ANL-ZPR-480

**ZPPR PROGRESS REPORT:
AUGUST 1987 THROUGH OCTOBER 1987**

edited by

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ABSTRACT

Results are presented from the axially heterogeneous assembly ZPPR-17, a part of the JUPITER-III program. The loading of the ZPPR-17B assembly, with 25 control rod positions, is described along with operational measurements, calculation models, measurements and predictions of criticality and measured axial worth profiles for B₄C. From ZPPR-17A, calculated and measured results are given for banks of control rod positions along with revised measured values for various single, central control rods.

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1. PROGRAM STATUS (S. B. Brumbach, P. J. Collins and R. W. Schaefer)

This report describes the progress in the period August through October, 1987 in the JUPITER-III program, a cooperative study between the USDOE and PNC of Japan. Most of the period was spent converting from the axially heterogeneous assembly ZPPR-17 to the very large, homogeneous assembly ZPPR-18. The initial configuration, ZPPR-18A, has a core volume of slightly over 8000 liters and contains 24 control rod positions. Construction of ZPPR-18A was completed on October 16, 1987. A feature of the ZPPR-18 assemblies is the presence of two outer core zones; one with plutonium fuel along the x-axis and one with uranium fuel along the y-axis. The design of the assembly was chosen to enable measurements to be made along the x-axis, which are representative of an 1100 MWe-size plutonium fuelled LMR design. Total fissile mass of ZPPR-18A is slightly over 3400 kg.

Several measurements have been completed in ZPPR-18A. These include all operational measurements, kinetic parameters (noise and boron oscillator) reaction rate distributions and gamma ray dose distributions.

Calculations for the reference loadings of ZPPR-17A, 17B and 17C have been made using nodal diffusion and nodal transport methods using xyz-geometry models. An improved cross section library is being produced using group-dependent bucklings for different cell types obtained from the initial ZPPR-17A calculation.

Processing of control worth measurements made in ZPPR-17A is complete and the results are included in this report. Processing of the ZPPR-17B control worth data was delayed due to an error in the source specifications in the DIF3D code. This problem has now been resolved and the data reduction is nearing completion.

Data from the foil irradiations in ZPPR-17A, including adjustment to cell-average values are now available and the results will be included in the next report. Several additional in-cell measurements for positions

adjacent to control positions in ZPPR-17B and adjacent to control rods in ZPPR-17C are presently being processed.

Analysis of reactivity experiments performed in ZPPR-17A are in progress. Calculations have been done for all the radial tube and axial tube small-sample worth experiments. For these experiments, xyz geometry and nodal diffusion theory were used to get basic results, and then calculated corrections were applied. The corrections are for transport effects, intra-node position, and presence of the tube (in axial measurements). Despite all these adjustments, unusually large C/E variations exist. This stimulated the cross section improvement effort mentioned above. In addition, the bowing oscillator experiment has been analyzed, again including a number of refinements. The C/E for this experiment is approximately 1.3. There are many other reactivity experiments still to be analyzed.

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

The second phase of the ZPPR-17 axially heterogeneous benchmark program was represented by a configuration designated ZPPR-17B. The primary difference between ZPPR-17B and its predecessor ZPPR-17A was the addition of 25 sodium-filled, two-by-two drawer, control rod positions (CRPs). In order to compensate for the reactivity lost by replacing fuel drawers with sodium-filled drawers, the ratio of double-fuel-column drawers to single-fuel-column drawers was increased. A total of 216 fuel drawers were converted from one to two fuel columns. In addition, the fission chamber which was in 256-45 in ZPPR-17A was moved to 257-45 in ZPPR-17B to accommodate a CRP. All other fission chambers, operating rods and zone boundaries were in their ZPPR-17A locations.

An interface diagram of ZPPR-17B is shown in Fig. 2.1. The CRPs contain "light" sodium over their entire 914 mm length. Atom densities for these drawers (master 601) were given in ANL-ZPR-476, p. 65.

The ZPPR-17B critical reference was established on May 8, 1987, in loading number 88, reactor run number 96. The excess reactivity, determined in a positive period measurement, was $11.7 \pm 0.1\%$ at an average core temperature of 27.09°C. The interface diagram is given in Fig. 2.1 with the matrix locations marked with an "X" containing double-fuel-column drawers. A loading summary is given in Table 2.1 and mass summaries for various regions are given in Table 2.2. For convenience, the term "inner core" is applied to that region of the core which contains the internal blanket.

The ZPPR-17B subcritical reference was established on May 7, 1987, in loading 87, reactor run number 95. The reactivity was $-22.4 \pm 0.2\%$ determined by inverse kinetics analysis of a rod drop. The interface diagram is given in Fig. 2.1 with the matrix locations marked with an "X" containing single-fuel-column drawers. The total fissile mass was 4.415 kg less in the subcritical reference than in the critical reference.

TABLE 2.1. Drawer Loading Summary for the
ZPPR-17B Critical Reference

<u>Inner Core - Drawers with Internal Blanket</u>	
Drawers with one column of fuel (Includes 23 drawers with fission chambers and 8 narrow drawers adjacent to PSRs)	888
Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	584
<u>Outer Core</u>	
Drawers with one column of fuel (Includes 28 drawers with fission chambers, two drawers with thermocouples, and 16 narrow drawers adjacent to PSRs)	1128
Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	760
<u>Control Rod Position Drawers</u>	
Drawers filled with sodium cans	200
<u>Radial Blanket</u>	
Radial blanket drawers (Includes 13 drawers with fission chambers)	1752
<u>Radial Reflector</u>	
Stainless-steel-filled reflector drawers (Includes one drawer with fission chamber)	1272

TABLE 2.2. Mass Summary for Various Regions in the
ZPPR-17B Critical Reference

Material	Mass, kg ^b					CRP
	Inner Core	Outer Core	Internal Blanket	Radial Blanket	Axial Blanket	
Total Pu	892.778	1656.825	---	---	---	---
Fissile Pu	787.030	1460.446	---	---	---	---
Total Fissile	796.303	1477.526	4.775	47.500	21.066	---
²³⁸ Pu	0.439	0.718	---	---	---	---
²³⁹ Pu	780.554	1448.947	---	---	---	---
²⁴⁰ Pu	103.600	192.665	---	---	---	---
²⁴¹ Pu ^a	6.477	11.499	---	---	---	---
²⁴² Pu	1.708	2.996	---	---	---	---
Americium ^a	9.473	17.498	---	---	---	---
²³⁵ U	9.272	17.080	4.775	47.500	20.066	---
²³⁸ U	4302.801	7918.418	2213.234	22109.920	9237.605	---
Total Heavy Metal	5214.320	9609.824	2218.009	22157.420	9257.672	---
O	614.954	1128.316	250.428	2515.876	671.492	0.020
Na	549.835	1004.801	239.571	678.242	1001.392	391.486
Mo	83.566	155.169	1.505	8.932	16.027	1.564
Steel ^c	2438.270	4453.914	980.128	4557.519	5552.960	776.287

^aMasses for all isotopes decayed to the date 5/11/87.

^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. Interface Diagram for the ZPPR-17B Reference Configurations.

3. OPERATIONAL MEASUREMENTS IN ZPPR-17B (R. W. Goin)

Operational measurements in ZPPR-17B were limited to the reactivities of the reference configurations (presented in Section 5 of this report), shim rod calibrations and a source term for the ex-core power monitors. Gap coefficient, temperature coefficient and delayed neutron parameters from ZPPR-17A were used for ZPPR-17B data processing.

Only shim rod 5 and poison safety rod 31 were calibrated. The rods were calibrated by driving them through their full range of travel for three full cycles, then fitting the resulting reactivity history to a fourth-order polynomial in rod position and a third-order polynomial in time. The resulting calibration coefficients are given in Table 3.1. The data were recorded in file 6 of the DATAZ17B.Z01 dataset. The measurement was done in reactor run 96.

The effective source term for the two ex-core power monitors was measured in reactor run 95 and the data recorded as file 3 on DATAZ17B.Z01. The measurement was done starting at 0.2×10^{-7} on EXP1 and dropping group 2 rods, which perturb the detector efficiency ratio least. The resulting source terms are $165.35 \pm 0.25 \Delta k/k$ counts s^{-1} for EXP1 and $139.25 \pm 0.23 \Delta k/k$ counts s^{-1} for EXP2.

TABLE 3.1. Shim Rod Calibration Coefficients^a

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, \$
SR 5	163-63	-8.1008	19.400	-22.768	37.873	0.057	0.1527 $\pm$ 0.0010
PSR 31	134-63	-6.5192	16.414	-22.407	38.661	0.031	0.1594 $\pm$ 0.0010

^a $R = (C_1X + C_2X^2 + C_3X^3 + C_4X^4)$, where X is the rod position in inches measured from the fully withdrawn position, and R is the reactivity in cents.

4. CALCULATION MODELS FOR ZPPR-17B (G. L. Grasseschi and P. J. Collins)

The initial calculations for ZPPR-17B used the multigroup cross sections processed for ZPPR-17A from the ENDF/B-V.2 data files. The cells were processed for resonance and spatial heterogeneities with the SDX code using asymptotic cell models and collapsed to 21 groups using a slab model in the axial dimension. The procedure is described in detail in ANL-ZPR-476, p. 17 et seq. Anisotropic transport cross sections, generated by the Benoist approximation were used in all calculations. Cross sections for boron in experimental control rods were processed at infinite-dilution, but data for the ZPPR shim-control rods came from a special cell model of the "narrow drawer" in order to homogenize the cross sections over the area of one matrix tube.

The reference calculation model assumed 1/8-core symmetry, neglecting minor asymmetries in the loading due to fission chamber and thermocouple drawers. The compositions of the principal drawer masters were represented individually. The xy map of the model is shown in Fig. 4.1 with the drawer masters identified by number. A description of the new drawer masters introduced in ZPPR-17B is given in Table 4.1. The majority of the drawer masters were the same as used in ZPPR-17A and are described in ANL-ZPR-476, Table 3.2, p. 22. Isotopic compositions for ZPPR-17B, derived for the weighted average of each drawer-type (e.g. single-column or double-column fuel) and for the different axial regions are given in Table 4.2. Average compositions for the inner core (defined as the fuel region above the internal blanket) and for the outer core are also given at the end of the table.

TABLE 4.1. Drawer Masters in ZPPR-17B

Zone	Master	Description ^a
Core Without	101	Fuel-SC
Internal Blanket	102	Fuel-SC
(Outer Core)	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
	226	Fuel-DC
	227	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 4.1. (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
Control Rod Position	803	Fuel-DC-PSR
	804	Fuel-DC-PSR
	601	CRP
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 4.2. 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 4.2. (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 4.2. (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 4.2. (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 4.2. (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

	-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	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	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	226	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	207	203	102	103	203	106	501	501	501	501	501	502	502	404	404	404	404	404	.	.	.	.	.	.	.
130	106	203	102	101	207	103	226	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	203	601	601	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	601	601	103	104	203	226	105	203	106	226	203	106	207	203	101	501	501	501	501	501	502	502	403	403	403	.	.	.	.	.
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	502	403	403	403	403	.	.	.	.
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	502	502	403	403	403	.	.	.	.
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	502	403	403	403	403	.	.	.
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	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	205	205	107	107	203	102	105	207	203	102	203	104	102	501	501	501	501	502	502	402	402	402	.	.
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	502	502	402	402	402	402	.
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	502	402	402	402	402	.
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	502	402	402	402	402	.
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	502	502	402	402	402	.
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	502	502	402	402	402	.
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	502	402	402	402	.
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	502	402	402	402	.
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	502	402	402	402	.
148	601	205	107	107	205	107	107	601	601	107	205	107	107	205	107	107	202	103	106	207	104	102	203	105	501	501	501	501	502	402	402	402	.

Fig. 4.1. The xyz Calculational Model for ZPPR-17B.

5. CALCULATED K-EFFECTIVE AND DELAYED NEUTRON PARAMETERS FOR ZPPR-17B
(G. L. Grasseschi and P. J. Collins)

The reference calculation for ZPPR-17B employed a nodal diffusion (NDT) solution in xyz geometry (Section 4). Nine axial nodes, chosen to follow the region boundaries and generally around 9 cm spacing, were used. However, two axial nodes of width 7.5 cm were used over the half height of the internal blanket. The nodal diffusion calculation was for the core with operating shim rods fully withdrawn and also with the shim rods inserted to the core/axial blanket interface for calculations of reaction rate distributions.

A nodal transport calculation (NTT) was also made for ZPPR-17B. For economy, this calculation was made only for the case with the shim rods inserted.

Since the transition to nodal diffusion calculations at ZPPR is not yet complete with respect to the various editing codes, a few finite-difference diffusion (FDDT) calculations were also performed in both 21 groups and in 6 groups. The 6 group calculations were used for control rod studies. The group condensation was performed with the 21 group fluxes from the xyz models on a region basis. Finally, an rz model, with the CRP banks represented as thin annuli to preserve their volume, was constructed for analytical studies.

The k-effectives from the various models of ZPPR-17B are given in Table 5.1. The effects of several modelling approximations 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 course 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.

A comparison of the k-effective results (C/E values) for ZPPR-17B and ZPPR-17A is given in Table 5.2. The experimental values of k-effective for ZPPR-17B are given in Table 5.3. The diffusion theory predictions for 17B are about 0.2% lower than those for 17A due to leakage effects in the CRPs. The nodal transport prediction for ZPPR-17B is 0.13% Δk lower than for ZPPR-17A. Note, however, that the results for ZPPR-17A (ANL-ZPR-476, p. 36) indicated that the nodal method in DIF3D underestimated the transport effect by 0.2% Δk . Previous tests of the nodal transport method* indicated that the methods accounted for at least 80% of the transport correction in the radially-heterogeneous core, ZPPR-13B/4. The present comparisons indicate that a little less than 70% of the S_4 transport effect is obtained by the nodal method.**

Delayed neutron parameters for ZPPR-17B have been calculated with the finite-diffusion model in xyz geometry and 21 groups (Case 4 in Table 5.1). The values are given in Table 5.4. The effective delayed neutron fraction is only 0.33% different from that for ZPPR-17A (ANL-ZPR-476, p. 37) while the prompt neutron lifetime changes by 5%.

*R. D. Lawrence, "Three-Dimensional Nodal Diffusion and Transport Methods for the Analysis of Fast-Reactor Critical Experiments," Proc. of the Topical Meeting on Reactor Physics and Shielding, September 17-19, 1984, Chicago, USA (1984).

**The rz transport effect calculated for ZPPR-17A has been independently confirmed by a transport calculation in xyz geometry. T. Takeda, Osaka University, private communication.

TABLE 5.1. 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	0.987700

^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 5.2. Comparison of Calculated k-effective Values for ZPPR-17B and ZPPR-17A

Calculation Model ^a	k-effective ZPPR-17B ^b	k-effective ZPPR-17A ^b
Nodal Diffusion	0.98434	0.98657
Finite Difference Diffusion	0.98640	0.98932
Nodal Transport ^c	0.98931	0.99063
Nodal Diffusion with TWODANT S4 Transport Correction	(0.99128) ^d	0.99260

^aAll calculations in 21 groups, xyz geometry with plate-cell streaming effects by Benoist method.

^bC/E result accounting for experimental excess reactivity.

^cCorrecting for reactivity of partially inserted shim rods (0.0415%Δk) from diffusion calculations.

^dAssuming TWODANT/NTT correction from ZPPR-17A.

TABLE 5.3. 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 5.4. 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 $4.895 \times 10^{-7} s$

6. CONTROL ROD WORTHS IN ZPPR-17A: CRP BANKS, REVISED CENTRAL ROD WORTHS AND CALCULATION RESULTS (S. B. Brumbach, T. Yamamoto* and P. J. Collins)

6.1. Introduction

Two series of control rod worth measurements were made in ZPPR-17A. The first series was a study of several single rod designs of varying geometry and boron enrichment made at the core center. The experimental worths for this series were determined both by inverse kinetics analysis and by subcritical multiplication and the results have been reported in ANL-ZPR-476, p. 65. The second series of measurements was made at the end of the ZPPR-17A experiments, prior to the conversion of the core to the ZPPR-17B configuration. These latter measurements were the worth of a bank of four control rods and four control rod positions (CRPs) relative to fuel and the worths of progressively loading the central CRP and the three CRP banks of the ZPPR-17B configuration.

Experimental worths for the control rod and CRP banks were determined by the modified subcritical multiplication method, using the McCRUNCH code together with calculated detector efficiencies and effective source ratios. By making one additional calculation for a central control rod, the least squares fitting method of McCRUNCH enabled a revision of the central rod worths to be made.

Calculated worths and comparisons with experiment, at this stage, are limited to the finite-difference diffusion results obtained during the course of the effective source calculations.

6.2 Details of the Experiments

The control worths were measured in the ZPPR-17A subcritical reference core described in ANL-ZPR-476, p. 4 with the single exception that

*On assignment from the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan.

the fission chamber originally in 256-45 was moved to 257-45. Prior to the control bank measurements, this reference loading was established and its reactivity determined by inverse kinetics analysis of a rod drop to be -29.27ϕ with an uncertainty (1σ) of 0.23ϕ .

The positions of the CRP banks and of the special banks of four rods are shown in Fig. 6.1. The control positions were made up of drawers filled with stainless-steel-clad sodium plates. The compositions are given in Section 4 of this report. A reference control rod design consisting of four drawers loaded with natural $B_{4}C$ plates was chosen for all control bank experiments in ZPPR-17. The composition of this rod (the 100% natural $B_{4}C$ plate rod, Master 604) is given in ANL-ZPR-476, p. 70.

The control worths were determined from the countrates of 64 ^{235}U fission chamber detectors which replaced sodium plates in the normal cells. Five additional fission chambers, which were 6.4 mm thick instead of 12.7 mm thick for the regular chambers were also present in the core. Countrates for these detectors were recorded, along with those for two ex-core ionization chambers, but were not included in the regular data reduction because of extensive modifications that would be required to the McCRUNCH code. Data from these additional chambers has negligible impact on the results from the regular 64 chambers, but their predictions were examined for consistency.

The control bank experiments were made between April 28, 1987, and May 1, 1987, in reactor runs 85 to 91 and the data were recorded on the 64-detector files 82 to 88.

The McCRUNCH analysis of the central control rods was made with respect to the subcritical reference file 45, with reactivity determined by inverse kinetics analysis of a rod drop to be -25.16ϕ ($1\sigma = 0.20\phi$). Countrate and other data were recorded on 64-detector files 45 to 57.

6.3. Calculations of Detector Efficiencies and Source Ratios

The standard calculation method for analysis of ZPPR assemblies is nodal diffusion theory with the DIF3D code. However, difficulties were encountered in applying the nodal method to ZPPR-17B and, for expediency in processing the experimental data, the finite difference method was used.

The forward and adjoint fluxes necessary for calculation of detector efficiencies and effective source ratios were obtained with an xyz model of the subcritical reference core (ANL-ZPR-476, p. 17). For economy, these calculations were made in a 6-group condensation of the 21-group data. The energy boundaries of the 6-group set were chosen to be close to those used by analysts at PNC, and are given in ANL-ZPR-476, p. 21. The data were collapsed from a 21-group xyz solution by axial regions (0-15 cm, 15-51 cm, 51-79 cm, 79-91 cm and 91-106 cm) and by radial regions defined by inner blanket, outer core, radial blanket, and radial reflector. Collapsed data 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.

Source-driven calculations for the real flux were made for cases with reactivity below one dollar subcritical. In these cases, the inherent source was proportional to the ^{240}Pu mass in each drawer of the loading. Cases with reactivity closer to critical used a homogeneous flux solution. Detector efficiencies and effective source ratios (defined below) were calculated from the real and adjoint fluxes using a local ZPPR edit core (AMS060) written by G. L. Grasseschi.

Control reactivities were obtained by processing of the experimental data files through the McCRUNCH code (ZPR-TM-365). The definition of the calculated quantities used by the code are gathered together here for convenience.

In the modified subcritical multiplication (MSM) method, an estimate of the reactivity ρ , relative to the reference reactivity ρ_0 , for a given detector, is given by

$$\rho_1 = \rho_0 \frac{R_0}{R_1} \frac{\epsilon_1}{\epsilon_0} \frac{S_1^e}{S_0^e}$$

where R_0 and R_1 are the detector countrates in the reference and subcritical states, ϵ_1/ϵ_0 is the detector efficiency ratio and S_1^e/S_0^e is the effective source ratio.

With f_0 and f_1 the calculated fission rates for the detector and using $\langle \rangle$ to indicate integration in space and energy over the whole reactor, the efficiency and source ratios are calculated using the following expressions:

$$\epsilon_1 = f_1 / \langle F \phi \rangle_1$$

$$S_1^e = \langle \phi_1^* S_1 \rangle / \langle F \phi \rangle_1$$

with similar expressions for ϵ_0 and S_0^e .

Here, S_1 and S_0 are the source strengths, and F_1 and F_0 are the fission production operators. Note that $S_0 = S_1$ and $F_0 = F_1$ for cases where source or fuel are not removed in going from the reference to the altered condition.

The McCRUNCH code provides three analyses of the experimental reactivity:

A) Using all 64 detectors to calculate a mean value. Usually, a few detectors are positioned where efficiencies are not calculated accurately (in relation to the counter statistics); for example, immediately adjacent to control rods. In this case, the value of chi-square is unacceptably high.

B) With automatic rejection of detectors giving reactivities that deviate from the mean by more than 3.6 standard deviations. This criterion is chosen so that there is less than 1% probability of rejecting a valid result assuming a normal distribution for 64 detectors.

C) Performing a linear least squares fit to the reactivities as a function of detector efficiency, with rejection of outliers until the value of chi-square is less than 1.3. This relation is based on the linear relation of asymptotic flux perturbations to a small reactivity perturbation and has been demonstrated by calculational tests. If no fuel is moved, the reactivity is obtained from the fit for an efficiency of unity.

In most cases, all three analyses yield mean reactivities that are consistent within the uncertainties. However, method C (LSFIT) is usually used to obtain the recommended reactivity since the statistical uncertainty is the least. The derived experimental value is insensitive to the accuracy of the calculated efficiency ratios.

Analysis of the more sensitive cores at ZPPR produced a steep gradient in the LSFIT method. This indicated significant errors in the calculated source ratio. This problem could be resolved by iterating on the calculations, for example by changing the boron density in a control rod case, until a good fit was obtained to the measured countrates. However, it was realized that the error in source ratio varied as the square of the error in detector efficiency (roughly because the source ratio is dependent upon the product $\phi\phi^*$). Hence, the initially calculated source ratio could be corrected by using the gradient produced by the LSFIT method. This procedure is described in ZPR-TM-454, p. 3.

In order to correct the source ratio, two additional factors are supplied to McCRUNCH. These are defined by

$$C_s = \frac{\langle \phi_o^* S_1 \rangle \langle F_1 \phi_o \rangle}{\langle \phi_o^* F_1 \phi_o \rangle} \bigg/ \frac{\langle \phi_o^* S_o \rangle \langle F_o \phi_o \rangle}{\langle \phi_o^* F_o \phi_o \rangle}$$

and

$$C_\epsilon = \frac{\langle F_o \phi_o \rangle}{\langle F_1 \phi_o \rangle}$$

Finally, for cases where fuel is removed, the reactivity obtained for the LSFIT method is calculated for an efficiency different from unity, given by

$$E_o = \langle F_o \phi_o \rangle / \langle F_1 \phi_o \rangle$$

The integrals required to form these three factors are calculated by the edit code AMS060 for each case.

6.4 Details of the Experimental Data Processing

This section records the processing of the experimental data in some detail. Results from all three analyses in McCRUNCH are given. The methods are referred to as (A) All, (B) 3.6σ and (C) LSFIT. For ZPPR-17A, any detector immediately adjacent to a control rod or CRP was rejected on input.

The estimated uncertainties are divided into statistical and total components. The statistical uncertainties result from the detector countrates together with a small component due to adjustment of the interface gap, temperature and ^{241}Pu decay relative to the reference. The total uncertainty includes a correlated component resulting from the calibration of the reference reactivity (about 0.8%) and also from the uncertainty in the calculated source ratio (ZPR-TM-454, p. 3).

The data processing for the special rods and CRP banks is summarized in Table 6.1. For simplicity, the worths are defined as positive reactivity changes.

Data processing for the central rods and CRPs was performed using detector efficiencies and source worths calculated for the solid natural B_4C rod and for the CRP. These values were used in the McCRUNCH code to process worths for all the central and near-central rod variations. The results are given in Table 6.2. and a comparison is made with the previously published worths in ANL-ZPR-476, p. 79. These cases are fit very well for the symmetrically loaded rods but rather less well for the off-center rods which produce an asymmetric flux perturbation. Even in these cases, at least 18 detectors are retained in the LSFIT analysis.

6.5 Recommended Worths and Comparison with Calculation

The recommended worths and uncertainties are the LSFIT values. As can be seen from Tables 6.1 and 6.2, the results differ among the three data reduction methods by less than 1% and in most cases by less than 0.3%.

The worths of the central rods and CRPS given in ANL-ZPR-476 should be replaced by the values in Table 6.2.

The worth of a single, central, CRP was measured in both series of experiments. In the first series (Table 6.2) the worth was measured as 0.084\$ and in the second series the worth was 0.076\$ (Table 6.1). In the first measurement, the worth was measured immediately following establishment of the subcritical reference with no other disturbance of the assembly. The second measurement was made after replacing four fuel locations by CRPs and control rods and then reloading the fuel. It is probable that the difference of 0.8¢ between the CRP worths is due to differences in fuel location between the reference and after the four-rod measurement. Therefore, the first measured value is preferred. As will be seen, this choice is supported by consistency in C/E results between the central CRP and the inner CRP banks. Based on this supposition, the worths of the subsequent CRP banks have been increased by 0.8¢.

The recommended control rod and CRP worths for the rod banks, CRP banks and the central control rod and CRP are given in Table 6.3. A comparison is made with the calculated values using the finite-difference diffusion model in xyz geometry and the six-group data. The worth of the four control rods near the center is overpredicted by 4% ($C/E = 1.01$) relative to the worth of the central rod ($C/E = 0.97$). This difference in prediction is rather surprising and may be connected with the fact that the central rod replaces four single-fuel-column drawers while each of the rods in the bank replaces two single-fuel-column drawers and two double-fuel-column drawers. The worths of the CRPs relative to fuel are overpredicted by 10% to 15% as is customary with diffusion calculations. An increasing trend of C/E with radius of the CRPs is clear from the results.

Fig. 6.1. Control Positions used in ZPPR-17A Measurements.

- n CRP location
- S Special measurements of four control rods and CRPs

TABLE 6.1. Data Processing for the Special Control Rod Bank and CRP Banks in ZPPR-17A

Case	File	Method	No. of FCs	χ^2 ^a	Source Ratio	Worth, \$ ^a	σ_s %	σ_t %	E_f	C_s	C_e
4 CRPs	83	All	63	1.26	0.9913	0.587	0.12	0.82	---	---	---
		3.6 σ	63	1.26	0.9913	0.587	0.12	0.82	---	---	---
		LSFIT	63	1.07	0.9927	0.588	0.11	0.92	1.0082	0.9971	1.0076
4 CRs	84	All	60	2.86	0.9778	3.350	0.14	0.85	---	---	---
		3.6 σ	57	1.71	0.9778	3.345	0.11	0.84	---	---	---
		LSFIT	60	1.14	0.9742	3.347	0.07	0.87	1.0050	0.9971	1.0076
Central CRP	85	All	61	0.81	0.9986	0.0756	0.40	1.02	---	---	---
		3.6 σ	61	0.81	0.9986	0.0756	0.39	1.01	---	---	---
		LSFIT	61	0.76	0.9986	0.0756 ^b	0.39	1.71	1.0014	0.9986	1.0013
Center, 6 Inner CRPs	86	All	61	1.90	0.9860	1.048	0.08	0.82	---	---	---
		3.6 σ	61	1.90	0.9860	1.048	0.08	0.82	---	---	---
		LSFIT	61	1.30	0.9860	1.046	0.07	0.89	1.0139	0.9861	1.0133
Center, 6 Inner, 6 middle, CRPS	87	All	59	3.24	0.9770	1.778	0.12	0.85	---	---	---
		3.6 σ	57	2.40	0.9770	1.779	0.10	0.85	---	---	---
		LSFIT	57	1.03	0.9768	1.768	0.08	0.88	1.0239	0.9765	1.0236
All 25 CRPs	88	All	64	3.13	0.9504	6.684	0.14	0.96	---	---	---
		3.6 σ	62	2.64	0.9504	6.689	0.13	0.96	---	---	---
		LSFIT	54	1.16	0.9476	6.641	0.13	0.87	0.9439	0.0439	1.0640

^aWorths are derived relative to the subcritical reference reactivity of $-29.27\phi \pm 0.23\phi$ with data recorded on file 82.

^bRecommended worth for the central CRP is taken from Table 6.2, see text.

TABLE 6.2. Data Processing for Central Control Rods in ZPPR-17A

Case	File	Method	FCs	χ^2	Ratio	Worth, \$ ^a	σ_s %	σ_t %	Difference from ZPR-476, %
2 x 2 CRP	46	All	61	1.090	0.9986	0.0838	0.12	0.90	
		3.6 σ	61	1.090	"	0.0838	0.12	0.90	
		LSFIT	61	1.05	0.9986	0.0837	0.12	1.45	+2
50/50 B ₄ C/Na 2 x 2	47	All	61	9.00	0.9965	0.779	0.15	0.82	
		3.6 σ	55	2.19	"	0.781	0.08	0.81	
		LSFIT	61	1.24	0.9972	0.778	0.06	0.89	-0.6
100% Nat. B ₄ C 2 x 2	48	All	61	3.94	0.9965	1.073	0.09	0.81	
		3.6 σ	57	1.36	"	1.071	0.06	0.81	
		LSFIT	61	0.80	0.9959	1.073	0.04	0.88	-0.7
100% Nat. B ₄ C 2 x 2 Half- inserted	49	All	61	28.6	0.9965	0.619	0.25	0.85	
		3.6 σ	47	1.74	"	0.623	0.08	0.81	
		LSFIT	57	1.24	0.9976	0.618	0.06	0.90	-0.2
Nat. B ₄ C Pins Tight Pack	50	All	61	19.6	0.9965	0.704	0.21	0.84	
		3.6 σ	54	2.22	"	0.708	0.08	0.81	
		LSFIT	61	0.86	0.9976	0.703	0.05	0.90	-0.5
Enr. B ₄ C Pins in Calandria	51	All	61	11.4	0.9965	1.187	0.19	0.83	
		3.6 σ	56	2.84	"	1.183	0.10	0.81	
		LSFIT	61	1.13	0.9951	1.188	0.06	0.88	-0.7
Enr. B ₄ C Pins Tight Pack	52	All	61	3.89	0.9965	1.083	0.11	0.82	
		3.6 σ	58	1.83	"	1.082	0.07	0.81	
		LSFIT	60	1.23	0.9959	1.083	0.06	0.88	-0.7
100% Enr. B ₄ C Half-inserted	53	All	61	4.79	0.9965	0.817	0.11	0.82	
		3.6 σ	57	1.34	0.9965	0.818	0.06	0.81	
		LSFIT	57	1.21	0.9966	0.817	0.06	0.89	-0.4

TABLE 6.2. (contd)

Case	File	Method	FCs	χ^2	Ratio	Worth, \$ ^a	σ_s %	σ_t %	Difference from ZPR-476, %
50% Enr. B ₄ C Plate	54	All	61	11.7	0.9965	1.194	0.19	0.83	
		3.6 σ	56	2.57	"	1.190	0.09	0.81	
		LSFIT	61	1.09	0.9951	1.195	0.06	0.88	-0.7
2 x 3 Nat. B ₄ C Plate	55	All	61	41.0	0.9965	1.387	0.40	0.90	
		3.6 σ	40	3.31	"	1.380	0.13	0.82	
		LSFIT	33	0.92	0.9918	1.395	0.13	0.89	-0.2
2 x 2 Nat. B ₄ C Plate Off-center	56	All	61	30.3	0.9965	1.117	0.31	0.87	
		3.6 σ	35	3.59	"	1.118	0.16	0.82	
		LSFIT	18	0.92	0.9955	1.107	0.10	0.89	-1.4
3 x 3 CRP	57	All	61	7.47	0.9986	0.305	0.15	0.83	
		3.6 σ	51	2.95	"	0.304	0.11	0.83	
		LSFIT	50	1.15	0.9981	0.306	0.07	0.97	+0.7
3 x 3 Nat. B ₄ C Plate	58	All	61	131.0	0.9965	1.710	0.65	1.04	
		3.6 σ	25	3.80	"	1.702	0.16	0.82	
		LSFIT	18	1.08	0.9917	1.721	0.13	0.88	0.0

^aDetector efficiencies and source ratios were calculated only for the case of the 2 x 2 CRP and for the 2 x 2 100% natural B₄C control rod.

^bWorths are derived relative to the subcritical reference reactivity of $-25.16\phi \pm 0.20\phi$ with data recorded on file 45.

TABLE 6.3. Recommended Control and CRP Worths 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 $\beta = 0.3385\%$.

7. AXIAL WORTH PROFILES FOR B₄C IN ZPPR-17B (S. G. Carpenter)

An important advantage of the axially heterogeneous LMR design over conventional cores is the more linear axial worth profile of the control rods which minimizes reactivity variation in seismic events. Axial worth profiles for B₄C were measured in ZPPR-17B in two experiments. In the first experiment, the worth of a four-drawer mockup rod in the central control position was measured for various B₄C insertions using the modified source multiplication technique. In the second experiment, reactivity versus axial location was measured for a one-drawer control rod using the long-drawer technique. In addition, data from an axial small-sample traverse experiment in ZPPR-17A were integrated to provide reactivity values corresponding to an inserted boron column.

7.1. Static Measurements

Measurements were made in a series of steps in the ZPPR-17B subcritical reference modified by only the presence of a control rod in the central control position. The control rod was two-by-two matrix tubes in size. The half-two matrix tubes contained two 914 mm-long drawers and the half-one matrix tube contained one 914 mm-long drawer. A 1.02 m-long absorber segment was formed using four 12.7 mm-wide columns of stainless-steel-clad B₄C in each of the half-two drawers. Sodium cans filled the remainder of the drawers axially above and below the absorber segment. Both sodium and B₄C cans were 0.102 m long, allowing the absorber column to "move" in 0.102 m steps from the core/axial blanket boundary to full insertion.

The modified source multiplication method was used to measure the subcritical reactivities. No calculated detector efficiency changes were generated, and the McCRUNCH data processing was not employed. However, estimates of the effects of efficiency changes on individual detectors are included based on the experimental results. Also, each measurement was accompanied by a rod drop and the two reactivity estimates agreed within about 1%.

The reference reactivity for the measurements was $-21.5 \pm 0.2\%$ as determined in a rod drop in the ZPPR-17B subcritical reference just before adding the control rod. The worth measurements were made in reactor runs 122 to 131 and 135 to 136. A foil irradiation was conducted between reactor runs 132 to 134 which involved the removal and replacement of many drawers. The reference reactivity measurement was repeated after the last rod insertion step and a value of -22.2% was obtained. The 0.7% difference for the same nominal configuration is larger than expected and suggests that unidentified changes the reactor occurred during the series of experiments. For this report, the -21.5% reference is used and an uncertainty of 0.9% is applied.

The reactivities associated with the various rod insertions are given in Table 7.1. Also given are the various drawer masters used to produce a given rod insertion. Atom densities for these masters are given in Table 7.2.

7.2. Long-Drawer Measurements

The long-drawer technique was used to measure the reactivity effect of inserting a column of B_4C into the assembly. The long drawers were loaded with cans of B_4C over 1.02 m of its length and sodium elsewhere. At the beginning of the measurement, the drawers were positioned such that the leading edge of the B_4C was 102 mm above the core/axial blanket boundary. The drawer was then driven 1.1176 m so that the B_4C exactly filled the core region. The drawer was then withdrawn to its starting point, and data was obtained for several in-out cycles.

Atom densities corresponding the the sodium-filled section of the long drawer are given in Table 7.2 for master 638 between 16 and 36 inches. Densities corresponding the the B_4C -filled section are the same as master 638 between 0 and 16 inches.

The measurement was made in the ZPPR-17B critical reference configuration modified only by the presence of the long drawer (loading number 126, reactor run number 139). The long drawer segments were in

149-49 (master 852 containing the B₄C and sodium) and in 249-49 (master 853 containing only sodium). The other three drawers in the central control position contained their standard sodium-filled drawers.

Reactivity values were obtained at one-inch intervals from an inverse kinetics analysis of the power history recorded by the two ex-core BF₃ chambers. Reactivity values at various rod insertions are given in Table 7.3. Statistical uncertainties in reactivities are about 0.02%.

7.3. Axial Tube Measurements in ZPPR-17A

In addition to the long drawer and static techniques in ZPPR-17B, the axial tube small sample oscillator technique was used to measure the axial worth profile of an enriched boron sample in ZPPR-17A. The ZPPR-17A measurement was made in location 159-49, in the region containing internal blanket but well away from the core center. There were no control positions in ZPPR-17A, and location 159-49 contained a double-fuel-column drawer. The enriched boron small sample was a cylinder 55.22 mm long and 10.19 mm in diameter with a ¹⁰B mass of 3.65 g. Reactivity measurements were made at about 51 mm intervals. In order to compare with the other techniques, the small sample reactivities were integrated over the core height. The reactivity versus position data for this boron sample will be reported later with other small-sample reactivity results.

7.4. Comparison of Worth Profiles

Results from the three worth profile measurements are shown in Fig. 7.1. Note that in Fig. 7.1 the rod position of zero corresponds to an insertion of 40 inches. 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. 7.1 shows, the three methods give essentially the same shape, even with a ¹⁰B 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.

Fig. 7.1. Comparison of Axial Worth Profiles of B_4C in ZPPR-17B.

TABLE 7.1. Reactivities for Various Rod Insertions in ZPPR-17B

<u>Reactor Run</u>	<u>Reactor Loading</u>	<u>Data File</u>	<u>Rod Insertion, mm</u>	<u>Reactivity, ρ</u>	<u>Drawer Masters</u>
122	111	115	---	-21.5	601
123	112	116	0 ^a	-29.1	617, 618, 619
124	113	117	101.6	-37.3	617, 620, 621
125	114	118	203.2	-49.6	617, 622, 623
126	115	119	304.8	-61.6	617, 624, 625
127	116	120	406.4	-70.8	617, 626, 627
128	117	121	508.0	-77.7	617, 628, 629
129	118	122	609.6	-85.5	628, 634, 635
130	119	123	711.2	-95.0	630, 636, 635
131	120	124	812.8	-106.4	631, 637, 635
135	123	125	914.4	-115.8	632, 638, 635
136	124	126	1016.0	-119.4	633, 635

^aZero insertion corresponds to the rod parked at the core/axial blanket interface.

TABLE 7.2. Control Rod Compositions
in ZPPR-17B

Isotope	Master 617	Master 618	Master 618
	0-36	0-20	20-36
B-10	---	---	0.0141573
B-11	---	---	0.0573997
C	0.0000328	0.0000308	0.0185744
O	0.0000013	0.0000013	---
Na	0.0182582	0.0183086	---
Si	0.0001700	0.0001692	0.0002231
Al	0.0000057	0.0000057	0.0000029
Mn	0.0002502	0.0002490	0.0002489
Cr	0.0030568	0.0030443	0.0029936
Fe	0.0108185	0.0107354	0.0107492
Ni	0.0013736	0.0013687	0.0013560
Cu	0.0000365	0.0000363	0.0000344
Mo	0.0000180	0.0000179	0.0000173
P	0.0000040	0.0000040	0.0000041
S	0.0000012	0.0000012	0.0000012
Cl	0.0000006	0.0000006	---
Ca	0.0000042	0.0000042	---
Co	0.0000038	0.0000038	0.0000039

TABLE 7.2. (contd)

Isotope	Master 619 0-24	Master 619 24-36	Master 620 0-16	Master 620 16-36	Master 621 0-20	Master 621 20-36
B-10	0.0142491	---	---	0.0141792	0.0142454	---
B-11	0.0577717	---	---	0.0574884	0.0577568	---
C	0.0186900	0.0000367	0.0000308	0.0186022	0.0186852	0.0000352
O	---	0.0000013	0.0000013	---	---	0.0000013
Na	---	0.0181487	0.0183016	---	---	0.0181954
Si	0.0002214	0.0001716	0.0001691	0.0002229	0.0002213	0.0001710
Al	0.0000029	0.0000057	0.0000057	0.0000029	0.0000029	0.0000057
Mn	0.0002460	0.0002524	0.0002488	0.0002485	0.0002458	0.0002517
Cr	0.0029616	0.0030796	0.0030430	0.0029890	0.0029598	0.0030722
Fe	0.0105490	0.0109768	0.0107306	0.0107158	0.0105426	0.0109217
Ni	0.0013432	0.0013827	0.0013683	0.0013541	0.0013425	0.0013796
Cu	0.0000338	0.0000370	0.0000363	0.0000343	0.0000338	0.0000368
Mo	0.0000170	0.0000182	0.0000179	0.0000172	0.0000170	0.0000181
P	0.0000040	0.0000041	0.0000040	0.0000041	0.0000040	0.0000041
S	0.0000012	0.0000013	0.0000012	0.0000012	0.0000012	0.0000012
Cl	---	0.0000006	0.0000006	---	---	0.0000006
Ca	---	0.0000042	0.0000042	---	---	0.0000042
Co	0.0000038	0.0000039	0.0000038	0.0000038	0.0000038	0.0000039

TABLE 7.2. (contd)

Isotope	Master 622 0-12	Master 622 12-36	Master 623 0-16	Master 623 16-36	Master 624 0-8	Master 624 08-36
B-10	---	0.0141939	0.0142399	---	---	0.0142043
B-11	---	0.0575478	0.0577344	---	---	0.0575902
C	0.0000308	0.0186207	0.0186779	0.0000344	0.0000308	0.0186340
O	0.0000013	---	---	0.0000013	0.0000013	---
Na	0.0182898	---	---	0.0182236	0.0182662	---
Si	0.0001691	0.0002227	0.0002211	0.0001707	0.0001690	0.0002226
Al	0.0000057	0.0000029	0.0000029	0.0000057	0.0000057	0.0000029
Mn	0.0002486	0.0002482	0.0002456	0.0002513	0.0002481	0.0002480
Cr	0.0030408	0.0029859	0.0029572	0.0030677	0.0030365	0.0029837
Fe	0.0107226	0.0106934	0.0105331	0.0108886	0.0107065	0.0106774
Ni	0.0013677	0.0013528	0.0013415	0.0013778	0.0013664	0.0013519
Cu	0.0000363	0.0000342	0.0000338	0.0000367	0.0000363	0.0000342
Mo	0.0000179	0.0000172	0.0000170	0.0000180	0.0000179	0.0000172
P	0.0000040	0.0000040	0.0000040	0.0000041	0.0000040	0.0000040
S	0.0000012	0.0000012	0.0000012	0.0000012	0.0000012	0.0000012
Cl	0.0000006	---	---	0.0000006	0.0000006	---
Ca	0.0000042	---	---	0.0000042	0.0000042	---
Co	0.0000038	0.0000038	0.0000038	0.0000038	0.0000039	0.0000038

TABLE 7.2. (contd)

Isotope	Master 625 0-12	Master 625 12-36	Master 626 0-4	Master 626 4-36	Master 627 0-8	Master 627 8-36
B-10	0.0142307	---	---	0.0142122	0.0142124	---
B-11	0.0576973	---	---	0.0576221	0.0576230	---
C	0.0186659	0.0000338	0.0000307	0.0186440	0.0186418	0.0000334
O	---	0.0000013	0.0000013	---	---	0.0000013
Na	---	0.0182424	0.0181960	---	---	0.0182558
Si	0.0002209	0.0001704	0.0001688	0.0002225	0.0002205	0.0001703
Al	0.0000029	0.0000057	0.0000057	0.0000029	0.0000029	0.0000057
Mn	0.0002452	0.0002510	0.0002465	0.0002478	0.0002444	0.0002508
Cr	0.0029528	0.0030647	0.0030235	0.0029821	0.0029440	0.0030625
Fe	0.0105172	0.0108664	0.0106586	0.0106654	0.0104854	0.0108505
Ni	0.0013399	0.0013765	0.0013626	0.0013513	0.0013366	0.0013756
Cu	0.0000337	0.0000367	0.0000363	0.0000341	0.0000337	0.0000366
Mo	0.0000170	0.0000180	0.0000180	0.0000172	0.0000169	0.0000180
P	0.0000040	0.0000040	0.0000039	0.0000040	0.0000039	0.0000040
S	0.0000012	0.0000012	0.0000013	0.0000012	0.0000012	0.0000012
Cl	---	0.0000006	0.0000006	---	---	0.0000006
Ca	---	0.0000042	0.0000042	---	---	0.0000042
Co	0.0000038	0.0000038	0.0000041	0.0000038	0.0000039	0.0000038

TABLE 7.2. (contd)

Isotope	Master 628 0-36	Master 629 0-4	Master 629 4-36	Master 630 0-32	Master 630 32-36	Master 631 0-28
B-10	0.0142061	0.0141578	---	0.0142537	---	0.0142517
B-11	0.0575975	0.0574015	---	0.0577903	---	0.0577823
C	0.0186358	0.0185699	0.0000330	0.0186961	0.0000480	0.0186935
O	---	---	0.0000013	---	0.0000013	---
Na	---	---	0.0182660	---	0.0177835	---
Si	0.0002223	0.0002191	0.0001701	0.0002217	0.0001760	0.0002217
Al	0.0000029	0.0000029	0.0000057	0.0000029	0.0000056	0.0000029
Mn	0.0002474	0.0002421	0.0002506	0.0002464	0.0002579	0.0002463
Cr	0.0029779	0.0029179	0.0030609	0.0029672	0.0031379	0.0029667
Fe	0.0106454	0.0103906	0.0108386	0.0105690	0.0114074	0.0105673
Ni	0.0013499	0.0013268	0.0013750	0.0013455	0.0014069	0.0013454
Cu	0.0000341	0.0000335	0.0000366	0.0000339	0.0000384	0.0000339
Mo	0.0000172	0.0000169	0.0000180	0.0000170	0.0000190	0.0000170
P	0.0000040	0.0000039	0.0000040	0.0000040	0.0000043	0.0000040
S	0.0000012	0.0000012	0.0000012	0.0000012	0.0000013	0.0000012
Cl	---	---	0.0000006	---	0.0000006	---
Ca	---	---	0.0000042	---	0.0000041	---
Co	0.0000038	0.0000041	0.0000038	0.0000037	0.0000044	0.0000038

TABLE 7.2. (contd)

Isotope	Master 631 28-36	Master 632 0-24	Master 632 24-36	Master 633 0-20	Master 633 20-36	Master 634 0-4
B-10	---	0.0142491	---	0.0142454	---	0.0141578
B-11	---	0.0577717	---	0.0577568	---	0.0574015
C	0.0000396	0.0186901	0.0000367	0.0186853	0.0000352	0.0185704
O	0.0000013	---	0.0000013	---	0.0000013	---
Na	0.0180560	---	0.0181487	---	0.0181954	---
Si	0.0001727	0.0002217	0.0001716	0.0002216	0.0001710	0.0002209
Al	0.0000057	0.0000029	0.0000057	0.0000029	0.0000057	0.0000029
Mn	0.0002538	0.0002462	0.0002524	0.0002461	0.0002517	0.0002437
Cr	0.0030944	0.0029661	0.0030796	0.0029653	0.0030722	0.0029449
Fe	0.0110861	0.0105650	0.0109768	0.0105618	0.0109217	0.0104860
Ni	0.0013889	0.0013452	0.0013827	0.0013449	0.0013796	0.0013389
Cu	0.0000374	0.0000339	0.0000370	0.0000339	0.0000368	0.0000339
Mo	0.0000184	0.0000170	0.0000182	0.0000170	0.0000181	0.0000172
P	0.0000041	0.0000040	0.0000041	0.0000040	0.0000041	0.0000039
S	0.0000013	0.0000012	0.0000013	0.0000012	0.0000012	0.0000013
Cl	0.0000006	---	0.0000006	---	0.0000006	---
Ca	0.0000041	---	0.0000042	---	0.0000042	---
Co	0.0000041	0.0000038	0.0000039	0.0000038	0.0000039	0.0000041

TABLE 7.2. (contd)

Isotope	Master 634 4-36	Master 635 0-36	Master 636 0-8	Master 636 8-36	Master 637 0-12	Master 637 12-36
B-10	---	---	0.0142124	---	0.0142307	---
B-11	---	---	0.0576230	---	0.0576973	---
C	0.0000330	0.0000327	0.0186420	0.0000334	0.0186660	0.0000338
O	0.0000013	0.0000013	---	0.0000013	---	0.0000013
Na	0.0182660	0.0182582	---	0.0182558	---	0.0182424
Si	0.0001701	0.0001698	0.0002214	0.0001703	0.0002215	0.0001704
Al	0.0000057	0.0000057	0.0000029	0.0000057	0.0000029	0.0000057
Mn	0.0002506	0.0002500	0.0002452	0.0002508	0.0002457	0.0002510
Cr	0.0030609	0.0030537	0.0029576	0.0030625	0.0029619	0.0030647
Fe	0.0108386	0.0108079	0.0105333	0.0108505	0.0105491	0.0108664
Ni	0.0013750	0.0013722	0.0013427	0.0013756	0.0013439	0.0013765
Cu	0.0000366	0.0000365	0.0000339	0.0000366	0.0000339	0.0000367
Mo	0.0000180	0.0000179	0.0000171	0.0000180	0.0000171	0.0000180
P	0.0000040	0.0000040	0.0000040	0.0000040	0.0000040	0.0000040
S	0.0000012	0.0000012	0.0000012	0.0000012	0.0000012	0.0000012
Cl	0.0000006	0.0000006	---	0.0000006	---	0.0000006
Ca	0.0000042	0.0000042	---	0.0000042	---	0.0000042
Co	0.0000038	0.0000038	0.0000039	0.0000038	0.0000038	0.0000038

TABLE 7.2. (contd)

Isotope	Master	Master
	638 0-16	638 16-36
B-10	0.0142399	---
B-11	0.0577344	---
C	0.0186780	0.0000344
O	---	0.0000013
Na	---	0.0182236
Si	0.0002216	0.0001707
Al	0.0000029	0.0000057
Mn	0.0002460	0.0002513
Cr	0.0029640	0.0030677
Fe	0.0105571	0.0108886
Ni	0.0013446	0.0013778
Cu	0.0000339	0.0000367
Mo	0.0000171	0.0000180
P	0.0000040	0.0000041
S	0.0000012	0.0000012
Cl	---	0.0000006
Ca	---	0.0000042
Co	0.0000038	0.0000038

TABLE 7.3. Reactivity Values for Various Rod Insertions Measured with the Long Drawer Technique

<u>Rod Insertion, mm</u>	<u>Reactivity, ϕ</u>
-101.6	0.00
-76.2	-0.23
-50.8	-0.59
-25.4	-1.02
0 ^a	-1.56
25.4	-2.18
50.8	-2.90
76.2	-3.75
101.6	-4.68
127.0	-5.70
152.4	-6.80
177.8	-8.02
203.2	-9.27
228.6	-10.51
254.0	-11.73
279.4	-12.96
304.8	-14.16
330.2	-15.23
355.6	-16.26
381.0	-17.19
406.4	-18.08
431.8	-18.90
457.2	-19.65
482.6	-20.40
508.0	-21.14
533.4	-21.87
558.8	-22.60
584.2	-23.38
609.6	-24.21
635.0	-25.08
660.4	-26.00
685.8	-26.98
711.2	-28.09
736.6	-29.22
762.0	-30.34
787.4	-31.46
812.8	-32.59
838.2	-33.63
863.6	-34.65
889.0	-35.59
914.4	-36.37
939.8	-37.08
965.2	-37.56
990.6	-37.87
1016.0	-38.08

^aZero insertion corresponds to the rod parked at the core/axial blanket interface.