/k$ counts s^{-1} for EXP 2.

TABLE 5.1. Subcritical Reference Reactivity

<u>Data File</u>	<u>Reactor Run</u>	<u>Average Temperature, °C^a</u>	<u>Date</u>	<u>Reactivity, \$</u>
22	25	27.47	2/26/87	0.2586 ± 0.0021
36	41	27.06	3/05/87	0.2587 ± 0.0021

^aAverage temperature from fifteen thermocouples.

TABLE 5.2. Individual Rod Pair Worths

Data File	Rods	Matrix Position	Worth \$	Detector Efficiency Ratios	
				EXP 1	EXP 2
13	PSR 22&23	1,253-30&31	0.4784 ± 0.004	1.0439 ± 0.0004	0.9131 ± 0.0004
14	PSR 10&19	1,253-36	0.3415 ± 0.001	1.0279 ± 0.0004	0.9499 ± 0.0003
18	PSR 6&7	1,263-47	0.3404 ± 0.001	0.9835 ± 0.0003	0.9595 ± 0.0004
17	SR 1&2	1,263-36	0.2665 ± 0.001	1.0105 ± 0.0003	0.9176 ± 0.0003

TABLE 5.3. Shim Rod Calibration Coefficients^a

Shim Rod	Position	$10^2 \times C_1$	$10^3 \times C_2$	$10^4 \times C_3$	$10^6 \times C_4$	RMS Deviation, ϕ	Total Worth, \$
1	163-36	-5.6993	15.053	-19.730	33.610	0.036	0.1398 ± .0010
2	263-36	-6.2993	16.168	-20.106	33.985	0.038	0.1373 ± .0010
3	134-63	-6.4164	16.555	-21.781	37.449	0.054	0.1510 ± .0010
4	234-63	-6.2970	16.764	-22.298	38.641	0.052	0.1529 ± .0010
5	163-63	-6.1811	16.313	-21.567	37.190	0.030	0.1492 ± .0010
6	263-63	-6.5307	16.945	-21.971	37.565	0.034	0.1530 ± .0010
PSR31	134-63	-5.5216	15.160	-19.792	32.980	0.068	0.1429 ± .0010
PSR30	234-63	-5.9051	16.108	-20.694	35.148	0.067	0.1425 ± .0010

^a $R = (C_1 X + C_2 X^2 + C_3 X^3 + C_4 X^4)$; where X is the rod position in inches measured from the fully withdrawn position (30 inches), and R is the reactivity in cents.

TABLE 5.4. Measured Delayed Neutron Fractions

<u>Group</u>	<u>λ_i (s⁻¹)</u>	<u>a_i</u>	<u>β_i</u>
1	0.012977	0.022666	0.00007595
2	0.031432	0.214534	0.00071890
3	0.13551	0.184041	0.00061672
4	0.34570	0.357660	0.00119852
5	1.3668	0.172599	0.00057838
6	3.7513	0.048501	0.00016253
Total		1.000000	0.00335100

6. SODIUM VOID WORTH MEASUREMENTS IN ZPPR-17A (S. B. Brumbach and R. W. Goin)

6.1 Introduction

The worth of sodium removal in ZPPR-17A was measured using two different techniques. One technique substituted empty cans for sodium-filled cans in two different zones of the assembly. Voiding was done in a series of axial steps. The second technique used new self-contained oscillator devices to move a single column of sodium in and out of the core and axial blanket regions in drawers in ten assembly locations.

6.2 Plate Substitution Measurements

The reference configuration for the plate substitution measurements was the ZPPR-17A subcritical reference. The reactivity of this configuration was measured twice during the sodium void sequence (reactor runs 39 and 46). The two reactivities derived from inverse kinetics analysis of rod drops were -25.64ϕ and -25.44ϕ . An average reactivity of -25.54ϕ with an uncertainty due to reproducibility of $\pm 0.20\phi$ was assumed.

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. 6.1. Drawers containing fission chambers (150-33 in the outer zone and 250-51 in the central zone) and drawers opposite fission-chamber drawers were not voided. The sodium carbonate in double-fuel-column drawers was not included in the voiding. Reactivity changes were measured using the modified source multiplication technique.

Both zones were voided in a series of cumulative axial steps which corresponded to the lengths of 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 - 152 mm) and finally the external axial blanket to ± 787 mm.

The reactivity values after the various loading steps are given in Table 6.1. The uncertainty is dominated by the 0.2 cent contribution from reproducibility. Other, smaller, components from reactivity scale calibration (0.7%) and statistical uncertainties (0.04¢) are included. Reactivities of the individual steps are given in Table 6.2. In the measurements, the steel mass changed slightly with each void step due to mass differences between sodium 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 are made to the step worths in Table 6.2.

6.3 Oscillator Measurements

Sodium worth was measured using new devices called self-contained oscillators. These devices 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 any 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. For the measurements described here, 12.7 mm-wide sodium cans were held together in a column by mylar tape and oscillated the full 660 mm. Oscillation speed was 150 mm per minute.

Sodium worth oscillator measurements were made in ten locations which are shown in Fig. 6.1. 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. The loading of the single-fuel-column drawers was

modified by removing one column of iron oxide in order for the sodium column to move freely. The radial blanket drawers were rearranged to accommodate a single 12.7 mm-wide sodium column, and a 6.4 mm-wide uranium oxide column was replaced with a 3.2 mm-wide column.

Reactivity was derived as a function of column position by inverse kinetics analysis of the 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. Reactor power was about 150 watts. Measurements were made between March 19 and April 1, 1987, in reactor runs 52 to 62.

Results for the ten locations are given in Figs. 6.2 to 6.11. The values in the figures 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 seven core locations, the sodium worth is small and positive in the axial blanket, reaches a maximum positive values between 10 and 20 inches from the interface and is negative near the interface. At the outermost portion of the core (147-27) the worth is essentially always positive, and increases monotonically toward the axial center of the core. 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.

Reactivity values for the sodium columns in the various locations are shown in Tables 6.3 to 6.5 for the axial locations corresponding to the points in Figs. 6.2 to 6.11. The oscillator measurements were made twice in location 148-49; once with the central zone voided of its sodium (first column of Table 6.3) and again with all the sodium in place (second column of Table 6.3). Sodium worths near the

axial center of the core are more negative for the voided-zone case. Uncertainties associated with the inverse kinetics processing of the reactivities in Tables 6.3 to 6.5 are about 0.0015 cents.

The worth profiles in some representative locations are compared on a single plot in Fig. 6.12.

TABLE 6.1 Sodium Voiding Reactivities in ZPPR-17A

<u>State</u>	<u>Data File</u>	<u>Loading Number</u>	<u>Reactivity^a Difference, ϕ</u>	<u>σ, ϕ</u>
<u>Outer Core</u>				
± 203 mm	60	42	+6.82	0.21
± 406 mm	61	43	+8.50	0.21
± 508 mm	63	44	+6.41	0.21
± 787 mm	64	45	+2.54	0.20
<u>Inner Core</u>				
± 152 to ± 330 mm	66	47	+4.92	0.21
± 152 to ± 508 mm	67	48	+6.27	0.21
± 508 mm	68	49	+14.25	0.23
± 787 mm	69	50	+9.73	0.22

^aWith respect to subcritical reference reactivity of -25.54ϕ , the average value from inverse kinetics analysis of rod drops in two measurements in loadings 41 and 46.

TABLE 6.2 Step Reactivity Worths for Sodium Voiding in ZPPR-17A

Step ^a	Mass Sodium Voided, kg	Mass Steel Added, kg	Measured Reactivity Change, ϕ	σ , ϕ	Specific Reactivity $\phi/\text{kg (Na)}$
<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	-0.41	0.30	-0.066
508 - 787 mm	21.097	0.071	-4.28	0.30	-0.203
<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.

TABLE 6.3 Axial Sodium Worth Profiles, in cents, in Core
Locations with Internal Blanket in ZPPR-17A

<u>Location</u> <u>Displacement,</u> <u>Inches</u>	<u>148-49</u> <u>Voided</u> <u>Zone</u>	<u>148-49</u> <u>Flooded</u> <u>Zone</u>	<u>147-39</u>	<u>148-35</u>	<u>148-34</u>
0	-0.0733	-0.0599	-0.0657	-0.0714	-0.0557
1	-0.0625	-0.0473	-0.0527	-0.0536	-0.0472
2	-0.0544	-0.0402	-0.0454	-0.0476	-0.0365
3	-0.0445	-0.0307	-0.0371	-0.0376	-0.0273
4	-0.0373	-0.0211	-0.0287	-0.0267	-0.0142
5	-0.0323	-0.0215	-0.0208	-0.0229	-0.0082
6	-0.0278	-0.0146	-0.0212	-0.0097	-0.0031
7	-0.0226	-0.0118	-0.0137	-0.0024	0.0079
8	-0.0167	-0.0054	-0.0054	0.0054	0.0205
9	-0.0040	-0.0042	-0.0040	0.0148	0.0284
10	-0.0036	0.0008	0.0035	0.0250	0.0316
11	0.0076	0.0067	0.0086	0.0342	0.0407
12	0.0162	0.0165	0.0127	0.0403	0.0529
13	0.0177	0.0188	0.0176	0.0435	0.0541
14	0.0236	0.0275	0.0197	0.0464	0.0508
15	0.0302	0.0336	0.0296	0.0494	0.0577
16	0.0306	0.0284	0.0321	0.0545	0.0551
17	0.0304	0.0266	0.0276	0.0485	0.0524
18	0.0321	0.0310	0.0284	0.0432	0.0502
19	0.0257	0.0266	0.0274	0.0398	0.0378
20	0.0216	0.0188	0.0204	0.0305	0.0357
21	0.0189	0.0146	0.0170	0.0210	0.0221
22	0.0073	0.0116	0.0058	0.0173	0.0198
23	0.0086	0.0067	0.0018	0.0136	0.0175
24	0.0059	0.0027	0.0033	0.0081	0.0068
25	-0.0002	0.0024	0.0028	0.0009	0.0011
26	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE 6.4 Axial Sodium Worth Profiles,
in cents, in Core Locations
without Internal Blanket
in ZPPR-17A

<u>Location</u> <u>Displacement,</u> <u>Inches</u>	<u>147-33</u>	<u>148-32</u>	<u>147-27</u>
0	-0.0557	-0.0398	0.0660
1	-0.0473	-0.0293	0.0639
2	-0.0329	-0.0195	0.0584
3	-0.0242	-0.0071	0.0607
4	-0.0149	-0.0025	0.0611
5	-0.0065	0.0129	0.0545
6	0.0017	0.0171	0.0518
7	0.0108	0.0249	0.0531
8	0.0175	0.0335	0.0461
9	0.0272	0.0427	0.0484
10	0.0370	0.0471	0.0466
11	0.0406	0.0506	0.0423
12	0.0448	0.0564	0.0336
13	0.0494	0.0553	0.0355
14	0.0563	0.0559	0.0313
15	0.0557	0.0565	0.0322
16	0.0492	0.0594	0.0268
17	0.0485	0.0488	0.0203
18	0.0387	0.0460	0.0188
19	0.0360	0.0358	0.0130
20	0.0296	0.0324	0.0115
21	0.0170	0.0188	0.0043
22	0.0126	0.0203	0.0065
23	0.0113	0.0132	0.0023
24	0.0047	0.0095	0.0005
25	0.0012	0.0022	-0.0042
26	0.0000	0.0000	0.0000

TABLE 6.5 Axial Sodium Worth Profiles,
in cents, in Radial Blanket
Locations in ZPPR-17A

<u>Location</u>	<u>148-25</u>	<u>148-23</u>
<u>Displacement,</u> <u>Inches</u>		
0	0.0675	0.0171
1	0.0573	0.0157
2	0.0581	0.0096
3	0.0520	0.0101
4	0.0478	0.0122
5	0.0411	0.0131
6	0.0418	0.0110
7	0.0388	0.0071
8	0.0357	0.0100
9	0.0284	0.0041
10	0.0286	0.0075
11	0.0236	0.0049
12	0.0203	0.0045
13	0.0148	0.0062
14	0.0156	0.0024
15	0.0069	0.0026
16	0.0079	0.0019
17	0.0054	0.0011
18	0.0051	0.0064
19	0.0044	0.0024
20	0.0057	0.0001
21	0.0000	0.0024
22	-0.0029	0.0031
23	-0.0040	-0.0009
24	-0.0021	0.0031
25	0.0010	0.0044
26	0.0000	0.0000

\ Void Zones
 ■ Oscillator Measurement

Fig. 6.1. Locations of Sodium Void Worth Measurements in ZPPR-17A.

Fig. 6.2. Reactivity versus Sodium Column Displacement in Location 148-49 in ZPPR-17A.

Fig. 6.3. Reactivity versus Sodium Column Displacement in Location 148-43 in ZPPR-17A.

Fig. 6.4. Reactivity versus Sodium Column Displacement in Location 147-39 in ZPPR-17A.

Fig. 6.5. Reactivity versus Sodium Column Displacement in Location 148-35 in ZPPR-17A.

Fig. 6.6. Reactivity versus Sodium Column Displacement in Location 148-34 in ZPPR-17A.

Fig. 6.7. Reactivity versus Sodium Column Displacement in Location 147-33 in ZPPR-17A.

Fig. 6.8. Reactivity versus Sodium Column Displacement in Location 148-32 in ZPPR-17A.

Fig. 6.9. Reactivity versus Sodium Column Displacement in Location 147-27 in ZPPR-17A.

Fig. 6.10. Reactivity versus Sodium Column Displacement in Location 148-25 in ZPPR-17A.

Fig. 6.11. Reactivity versus Sodium Column Displacement in Location 148-23 in ZPPR-17A.

Fig. 6.12. Reactivity versus Sodium Column Displacement for Various Locations in ZPPR-17A.

7. CONTROL ROD WORTH MEASUREMENTS IN ZPPR-17A (S. B. Brumbach and S. G. Carpenter)

The ZPPR-17A reference configurations did not have control rod positions. However, a few control rod worth measurements were made in ZPPR-17A, and all the worths were measured with respect to fuel. The measurements focused on the worth of a single, central rod as a function of rod size, geometry and composition.

Most of the rods were two-by-two drawers in size at the core center (matrix locations 148-49, 148-50, 149-49, 149-50; fuel master 107). One rod was two-by-three drawers in size and included locations 148-48 and 149-48 (fuel master 205). Two rods were three-by-three drawers in size and included locations 150-48 (fuel master 107), 150-49 and 150-50 (fuel master 205). For comparison, a two-by-two-drawer rod was measured off center in columns 48 and 49 and rows 148 and 149. Except for the drawers occupied by the control rod, the reactor was in the ZPPR-17A subcritical reference configuration.

Both pin- and plate-type control rods were measured. All plate-type rod drawers contained natural or 90% enriched B_4C over their first 20 inches, and sodium cans from 20 to 36 inches. There were two different pin type rods. The first used sodium-filled calandria and enriched B_4C pellets over the first 20 inches, stainless steel pins from 20 to 24 inches and a "back drawer" (master 614) with seven inches of sodium and a five-inch-long mild steel block. The second pin rod had 9.52 mm-diameter B_4C pellets and stainless steel pins closely packed in the first 20 inches of the drawer with 3.18 mm-thick stainless steel plates around the edges as shown in Fig. 7.1. Drawers and matrix tubes are not shown to scale in Fig. 7.1. Sodium cans filled the remaining 16 inches of the drawer. Control rod position (CRP) drawers contained sodium cans over their entire 36-inch length.

A summary of the rod types measured and the drawer types used in the rods is given in Table 7.1. Atom densities for these drawer masters are given in Table 7.2.

All measurements were made using both the modified source multiplication (MSM) method and a rod drop. The reference reactivity was measured before and after the rod worth measurements. The average value of the reference reactivities was $-26.4\phi \pm 0.3\phi$. This uncertainty has a component of 0.7% due to calibration and 0.2ϕ based on an estimate of reproducibility. The two subcritical reference values differed by 0.3ϕ .

The measured rod worths, with respect to the subcritical reference, are given in Table 7.3. The values are those obtained by the MSM method. The data were not processed through the McCRUNCH code. The uncertainties include the 0.2ϕ reproducibility component, the 0.7% calibration component and an uncorrelated component of 1% on the difference between the reference and any particular value.

TABLE 7.1 Control Rod Worth Measurements in ZPPR-17A

Reactor Run Number	Reactor Loading Number	Data File Number	Rod Descriptions	Drawer Masters Used
25	27	45	Subcritical Reference	---
26	28	46	CRP	601
27	29	47	50% Natural B C Plate	602
28	30	48	100% Natural B C Plate	604
29	31	49	Half Inserted 100% Natural B C Plate	604
30	32	50	Tight-packed Natural B C Pellets	605, 606, 609, 610
31	33	51	Enriched B C Pellets in Calandria	613
32	34	52	Tight-packed Enriched B C Pellets	607, 608, 611, 612
33	35	53	Half Inserted 100% Enriched B C Plates	615
34	36	54	50% Enriched B C Plates	616
35	37	55	2 x 3 100% Natural B C Plates	604
36	38	56	2 x 2 100% Natural B C Plates Off Center	604
37	39	57	3 x 3 CRP	601
38	40	58	3 x 3 100% Natural B C Plates	604
39	41	59	Subcritical Reference	---

TABLE 7.2 Control Rod Compositions for ZPPR-17A (atoms/barn-cm)

Isotopes	Master 601 0-6	Master 601 6-20	Master 601 20-31	Master 601 31-36	Master 602 0-6	Master 602 6-20
B-10	---	---	---	---	0.0071434	0.0071648
B-11	---	---	---	---	0.0289640	0.0290522
C	0.0000307	0.0000309	0.0000309	0.0000447	0.0093854	0.0094136
O	0.0000013	0.0000013	0.0000013	0.0000013	0.0000006	0.0000006
Na	0.0180431	0.0183971	0.0184407	0.0179928	0.0082828	0.0083768
Si	0.0001648	0.0001649	0.0001649	0.0001705	0.0002023	0.0002037
Al	0.0000043	0.0000048	0.0000049	0.0000048	0.0000054	0.0000051
Mn	0.0002412	0.0002442	0.0002443	0.0002512	0.0002583	0.0002609
Cr	0.0029392	0.0029644	0.0029657	0.0030388	0.0031523	0.0031823
Fe	0.0103736	0.0104649	0.0104697	0.0110019	0.0111530	0.0112611
Ni	0.0013184	0.0013274	0.0013281	0.0013586	0.0014321	0.0014436
Cu	0.0000357	0.0000353	0.0000353	0.0000370	0.0000362	0.0000362
Mo	0.0000175	0.0000174	0.0000173	0.0000183	0.0000178	0.0000179
P	0.0000040	0.0000040	0.0000040	0.0000042	0.0000040	0.0000040
S	0.0000013	0.0000012	0.0000012	0.0000013	0.0000013	0.0000012
Cl	0.0000006	0.0000006	0.0000006	0.0000006	0.0000003	0.0000003
Ca	0.0000041	0.0000042	0.0000042	0.0000041	0.0000019	0.0000019
Co	0.0000040	0.0000037	0.0000037	0.0000043	0.0000040	0.0000037

TABLE 7.2 (contd)

Isotope	Master 602 20-31	Master 602 31-36	Master 603 0-6	Master 603 6-20	Master 603 20-31	Master 603 31-36
B-10	---	---	0.0158704	0.0151769	---	---
B-11	---	---	0.0643536	0.0615467	---	---
C	0.0000308	0.0000447	0.0203704	0.0197666	0.0000308	0.0000447
O	0.0000013	0.0000013	0.0001353	0.0000534	0.0000013	0.0000013
Na	0.0181363	0.0176957	---	---	0.0181363	0.0176957
Si	0.0001651	0.0001707	0.0002522	0.0002235	0.0001651	0.0001707
Al	0.0000043	0.0000042	0.0000021	0.0000028	0.0000043	0.0000042
Mn	0.0002432	0.0002501	0.0002004	0.0002204	0.0002432	0.0002501
Cr	0.0029562	0.0030295	0.0023506	0.0026105	0.0029562	0.0030295
Fe	0.0104363	0.0109693	0.0084649	0.0093681	0.0104363	0.0109693
Ni	0.0013233	0.0013539	0.0010327	0.0011621	0.0013233	0.0013539
Cu	0.0000357	0.0000374	0.0000314	0.0000325	0.0000357	0.0000374
Mo	0.0000174	0.0000183	0.0000157	0.0000162	0.0000174	0.0000183
P	0.0000040	0.0000042	0.0000040	0.0000040	0.0000040	0.0000042
S	0.0000012	0.0000013	0.0000013	0.0000012	0.0000012	0.0000013
Cl	0.0000006	0.0000006	---	---	0.0000006	0.0000006
Ca	0.0000042	0.0000041	---	---	0.0000042	0.0000041
Co	0.0000037	0.0000043	0.0000040	0.0000037	0.0000037	0.0000043

TABLE 7.2. (contd)

Isotope	Master 604 0-6	Master 604 6-20	Master 604 20-31	Master 604 31-36	Master 605 0-6	Master 605 6-20
B-10	0.0158704	0.0151625	---	---	0.0064917	0.0065252
B-11	0.0643536	0.0614842	---	---	0.0265916	0.0267289
C	0.0203704	0.0197463	0.0000308	0.0000447	0.0081572	0.0081995
O	0.0001353	0.0000534	0.0000013	0.0000013	---	---
Na	---	---	0.0181363	0.0176957	---	---
Si	0.0002522	0.0002235	0.0001651	0.0001707	0.0003240	0.0003166
Al	0.0000021	0.0000028	0.0000043	0.0000042	0.0000007	0.0000007
Mn	0.0002004	0.0002204	0.0002432	0.0002501	0.0004590	0.0004637
Cr	0.0023506	0.0026105	0.0029562	0.0030295	0.0066140	0.0067020
Fe	0.0084649	0.0093681	0.0104363	0.0109693	0.0236747	0.0240177
Ni	0.0010327	0.0011621	0.0013233	0.0013539	0.0026819	0.0027122
Cu	0.0000314	0.0000325	0.0000357	0.0000374	0.0000634	0.0000651
Mo	0.0000157	0.0000162	0.0000174	0.0000183	0.0000268	0.0000283
P	0.0000040	0.0000040	0.0000040	0.0000042	0.0000154	0.0000155
S	0.0000013	0.0000012	0.0000012	0.0000013	0.0000114	0.0000114
Cl	---	---	0.0000006	0.0000006	---	---
Ca	---	---	0.0000042	0.0000041	---	---
Co	0.0000040	0.0000037	0.0000037	0.0000043	0.0000193	0.0000191

TABLE 7.2. (contd)

Isotope	Master 605 20-31	Master 605 31-36	Master 606 0-6	Master 606 6-20	Master 606 20-31	Master 606 31-36
B-10	---	---	0.0064917	0.0065252	---	---
B-11	---	---	0.0265916	0.0267289	---	---
C	0.0000308	0.0000447	0.0081572	0.0081995	0.0000308	0.0000447
O	0.0000013	0.0000013	---	---	0.0000013	0.0000013
Na	0.0181363	0.0176957	---	---	0.0181363	0.0176957
Si	0.0001651	0.0001707	0.0003240	0.0003166	0.0001651	0.0001707
Al	0.0000043	0.0000042	0.0000007	0.0000007	0.0000043	0.0000042
Mn	0.0002432	0.0002501	0.0004590	0.0004637	0.0002432	0.0002501
Cr	0.0029562	0.0030295	0.0066140	0.0067020	0.0029562	0.0030295
Fe	0.0104363	0.0109693	0.0236747	0.0240177	0.0104363	0.0109693
Ni	0.0013233	0.0013539	0.0026819	0.0027122	0.0013233	0.0013539
Cu	0.0000357	0.0000374	0.0000634	0.0000651	0.0000357	0.0000374
Mo	0.0000174	0.0000183	0.0000268	0.0000283	0.0000174	0.0000183
P	0.0000040	0.0000042	0.0000154	0.0000155	0.0000040	0.0000042
S	0.0000012	0.0000013	0.0000114	0.0000114	0.0000012	0.0000013
Cl	0.0000006	0.0000006	---	---	0.0000006	0.0000006
Ca	0.0000042	0.0000041	---	---	0.0000042	0.0000041
Co	0.0000037	0.0000043	0.0000193	0.0000191	0.0000037	0.0000043

TABLE 7.2. (contd)

Isotope	Master 607 0-6	Master 607 6-20	Master 607 20-31	Master 607 31-36	Master 608 0-6	Master 608 6-20
B-10	0.0320920	0.0322578	---	---	0.0320920	0.0322578
B-11	0.0027949	0.0028093	---	---	0.0027949	0.0028093
C	0.0091012	0.0091484	0.0000308	0.0000447	0.0091012	0.0091484
O	0.0000304	0.0000305	0.0000013	0.0000013	0.0000304	0.0000305
Na	---	---	0.0181363	0.0176957	---	---
Si	0.0003247	0.0003174	0.0001651	0.0001707	0.0003247	0.0003174
Al	0.0000014	0.0000014	0.0000043	0.0000042	0.0000014	0.0000014
Mn	0.0004582	0.0004629	0.0002432	0.0002501	0.0004582	0.0004629
Cr	0.0066140	0.0067020	0.0029562	0.0030295	0.0066140	0.0067020
Fe	0.0236395	0.0239823	0.0104363	0.0109693	0.0236395	0.0239823
Ni	0.0026828	0.0027131	0.0013233	0.0013539	0.0026828	0.0027131
Cu	0.0000624	0.0000641	0.0000357	0.0000374	0.0000624	0.0000641
Mo	0.0000268	0.0000283	0.0000174	0.0000183	0.0000268	0.0000283
P	0.0000154	0.0000155	0.0000040	0.0000042	0.0000154	0.0000155
S	0.0000114	0.0000114	0.0000012	0.0000013	0.0000114	0.0000114
Cl	---	---	0.0000006	0.0000006	---	---
Ca	0.0000036	0.0000036	0.0000042	0.0000041	0.0000036	0.0000036
Co	0.0000182	0.0000180	0.0000037	0.0000043	0.0000182	0.0000180

TABLE 7.2. (contd)

Isotope	Master 608 20-31	Master 608 31-36	Master 609 0-6	Master 609 6-20	Master 609 20-31	Master 609 31-36
B-10	---	---	0.0064917	0.0065252	---	---
B-11	---	---	0.0265916	0.0267289	---	---
C	0.0000308	0.0000447	0.0081572	0.0081995	0.0000308	0.0000447
O	0.0000013	0.0000013	---	---	0.0000013	0.0000013
Na	0.0181363	0.0176957	---	---	0.0181363	0.0176957
Si	0.0001651	0.0001707	0.0003240	0.0003166	0.0001651	0.0001707
Al	0.0000043	0.0000042	0.0000007	0.0000007	0.0000043	0.0000042
Mn	0.0002432	0.0002501	0.0004590	0.0004637	0.0002432	0.0002501
Cr	0.0029562	0.0030295	0.0066140	0.0067020	0.0029562	0.0030295
Fe	0.0104363	0.0109693	0.0236747	0.0240177	0.0104363	0.0109693
Ni	0.0013233	0.0013539	0.0026819	0.0027122	0.0013233	0.0013539
Cu	0.0000357	0.0000374	0.0000634	0.0000651	0.0000357	0.0000374
Mo	0.0000174	0.0000183	0.0000268	0.0000283	0.0000174	0.0000183
P	0.0000040	0.0000042	0.0000154	0.0000155	0.0000040	0.0000042
S	0.0000012	0.0000013	0.0000114	0.0000114	0.0000012	0.0000013
Cl	0.0000006	0.0000006	---	---	0.0000006	0.0000006
Ca	0.0000042	0.0000041	---	---	0.0000042	0.0000041
Co	0.0000037	0.0000043	0.0000193	0.0000191	0.0000037	0.0000043

TABLE 7.2. (contd)

Isotope	Master 610 0-6	Master 610 6-20	Master 610 20-31	Master 610 31-36	Master 611 0-6	Master 611 6-20
B-10	0.0064917	0.0065252	---	---	0.0320920	0.0322578
B-11	0.0265916	0.0267289	---	---	0.0027949	0.0028093
C	0.0081572	0.0081995	0.0000308	0.0000447	0.0091012	0.0091484
O	---	---	0.0000013	0.0000013	0.0000304	0.0000305
Na	---	---	0.0181363	0.0176957	---	---
Si	0.0003240	0.0003166	0.0001651	0.0001707	0.0003247	0.0003174
Al	0.0000007	0.0000007	0.0000043	0.0000042	0.0000014	0.0000014
Mn	0.0004590	0.0004637	0.0002432	0.0002501	0.0004582	0.0004629
Cr	0.0066140	0.0067020	0.0029562	0.0030295	0.0066140	0.0067020
Fe	0.0236747	0.0240177	0.0104363	0.0109693	0.0236395	0.0239823
Ni	0.0026819	0.0027122	0.0013233	0.0013539	0.0026828	0.0027131
Cu	0.0000634	0.0000651	0.0000357	0.0000374	0.0000624	0.0000641
Mo	0.0000268	0.0000283	0.0000174	0.0000183	0.0000268	0.0000283
P	0.0000154	0.0000155	0.0000040	0.0000042	0.0000154	0.0000155
S	0.0000114	0.0000114	0.0000012	0.0000013	0.0000114	0.0000114
Cl	---	---	0.0000006	0.0000006	---	---
Ca	---	---	0.0000042	0.0000041	0.0000036	0.0000036
Co	0.0000193	0.0000191	0.0000037	0.0000043	0.0000182	0.0000180

TABLE 7.2. (contd)

Isotope	Master 611 20-31	Master 611 31-36	Master 612 0-6	Master 612 6-20	Master 612 20-31	Master 612 31-36
B-10	---	---	0.0320920	0.0322578	---	---
B-11	---	---	0.0027949	0.0028093	---	---
C	0.0000308	0.0000447	0.0091012	0.0091484	0.0000308	0.0000447
O	0.0000013	0.0000013	0.0000304	0.0000305	0.0000013	0.0000013
Na	0.0181363	0.0176957	---	---	0.0181363	0.0176957
Si	0.0001651	0.0001707	0.0003247	0.0003174	0.0001651	0.0001707
Al	0.0000043	0.0000042	0.0000014	0.0000014	0.0000043	0.0000042
Mn	0.0002432	0.0002501	0.0004582	0.0004629	0.0002432	0.0002501
Cr	0.0029562	0.0030295	0.0066140	0.0067020	0.0029562	0.0030295
Fe	0.0104363	0.0109693	0.0236395	0.0239823	0.0104363	0.0109693
Ni	0.0013233	0.0013539	0.0026828	0.0027131	0.0013233	0.0013539
Cu	0.0000357	0.0000374	0.0000624	0.0000641	0.0000357	0.0000374
Mo	0.0000174	0.0000183	0.0000268	0.0000283	0.0000174	0.0000183
P	0.0000040	0.0000042	0.0000154	0.0000155	0.0000040	0.0000042
S	0.0000012	0.0000013	0.0000114	0.0000114	0.0000012	0.0000013
Cl	0.0000006	0.0000006	---	---	0.0000006	0.0000006
Ca	0.0000042	0.0000041	0.0000036	0.0000036	0.0000042	0.0000041
Co	0.0000037	0.0000043	0.0000182	0.0000180	0.0000037	0.0000043

TABLE 7.2. (contd)

Isotope	Master 613 0-6	Master 613 6-20	Master 613 20-31	Master 613 31-36	Master 614 0-7	Master 614 7-12
B-10	0.0303603	0.0303602	---	---	---	---
B-11	0.0026441	0.0026441	---	---	---	---
C	0.0085390	0.0085401	0.0000564	0.0000187	0.0000307	0.0005925
O	0.0000287	0.0000287	---	---	0.0000013	---
Na	0.0092937	0.0092940	0.0033792	---	0.0183592	---
Si	0.0001411	0.0001451	0.0001710	0.0000683	0.0001224	0.0000724
Al	0.0000042	0.0000042	0.0000011	---	0.0000049	---
Mn	0.0001914	0.0001977	0.0002470	0.0001059	0.0002440	0.0006778
Cr	0.0025201	0.0025901	0.0039716	0.0011891	0.0029680	0.0018719
Fe	0.0088680	0.0091202	0.0143059	0.0042791	0.0104602	0.0772265
Ni	0.0011124	0.0011407	0.0016121	0.0004802	0.0013012	0.0007425
Cu	0.0000219	0.0000230	0.0000386	0.0000172	0.0000300	0.0000242
Mo	0.0000099	0.0000103	0.0000110	0.0000083	0.0000145	0.0000119
P	0.0000041	0.0000043	0.0000077	0.0000028	0.0000045	0.0000237
S	0.0000020	0.0000021	0.0000048	0.0000007	0.0000011	0.0000322
Cl	---	---	---	---	0.0000006	---
Ca	0.0000034	0.0000034	---	---	0.0000042	---
Co	0.0000062	0.0000062	0.0000126	---	---	---

TABLE 7.2. (contd)

Isotope	Master 614 12-23	Master 615 0-6	Master 615 6-20	Master 615 20-31	Master 615 31-36	Master 616 0-6
B-10	---	0.0631433	0.0632983	---	---	0.0313728
B-11	---	0.0059024	0.0058759	---	---	0.0029308
C	0.0000354	0.0212450	0.0209466	0.0000308	0.0000447	0.0105561
O	---	0.0000425	0.0000457	0.0000013	0.0000013	0.0000218
Na	---	---	---	0.0181363	0.0176957	0.0082828
Si	0.0000726	0.0001111	0.0001112	0.0001651	0.0001707	0.0001493
Al	---	---	---	0.0000043	0.0000042	0.0000032
Mn	0.0001664	0.0001603	0.0001619	0.0002432	0.0002501	0.0002182
Cr	0.0018830	0.0018148	0.0018260	0.0029562	0.0030295	0.0026165
Fe	0.0068638	0.0065099	0.0065526	0.0104363	0.0109693	0.0092644
Ni	0.0007560	0.0007583	0.0007603	0.0013233	0.0013539	0.0011576
Cu	0.0000246	0.0000290	0.0000290	0.0000357	0.0000374	0.0000337
Mo	0.0000121	0.0000147	0.0000146	0.0000174	0.0000183	0.0000168
P	0.0000046	0.0000040	0.0000040	0.0000040	0.0000042	0.0000040
S	0.0000012	0.0000013	0.0000012	0.0000012	0.0000013	0.0000013
Cl	---	---	---	0.0000006	0.0000006	0.0000003
Ca	---	---	---	0.0000042	0.0000041	0.0000019
Co	---	0.0000040	0.0000037	0.0000037	0.0000043	0.0000040

TABLE 7.2. (contd)

Isotope	Master 616 6-20	Master 616 20-31	Master 616 31-36
B-10	0.0316774	---	---
B-11	0.0029410	---	---
C	0.0105002	0.0000308	0.0000447
O	0.0000235	0.0000213	0.0000013
Na	0.0083768	0.0181363	0.0176957
Si	0.0001495	0.0001651	0.0001707
Al	0.0000031	0.0000043	0.0000042
Mn	0.0002200	0.0002432	0.0002501
Cr	0.0026328	0.0029562	0.0030295
Fe	0.0093247	0.0104363	0.0109693
Ni	0.0011622	0.0013233	0.0013539
Cu	0.0000338	0.0000357	0.0000374
Mo	0.0000167	0.0000174	0.0000183
P	0.0000040	0.0000040	0.0000042
S	0.0000012	0.0000012	0.0000013
Cl	0.0000003	0.0000006	0.0000006
Ca	0.0000019	0.0000042	0.0000041
Co	0.0000037	0.0000037	0.0000043

TABLE 7.3 Rod Worths in ZPPR-17A

Rod Description	Worth, ϕ^a
CRP	-8.2 ± 0.2
50% Natural Plate	-78.3 ± 1.0
100% Natural Plate	-108.1 ± 1.3
Half-inserted 100% Natural Plate	-62.0 ± 0.8
Tight-packed Natural Pellets	-70.7 ± 0.9
Enriched Pellets in Calandria	-119.6 ± 1.5
Tight-packed Enriched Pellets	-109.1 ± 1.3
Half-inserted 100% Enriched Plates	-82.0 ± 1.0
50% Enriched Plates	-120.4 ± 1.5
2 x 3 100% Natural Plates	-139.8 ± 1.7
2 x 2 100% Natural Plates Off Center	-112.4 ± 1.4
3 x 3 CRP	-30.4 ± 0.4
3 x 3 100% Natural Plates	-172.1 ± 2.1

^aWith respect to subcritical reference reactivity of $-26.4 \pm 0.3\phi$.

Fig. 7.1. Loading Pattern for Close-packed Pin Control Rod.