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**ZPPR PROGRESS REPORT:
NOVEMBER 1987 THROUGH JANUARY 1988**

edited by

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TABLE OF CONTENTS

		<u>Page</u>
1.	<u>PROGRAM STATUS</u> (S. B. Brumbach, P. J. Collins and R. W. Schaefer)	1
2.	<u>REFERENCE CONFIGURATIONS FOR THE ZPPR-17C ASSEMBLY</u> (S. B. Brumbach)	4
3.	<u>OPERATIONAL MEASUREMENTS IN ZPPR-17C</u> (R. W. Goin)	9
4.	<u>CALCULATION MODELS FOR ZPPR-17C</u> (G. L. Grasseschi and P. J. Collins)	11
5.	<u>CALCULATED K-EFFECTIVE AND DELAYED NEUTRON PARAMETERS FOR ZPPR-17C</u> (G. L. Grasseschi and P. J. Collins)	23
6.	<u>MEASUREMENTS AND ANALYSIS OF REACTION RATES IN ZPPR-17A</u> (P. J. Collins, J. M. Gasidlo, D. W. Maddison and G. L. Grasseschi)	28
7.	<u>BASIC DATA FOR REACTION RATE DISTRIBUTION IN ZPPR-17A</u> (D. W. Maddison and J. M. Gasidlo)	80
8.	<u>IN-CELL REACTION RATE MEASUREMENTS AND CELL FACTORS FOR ZPPR-17A</u> (J. M. Gasidlo and D. W. Maddison)	90
9.	<u>IMPROVED CROSS SECTIONS FOR ZPPR-17</u> (R. W. Schaefer)	106
10.	<u>BOWING, EXPANSION AND SMALL-SAMPLE WORTH MEASUREMENTS IN ZPPR-17A</u> (R. W. Schaefer and R. W. Goin)	113
11.	<u>REVISIONS TO EXPERIMENTAL CONTROL ROD WORTHS IN ZPPR-15D</u> (P. J. Collins and D. M. Smith)	185
12.	<u>MEASUREMENT AND ANALYSIS OF 238U DOPPLER REACTIVITY IN ZPPR-15</u> (R. E. Kaiser, J. M. Gasidlo and R. W. Goin)	189

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ABSTRACT

Further results are presented from the axially heterogeneous assembly ZPPR-17, a part of the JUPITER-III program. The loading of the ZPPR-17C assembly, with 13 half-inserted control rods, is described along with operational measurements, calculation models, and measurements and prediction of criticality. From ZPPR-17A, calculated and measured results are given for reaction rates and measured results for bowing, expansion and small sample worth experiments.

From the earlier metal-fuel ZPPR-15 program results are given for measurements and calculations of Doppler reactivity coefficients.

February 15, 1988

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

During the period November 1987 to January 1988 the ZPPR-18 experiments, part of the JUPITER-III program, were completed. The ZPPR-18 assemblies were large (8,000 liter core volume) with 24 control positions and 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 assemblies was chosen to enable measurements to be made along the x-axis which are representative of an 1100 MWe-size plutonium-fuelled LMR design. The first ZPPR-18 assembly, designated ZPPR-18A had only sodium plates in the control positions. Final measurements in ZPPR-18A in the period measured the worths of 51 control rod patterns. These measurements included single rods and rod pairs at various radii along the x-axis as well as numerous bank and partial bank configurations.

The second assembly in the series, ZPPR-18B, had 18 half-inserted mockup control rods in the inner and outer control rings. The ZPPR-18B measurements were limited to reaction rate and gamma ray dose distributions, the worth of the middle control bank and a few kinetic parameters.

The final assembly, ZPPR-18C, had one of the outer control rods missing. The only experiment in this configuration was of reaction rate distributions.

Beginning in January 1988, the JUPITER-III program was extended in a satellite program called Io. Experiments in Io will be performed in the ZPPR-19 assembly. There are two primary objectives of the Io program. The first is to determine eigenvalue separation and spatial flux sensitivity in an 8,000 liter homogeneous core with small eigenvalue separation. The second is to determine the effect of the ^{235}U fuel distribution on spatially sensitive parameters.

The first Io assembly, ZPPR-19A, had the outlines of ZPPR-18A including distinct plutonium and ^{235}U fuel zones in the outer core, but had six fully inserted control rods in the inner control ring. The effect of the six control rods is to reduce by about a factor of two the eigenvalue separation

compared with that of ZPPR-18A. Eigenvalue separation was measured using a noise technique and by analysis of in-core fission chamber data with and without additional inserted control rods.

Following the ZPPR-19A measurements, both fuel and the inner bank control rods were removed from the assembly and outer core fuel drawers were interchanged to produce a configuration in which the ^{235}U and plutonium fuel drawers were uniformly distributed in the outer core. This final configuration is called ZPPR-19B and its criticality was achieved on January 31, 1988.

This report contains data for reaction rate measurements and reactivity worths, including bowing and expansion measurements, for ZPPR-17A. Data for gamma-ray dose measured with TLDs and kinetics measurements remain to be reported. Processing of experimental control rod worths for ZPPR-17B and ZPPR-17C is nearing completion and it is intended to include these data in the next report. Most of the data processing and initial analysis of control rod worth experiments in ZPPR-18A has been completed.

Analysis of reaction rate measurements in ZPPR-17B and ZPPR-17C awaits processing of the fine-structure experiments and application of foil/cell-average factors.

The gamma ray dose measurements in ZPPR-17A have been analyzed using the coupled neutron-gamma ray methodology which was recently developed at ANL for the IFR project. Calculated doses, relative to plutonium fission rates in the core agree quite well with experiment, within 5% for single-fuel-column drawers and blanket positions. A systematic underprediction of 10% is found for the double-fuel-column drawers which may be due to inadequacy in calculating fine structure in the unit cells. These results are being reported in a separate document.

Calculations have been completed in full xyz geometry for the reference loadings of ZPPR-18A, 18B, 19A and 19B. The model for ZPPR-18C requires full-xy and full-z representation and was deferred until results from the other cores are examined. A six-group cross section file together with

group and region dependent axial buckling terms has been constructed for processing of the numerous control rod experiments in ZPPR-18A.

The remaining data from the ZPPR-15 metal-fuel physics cores are being processed. These data include small sample worths in ZPPR-15B and ZPPR-15D, sodium void and reaction rates in the mixed Pu/U fuelled loading ZPPR-15C, sodium void in the "high-Zr" zone of ZPPR-15B and $^{10}\text{B}(n,\text{He})$ production rates in a mock-up control rod in ZPPR-15D.

A consistent analysis of small-sample worth experiments in ZPPR-15 Phases A, B and D is nearly complete. Radial tube oscillator experiments were done in each phase. Of particular interest here is the effect on worth C/E's of 1) the zirconium-for-steel substitution in going from Phase A to Phase B, and 2) the ^{235}U -for- ^{239}Pu fuel substitution in going from Phase B to Phase D. The zirconium substitution seems to affect worth C/E's of only materials with large scattering components. The ^{235}U substitution causes the worth C/E's to get smaller by several percent. Checks for consistency among the results from the different phases has lead to the revision of several worth results from ZPPR-15A that were reported in ZPR-TM-469, p. 135.

Two cores have been calculated with ENDF/B-V.2 data for addition to the critical assembly database for use in bias and uncertainty predictions for metal-fuel LMRs. These cores were ZPR-9-36 and ZPR-3/56B. ZPR-9 was a 9% enriched uranium core (known as U9) which is notable, together with the LANL "BIG-10" core, for exhibiting the most discrepant calculated values for k-effective and ^{238}U fission ratios. ZPR-3/56B was required because of the feature of a nickel/sodium reflector. Several Monte Carlo calculations have been made using the VIM code to refine calculated parameters in some vital cores. These included the two LANL FLATTOP cores and three of the ZEBRA-8 zero-leakage zones from the UK. A modification has been made to the MC²-II code to provide data for chosen sets of inelastic levels as an option. This facility is required to refine the treatment of data covariance files in the sensitivity analysis.

2. REFERENCE CONFIGURATIONS FOR THE ZPPR-17C ASSEMBLY (S. B. Brumbach)

2.1 Description of the Assembly

The ZPPR-17C assembly was the third in a series of axially heterogeneous benchmarks in the JUPITER-III program. The 17C configuration was distinguished by the presence of 13 half-inserted control rods.

The conversion from ZPPR-17B to ZPPR-17C was accomplished by replacing sodium-filled control rod position (CRP) drawers with boron-containing drawers in the outer control ring and central control position in half two of the assembly. Criticality was then achieved by converting single-fuel-column drawers to double-fuel-column drawers uniformly in the inner and outer core regions.

The control rod (CR) drawers contained only bare and stainless-steel-clad natural $B_{10}C$ plates in the first 787 mm (i.e., 100% $B_{10}C$ rods) and 127 mm of sodium cans in the remainder of the drawers. The 787 mm location corresponds to the axial blanket/axial reflector interface. Limitations to the $B_{10}C$ supply prevented a full-core-height $B_{10}C$ column for the half-inserted rods. Two nearly-identical CR drawer masters were used; master 639 in the outer ring and master 640 in the central position. An average composition for a control rod drawer is given in Section 4.

ZPPR-17C differed from ZPPR-17B only in the presence of the 13 half-inserted control rods and the higher ratio of double- to single-fuel-column drawers required to return the assembly to critical.

2.2 The ZPPR-17C Critical Reference Configuration

The ZPPR-17C critical reference was established on June 16, 1987, in loading number 136, reactor run number 152. The excess reactivity, determined in a positive period measurement, was $6.7 \pm 0.1\%$ at an average core temperature of 25.9°C. The interface diagram is given in Fig. 2.1 with the matrix locations marked with an "X" containing double-fuel-column

drawers. In half one, all control position drawers contain sodium. Corresponding half two control drawers contain B₂C in the central location and the twelve outer-ring locations. The other six half two locations contain sodium. A drawer loading summary is given in Table 2.1 and mass summaries for the principal materials in 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.

2.3. The ZPPR-17C Subcritical Reference Configuration

The ZPPR-17C subcritical reference was established on June 12, 1987, in loading number 135, reactor run number 150. The reactivity was $-25.2 \pm 0.2\%$ 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 4.456 kg less in the subcritical reference than in the critical reference.

TABLE 2.1 Drawer Loading Summary for the
ZPPR-17C 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)	704
Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	768
<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)	888
Drawers with two columns of fuel (Includes 8 narrow drawers adjacent to PSRs)	1000
<u>Control Rod Position</u>	
Sodium-filled drawers	148
<u>Control Rod</u>	
B ₄ C-filled drawers	52
<u>Radial Blanket</u>	
Radial blanket drawers (Includes 13 drawers with fission chambers)	1752
<u>Radial Reflector</u>	
Stainless-steel-filled drawers (Includes one drawer with fission chamber)	1272

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

Material	Mass, kg ^b					
	Inner Core	Outer Core	Internal Blanket	Radial Blanket	Axial Blanket	Control Rods
Total Pu	972.945	1806.354	----	----	----	----
Fissile Pu	857.722	1592.235	----	----	----	----
Total Fissile	867.424	1610.133	4.775	47.500	20.066	----
²³⁸ Pu	0.456	0.795	----	----	----	----
²³⁹ Pu	850.826	1579.677	----	----	----	----
²⁴⁰ Pu	112.953	210.031	----	----	----	----
²⁴¹ Pu ^a	6.896	12.558	----	----	----	----
²⁴² Pu	1.813	3.293	----	----	----	----
Americium ^a	10.308	19.157	----	----	----	----
²³⁵ U	9.702	17.898	4.775	47.500	20.066	----
²³⁸ U	4497.820	8289.254	2213.234	22109.920	9237.605	----
Total Heavy Metal	5490.777	10132.660	2218.009	22157.420	9257.672	----
O	625.131	1147.273	250.428	2515.876	671.492	0.281
Na	545.761	996.566	239.571	678.242	1001.405	303.896
Mo	90.817	168.764	1.535	8.932	16.154	1.523
Steel ^c	2420.712	4419.553	979.296	4557.519	5550.580	747.117
¹⁰ B	----	----	----	----	----	32.497
¹¹ B	----	----	----	----	----	144.897
C	38.575	71.901	0.455	2.716	3.048	50.910

^aMasses for all isotopes decayed to the date 6/15/87.

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

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

- Single Fuel Column
- Double Fuel Column
- Operating Rod
- × Single Column In Subcritical Reference
- Double Column In Critical Reference

- + Reflector
- / Blanket

Fig. 2.1 Interface Diagram for the ZPPR-17C Reference Configuration.

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

Operational measurements in ZPPR-17C 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-17C data processing.

Four shim rods were calibrated in Assembly 17C: shim rods 1, 2, 3 and 4. The rods were calibrated by driving them through their full range of travel, with three full cycles of travel, 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 as files 10 and 11 of the DATAZ17C.Z01 dataset. To account for the change in detector efficiency caused by moving a particular rod, the inverse kinetics used various combinations of the ex-core BF₃ flux monitors based upon results of the detector efficiency ratios obtained from rod drops and from 64-fission detector measurements.

The source terms for point inverse kinetics, appropriate for the ex-core neutron detectors in Assembly 17C, were measured in reactor run 151. This was done using the rod drop technique. The data were recorded in file 8 of dataset DATAZ17C.Z01. The measurement was done starting at 0.9×10^{-7} on EXP1 and dropping a group of eight symmetrically equivalent rods which perturb the detector efficiency ratio least. The resulting source terms are $177.61 \pm 0.08 \Delta k/k$ counts sec^{-1} for EXP1 and $149.25 \pm 0.07 \Delta k/k$ counts sec^{-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	Total Worth, \$
						Deviation, ϕ	
1	163-36	-7.0123	19.169	-27.223	52.209	0.052	0.1592 $\pm$.0010
2	263-36	-3.7235	9.4695	-9.4861	11.580	0.031	0.0851 $\pm$.0010
3	134-63	-8.3750	22.126	-30.404	58.532	0.062	0.1713 $\pm$.0010
4	234-63	-2.9634	8.3214	-9.1160	10.947	0.046	0.0862 $\pm$.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-17C (G. L. Grassechi and P. J. Collins)

The present calculations for ZPPR-17C use the cross section library processed from the ENDF/B-V.2 files to 21 energy groups for ZPPR-17A. The cross sections processing is described in ANL-ZPR-476, p. 17 et seq. No special processing was used for the sodium-steel control rod positions (CRPs) or for the B₄C control rods (CRs) which were present in the ZPPR-17C reference loading. Macroscopic data for the CRPs were mixed from the homogeneous isotopic cross sections processed for the fuel cells. Cross sections for boron in the control rods were collapsed at infinite-dilution in the fuel spectra.

The reference calculation model used xyz geometry with 1/4-core symmetry in the xy plane and full z representation because of the half-inserted control rods. Drawer master compositions were treated individually except that fission chamber and thermocouple drawers were modelled as standard drawers because of their asymmetric dispositions. The xy map of the model is shown in Fig. 4.1 for half-one of the assembly. The only difference for half-two was in replacement of 13 CRPs (master 601) in the central and outer bank positions with control rods (masters 640 and 639 respectively).

The drawer masters for ZPPR-17C are listed in Table 4.1. Most of these masters were the same as those used in ZPPR-17A and 17B. Compositions for variants of a parent master (e.g. single- or double-fuel-column drawer) differ only slightly (order of one percent or less in individual isotopic densities) due to variations in fuel-vendor types or piece-length distributions. The average compositions for each drawer-type (parent master) are given in Table 4.2. Axial ranges in Table 4.2 are quoted in inches (viz 6-20) for simplicity. Average compositions for the inner core, defined as the fuel region above the internal blanket, and for the outer core are given at the end of the table.

TABLE 4.1 Drawer Masters in ZPPR-17C

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
	226	Fuel-DC
	227	Fuel-DC
	230	Fuel-DC
	231	Fuel-DC
	232	Fuel-DC
	233	Fuel-DC
	235	Fuel-DC
	236	Fuel-DC
	237	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
	228	Fuel-DC
	229	Fuel-DC
	234	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
Control Rod Position	601	CRP
Control Rod	639	CR
	640	CR
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 17C: Atom Densities by Zone

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

TABLE 4.2 (contd)

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

TABLE 4.2 (contd)

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

Table 4.2 (contd)

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

TABLE 4.2 (contd)

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

TABLE 4.2 (contd)

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

TABLE 4.2 (contd)

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

Table 4.2 (contd)

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

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

Fig. 4.1. The xyz Calculational Model for ZPPR-17C (half one)

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

The reference calculation for ZPPR-17C used a nodal diffusion (NDT) solution in xyz geometry (Section 4). The model required a full z representation in order to include the half-inserted control rods. Axial node spacings were the same as used for the ZPPR-17B model (ANL-ZPR-480, p. 18), generally around 7 cm to 9 cm, chosen to match region boundaries.

The initial calculations, reported here, used the 21 group cross sections processed for asymptotic cells in ZPPR-17A (ANL-ZPR-476, p. 17). A nodal diffusion calculation was made for the core with operating shim rods fully withdrawn. A nodal transport calculation (NTT) was made with the operating shim rods inserted to the core/axial blanket interface for calculation of reaction rate distributions.

A finite-difference diffusion calculation (FDDT) was made with the 21 group cross sections for calculations of delayed neutron parameters. This model was also used to collapse the cross sections to a 6 group set for control rod calculations. The FDDT model did not use individual drawer master compositions, in order to simplify the group collapse, and used the average compositions for each generic drawer type given in Table 4.2. An rz model, with the control rod and CPR banks represented as thin annuli with the same volume as for the banks of rectangular rods, was used for economy in analytical studies.

The k-effectives for the various models of ZPPR-17C are given in Table 5.1. The modelling effects derivable from the present calculations are only approximate due to differences in core models. The transport correction to the nodal diffusion k-effective is +0.57% Δk taking into account a correction of +0.04 % Δk for difference in the shim rod positions (calculated for ZPPR-17B). This compares with a transport correction of +0.50% Δk calculated for ZPPR-17B (ANL-ZPR-480, p. 18). The error due to coarse mesh size in FDDT appears to be +0.58% Δk . However, differences of one or two tenths of a percent may arise from use of generic master compositions in the FDDT model. Modelling effects that are somewhat

different to those for ZPPR-17B are to be expected due to the presence of the control rods.

The experimental values for k-effective for ZPPR-17C are given in Table 5.2. The nodal diffusion prediction for ZPPR-17C differs by only 0.0001 Δk from that for ZPPR-17B (ANL-ZPR-480, Table 5.3, p. 22).

Delayed neutron parameters for ZPPR-17C were calculated with the FDDT xyz model and the VARI3D edit code. The results are given in Table 5.3.

TABLE 5.1. k-effective Calculations for Several Models of ZPPR-17C

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

^aC = critical reference.

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

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

^dNot C/E values.

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

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

^aOn a scale with arbitrary zero.

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

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

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

^eUsing calculated β -effective 0.003357.

TABLE 5.3 Delayed Neutron
Parameters for ZPPR-17C

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

β -effective 0.3357%

Prompt neutron lifetime $4.235 \times 10^{-7}s$

6. MEASUREMENTS AND ANALYSIS OF REACTION RATES IN ZPPR-17A
P. J. Collins, J. M. Gasidlo, D. W. Maddison, and G. L. Grasseschi

6.1 Introduction

ZPPR-17A was the first core in a series of axially-heterogeneous LMR experiments for the first part of the JUPITER-III program. The core contained 2300 kg fissile plutonium loading and had a large internal blanket region, radius 87 cm and thickness 30 cm; composed of depleted uranium oxide, sodium and steel. No control rod positions were present in this phase of the program. Reaction rate measurements in ZPPR-17A were designed to map the core in detail with particular attention to the influence of the internal blanket on the distributions.

This section contains the cell-averaged experimental reaction rates and the results of analysis with a nodal transport model. Following sections record the basic data from foil measurements and describe the derivation of factors relating the basic data to cell-average quantities.

6.2 Description of the Measurements

The measurements were made in the ZPPR-17A reference core, described in ANL-ZPR-476, p. 4, in loading 62, reactor run 65, on April 6, 1978. During the foil irradiation, eight ZPPR shim control rods, in location 134-63 and the symmetric locations in the other seven octants, were inserted to a distance of 51.0 cm from the midplane and had a total worth of 4.5 ϕ . Some additional data for reaction rate fine structure in the unit cells (Section 8) were obtained in subsequent irradiations in ZPPR-17B and ZPPR-17C.

Reaction rates were measured with the standard ZPPR foil techniques described in ANL-82-38. However, for ZPPR-17A the reaction rates were recalibrated using the latest reference data (ANL-87-5).

It is anticipated that a further recalibration of the ^{238}U (n,f) reaction rate will be made during 1988.

The statistical uncertainties on the measured reaction rates are in the range 0.5% to 0.7% for fission in ^{235}U and ^{239}Pu and for capture in ^{238}U , within the core and internal blanket regions, increasing to 0.9% in the axial blanket. For fission in ^{238}U , statistical uncertainties are about 1.5% in the fuel regions, 4% in the internal blanket and 4% (near core boundary) to 15% in the axial blanket. The uncertainties are given in detail, for each measurement, in Section 7.

The reaction rate measurements were as follows:

- (i) Radial distributions along the x-axis at 5 cm (through the internal blanket), at 18 cm (just above the internal blanket) and at 28 cm from the midplane.
- (ii) Axial distributions at the core center, just outside the radial edge of the internal blanket (peak flux region) and about halfway between the internal and radial blankets.
- (iii) The distribution along the y-axis using only ^{235}U and ^{238}U foils.
- (iv) The distribution at 45° to the axes using only ^{235}U foils.
- (v) Two groups of five ^{235}U foils at the x and y axes symmetric to positions measured in the more detailed distributions.

The foil locations are shown in xy and xz sections of the assembly in Figures 6.1 and 6.2.

6.3 Calculation Methods

Calculations were made with ENDF/B-V.2 cross sections in 21 energy groups using an xyz model and the nodal transport option of the DIF3D code (ANL-ZPR-476, p. 17). The initial calculations for ZPPR-17 used asymptotic-cell models for treatment of cell heterogeneities. Subsequently, a second

multigroup cross-section library was generated using group dependent bucklings impressed on the cell models in the SDX code. The bucklings were generated in the DIF3D edit for an average over all occurrences of the cell in a given reactor region. This procedure is described in Section 9 and corresponds to the method used for the radially-heterogeneous cores in the ZPPR-13 series. Anisotropic transport cross sections generated by the Benoist method were used in the xyz model.

The ZPPR shim rods were included in the model, using boron carbide cross sections shielded for the B_4C blade and averaged over a matrix area, through a special calculation with the SDX code. The rods were inserted in the node at the core/axial blanket interface close to the experimental insertion. The calculated k-effective was 0.986869 compared to the reference value of 0.987075 in an xyz diffusion model, giving a shim reactivity of 6.3¢ which is sufficiently close to the experimental value of 4.5¢ in view of the small reactivity.

Calculated reaction rates were interpolated to the foil locations using the nodal polynomial interpolation described in ZPR-TM-460, p. 53. The appropriate cell-average cross sections were used in each location. For plutonium foils in blanket regions, cross sections self-shielded for the foils were generated in a special SDX calculation.

For comparison with experiment (E), the calculated data (C) were normalized so as to give a mean C/E of unity for the 74 measurements of plutonium fission in the fuel regions.

6.4 Experimental Results and Comparison with Calculation

The data in the tables have been organized into distributions along the x and y axes, at 45° to the axes and into axial distributions. The results are shown, for simplicity, by matrix position only. The precise x, y, and z locations of the foils are recorded with the "basic data" in Section 7. As an aid, the reactor zones are shown as IB (internal blanket), RB (radial blanket), AB (axial blanket), RR (radial reflector) and AR (axial

reflector). The fuel region above the internal blanket is denoted by IC and the outer fuel region by OC, although these regions have the same average enrichment. In addition, the single-fuel-column drawers are labeled with an S (viz OCS) and the double-fuel-column drawers are labeled with a D (viz OCD).

Experimental results are given in units of 10^{-18} reactions per atom per second at a reactor power of approximately 1 watt.

Radial reaction rate distributions for positions close to the mid-plane are given in Tables 6.1 to 6.5. The results along the x-axis are also plotted in Figures 6.3 to 6.6. These distributions pass through the internal blanket in the inner part of the core. Several observations may be made from these data:

- (i) All four reactions show an increasing C/E with distance from the core center within the internal blanket. For ^{239}Pu fission the increase is 5%, for ^{235}U fission it is 4% and for ^{238}U capture it is 3%. The same trend exists for ^{238}U fission but is masked by statistical fluctuations due to the lower countrates in the blanket region.
- (ii) Predictions across the outer core are reasonably consistent within the experimental statistics, but results for ^{238}U show a correlation of C/E with drawer type, capture being predicted 2-3% higher in the DCF drawers while fission is predicted about 3% lower in the DCF drawers.
- (iii) The ^{238}U fission rate is inconsistently predicted between adjacent blanket and fuel drawers with jumps of 5% for IB/DCF and of 10% for SCF/RB (Tables 6.1 and 6.3).
- (iv) Measured ^{235}U fission distributions are symmetric between the x-axis and the y-axis (Table 6.2). On the other hand, the calculated fission rates are markedly lower at the y-axis with the C/E values lower by 1-2% in the outer core region (but

consistent is the radial blanket). Since shim rod perturbations at the midplane are quite small (tenths of a percent) and supposedly adequately calculated at this level, suspicion is cast upon the treatment of plate-cell streaming effects. The assumption of long columns of diluent plates is less applicable in the 'diamond' loading of ZPPR-17.

- (v) Measured reaction rates are possibly lower along the negative x-axis (Table 6.4) and are definitely lower, by 1% an average, at the bottom of the matrix (negative y-axis) than at the top of the matrix. This asymmetry is similar to that observed in ZPPR-13 and shown to be due to the matrix halves being closer together at the top right hand corner of half-one with a gap of about 1 mm at the bottom of the matrix. (ZPR-TM-436)
- (vi) ^{235}U fission and ^{238}U capture are predicted quite consistently through the radial blanket up to the last drawer. Plutonium fission shows a 6% variation in C/E through the radial blanket. This latter trend may be due to inadequate foil-shielded cross sections. Calculated results for ^{235}U fission in the thin radial reflector are quite worthless because the free boundary condition in the model forces the fluxes to fall off rapidly whereas the foil measurements see neutrons reflected from the ZPPR structure.

Reaction rate distributions along the x-axis at heights of 17.9 cm and 28.0 cm from the midplane are given in Tables 6.6 and 6.7 and in Figures 6.7 to 6.14. The trends in the analysis are similar to those near to the midplane. In particular:

- (vii) All radial distributions shown an increasing C/E with radius through the inner core.
- (viii) The predictions of ^{238}U reaction rates show the same systematic differences between the two types of fuel drawers

noted in (ii). This has been a long standing feature in the analysis of oxide-fueled LMR critical assemblies at ZPPR.

The radial reaction rate analysis is summarized in Table 6.8. In order to distill the vast amount of data and to reduce statistical fluctuations between neighboring regions, the C/E results have been averaged for each group of four successive matrix positions, (omitting the last position in the radial blanket). The monotonic increases in C/E throughout the inner core are evident for each reaction, as are discontinuities of a few percent in prediction of reaction rates across the internal blanket/outer core interface. Reaction rates across the outer core are well-predicted in spite of the rapid fall-off of the distributions.

Axial reaction rate distributions at the core center, just outside the radial edge of the internal blanket and near the middle of the outer core, are given in Tables 6.9 to 6.11 and plotted in Figures 6.15 to 6.26. We observe

- (ix) Axial distributions are well predicted with the core and internal blanket regions with regard to the statistical fluctuation of the data. There is a tendency for the C/E to be about 1% lower than average at the last point in the core about 2 cm from the axial blanket interface. ^{235}U fission is predicted 1-2% higher in the internal blanket than in the core region. Predictions of ^{238}U fission fluctuate up to 10% across core/blanket interfaces with the higher C/E values in the blanket region.

6.4 Reaction Rate Ratios

Reaction rate ratios, relative to ^{239}Pu fission are given in Tables 6.12 to 6.17. The ratios are simply calculated from the results at the positions of the foils. Neither the measurement nor the calculation are adjusted to a common foil position in the cell so that C/E results are

unaffected by this definition. For simplicity in the tables, the reaction rates are abbreviated to F9, F5, C8, and F8 for fission in ^{239}Pu , etc.

The C/E results for the ratios are summarized in Table 6.18. Because of the similar radial variations in prediction for each reaction type, the standard deviations for the ratios, when averaged over a given cell type (IB, SCF, DCF), are consistent with experimental statistics. Wide variations are generally seen within the radial and axial blankets.

The overall results of the analysis are as follows:

F5/F9 C/E = 1.034 Internal Blankets
 1.000 Fuel Regions (SC or DC)

C8/F9 C/E = 1.049 Internal Blankets
 1.043 Fuel SC
 1.063 Fuel DC

F8/F9 C/E = 1.012 Internal Blanket
 1.008 Fuel SC
 0.995 Fuel OC

6.5 Summary

As is usual for a moderately decoupled LMR core, the radial reaction rates show an increasing misprediction with distance from the core center. For the three non-threshold reactions the increase in C/E is 3 to 4% on average. For ^{238}U fission the variation is a little greater. Reaction rates in the outer core along the y-axis have a lower C/E by 1% than for equivalent positions along the x-axis, indicating inadequacy in treating of streaming effects in the plate cells.

Reaction rates are rather well predicted, in view of the large variation in measured values, across the outer core and for ^{238}U between the internal blanket and the fuel regions.

The "buckling recycle method" produces some improvement in relative prediction (i.e., between different cell types) but is not entirely adequate. Systematic differences in C/E are evident between single and double fuel column cells and across blanket/fuel boundaries. These differences are most marked for fission in ^{238}U .

The calculated ^{235}U fission to ^{239}Pu fission ratio is in good agreement with experiment in fuel regions. In previous analyses with ENDF/B-V.2 data for ZPPR-12 and ZPPR-13, this ratio was overestimated by 1%. This ratio is overestimated by 3% in the internal blanket. It would be interesting to attribute this difference to the different spectrum regimes, but at this stage one must beware of inadequacies in the calculation methods.

The ^{238}U capture to ^{239}Pu fission ratio is overestimated, by 5% on average both for core and blanket regions. The traditional result of 2% higher C/E values in double-fuel-column cells is clearly evident.

The ^{238}U fission to ^{239}Pu fission ratio is predicted well in fuel regions on average and 1% high in the internal blankets. This result is 1-2% higher than in previous analyses. Again, the lower C/Es in double-fuel-column drawers are obtained.

TABLE 6.1 ZPPR-17A: Radial Reaction Rate Distributions along the X-axis near to the Midplane

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

TABLE 6.2 ZPPR-17A: Near-Midplane Radial $^{235}\text{U}(n,f)$ Distribution
along the Y-axis and Comparison with X-axis Analysis

Matrix	Zone	Y-axis		Matrix	X-axis		Ratio of C/E's Y/X
		Exp.	C/E		Exp.	C/E	
148 50	IB	8.016	0.993	148 50	8.016	0.993	1.000
147 50	IB	8.175	0.992	148 51	8.109	0.997	0.995
146 50	IB	8.141	1.002	148 52	8.156	0.997	1.005
145 50	IB	8.216	1.001	148 53	8.168	1.004	0.997
144 50	IB	8.330	0.999	148 54	8.256	1.005	0.994
143 50	IB	8.404	1.004	148 55	8.329	1.011	0.993
142 50	IB	8.537	1.005	148 56	8.495	1.009	0.996
141 50	IB	8.689	1.006	148 57	8.650	1.011	0.995
140 50	IB	8.820	1.013	148 58	8.865	1.009	1.004
139 50	IB	9.005	1.014	148 59	9.022	1.015	0.999
138 50	IB	9.171	1.018	148 60	9.220	1.018	1.000
137 50	IB	9.406	1.014	148 61	9.379	1.024	0.990
136 50	IB	9.442	1.028	148 62	9.517	1.028	1.000
135 50	IB	9.589	1.020	148 63	9.582	1.033	0.987
134 50	IB	9.420	1.033	148 64	9.509	1.037	0.996
133 50	IB	9.304	1.016	148 65	9.241	1.037	0.980
132 50	OC D	8.668	1.003	148 66	8.680	1.022	0.981
131 50	OC S	8.465	1.009	148 67	8.454	1.024	0.985
130 50	OC S	8.158	1.011	148 68	8.201	1.018	0.993
129 50	OC D	7.694	1.004	148 69	7.767	1.014	0.990
128 50	OC S	7.149	1.005	148 70	7.134	1.024	0.981
127 50	OC S	6.452	1.007	148 71	6.461	1.019	0.988
126 50	OC D	5.577	1.005	148 72	5.615	1.023	0.982
125 50	OC S	4.825	1.000	148 73	4.869	1.005	0.995
124 50	RB	4.066	1.016	148 74	4.123	1.014	1.002
123 50	RB	3.233	1.020	148 75	3.260	1.023	0.997
122 50	RB	2.534	1.017	148 76	2.575	1.009	1.008
121 50	RB	2.003	1.015	148 77	2.022	1.007	1.008
120 50	RB	1.660	1.051	148 78	1.659	1.041	1.010
119 50	RR	1.570	1.087	148 79	1.665	1.079	1.007
118 50	RR	1.103	0.974	148 80	1.350	1.026	0.949

TABLE 6.3 ZPPR-17A: Near-Midplane Radial Distributions of
Capture and Fission in ^{238}U along the Y-axis

Matrix	Zone	$^{238}\text{U}(n,\gamma)$		Ratio to C/E at X-axis	$^{238}\text{U}(n,f)$		Ratio to C/E at X-axis
		Exp.	C/E		EXP.	C/E	
148 50	IB	0.9636	1.019	1.000	0.0538	0.899	1.000
147 50	IB	0.9621	1.029	1.018	0.0435	0.986	0.983
146 50	IB	0.9738	1.022	1.002	0.0457	0.935	1.000
145 50	IB	0.9708	1.034	1.013	0.0456	0.945	0.962
144 50	IB	0.9920	1.024	1.009	0.0431	1.016	1.067
143 50	IB	0.9985	1.032	1.009	0.0430	1.024	1.059
142 50	IB	1.0200	1.028	1.000	0.0438	1.024	1.064
141 50	IB	1.0380	1.031	1.006	0.0477	0.968	0.915
140 50	IB	1.0620	1.031	1.003	0.0474	0.993	0.958
139 50	IB	1.0830	1.036	1.004	0.0492	0.996	0.957
138 50	IB	1.1100	1.038	1.012	0.0497	1.042	1.037
137 50	IB	1.1320	1.044	1.002	0.0539	1.022	1.070
136 50	IB	1.1600	1.043	1.001	0.0565	1.077	1.079
135 50	IB	1.1790	1.042	0.994	0.0675	1.041	1.034
134 50	IB	1.1820	1.045	1.002	0.0792	1.082	1.001
133 50	IB	1.1760	1.033	0.997	0.1084	1.078	1.018
132 50	OC D	1.1040	1.066	0.998	0.2046	0.991	0.987
131 50	OC S	1.1290	1.034	0.977	0.2104	0.997	0.965
130 50	OC S	1.0770	1.044	0.991	0.2093	1.032	0.998
129 50	OC D	0.9685	1.071	0.987	0.2236	0.995	0.976
128 50	OC S	0.9265	1.056	0.995	0.1872	1.024	0.983
127 50	OC S	0.8451	1.048	0.989	0.1683	1.022	0.968
126 50	OC D	0.7009	1.082	0.985	0.1574	0.968	0.942
125 50	OC S	0.6208	1.076	1.002	0.1089	0.948	0.991
124 50	RB	0.5109	1.049	1.001	0.0431	1.132	1.067
123 50	RB	0.3958	1.069	0.986	0.0241	1.047	1.071
122 50	RB	0.3052	1.057	1.000	0.0150	0.919	0.912
121 50	RB	0.2295	1.056	0.996	0.0097	0.791	1.030
120 50	RB	0.1868	1.003	1.004	0.0038	1.156	1.509

TABLE 6.4 ZPPR-17A: Comparison of Results for $^{235}\text{U}(n,f)$ in Symmetric Positions at the Axes and Near the Midplane

Matrix	Zone	Neg. X-axis		Pos. X-axis		Pos. Y-Axis		Neg. Y-axis	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
148 71	OC S	6.468	1.023	6.461	1.019	6.452	1.007	6.411	1.013
148 70	OC S	7.168	1.021	7.134	1.024	7.149	1.005	7.044	1.020
148 69	OC D	--	--	7.767	1.014	7.694	1.004	7.586	1.018
148 68	OC S	8.147	1.029	8.201	1.018	8.158	1.011	8.090	1.019
148 67	OC S	8.371	1.036	8.454	1.024	8.465	1.009	8.405	1.016
		-----		-----		-----		-----	
		Mean C/E	1.027		1.020		1.007		1.017
		S.D.	0.007		0.004		0.003		0.003

^aMatrix positions on the positive x-axis, those on the other three axes are symmetric.

TABLE 6.5 ZPPR-17A: Radial Distribution
for $^{235}\text{U}(n,f)$ at 45° to the Axes
and Near the Midplane

<u>Matrix</u>	<u>Zone</u>	<u>Experiment</u>	<u>C/E</u>
146 51	IB	8.141	1.011
146 52	IB	8.141	1.011
145 53	IB	8.384	0.999
145 54	IB	8.450	1.003
144 54	IB	8.494	1.009
143 55	IB	8.759	1.007
143 56	IB	8.826	1.017
142 56	IB	9.043	1.009
142 57	IB	9.176	1.012
141 57	IB	9.322	1.013
141 58	IB	9.467	1.016
140 58	IB	9.571	1.019
140 59	IB	9.696	1.019
139 59	IB	9.663	1.028
138 60	IB	9.482	1.033
138 61	IB	9.293	1.024
137 61	OC D	8.802	1.014
137 62	OC S	8.721	1.008
136 62	OC D	8.547	1.002
136 63	OC D	8.312	1.006
135 63	OC S	8.054	1.006
135 64	OC S	7.642	1.020
134 64	OC D	7.291	1.005
133 65	OC S	6.156	1.022
133 66	OC D	5.628	1.006
132 66	OC S	5.011	1.011
132 67	RB	4.448	1.033
131 67	RB	3.903	1.021
130 68	RB	2.794	1.025
130 69	RB	2.367	1.026
129 69	RB	2.069	1.032

TABLE 6.6 ZPPR-17A: Radial Reaction Rate Distributions along the X-axis at z = 17.86 cm

Matrix	Zone	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IC S	6.274	0.965	7.154	0.980	0.9323	1.027	0.1337	0.975
148 51	IC D	--	--	7.124	0.967	0.9047	1.025	0.1510	0.950
148 52	IC S	6.344	0.961	7.229	0.982	0.9459	1.023	0.1343	0.961
148 53	IC S	--	--	7.266	0.983	0.9498	1.026	0.1323	0.989
148 54	IC D	6.364	0.966	7.249	0.973	0.9374	1.013	0.1577	0.926
148 55	IC S	--	--	7.461	0.982	0.9700	1.030	0.1382	0.960
148 56	IC S	6.616	0.965	7.486	0.992	0.9877	1.027	0.1399	0.970
148 57	IC D	--	--	7.505	0.985	0.9724	1.025	0.1576	0.968
148 58	IC S	6.835	0.973	7.731	1.001	1.0160	1.040	0.1440	0.971
148 59	IC S	--	--	7.953	0.993	1.0400	1.038	0.1477	0.976
148 60	IC D	7.093	0.975	8.045	0.983	1.0330	1.034	0.1700	0.964
148 61	IC S	7.311	0.981	8.297	0.999	1.0970	1.035	0.1542	0.983
148 62	IC S	7.426	0.992	8.416	1.004	1.0920	1.061	0.1605	0.988
148 63	IC D	7.506	1.000	8.475	0.995	1.0690	1.068	0.1830	1.000
148 64	IC S	7.594	1.018	8.546	1.016	1.1090	1.074	0.1751	0.997
148 65	IC S	7.801	1.008	8.582	1.006	1.1000	1.077	0.1845	1.042
148 66	OC D	7.716	1.022	8.260	1.019	1.0350	1.098	0.2217	0.997
148 67	OC S	7.627	1.026	8.090	1.022	1.0770	1.049	0.2018	1.062
148 68	OC S	7.431	1.024	7.839	1.015	1.0200	1.065	0.2072	1.032
148 69	OC D	6.997	1.029	7.349	1.017	0.9318	1.079	0.2148	1.014
148 70	OC S	6.427	1.025	6.765	1.019	0.8865	1.060	0.1764	1.050
148 71	OC S	5.741	1.030	6.062	1.021	0.7993	1.061	0.1564	1.055
148 72	OC D	4.988	1.026	5.327	1.011	0.6761	1.082	0.1409	1.051
148 73	OC S	4.079	1.021	4.589	0.997	0.5918	1.073	0.1025	0.968
148 74	RB	3.455	1.009	3.856	1.013	0.4754	1.071	0.0428	1.111
148 75	RB	2.717	0.984	3.057	1.018	0.3719	1.079	0.0252	0.971
148 76	RB	2.073	0.973	2.384	1.015	0.2874	1.061	0.0124	1.074
148 77	RB	1.650	0.932	1.866	1.017	0.2186	1.042	0.0097	0.759
148 78	RB	1.396	0.902	1.569	1.024	0.1726	1.011	0.0057	0.729

TABLE 6.7 ZPPR-17A: Radial Reaction Rate Distributions along the X-axis at Z = 28.02 cm

Matrix	Zone	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IC S	6.317	0.976	6.784	0.974	0.8933	1.012	0.1702	0.999
148 51	IC D	6.326	0.976	6.811	0.972	0.8652	1.031	0.1833	0.970
148 52	IC S	6.372	0.974	6.891	0.970	0.9088	1.007	0.1702	0.982
148 53	IC S	6.333	0.986	6.915	0.970	0.9164	1.003	0.1724	0.986
148 54	IC D	6.486	0.970	6.955	0.971	0.8880	1.025	0.1881	0.958
148 55	IC S	6.479	0.983	7.050	0.974	0.9153	1.028	0.1732	0.989
148 56	IC S	6.581	0.980	7.122	0.974	0.9352	1.017	0.1765	0.994
148 57	IC D	6.666	0.981	7.195	0.977	0.9151	1.035	0.1951	0.960
148 58	IC S	6.769	0.985	7.303	0.985	0.9588	1.028	0.1760	1.017
148 59	IC S	6.940	0.978	7.460	0.978	0.9766	1.024	0.1807	1.019
148 60	IC D	6.985	0.989	7.495	0.989	0.9553	1.047	0.2017	0.978
148 61	IC S	7.147	0.988	7.625	0.996	1.0100	1.031	0.1857	1.020
148 62	IC S	7.179	1.001	7.736	0.995	1.0160	1.039	0.1941	1.005
148 63	IC D	7.252	1.004	7.695	1.010	0.9797	1.071	0.2120	0.982
148 64	IC S	7.283	1.014	7.873	1.000	1.0220	1.055	0.1938	1.030
148 65	IC S	7.352	1.009	7.799	1.008	1.0180	1.057	0.1997	1.016
148 66	OC D	7.267	1.013	7.637	1.009	0.9568	1.084	0.2205	1.002
148 67	OC S	7.045	1.023	7.424	1.018	0.9716	1.060	0.1928	1.048
148 68	OC S	6.683	1.037	7.089	1.020	0.9280	1.063	0.1867	1.052
148 69	OC D	6.373	1.021	6.633	1.018	0.8430	1.077	0.1901	1.035
148 70	OC S	5.758	1.026	6.121	1.012	0.8056	1.048	0.1621	1.022
148 71	OC S	5.164	1.022	5.429	1.021	0.7140	1.064	0.1455	1.008
148 72	OC D	4.488	1.014	4.751	1.012	0.6037	1.081	0.1322	0.991
148 73	OC S	3.673	1.007	4.041	1.009	0.5279	1.071	0.0932	0.941
148 74	RB	3.081	1.005	3.397	1.024	0.4185	1.081	0.0381	1.098
148 75	RB	2.405	0.986	2.712	1.020	0.3279	1.086	0.0215	1.001
148 76	RB	1.840	0.973	2.122	1.013	0.2520	1.072	0.0115	1.016
148 77	RB	1.457	0.936	1.678	1.005	0.1865	1.082	0.0092	0.704
148 78	RB	1.213	0.922	1.366	1.046	0.1524	1.014	0.0040	0.918

TABLE 6.8 ZPPR-17A: Summary of Radial Reaction Rate Distribution C/E Values^a

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

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

TABLE 6.9 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-50 (Core Center)

Zone	z (mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
IB	26.2	7.049	0.958	8.060	1.006	0.9777	1.013	0.0434	0.906
IB	49.6	7.115	0.947	8.055	1.001	0.9742	1.013	0.0417	1.015
IB	77.0	6.983	0.962	8.016	0.993	0.9636	1.019	0.0538	0.899
IB	100.4	6.912	0.966	7.889	0.994	0.9624	1.011	0.0600	0.953
IB	127.8	6.813	0.971	7.669	0.996	0.9414	1.018	0.0719	0.998
Zone Average C/E			0.961	0.988		1.015		0.954	
Standard Deviation			0.009	0.005		0.003		0.052	
IC S	178.6	6.274	0.965	7.154	0.980	0.9323	1.027	0.1337	0.975
IC S	229.4	6.399	0.960	6.947	0.974	0.8978	1.032	0.1576	1.000
IC S	280.2	6.317	0.976	6.784	0.974	0.8933	1.012	0.1702	0.999
IC S	331.0	6.188	0.979	6.574	0.979	0.8623	1.020	0.1691	0.997
IC S	381.8	5.827	0.989	6.286	0.976	0.8267	1.015	0.1595	0.996
IC S	432.6	5.460	0.970	5.826	0.981	0.7715	1.014	0.1410	0.991
IC S	483.4	4.901	0.960	5.405	0.970	0.7189	1.001	0.1183	0.925
Zone Average C/E			0.971	0.976		1.017		0.983	
Standard Deviation			0.011	0.004		0.010		0.027	
AB	534.2	4.604	0.954	5.115	0.970	0.6556	1.008	0.0611	0.924
AB	585.0	4.153	0.934	4.637	0.978	0.5819	1.020	0.0364	0.871
AB	635.8	3.675	0.922	4.221	0.965	0.5176	1.007	0.0241	0.730
AB	686.6	3.291	0.901	3.756	0.972	0.4435	1.016	0.0162	0.739
AB	737.4	3.070	0.884	3.450	0.997	0.4033	0.985	0.0105	0.714
Zone Average C/E			0.919	0.976		1.007		0.796	
Standard Deviation			0.027	0.012		0.014		0.095	
AR	839.0	--	--	3.741	1.126	--	--	--	--
AR	889.8	--	--	3.713	1.064	--	--	--	--
AR	946.9	--	--	2.641	1.119	--	--	--	--
AR	997.7	--	--	1.937	0.988	--	--	--	--

TABLE 6.10 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-66 (Outer Core)

Zone	z(mm)	$^{239}\text{Pu}(n,f)$		$^{235}\text{U}(n,f)$		$^{238}\text{U}(n,\gamma)$		$^{238}\text{U}(n,f)$	
		Exp.	C/E	Exp.	C/E	Exp.	C/E	Exp.	C/E
OC D	51.6	7.925	1.013	8.680	1.022	1.1250	1.068	0.1997	1.004
OC D	102.4	7.950	1.006	8.496	1.031	1.0900	1.087	0.2119	0.971
OC D	178.6	7.716	1.022	8.260	1.019	1.0350	1.098	0.2217	0.997
OC D	229.4	7.586	1.013	7.993	1.014	0.9971	1.096	0.2185	1.033
OC D	280.2	7.267	1.013	7.637	1.009	0.9568	1.084	0.2205	1.002
OC D	331.0	6.870	1.005	7.206	1.003	0.9086	1.071	0.2027	1.018
OC D	381.8	6.244	1.012	6.580	1.009	0.8377	1.068	0.1781	1.048
OC D	432.6	5.539	1.014	5.936	1.007	0.7507	1.076	0.1539	1.039
OC D	483.4	4.795	1.005	5.264	1.007	0.6661	1.078	0.1202	1.008

Zone Average C/E			1.011			1.080		1.013	
Standard Deviation			0.005			0.012		0.024	
AB	534.2	4.410	0.987	4.825	1.015	0.6114	1.072	0.0614	0.891
AB	585.0	3.865	0.973	4.356	1.002	0.5305	1.082	0.0365	0.927
AB	635.8	3.341	0.959	3.781	1.008	0.4655	1.055	0.0230	0.913
AB	686.6	2.937	0.933	3.307	1.011	0.3939	1.059	0.0155	0.801
AB	737.4	2.632	0.931	2.954	1.044	0.3356	1.073	0.0114	0.643

Zone Average C/E			0.957			1.068		0.835	
Standard Deviation			0.025			0.011		0.118	
AR	839.0	--	--	3.043	1.188	--	--	--	--
AR	889.8	--	--	2.883	1.162	--	--	--	--

TABLE 6.11 ZPPR-17A: Axial Reaction Rate Distributions in Matrix 148-70 (Outer Core)

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

TABLE 6.12 ZPPR-17A: Reaction Rate Ratios along the
X-axis near to the Midplane

Matrix	Zone	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IB	1.148	1.032	0.1380	1.059	0.00771	0.935
148 51	IB	1.151	1.040	0.1390	1.054	0.00607	1.046
148 52	IB	1.152	1.039	0.1380	1.063	0.00646	0.974
148 53	IB	1.152	1.038	0.1388	1.056	0.00619	1.016
148 54	IB	1.160	1.031	0.1408	1.041	0.00646	0.976
148 55	IB	1.155	1.036	0.1399	1.048	0.00633	0.991
148 56	IB	1.147	1.043	0.1381	1.063	0.00632	0.995
148 57	IB	1.155	1.036	0.1399	1.050	0.00583	1.084
148 58	IB	1.161	1.030	0.1402	1.049	0.00597	1.058
148 59	IB	1.155	1.034	0.1400	1.051	0.00605	1.060
148 60	IB	1.154	1.031	0.1417	1.040	0.00648	1.018
148 61	IB	1.156	1.026	0.1412	1.044	0.00715	0.957
148 62	IB	1.147	1.026	0.1417	1.040	0.00741	0.996
148 63	IB	1.132	1.030	0.1404	1.045	0.00831	1.004
148 64	IB	1.116	1.028	0.1412	1.034	0.00938	1.071
148 65	IB	1.104	1.013	0.1423	1.012	0.01337	1.034
Zone Average C/E			1.032		1.047		1.013
Standard Deviation			0.007		0.013		0.043
148 66	OC D	1.095	1.009	0.1420	1.054	0.02520	0.991
148 67	OC S	1.077	0.994	0.1429	1.027	0.02626	1.003
148 68	OC S	1.056	0.995	0.1398	1.029	0.02744	1.007
148 69	OC D	1.051	0.990	0.1322	1.060	0.03020	0.995
148 70	OC S	1.035	1.012	0.1375	1.039	0.02728	1.030
148 71	OC S	1.054	0.993	0.1388	1.033	0.02712	1.029
148 72	OC D	1.053	0.999	0.1332	1.072	0.02886	1.004
148 73	OC S	1.105	0.994	0.1434	1.062	0.02530	0.947
Zone Average C/E			0.998		1.047		1.001
Standard Deviation			0.008		0.017		0.026
148 74	RB	1.100	1.018	0.1389	1.052	0.01286	1.064
148 75	RB	1.135	1.024	0.1383	1.085	0.00937	0.979
148 76	RB	1.143	1.050	0.1375	1.100	0.00630	1.049
148 77	RB	1.150	1.072	0.1313	1.129	0.00588	0.818
148 78	RB	1.133	1.125	0.1283	1.080	0.00399	0.828
Zone Average C/E			1.058		1.089		0.948
Standard Deviation			0.043		0.028		0.118

TABLE 6.13 ZPPR-17A: Reaction Rate Ratios along the X-axis at Z = 17.86 cm

Matrix	Zone	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IC S	1.140	1.016	0.1486	1.064	0.02131	1.010
148 52	IC S	1.140	1.022	0.1491	1.065	0.02117	1.000
148 54	IC D	1.139	1.007	0.1473	1.049	0.02478	0.959
148 56	IC S	1.131	1.028	0.1493	1.064	0.02115	1.005
148 58	IC S	1.131	1.029	0.1486	1.069	0.02107	0.998
148 60	IC D	1.134	1.008	0.1456	1.061	0.02397	0.989
148 61	IC S	1.135	1.018	0.1500	1.055	0.02109	1.002
148 62	IC S	1.133	1.012	0.1471	1.070	0.02161	0.996
148 63	IC D	1.129	0.995	0.1424	1.068	0.02438	1.000
148 64	IC S	1.125	0.998	0.1460	1.055	0.02306	0.979
148 65	IC S	1.100	0.998	0.1410	1.068	0.02365	1.034
Zone Average C/E			1.012		1.063		0.997
Standard Deviation			0.012		0.007		0.019
148 66	OC D	1.071	0.997	0.1341	1.074	0.02873	0.976
148 67	OC S	1.061	0.996	0.1412	1.022	0.02646	1.035
148 68	OC S	1.055	0.991	0.1373	1.040	0.02788	1.008
148 69	OC D	1.050	0.988	0.1332	1.049	0.03070	0.985
148 70	OC S	1.053	0.994	0.1379	1.034	0.02745	1.024
148 71	OC S	1.056	0.991	0.1392	1.030	0.02724	1.024
148 72	OC D	1.068	0.985	0.1355	1.055	0.02825	1.024
148 73	OC S	1.125	0.976	0.1451	1.051	0.02513	0.948
Zone Average C/E			0.990		1.044		1.003
Standard Deviation			0.007		0.016		0.030
148 74	RB	1.116	1.004	0.1376	1.061	0.01238	1.101
148 75	RB	1.125	1.035	0.1369	1.097	0.00926	0.987
148 76	RB	1.150	1.043	0.1386	1.090	0.00597	1.104
148 77	RB	1.131	1.091	0.1325	1.118	0.00588	0.814
148 78	RB	1.124	1.135	0.1236	1.121	0.00407	0.808
Zone Average C/E			1.062		1.017		0.963
Standard Deviation			0.052		0.024		0.146

TABLE 6.14 ZPPR-17A: Reaction Rate Ratios along the X-axis at Z = 28.02 cm

Matrix	Zone	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
148 50	IC S	1.074	0.998	0.1414	1.037	0.02694	1.024
148 51	IC D	1.077	0.996	0.1368	1.056	0.02898	0.994
148 52	IC S	1.081	0.996	0.1426	1.034	0.02671	1.008
148 53	IC S	1.092	0.984	0.1447	1.017	0.02722	1.000
148 54	IC D	1.072	1.001	0.1369	1.057	0.02900	0.988
148 55	IC S	1.088	0.991	0.1413	1.046	0.02673	1.006
148 56	IC S	1.082	0.994	0.1421	1.038	0.02682	1.014
148 57	IC D	1.079	0.996	0.1373	1.055	0.02927	0.979
148 58	IC S	1.079	1.000	0.1416	1.044	0.02600	1.032
148 59	IC S	1.075	1.000	0.1407	1.047	0.02604	1.042
148 60	IC D	1.073	1.000	0.1368	1.059	0.02888	0.989
148 61	IC S	1.067	1.008	0.1413	1.044	0.02598	1.032
148 62	IC S	1.078	0.994	0.1415	1.038	0.02704	1.004
148 63	IC D	1.061	1.006	0.1351	1.067	0.02923	0.978
148 64	IC S	1.081	0.986	0.1403	1.040	0.02661	1.016
148 65	IC S	1.061	0.999	0.1385	1.048	0.02716	1.007
Zone Average C/E			0.996		1.045		1.007
Standard Deviation			0.006		0.012		0.019
148 66	OC D	1.051	0.996	0.1317	1.070	0.03034	0.989
148 67	OC S	1.054	0.995	0.1379	1.036	0.02737	1.024
148 68	OC S	1.061	0.984	0.1389	1.025	0.02794	1.014
148 69	OC D	1.041	0.997	0.1323	1.055	0.02983	1.014
148 70	OC S	1.063	0.986	0.1399	1.021	0.02815	0.996
148 71	OC S	1.051	0.999	0.1383	1.041	0.02818	0.986
148 72	OC D	1.059	0.998	0.1345	1.066	0.02946	0.977
148 73	OC S	1.100	1.002	0.1437	1.064	0.02538	0.934
Zone Average C/E			0.995		1.046		0.992
Standard Deviation			0.006		0.020		0.028
148 74	RB	1.103	1.019	0.1358	1.076	0.01238	1.093
148 75	RB	1.128	1.034	0.1363	1.101	0.00893	1.015
148 76	RB	1.153	1.041	0.1370	1.102	0.00624	1.044
148 77	RB	1.152	1.074	0.1280	1.156	0.00630	0.752
148 78	RB	1.126	1.134	0.1256	1.100	0.00326	0.996
Zone Average C/E			1.060		1.107		0.980
Standard Deviation			0.046		0.029		0.133

TABLE 6.15 ZPPR-17A: Reaction Rate Ratios in Matrix 148-50 (Core Center)

Zone	z(mm)	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
IB	26.2	1.143	1.050	0.1387	1.057	0.00616	0.946
IB	49.6	1.132	1.057	0.1369	1.070	0.00586	1.072
IB	77.0	1.148	1.032	0.1380	1.059	0.00771	0.935
IB	100.4	1.141	1.029	0.1392	1.047	0.00868	0.987
IB	127.8	1.126	1.026	0.1382	1.048	0.01055	1.028
Zone Average C/E			1.039		1.056		0.994
Standard Deviation			0.014		0.009		0.057
IC S	178.6	1.140	1.016	0.1486	1.064	0.02131	1.010
IC S	229.4	1.086	1.015	0.1403	1.075	0.02463	1.042
IC S	280.2	1.074	0.998	0.1414	1.037	0.02694	1.024
IC S	331.0	1.062	1.000	0.1394	1.042	0.02733	1.018
IC S	381.8	1.079	0.987	0.1419	1.026	0.02737	1.007
IC S	432.6	1.067	1.011	0.1413	1.045	0.02582	1.022
IC S	483.4	1.103	1.010	0.1467	1.043	0.02414	0.964
Zone Average C/E			1.005		1.047		1.012
Standard Deviation			0.011		0.017		0.024
AB	534.2	1.111	1.017	0.1424	1.057	0.01328	0.969
AB	585.0	1.117	1.047	0.1401	1.092	0.00877	0.933
AB	635.8	1.149	1.047	0.1408	1.092	0.00656	0.792
AB	686.6	1.141	1.079	0.1348	1.128	0.00491	0.820
AB	737.4	1.124	1.128	0.1314	1.114	0.00344	0.808
Zone Average C/E			1.064		1.096		0.864
Standard Deviation			0.042		0.026		0.081

TABLE 6.16 ZPPR-17A: Reaction Rate Ratios in Matrix 148-66 (Outer Core)

Zone	z(mm)	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC D	51.6	1.095	1.009	0.1420	1.054	0.02520	0.991
OC D	102.4	1.069	1.025	0.1371	1.081	0.02665	0.965
OC D	178.6	1.071	0.997	0.1341	1.074	0.02873	0.976
OC D	229.4	1.054	1.001	0.1314	1.082	0.02880	1.020
OC D	280.2	1.051	0.996	0.1317	1.070	0.03034	0.989
OC D	331.0	1.049	0.998	0.1323	1.066	0.02951	1.013
OC D	381.8	1.054	0.997	0.1342	1.055	0.02852	1.036
OC D	432.6	1.072	0.993	0.1355	1.061	0.02778	1.025
OC D	483.4	1.098	1.002	0.1389	1.073	0.02507	1.003
Zone Average C/E			1.002	1.068		1.002	
Standard Deviation			0.010	0.010		0.024	
AB	534.2	1.094	1.028	0.1386	1.086	0.01393	0.903
AB	585.0	1.127	1.030	0.1373	1.112	0.00944	0.953
AB	635.8	1.132	1.051	0.1393	1.100	0.00689	0.952
AB	686.6	1.126	1.084	0.1341	1.135	0.00527	0.859
AB	737.4	1.122	1.121	0.1275	1.153	0.00432	0.691
Zone Average C/E			1.063	1.117		0.872	
Standard Deviation			0.040	0.027		0.109	

TABLE 6.17 ZPPR-17A: Reaction Rate Ratios in Matrix 148-70 (Outer Core)

Zone	z(mm)	F5/F9		C8/F9		F8/F9	
		Exp.	C/E	Exp.	C/E	Exp.	C/E
OC S	51.6	1.035	1.012	0.1375	1.039	0.02728	1.030
OC S	102.4	1.047	0.999	0.1389	1.027	0.02812	0.999
OC S	178.6	1.053	0.994	0.1379	1.034	0.02745	1.024
OC S	229.4	1.052	0.995	0.1397	1.022	0.02776	1.012
OC S	280.2	1.063	0.986	0.1399	1.021	0.02815	0.996
OC S	331.0	1.060	0.991	0.1403	1.022	0.02729	1.020
OC S	381.8	1.058	1.001	0.1405	1.030	0.02739	0.999
OC S	432.6	1.064	1.011	0.1409	1.047	0.02546	1.028
OC S	483.4	1.090	1.020	0.1449	1.054	0.02344	0.989
Zone Average C/E			1.001		1.033		1.009
Standard Deviation			0.011		0.012		0.020
AB	534.2	1.109	1.013	0.1429	1.053	0.01433	0.917
AB	585.0	1.144	1.015	0.1415	1.081	0.00942	0.915
AB	635.8	1.151	1.037	0.1415	1.088	0.00637	0.890
AB	686.6	1.126	1.084	0.1348	1.129	0.00489	0.897
AB	737.4	1.121	1.123	0.1265	1.161	0.00495	0.615
Zone Average C/E			1.054		1.102		0.847
Standard Deviation			0.048		0.043		0.130

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

Distribution	Zone	F5/F9			C8/F9			F8/F9		
		No.	C/E	S.D.	No.	C/E	S.D.	No.	C/E	S.D.
X-Axis Z=5 cm	IB	16	1.032	0.007	16	1.047	0.013	16	1.013	0.043
	OC	8	0.998	0.006	8	1.047	0.017	8	1.001	0.026
	RB	5	1.058	0.043	5	1.089	0.025	5	0.948	0.118
X-Axis Z=18 cm	IC	11	1.012	0.012	11	1.063	0.007	11	0.997	0.019
	OC	8	0.990	0.007	8	1.044	0.016	8	1.003	0.030
	RB	5	1.062	0.052	5	1.017	0.024	5	0.963	0.146
X-Axis Z=28 cm	IC	16	0.996	0.006	16	1.045	0.012	16	1.007	0.019
	OC	8	0.995	0.006	8	1.020	0.020	8	0.992	0.028
	RB	5	1.060	0.046	5	1.107	0.029	5	0.980	0.133
Axial 148-50	IB	5	1.039	0.014	5	1.056	0.009	5	0.994	0.057
	IC S	7	1.005	0.011	7	1.047	0.017	7	1.012	0.024
	AB	5	1.064	0.042	5	1.096	0.026	5	0.864	0.081
Axial 148-66	OC D	9	1.002	0.010	9	1.068	0.010	9	1.002	0.024
	AB	5	1.063	0.040	5	1.117	0.027	5	0.872	0.109
Axial 148-70	OC S	9	1.001	0.011	9	1.033	0.012	9	1.009	0.020
	AB	5	1.054	0.048	5	1.102	0.043	5	0.847	0.130

All Internal Blanket		21	1.034	0.009	20	1.049	1.012	20	1.012	0.044
All Fuel Region		76	1.000	0.011	70	1.050	0.017	70	1.004	0.023
All Single Col. Fuel		49	1.001	0.012	46	1.043	0.015	46	1.008	0.024
All Double Col. Fuel		25	0.999	0.008	24	1.063	0.009	24	0.995	0.019

ZPPR-17A

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

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

ZPPR-17A RADIAL PU239(N,F) AT Z=5.2 CM

Fig. 6.3 Radial ^{239}Pu Fission Distribution at 5 cm from the Midplane

ZPPR-17A RADIAL U235(N,F) AT Z=3.8 CM

Fig. 6.4 Radial ^{235}U Fission Distribution at 4 cm from the Midplane

ZPPR-17A RADIAL U238(N,G) AT Z=5.2 CM

Fig. 6.5 Radial ^{238}U Capture Distribution at 5 cm from the Midplane

ZPPR-17A RADIAL U238(N,F) AT Z=5.2 CM

Fig. 6.6 Radial ^{238}U Fission Distribution at 5 cm from the Midplane

ZPPR-17A RADIAL PU239(N,F) AT Z=17.9 CM

Fig. 6.7 Radial ^{239}Pu from Distribution at 18 cm from the Midplane

ZPPR-17A RADIAL U235(N,F) AT Z=17.9 CM

Fig. 6.8 Radial ^{235}U Fission Distribution at 18 cm from the Midplane

ZPPR-17A RADIAL U238(N,G) AT Z=17.9 CM

Fig. 6.9 Radial ^{238}U Capture Distribution at 18 cm from the Midplane

ZPPR-17A RADIAL U238(N,F) AT Z=17.9 CM

Fig. 6.10 Radial ^{238}U Fission Distribution at 18 cm from the Midplane

ZPPR-17A RADIAL PU239(N,F) AT Z=28.0 CM

Fig. 6.11 Radial ^{239}Pu Fission Distribution at 28 cm from the Midplane

ZPPR-17A RADIAL U235(N,F) AT Z=28.0 CM

Fig. 6.12 Radial ^{235}U Fission Distribution at 28 cm from the Midplane

ZPPR-17A RADIAL U238(N,G) AT Z=28.0 CM

Fig. 6.13 Radial ^{238}U Capture Distribution at 28 cm from the Midplane

ZPPR-17A RADIAL U238(N,F) AT Z=28.0 CM

Fig. 6.14 Radial ^{238}U Fission Distribution at 28 cm from the Midplane

ZPPR-17A AXIAL PU239(N,F) IN MATRIX 148-50

Fig. 6.15 Axial ^{239}Pu Fission Distribution at the Core Center

ZPPR-17A AXIAL U235(N,F) IN MATRIX 148-50

Fig. 6.16 Axial ^{235}U Fission Distribution at the Core Center

ZPPR-17A AXIAL U238(N,G) IN MATRIX 148-50

Fig. 6.17 Axial ^{238}U Capture Distribution at the Core Center

ZPPR-17A AXIAL U238(N,F) IN MATRIX 148-50

Fig. 6.18 Axial ^{238}U Fission Distribution at the Core Center

ZPPR-17A AXIAL PU239(N,F) IN MATRIX 148-66

Fig. 6.19 Axial ^{239}Pu Fission Distribution Near the Edge of the Internal Blanket

ZPPR-17A AXIAL U235(N,F) IN MATRIX 148-66

Fig. 6.20 Axial ^{235}U Fission Distribution Near the Edge of the Internal Blanket

ZPPR-17A AXIAL U238(N,G) IN MATRIX 148-66

Fig. 6.21 Axial ^{238}U Capture Distribution Near the Edge of the Internal Blanket

ZPPR-17A AXIAL U238(N,F) IN MATRIX 148-66

Fig. 6.22 Axial ^{238}U Fission Distribution Near the Edge of the Internal Blanket

ZPPR-17A AXIAL PU239(N,F) IN MATRIX 148-70

Fig. 6.23 Axial ^{239}Pu Fission Distribution in the Outer Core

ZPPR-17A AXIAL U235(N,F) IN MATRIX 148-70

Fig. 6.24 Axial ^{235}U Fission Distribution in the Outer Core

ZPPR-17A AXIAL U238(N,G) IN MATRIX 148-70

Fig. 6.25 Axial ^{238}U Capture Distribution in the Outer Core

ZPPR-17A AXIAL U238(N,F) IN MATRIX 148-70

Fig. 6.26 Axial ^{238}U Fission Distribution in the Outer Core

7. BASIC DATA FOR REACTION RATE DISTRIBUTIONS IN ZPPR-17A (D. W. Maddison and J. M. Gasidlo)

7.1 Introduction

Reaction rate maps are measured by first choosing a location in a cell to place the irradiation foil. These "mapping" foils are always placed in the same location in a drawer for a specific type of cell. Then, a pattern of drawers is chosen to provide the reactor distribution desired, such as a radial map or an axial traverse.

7.2 Discussion of Foil Locations

The foils were first placed in stainless steel foil holders which were then loaded into the drawers between the vertical columns* of materials. For drawers with one fuel column, the foil was placed adjacent to the fuel on the side closest to the core center. For drawers with two fuel columns, the foil was placed adjacent to the fuel plate closest to the core center on the side of the plate closest to the drawer center. The mapping foil locations for any location in the reactor are given below.

Reactor Half 1	<u>Matrix Column $\leq$ 49</u>		<u>Matrix Column $\geq$ 50</u>	
	<u>SC</u>	<u>DC</u>	<u>SC</u>	<u>DC</u>
CB	HI	HI	HI	HI
Core	IJ	JK	GH	FG
AB	IJ	IJ	GH	GH
RB		IJ		GH
RR/AR		TC		TC

*ZPPR drawers are divided into sixteen 3.175 mm (1/8 in.) wide vertical columns designed by letters A through P. The letter A denotes the column at the left as one faces the drawer. The letters FG, for example, indicate the foil is between columns F and G, and is centered 19.050 mm (0.750 in.) from the left side of the drawer.

Matrix Column $\leq$ 49Matrix Column $\geq$ 50

Reactor Half 2

CB	HI	HI	HI	HI
Core	GH	FG	IJ	JK
AB	GH	GH	IJ	IJ
RB	GH		IJ	
RR/AR	TC		TC	

Where SC is a drawer with one fuel column, DC is a drawer with two fuel columns CB is the central blanket region, core is the fuelled region, AB is the axial blanket region, and RB is the radial blanket. There are some ^{235}U foils in the axial and radial reflectors which are given a drawer location of "TC". For this location, the foil holder is placed horizontally across the top of the drawer. The foil is centered above drawer columns HI and the foil is centered 25.654 mm above the mid-height of the drawer.

The basic data for the three radial traverses along the x-axis are given in Table 7.1. For these data, the foils were centered on the listed axial position with the ^{235}U foil 13.8 mm above, the ^{238}U foil on, and the ^{239}Pu foil 13.8 mm below the mid-height of the drawer.

The basic data for the radial traverse along the y-axis are given in Table 7.2. For these data, both the ^{235}U and ^{238}U foils were centered at the mid-height of the drawer. The ^{235}U and ^{238}U foils were located 37.7 mm and 51.6 mm from the reactor interface respectively.

The basic data for the radial traverse at 45 degrees and the data for the symmetry locations are given in Table 7.3. The ^{235}U foils were centered at the mid-height of the drawer and were located 37.7 mm from the reactor interface.

The basic data for the axial traverses are given in Table 7.4. The foils were centered on the listed axial position with the ^{235}U foil centered 13.8 mm above, the ^{238}U foil centered on and the ^{239}Pu foil centered 13.8 mm below the mid-height of the drawer.

7.3. Discussion of Foil Data and Uncertainties

In all of the tables, the data are given in units of 10^{-18} fissions or captures per sec per atom in the irradiation foil at an estimated reactor power of one watt. The second number associated with each reaction rate is a one standard deviation estimate of the uncertainty. The uncertainties given in the tables are solely due to counting statistics and data reduction. They include the effects of peak integration, interference peak corrections, corrections for other reactions in the foils, irradiation history and foil positioning in the counter system. Other uncertainties due to cell-averaging factors are discussed in Section 8. Other uncertainties such as those due to detector calibrations are not included. The uncertainties are discussed in greater detail by Brumbach and Gasidlo.¹

REFERENCES

1. "In-Cell Reaction Rate Distributions and Cell-Average Reaction Rates in Fast Critical Assemblies," ANL-85-44, August 1985.

TABLE 7.1 Basic Data for Reaction Rate Distributions Measured
Along the X-Axis

Matrix	Loc ^a	²³⁹ Pu(n,f) ^b	²³⁵ U(n,f) ^b	²³⁸ U(n,f) ^b	²³⁸ U(n,γ) ^b
Radial Traverse at z = 51.6 mm ^c					
148 51	HI	7.045 0.045	8.119 0.039	0.0429 0.0018	0.9180 0.0054
148 52	HI	7.079 0.041	8.166 0.038	0.0458 0.0018	0.9158 0.0056
148 53	HI	7.090 0.037	8.178 0.040	0.0440 0.0018	0.9231 0.0055
148 54	HI	7.115 0.040	8.266 0.038	0.0461 0.0018	0.9398 0.0055
148 55	HI	7.211 0.041	8.339 0.042	0.0457 0.0022	0.9460 0.0059
148 56	HI	7.408 0.041	8.505 0.040	0.0469 0.0021	0.9590 0.0057
148 57	HI	7.492 0.044	8.660 0.038	0.0438 0.0017	0.9825 0.0060
148 58	HI	7.633 0.045	8.876 0.043	0.0457 0.0020	1.0036 0.0062
148 59	HI	7.812 0.046	9.033 0.042	0.0473 0.0023	1.0263 0.0068
148 60	HI	7.991 0.043	9.231 0.041	0.0519 0.0022	1.0614 0.0060
148 61	HI	8.115 0.044	9.391 0.041	0.0581 0.0021	1.0745 0.0063
148 62	HI	8.295 0.046	9.528 0.044	0.0616 0.0021	1.1017 0.0063
148 63	HI	8.467 0.045	9.593 0.042	0.0705 0.0020	1.1153 0.0062
148 64	HI	8.522 0.043	9.521 0.041	0.0801 0.0021	1.1278 0.0066
148 65	HI	8.368 0.042	9.252 0.041	0.1121 0.0026	1.1168 0.0068
148 67	GH	7.933 0.042	8.475 0.037	0.2153 0.0032	1.2096 0.0065
148 68	GH	7.849 0.040	8.221 0.037	0.2226 0.0036	1.1701 0.0072
148 69	FG	7.466 0.038	7.779 0.035	0.2293 0.0030	1.0940 0.0065
148 71	GH	6.200 0.036	6.477 0.033	0.1738 0.0026	0.9181 0.0062
148 72	FG	5.385 0.030	5.623 0.028	0.1580 0.0025	0.7948 0.0052
148 73	GH	4.474 0.027	4.859 0.025	0.1140 0.0020	0.7005 0.0047
148 74	GH	3.747 0.024	4.114 0.021	0.0528 0.0017	0.5088 0.0037
148 75	GH	2.871 0.020	3.277 0.017	0.0272 0.0014	0.3904 0.0029
148 76	GH	2.253 0.020	2.588 0.016	0.0144 0.0013	0.3045 0.0028
148 77	GH	1.759 0.017	2.032 0.014	0.0105 0.0013	0.2271 0.0025
148 78	GH	1.464 0.017	1.694 0.013	0.0070 0.0011	0.1787 0.0022
148 79	TC		1.665 0.012		
148 80	TC		1.350 0.011		
148 81	TC		0.829 0.008		
Radial Traverse at z = 178.6 mm ^c					
148 51	FG		7.143 0.034	0.1541 0.0032	1.0471 0.0070
148 52	GH	6.492 0.036	7.232 0.034	0.1431 0.0029	1.0678 0.0062
148 53	GH		7.269 0.034	0.1410 0.0030	1.0722 0.0070
148 54	FG	6.436 0.035	7.268 0.037	0.1609 0.0033	1.0849 0.0066
148 55	GH		7.464 0.037	0.1473 0.0031	1.0951 0.0065
148 56	GH	6.771 0.037	7.489 0.037	0.1491 0.0030	1.1150 0.0064
148 57	FG		7.525 0.034	0.1608 0.0032	1.1254 0.0066
148 58	GH	6.994 0.043	7.734 0.036	0.1535 0.0030	1.1470 0.0066
148 59	GH		7.956 0.040	0.1575 0.0029	1.1746 0.0068

TABLE 7.1 (contd)

Matrix	Loc ^a	²³⁹ Pu(n,f) ^b	²³⁵ U(n,f) ^b	²³⁸ U(n,f) ^b	²³⁸ U(n,γ) ^b
148 60	FG	7.174 0.042	8.066 0.036	0.1734 0.0028	1.1952 0.0072
148 61	GH	7.482 0.042	8.300 0.038	0.1644 0.0032	1.2382 0.0071
148 62	GH	7.599 0.042	8.419 0.038	0.1711 0.0033	1.2334 0.0069
148 63	FG	7.591 0.040	8.497 0.040	0.1867 0.0034	1.2373 0.0070
148 64	GH	7.771 0.039	8.550 0.040	0.1867 0.0029	1.2516 0.0068
148 65	GH	7.983 0.041	8.585 0.039	0.1967 0.0031	1.2418 0.0073
148 67	GH	7.711 0.041	8.111 0.036	0.2108 0.0032	1.1613 0.0068
148 68	GH	7.514 0.040	7.858 0.035	0.2166 0.0032	1.1002 0.0062
148 69	FG	7.066 0.036	7.361 0.034	0.2206 0.0033	1.0429 0.0060
148 71	GH	5.805 0.034	6.078 0.030	0.1634 0.0027	0.8620 0.0054
148 72	FG	5.036 0.029	5.335 0.027	0.1447 0.0023	0.7567 0.0050
148 73	GH	4.141 0.026	4.580 0.024	0.1048 0.0022	0.6561 0.0046
148 74	GH	3.455 0.024	3.847 0.019	0.0469 0.0015	0.4647 0.0033
148 75	GH	2.717 0.019	3.072 0.017	0.0255 0.0013	0.3656 0.0029
148 76	GH	2.073 0.019	2.396 0.016	0.0125 0.0012	0.2825 0.0030
148 77	GH	1.650 0.018	1.875 0.013	0.0098 0.0012	0.2149 0.0023
148 78	GH	1.396 0.017	1.602 0.012	0.0068 0.0011	0.1642 0.0020

Radial Traverse at z = 280.2 mm^c

148 51	FG	6.393 0.038	6.837 0.033	0.1860 0.0034	0.9833 0.0057
148 52	GH	6.426 0.037	6.892 0.034	0.1786 0.0032	0.9908 0.0060
148 53	GH	6.386 0.037	6.917 0.033	0.1809 0.0032	0.9991 0.0079
148 54	FG	6.555 0.038	6.982 0.035	0.1910 0.0033	1.0092 0.0062
148 55	GH	6.534 0.036	7.051 0.036	0.1818 0.0037	0.9979 0.0062
148 56	GH	6.637 0.038	7.123 0.036	0.1852 0.0038	1.0196 0.0070
148 57	FG	6.736 0.041	7.223 0.035	0.1980 0.0032	1.0400 0.0059
148 58	GH	6.826 0.043	7.304 0.037	0.1847 0.0032	1.0453 0.0061
148 59	GH	6.999 0.044	7.461 0.037	0.1896 0.0031	1.0648 0.0061
148 60	FG	7.059 0.041	7.524 0.035	0.2048 0.0035	1.0857 0.0062
148 61	GH	7.207 0.043	7.626 0.036	0.1948 0.0039	1.1016 0.0068
148 62	GH	7.240 0.044	7.737 0.036	0.2037 0.0032	1.1075 0.0064
148 63	FG	7.329 0.039	7.725 0.035	0.2153 0.0031	1.1134 0.0062
148 64	GH	7.345 0.041	7.874 0.036	0.2034 0.0029	1.1145 0.0061
148 65	GH	7.414 0.041	7.800 0.035	0.2095 0.0031	1.1097 0.0068
148 67	GH	7.123 0.037	7.442 0.034	0.2014 0.0030	1.0479 0.0064
148 68	GH	6.757 0.037	7.106 0.034	0.1951 0.0032	1.0009 0.0057
148 69	FG	6.435 0.036	6.644 0.032	0.1952 0.0030	0.9435 0.0060

TABLE 7.1 (contd)

Matrix	Loc ^a	²³⁹ Pu(n,f) ^b	²³⁵ U(n,f) ^b	²³⁸ U(n,f) ^b	²³⁸ U(n,γ) ^b
148 71	GH	5.222 0.031	5.442 0.029	0.1521 0.0024	0.7701 0.0051
148 72	FG	4.531 0.029	4.758 0.025	0.1358 0.0024	0.6757 0.0052
148 73	GH	3.729 0.025	4.033 0.022	0.0953 0.0022	0.5853 0.0042
148 74	GH	3.081 0.025	3.389 0.018	0.0418 0.0015	0.4091 0.0039
148 75	GH	2.405 0.019	2.726 0.015	0.0217 0.0012	0.3224 0.0026
148 76	GH	1.840 0.015	2.133 0.013	0.0116 0.0012	0.2478 0.0022
148 77	GH	1.457 0.016	1.686 0.012	0.0093 0.0011	0.1833 0.0021
148 78	GH	1.213 0.016	1.395 0.010	0.0047 0.0014	0.1450 0.0019

^aIn-drawer column which designates the foil location in the drawer. The ²³⁵U foils were centered 13.8 mm above, the ²³⁸U foils were centered on, and the ²³⁹Pu foils were centered 13.8 mm below the mid-height of the drawer.

^bExperimental results in units of 10⁻¹⁸ fissions or captures per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

^cDistance from the reactor interface to the center of the foil.

TABLE 7.2 Basic Data for Reaction Rate Distributions
Measured Along the Y-Axis

Matrix	Loc ^a	$^{235}\text{U}(n,f)^b$	$^{238}\text{U}(n,f)^b$	$^{238}\text{U}(n,\gamma)^b$
118 50	TC	1.103 0.010		
119 50	TC	1.570 0.012		
120 50	GH	1.696 0.011	0.0045 0.0011	0.1778 0.0021
121 50	GH	2.014 0.014	0.0098 0.0013	0.2256 0.0024
122 50	GH	2.547 0.017	0.0152 0.0012	0.3001 0.0031
123 50	GH	3.250 0.017	0.0244 0.0014	0.3892 0.0030
124 50	GH	4.057 0.022	0.0473 0.0020	0.4995 0.0038
125 50	GH	4.816 0.059	0.1113 0.0021	0.6882 0.0047
126 50	FG	5.586 0.027	0.1616 0.0027	0.7845 0.0052
127 50	GH	6.469 0.032	0.1758 0.0031	0.9115 0.0059
128 50	GH	7.167 0.035	0.1956 0.0029	0.9992 0.0061
129 50	FG	7.706 0.037	0.2296 0.0033	1.0839 0.0065
130 50	GH	8.178 0.039	0.2187 0.0030	1.1610 0.0069
131 50	GH	8.486 0.038	0.2198 0.0033	1.2177 0.0077
132 50	FG	8.732 0.041	0.2127 0.0032	1.2595 0.0072
133 50	HI	9.315 0.042	0.1086 0.0023	1.1027 0.0066
134 50	HI	9.432 0.045	0.0793 0.0020	1.1081 0.0066
135 50	HI	9.601 0.043	0.0677 0.0020	1.1059 0.0071
136 50	HI	9.453 0.044	0.0567 0.0018	1.0873 0.0065
137 50	HI	9.418 0.042	0.0540 0.0018	1.0620 0.0065
138 50	HI	9.182 0.040	0.0498 0.0018	1.0407 0.0063
139 50	HI	9.016 0.040	0.0493 0.0018	1.0156 0.0061
140 50	HI	8.830 0.039	0.0475 0.0019	0.9955 0.0068
141 50	HI	8.700 0.039	0.0478 0.0018	0.9729 0.0061
142 50	HI	8.547 0.039	0.0439 0.0017	0.9562 0.0059
143 50	HI	8.414 0.037	0.0431 0.0016	0.9363 0.0057
144 50	HI	8.340 0.038	0.0432 0.0016	0.9303 0.0064
145 50	HI	8.225 0.036	0.0457 0.0016	0.9104 0.0063
146 50	HI	8.151 0.038	0.0458 0.0016	0.9132 0.0056
147 50	HI	8.184 0.037	0.0436 0.0016	0.9022 0.0060

^aIn-drawer column which designates the foil location in the drawer. All foils were centered on the mid-height of the drawer. The ^{235}U and ^{238}U foils were centered 37.7 and 51.6, respectively from the reactor interface.

^bExperimental results in units of 10^{-18} fissions or captures per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

TABLE 7.3 Basic Data for Reaction Rate Distributions
Measured at 45° and Symmetric Locations

Matrix	Loc ^a	²³⁵ U(n,f) ^b	Matrix	Loc ^a	²³⁵ U(n,f) ^b
45 Degree Locations					
147 51	HI	8.135 0.039	138 61	HI	9.304 0.045
146 52	HI	8.150 0.039	136 62	FG	8.561 0.043
145 53	HI	8.394 0.042	137 62	GH	8.743 0.043
144 54	HI	8.504 0.042	135 63	GH	8.075 0.040
145 54	HI	8.460 0.045	136 63	FG	8.325 0.040
143 55	HI	8.769 0.043	134 64	FG	7.302 0.035
142 56	HI	9.054 0.043	135 64	GH	7.661 0.035
143 56	HI	8.837 0.041	133 65	GH	6.171 0.030
141 57	HI	9.333 0.044	132 66	GH	5.001 0.026
142 57	HI	9.187 0.048	133 66	FG	5.637 0.028
140 58	HI	9.583 0.042	131 67	GH	3.923 0.023
141 58	HI	9.479 0.045	132 67	GH	4.438 0.026
139 59	HI	9.674 0.042	130 68	GH	2.808 0.019
140 59	HI	9.707 0.046	129 69	GH	2.080 0.016
138 60	HI	9.493 0.042	130 69	GH	2.379 0.017
137 61	FG	8.868 0.042			
Symmetry Locations					
166 50	GH	8.426 0.038	148 32	IJ	8.392 0.036
167 50	GH	8.110 0.035	148 31	IJ	8.167 0.036
168 50	FG	7.598 0.035	149 30	JK	7.731 0.033
169 50	GH	7.062 0.031	148 29	IJ	7.186 0.033
170 50	GH	6.427 0.031	148 28	IJ	6.485 0.030

^aIn-drawer column which designates the foil location in the drawer. The foils were centered on the mid-height of the drawer at a distance of 37.7 mm from the reactor interface.

^bExperimental results in units of 10^{-18} fissions per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

TABLE 7.4 Basic Data for Reaction Rates Measured for Axial Distributions

z, mm^a	Loc^b	$^{239}\text{Pu}(n,f)^c$	$^{235}\text{U}(n,f)^c$	$^{238}\text{U}(n,f)^c$	$^{238}\text{U}(n,\gamma)^c$
Axial Traverse in 148 50					
26.2	HI	7.049 0.041	8.070 0.034	0.0435 0.0021	0.9142 0.0063
49.6	HI	7.115 0.043	8.065 0.035	0.0418 0.0017	0.9135 0.0060
77.0	HI	6.983 0.037	8.026 0.036	0.0539 0.0025	0.9061 0.0063
100.4	HI	6.912 0.039	7.898 0.036	0.0600 0.0020	0.9071 0.0055
127.8	HI	6.813 0.041	7.679 0.034	0.0717 0.0024	0.8893 0.0056
178.6	GH	6.420 0.037	7.157 0.032	0.1425 0.0029	1.0525 0.0067
229.4	GH	6.501 0.042	6.949 0.030	0.1665 0.0028	0.9959 0.0064
280.2	GH	6.371 0.041	6.786 0.030	0.1785 0.0031	0.9739 0.0059
331.0	GH	6.257 0.042	6.590 0.031	0.1771 0.0034	0.9350 0.0058
381.8	GH	5.908 0.035	6.316 0.031	0.1667 0.0034	0.8916 0.0057
432.6	GH	5.520 0.037	5.838 0.030	0.1476 0.0029	0.8364 0.0052
483.4	GH	4.941 0.030	5.401 0.027	0.1241 0.0029	0.7835 0.0051
534.2	GH	4.604 0.028	5.112 0.025	0.0566 0.0021	0.7438 0.0048
585.0	GH	4.152 0.028	4.635 0.025	0.0337 0.0016	0.6829 0.0046
635.8	GH	3.675 0.025	4.219 0.024	0.0223 0.0014	0.6206 0.0043
686.6	GH	3.291 0.025	3.754 0.020	0.0149 0.0012	0.5507 0.0037
737.4	GH	3.070 0.021	3.448 0.020	0.0098 0.0012	0.5160 0.0040
839.0	TC		3.740 0.021		
889.8	TC		3.712 0.024		
946.9	TC		2.641 0.017		
997.7	TC		1.937 0.015		
Axial Traverse in 148 66					
51.6	FG	7.982 0.043	8.744 0.039	0.2076 0.0038	1.2837 0.0075
102.4	FG	8.007 0.045	8.559 0.038	0.2169 0.0036	1.2468 0.0081
178.6	FG	7.804 0.048	8.281 0.038	0.2262 0.0040	1.1985 0.0071
229.4	FG	7.668 0.046	8.018 0.036	0.2225 0.0040	1.1435 0.0068
280.2	FG	7.344 0.040	7.667 0.035	0.2239 0.0035	1.0874 0.0066
331.0	FG	6.937 0.040	7.217 0.034	0.2069 0.0038	1.0247 0.0069
381.8	FG	6.300 0.037	6.575 0.031	0.1829 0.0036	0.9376 0.0059
432.6	FG	5.612 0.036	5.947 0.029	0.1606 0.0036	0.8509 0.0055
483.4	FG	4.878 0.031	5.287 0.025	0.1276 0.0029	0.7648 0.0050
534.2	GH	4.410 0.030	4.832 0.023	0.0577 0.0023	0.7087 0.0050
585.0	GH	3.865 0.029	4.353 0.023	0.0337 0.0019	0.6345 0.0045
635.8	GH	3.340 0.025	3.779 0.020	0.0213 0.0014	0.5581 0.0046
686.6	GH	2.937 0.023	3.305 0.017	0.0143 0.0012	0.4892 0.0037
737.4	GH	2.632 0.023	2.953 0.017	0.0105 0.0015	0.4293 0.0035
839.0	TC		3.043 0.018		
889.8	TC		2.883 0.017		

TABLE 7.4 (contd)

z, mm^a	Loc ^b	$^{239}\text{Pu}(n, f)^c$	$^{235}\text{U}(n, f)^c$	$^{238}\text{U}(n, f)^c$	$^{238}\text{U}(n, \gamma)^c$
Axial Traverse in 148 70					
51.6	GH	6.972 0.040	7.152 0.032	0.1965 0.0037	1.0228 0.0068
102.4	GH	6.815 0.035	7.071 0.033	0.1980 0.0036	1.0095 0.0063
178.6	GH	6.498 0.037	6.782 0.030	0.1843 0.0037	0.9561 0.0060
229.4	GH	6.232 0.036	6.499 0.031	0.1788 0.0033	0.9282 0.0059
280.2	GH	5.822 0.034	6.137 0.030	0.1694 0.0034	0.8689 0.0056
331.0	GH	5.364 0.034	5.638 0.028	0.1513 0.0036	0.8025 0.0053
381.8	GH	4.862 0.034	5.102 0.027	0.1376 0.0031	0.7287 0.0050
432.6	GH	4.312 0.034	4.548 0.024	0.1138 0.0029	0.6516 0.0052
483.4	GH	3.764 0.027	4.066 0.022	0.0918 0.0027	0.5899 0.0043
534.2	GH	3.344 0.028	3.708 0.020	0.0443 0.0020	0.5421 0.0044
585.0	GH	2.865 0.024	3.275 0.018	0.0250 0.0017	0.4758 0.0037
635.8	GH	2.487 0.022	2.862 0.019	0.0147 0.0015	0.4222 0.0035
686.6	GH	2.174 0.020	2.447 0.016	0.0098 0.0013	0.3640 0.0034
737.4	GH	1.952 0.019	2.188 0.015	0.0090 0.0011	0.3162 0.0029

^aDistance from the reactor interface to the center of the foil.

^bIn-drawer column which designates the foil location in the drawer. The ^{235}U foils were centered 13.8 mm above, the ^{238}U foils were centered on, and the ^{239}Pu foils were centered 13.8 mm below the mid-height of the drawer.

^cExperimental results in units of 10^{-18} fissions or captures per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

8. IN-CELL REACTION RATE MEASUREMENTS AND CELL FACTORS FOR ZPPR-17A
(J. M. Gasidlo and D. W. Maddison)

8.1 Introduction

Reaction rate maps are measured by placing foils in matrix positions chosen to measure specific distributions such as a radial map or an axial traverse. These "mapping" foils are always placed in the same location in a drawer for a specific type of cell. Then, cell factors are used to convert the reaction rates measured in the mapping foil to reaction rates averaged over the materials used to construct the cell.

8.2 Description of the In-Cell Measurements

Cell factors were measured in special experiments where the ordinary plates used to build the reactor were replaced with special plates. Ordinary ZPPR fuel plates were replaced with two half-thickness fuel plates for which the sum of the fuel alloy is equal to one ordinary fuel plate. Foils were placed between and on the outer surfaces of the two half-thickness fuel plates. The 6.35 mm U_3O_8 and 3.175 mm depleted uranium metal plates were replaced with special plates that have slots machined across the width of the plates in which special foils can be placed to measure the integral of the reaction rate across the width of the plate. Because the number of special plates is limited, the 6.35 mm U_3O_8 plates were sometimes replaced with two 3.175 mm U_3O_8 plates (the 3.175 mm depleted uranium metal plates with 1.588 mm plates) and the plate average was measured by a foil placed between the two plates.

The foils were first placed in stainless steel or aluminum holders, or in the slots of the special plates. The foil holders were then placed between the vertical columns* of materials in the drawers. The

*ZPPR drawers are divided into sixteen 3.185 mm (1/8 in) wide vertical columns designated by letters A through P. The letter A denotes the column at the left as one faces the drawer. The letters FG, for example, indicate the foil is between columns F and G, and is centered 19.050 mm (0.750 in.) from the left side of the drawer.

special plates replaced the normal plates used in the drawers. (These plates are designated by a negative sign in front of the in-drawer column location.) Foils were placed in, between, or on the surface of any plates containing the foil material: ^{239}Pu foils are used only at fuel plates whereas ^{235}U and ^{238}U foils are used at fuel plates, depleted uranium metal plates and depleted uranium oxide plates. In all cells, at least one foil of each type was placed in the "mapping foil" location.

The basic data for the in-cell measurements are given in Tables 8.1 - 8.3. The data are given in units of 10^{-18} fission or captures per second per atom in the irradiation foil at an estimated reactor power of one watt. The second number associated with each reaction is a one standard deviation estimate of the uncertainty. As described in Section 7, the uncertainties given in the tables are solely due to counting statistics and data reduction. They include the effects of peak integration, interference peak corrections, corrections for other reactions in the foils, irradiation history and foil positioning in the counter system.

The basic data reported here were derived from the foil counting data before the end of the Assembly 17 program. After the end of the Assembly 17 experiments, special calibration experiments resulted in a change of calibration factors for the foil-counting detectors. Because the calibrations were changed by a single factor for each reaction rate, and since cell factors are determined from the ratio of foil data, the effects of changing the calibration will cancel for cell factors.

8.3 Derivation of Cell-Averaging Factors

The results of special experiments (see Brumbach and Gasidlo, ANL-85-44) were used to convert the data from the special plate measurements to in-plate or plate-averaged reaction rates. These plate-averaged reaction rates were divided by calculated values to remove the effects of the gross reactor flux distribution, atom-weighted plate-by-plate to determine the cell-averaged reaction rate, and divided by the mapping foil value to determine the cell factor. This process is described in greater detail in ANL-85-44.

8.4 Discussion of Cell Factors and Uncertainties

The cell factors are given in Table 8.4. The second number associated with each cell factor is a one standard deviation estimate of the uncertainty. The uncertainties in the cell factors are solely due to propagation of the uncertainties in the basic data tables. They are systematic for the use of a single cell factor, but they are random when applied to the cell-averaged reaction rates for different cell factors. The listed uncertainties do not include systematic uncertainties such as deriving plate-averaged reaction rates from half-thickness plate data or other uncertainties such as those due to detector calibrations. See ANL-85-44 for a discussion of these additional uncertainties.

Under the heading "REG./ENV." is listed the reactor region in which the cell factor can be used, and the type of cell and cell environment for which the cell factor is applicable. The key for reactor regions is: IC is a fueled drawer containing a central blanket region, OC is a fueled drawer not containing a central blanket region, RB is a radial blanket drawer and RR is a radial reflector drawer. For the second part, the mapping foil is always located in the center drawer, and is adjacent to the drawer types listed on either side. The key is: SC is a drawer with one fuel column DC is a drawer with two fuel columns, F is any fueled drawer, RB is a radial blanket drawer and RR is a radial reflector drawer. The code OCF/SC/RB means that the cell factor is used in the outer core for a drawer with one fuel column that has any fueled drawer on one side and a radial blanket drawer on the other.

The cell factors for the axial traverses are listed for the matrix position in which they were used. Cell factors were not measured for every position listed in the table, for example $z = 229.4$ or 331.0 . These cell factors were derived by averaging the cell factors and uncertainties from the axial positions on either side, i.e., the cell factor at 229.4 is the average of the cell factors 178.6 and 280.2 .

One limitation on the use of cell factors must be discussed. Note that the cell factors for $^{239}\text{Pu}(n,f)$ in all blanket regions and $^{235}\text{U}(n,f)$ in

the radial reflector are given as unity. Also note that the "measured" cell factors for $^{235}\text{U}(n,f)$ are nearly unity everywhere. As foil positions in the blankets and reflectors are displaced farther from the fueled regions, neutron self-shielding in the mapping foil becomes increasingly important. This self-shielding can vary from -1% near the core to >5% at the blanket and reflector boundaries. Hence, cross sections self-shielded for the mapping foils must be used in these regions. This is true even for the "cell-averaged" $^{235}\text{U}(n,f)$ mapping foils. (Since the cell factor is a ratio of measured reaction rates, the self-shielding will cancel.) Note that for ^{238}U measurements in the blankets, the mapping foils are self-shielded by the blanket materials. Hence, neutron self-shielding in the ^{238}U mapping foils will be much smaller than for ^{239}Pu and ^{235}U foils.

TABLE 8.1 Basic Data for In-Cell Measurements of $^{239}\text{Pu}(n,f)$

Matrix	Loc ^a	z, mm ^b	$^{239}\text{Pu}(n,f)^c$	z, mm ^b	$^{239}\text{Pu}(n,f)^c$
Measurements in Core Cells With One Fuel Column					
149 59	GH	178.6	7.040 0.028	280.2	6.887 0.030
148 59	GH	178.6	6.986 0.027	280.2	6.839 0.027
148 59	HI	178.6	6.662 0.027	280.2	6.728 0.027
148 59	IJ	178.6	6.973 0.027	280.2	6.847 0.032
149 59	IJ	178.6	7.020 0.027	280.2	6.836 0.027
149 52	GH	381.8	5.902 0.030	483.4	4.891 0.027
148 52	GH	381.8	5.917 0.032	483.4	4.934 0.029
148 52	HI	381.8	5.775 0.034	483.4	4.837 0.026
148 52	IJ	381.8	5.960 0.032	483.4	4.897 0.027
149 52	IJ	381.8	5.919 0.031	483.4	4.984 0.027
149 73	GH	77.0	4.421 0.022		
148 73	GH	77.0	4.413 0.021		
148 73	HI	77.0	4.255 0.021		
148 73	IJ	77.0	4.260 0.021		
Measurements in Core Cells With Two Fuel Columns					
149 54	JK	178.6	6.357 0.030	280.2	6.397 0.031
148 54	JK	178.6	6.395 0.033	280.2	6.403 0.033
148 54	KL	178.6	6.237 0.031	280.2	6.274 0.029
148 54	LM	178.6	6.462 0.035	280.2	6.372 0.029
149 60	JK	381.8	6.259 0.029	483.4	5.081 0.044
148 60	JK	381.8	6.261 0.031	483.4	5.129 0.042
148 60	KL	381.8	6.157 0.030	483.4	4.983 0.026
148 60	LM	381.8	6.270 0.035	483.4	5.090 0.029

TABLE 8.1 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁹ Pu(n,f) ^c	z, mm ^b	²³⁹ Pu(n,f) ^c
249 66	LM	51.6	8.157 0.036	102.4	8.145 0.035
249 66	KL	51.6	7.898 0.035	102.4	7.888 0.035
249 66	JK	51.6	7.984 0.035	102.4	7.988 0.034
248 66	JK	51.6	7.898 0.034	102.4	7.937 0.035
149 66	JK	51.6	8.089 0.035	102.4	8.024 0.037
148 66	JK	51.6	7.983 0.034	102.4	7.889 0.035
148 66	KL	51.6	7.837 0.034	102.4	7.771 0.033
148 66	LM	51.6	7.956 0.036	102.4	7.901 0.033

^aIn-drawer column which designates the foil location in the drawer. The ²³⁹Pu foils were centered 13.8 mm below the mid-height of the drawer.

^bDistance from the reactor interface to the center of the foil.

^cExperimental results in units of 10⁻¹⁸ fissions per sec per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

TABLE 8.2 Basic Data for In-Cell Measurements of $^{235}\text{U}(n,f)$

Matrix	Loc ^a	z,mm ^b	$^{235}\text{U}(n,f)^c$	z,mm ^b	$^{235}\text{U}(n,f)^c$
Measurements in Cells with One Fuel Column					
Central Blanket Cells					
148 53	AB	26.2	8.308 0.036	77.0	8.130 0.034
148 53	HH	26.2	8.224 0.038	77.0	8.003 0.034
149 53	HI	26.2	8.243 0.038	77.0	8.091 0.038
148 53	II	26.2	8.158 0.035	77.0	8.041 0.035
148 53	OP	26.2	8.420 0.037	77.0	8.195 0.034
148 53	AB	127.8	7.702 0.034		
148 53	HH	127.8	7.737 0.033		
149 53	HI	127.8	7.771 0.035		
148 53	II	127.8	7.797 0.035		
148 53	OP	127.8	7.848 0.033		
Core Cells					
148 53	AB	178.6	7.298 0.034	280.2	6.922 0.032
149 53	AB	178.6	7.365 0.034	280.2	6.848 0.031
149 59	GH	178.6	7.922 0.030	280.2	7.385 0.028
148 59	GH	178.6	7.909 0.030	280.2	7.406 0.028
148 59	HI	178.6	7.678 0.030	280.2	7.315 0.028
148 59	IJ	178.6	7.904 0.030	280.2	7.424 0.028
149 59	IJ	178.6	7.966 0.031	280.2	7.406 0.028
149 53	OP	178.6	7.288 0.032	280.2	6.907 0.033
148 53	OP	178.6	7.256 0.030	280.2	6.877 0.030
148 53	AB	381.8	6.333 0.028	483.4	5.485 0.027
149 53	AB	381.8	6.298 0.029	483.4	5.509 0.026
149 52	GH	381.8	6.310 0.031	483.4	5.508 0.030
148 52	GH	381.8	6.295 0.031	483.4	5.443 0.027
148 52	HI	381.8	6.188 0.030	483.4	5.331 0.027
148 52	IJ	381.8	6.329 0.032	483.4	5.491 0.030
149 52	IJ	381.8	6.300 0.031	483.4	5.409 0.027
149 53	OP	381.8	6.337 0.029	483.4	5.535 0.026
148 53	OP	381.8	6.327 0.030	483.4	5.465 0.027
149 73	AB	77.0	5.063 0.024		
149 73	GH	77.0	4.875 0.024		
148 73	GH	77.0	4.840 0.025		
148 73	HI	77.0	4.705 0.023		
148 73	IJ	77.0	4.653 0.023		
149 73	OP	77.0	4.539 0.021		

TABLE 8.2 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁵ U(n, f) ^c	z, mm ^b	²³⁵ U(n, f) ^c
Axial Blanket Cells					
148 52	AB	534.2	5.149 0.025	585.0	4.734 0.026
148 52	GG	534.2	4.999 0.025	585.0	4.642 0.028
149 52	GH	534.2	5.170 0.028	585.0	4.665 0.025
149 53	GH	534.2	5.137 0.027	585.0	4.666 0.024
148 53	GG	534.2	5.095 0.026	585.0	4.680 0.024
148 53	AB	534.2	5.144 0.025	585.0	4.692 0.023
148 52	AB	635.8	4.234 0.023	686.6	3.780 0.022
148 52	GG	635.8	4.144 0.023	686.6	3.747 0.023
149 52	GH	635.8	4.187 0.024	686.6	3.756 0.022
148 52	AB	737.4	3.464 0.021		
148 52	GG	737.4	3.430 0.021		
149 52	GH	737.4	3.434 0.020		
Measurements in Cells with Two Fuel Columns					
Central Blanket Cells					
149 57	HI	77.0	8.603 0.040	127.8	8.198 0.040
148 57	II	77.0	8.551 0.037	127.8	8.198 0.037
148 57	OP	77.0	8.740 0.038	127.8	8.425 0.037
Core Cells					
148 54	AB	178.6	7.223 0.032	280.2	6.903 0.032
149 54	FG	178.6	7.212 0.034	280.2	6.857 0.033
149 54	JK	178.6	7.198 0.032	280.2	6.867 0.032
148 54	JK	178.6	7.236 0.033	280.2	6.909 0.035
148 54	KL	178.6	7.129 0.033	280.2	6.822 0.032
148 54	LM	178.6	7.311 0.034	280.2	6.892 0.051
148 54	OP	178.6	7.341 0.032	280.2	6.980 0.031
148 54	AB	381.8	6.344 0.028	483.4	5.445 0.025
149 54	FG	381.8	6.303 0.036	483.4	5.376 0.026
149 60	JK	381.8	6.723 0.032	483.4	5.621 0.029
148 60	JK	381.8	6.693 0.033	483.4	5.655 0.029
148 60	KL	381.8	6.718 0.033	483.4	5.534 0.028
148 60	LM	381.8	6.768 0.033	483.4	5.636 0.029
148 54	OP	381.8	6.390 0.029	483.4	5.491 0.026
248 66	OP	51.6	9.038 0.037	102.4	8.928 0.040
249 66	LM	51.6	8.925 0.038	102.4	8.810 0.038
249 66	KL	51.6	8.732 0.039	102.4	8.672 0.038
249 66	JK	51.6	8.803 0.037	102.4	8.710 0.038
248 66	JK	51.6	8.776 0.037	102.4	8.706 0.038

TABLE 8.2 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁵ U(n,f) ^c	z, mm ^b	²³⁵ U(n,f) ^c
149 66	JK	51.6	8.684 0.036	102.4	8.572 0.037
148 66	JK	51.6	8.754 0.039	102.4	8.632 0.036
148 66	KL	51.6	8.529 0.036	102.4	8.458 0.036
148 66	LM	51.6	8.657 0.039	102.4	8.546 0.036
149 66	OP	51.6	8.592 0.035	102.4	8.498 0.035

Axial Blanket Cells

149 57	GH	534.2	5.228 0.025	585.0	4.807 0.026
148 57	JJ	534.2	5.225 0.026	585.0	4.745 0.025
148 57	OP	534.2	5.273 0.027	585.0	4.808 0.024

Measurements in Radial Blanket Cells

248 74	BC	77.0	3.805 0.022
248 74	GG	77.0	3.897 0.019
248 74	HI	77.0	4.006 0.019
249 74	IJ	77.0	4.077 0.020
149 74	GH	77.0	4.098 0.020
248 74	JJ	77.0	4.105 0.022
248 74	NO	77.0	4.320 0.021
248 76	BC	77.0	2.347 0.016
248 76	GG	77.0	2.452 0.018
248 76	HI	77.0	2.488 0.016
249 76	IJ	77.0	2.594 0.018
149 76	GH	77.0	2.562 0.016
248 76	JJ	77.0	2.571 0.018
248 76	NO	77.0	2.774 0.018
248 78	BC	77.0	1.623 0.012
248 78	GG	77.0	1.634 0.012
248 78	HI	77.0	1.662 0.014
249 78	IJ	77.0	1.687 0.013
149 78	GH	77.0	1.687 0.014
248 78	JJ	77.0	1.667 0.013
248 78	NO	77.0	1.775 0.014

^aIn-drawer column which designates the foil location in the drawer. The ²³⁵U foils were centered 13.8 mm above the mid-height of the drawer.

^bDistance from the reactor interface to the center of the foil.

^cExperimental results in units of 10⁻¹⁸ fissions per sec per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

TABLE 8.3 Basic Data for In-Cell Measurements of
 $^{238}\text{U}(n,f)$ and $^{238}\text{U}(n,\gamma)$

Matrix	Loc ^a	z,mm ^b	²³⁸ U(n,f) ^c		²³⁸ U(n,γ) ^c	
Measurements in Cells with One Fuel Column						
Central Blanket Cells						
148 52	-AB	26.2	0.0386	0.0015	1.0523	0.0058
148 52	-HH	26.2	0.0393	0.0013	0.9245	0.0047
149 52	HI	26.2	0.0380	0.0013	0.9150	0.0045
148 52	-II	26.2	0.0371	0.0014	0.9560	0.0049
148 52	-OP	26.2	0.0388	0.0013	1.0666	0.0053
148 58	-HH	77.0	0.0512	0.0021	1.0033	0.0060
149 58	HI	77.0	0.0567	0.0019	0.9851	0.0060
148 58	-II	77.0	0.0563	0.0019	0.9847	0.0059
148 58	-OP	77.0	0.0529	0.0021	1.1378	0.0071
148 58	-HH	127.8	0.0756	0.0021	0.9797	0.0064
149 58	HI	127.8	0.0780	0.0020	0.9701	0.0053
148 58	-II	127.8	0.0767	0.0023	0.9985	0.0060
148 58	-OP	127.8	0.0823	0.0021	1.0952	0.0064
Core Cells						
148 59	-AB	178.6	0.1274	0.0024	1.0386	0.0058
149 59	GH	178.6	0.1578	0.0023	1.1546	0.0061
148 59	GH	178.6	0.1565	0.0026	1.1533	0.0062
148 59	HI	178.6	0.1681	0.0025	1.0088	0.0060
148 59	IJ	178.6	0.1599	0.0023	1.1553	0.0061
149 59	IJ	178.6	0.1560	0.0026	1.1682	0.0067
148 59	-OP	178.6	0.1384	0.0025	1.0506	0.0067
148 59	-AB	280.2	0.1634	0.0028	0.9850	0.0060
149 59	GH	280.2	0.1911	0.0024	1.0518	0.0063
148 59	GH	280.2	0.1912	0.0025	1.0504	0.0057
148 59	HI	280.2	0.2036	0.0026	0.9516	0.0058
148 59	IJ	280.2	0.1951	0.0026	1.0454	0.0057
149 59	IJ	280.2	0.1949	0.0024	1.0588	0.0058
148 59	-OP	280.2	0.1752	0.0032	0.9822	0.0072
148 52	-AB	381.8	0.1458	0.0020	0.8417	0.0048
149 52	GH	381.8	0.1632	0.0021	0.8990	0.0044
148 52	GH	381.8	0.1610	0.0019	0.8907	0.0044
148 52	HI	381.8	0.1719	0.0018	0.8196	0.0040
148 52	IJ	381.8	0.1635	0.0020	0.8933	0.0044
149 52	IJ	381.8	0.1629	0.0020	0.9037	0.0044
148 52	-OP	381.8	0.1424	0.0022	0.8482	0.0049

TABLE 8.3 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁸ U(n, f) ^c		²³⁸ U(n, γ) ^c	
148 52	-AB	483.4	0.1018	0.0018	0.7269	0.0039
149 52	GH	483.4	0.1142	0.0017	0.7940	0.0043
148 52	GH	483.4	0.1140	0.0016	0.7826	0.0039
148 52	HI	483.4	0.1223	0.0016	0.7032	0.0038
148 52	IJ	483.4	0.1150	0.0017	0.7810	0.0039
149 52	IJ	483.4	0.1183	0.0020	0.7944	0.0043
148 52	-OP	483.4	0.0980	0.0019	0.7272	0.0039
148 73	-AB	77.0	0.1096	0.0018	0.6681	0.0035
149 73	GH	77.0	0.1127	0.0016	0.7036	0.0034
148 73	GH	77.0	0.1075	0.0018	0.7013	0.0033
148 73	HI	77.0	0.1135	0.0016	0.6266	0.0031
148 73	IJ	77.0	0.0996	0.0016	0.6803	0.0034
148 73	-OP	77.0	0.0781	0.0019	0.6087	0.0032

Axial Blanket Cells

148 58	-JJ	534.2	0.0620	0.0017	0.6825	0.0041
149 58	IJ	534.2	0.0563	0.0012	0.7742	0.0041
148 58	-OP	534.2	0.0594	0.0015	0.6840	0.0041
148 58	-JJ	585.0	0.0336	0.0013	0.5938	0.0040
149 58	IJ	585.0	0.0315	0.0013	0.7008	0.0041
148 58	-OP	585.0	0.0350	0.0013	0.6058	0.0038
149 52	GH	635.8	0.0181	0.0010	0.6191	0.0034
148 52	-JJ	635.8	0.0189	0.0012	0.5065	0.0030
148 52	-OP	635.8	0.0201	0.0012	0.5323	0.0031
148 58	-JJ	661.2	0.0179	0.0012	0.4888	0.0035
149 58	IJ	661.2	0.0162	0.0010	0.6128	0.0037
148 58	-OP	661.2	0.0162	0.0011	0.5187	0.0033
149 52	GH	686.6	0.0105	0.0011	0.5542	0.0030
148 52	-JJ	686.6	0.0133	0.0012	0.4416	0.0029
148 52	-OP	686.6	0.0133	0.0010	0.4544	0.0027
148 58	-JJ	737.4	0.0087	0.0012	0.3947	0.0028
149 58	IJ	737.4	0.0091	0.0009	0.5090	0.0032
148 58	-OP	737.4	0.0106	0.0010	0.4025	0.0028

Measurements in Cells with Two Fuel Columns

Central Blanket Cells

148 57	-AB	77.0	0.0534	0.0024	1.0922	0.0057
148 57	-HH	77.0	0.0547	0.0021	0.9953	0.0056
149 57	HI	77.0	0.0505	0.0024	0.9759	0.0051

TABLE 8.3 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁸ U(n, f) ^c	²³⁸ U(n, γ) ^c
148 57	-AB	127.8	0.0762 0.0030	1.0623 0.0055
148 57	-HH	127.8	0.0762 0.0022	0.9823 0.0052
149 57	HI	127.8	0.0755 0.0022	0.9524 0.0047
Core Cells				
149 54	JK	178.6	0.1545 0.0022	1.0589 0.0054
148 54	JK	178.6	0.1559 0.0023	1.0740 0.0055
148 54	KL	178.6	0.1625 0.0024	0.9291 0.0049
148 54	LM	178.6	0.1517 0.0026	1.0004 0.0052
148 54	-OP	178.6	0.1323 0.0027	0.9706 0.0052
149 54	JK	280.2	0.1897 0.0026	0.9831 0.0051
148 54	JK	280.2	0.1871 0.0026	0.9978 0.0052
148 54	KL	280.2	0.1952 0.0028	0.8883 0.0052
148 54	LM	280.2	0.1848 0.0027	0.9345 0.0050
148 54	-OP	280.2	0.1652 0.0030	0.9047 0.0049
149 60	JK	381.8	0.1908 0.0026	0.9651 0.0051
148 60	JK	381.8	0.1863 0.0025	0.9637 0.0051
148 60	KL	381.8	0.1942 0.0028	0.8692 0.0050
148 60	LM	381.8	0.1820 0.0026	0.9188 0.0053
148 60	-OP	381.8	0.1623 0.0032	0.8884 0.0056
149 60	JK	483.4	0.1325 0.0025	0.8211 0.0045
148 60	JK	483.4	0.1354 0.0026	0.8283 0.0046
148 60	KL	483.4	0.1338 0.0024	0.7254 0.0042
148 60	LM	483.4	0.1267 0.0026	0.7746 0.0045
148 60	-OP	483.4	0.1096 0.0029	0.7479 0.0043
249 66	-OP	51.6	0.1563 0.0024	1.1830 0.0062
249 66	LM	51.6	0.1886 0.0025	1.2188 0.0059
249 66	KL	51.6	0.2098 0.0023	1.1448 0.0056
249 66	JK	51.6	0.2063 0.0024	1.2850 0.0062
248 66	JK	51.6	0.2113 0.0022	1.2731 0.0061
149 66	JK	51.6	0.2161 0.0024	1.2716 0.0064
148 66	JK	51.6	0.2142 0.0023	1.2667 0.0061
148 66	KL	51.6	0.2278 0.0024	1.1218 0.0055
148 66	LM	51.6	0.2184 0.0024	1.1748 0.0058
148 66	-OP	51.6	0.1926 0.0026	1.1214 0.0064
249 66	-OP	102.4	0.1673 0.0024	1.1823 0.0062
249 66	LM	102.4	0.1964 0.0021	1.2129 0.0059
249 66	KL	102.4	0.2165 0.0022	1.1317 0.0058
249 66	JK	102.4	0.2113 0.0023	1.2772 0.0064
248 66	JK	102.4	0.2136 0.0023	1.2590 0.0064
149 66	JK	102.4	0.2182 0.0024	1.2486 0.0061
148 66	JK	102.4	0.2153 0.0024	1.2458 0.0061
148 66	KL	102.4	0.2321 0.0024	1.1034 0.0057

TABLE 8.3 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁸ U(n, f) ^c	²³⁸ U(n, γ) ^c
148 66	LM	102.4	0.2216 0.0023	1.1601 0.0057
148 66	-OP	102.4	0.1967 0.0024	1.1225 0.0059

Axial Blanket Cells

148 57	-AB	534.2	0.0615 0.0027	0.6717 0.0042
148 57	-GG	534.2	0.0593 0.0022	0.6459 0.0038
149 57	GH	534.2	0.0567 0.0023	0.7615 0.0032
148 57	-AB	585.0	0.0357 0.0026	0.6100 0.0038
148 57	-GG	585.0	0.0372 0.0017	0.5847 0.0036
149 57	GH	585.0	0.0336 0.0026	0.7124 0.0038

Measurements in Radial Blanket Cells

148 74	-AB	77.0	0.0552 0.0016	0.5692 0.0032
148 74	-CD	77.0	0.0507 0.0021	0.5372 0.0030
148 74	-GG	77.0	0.0503 0.0013	0.5032 0.0030
149 74	GH	77.0	0.0498 0.0013	0.4998 0.0026
249 74	IJ	77.0	0.0500 0.0013	0.5006 0.0026
148 74	-HI	77.0	0.0420 0.0014	0.4906 0.0030
148 74	-JJ	77.0	0.0460 0.0013	0.4797 0.0029
148 74	-MN	77.0	0.0346 0.0014	0.4841 0.0027
148 74	-OP	77.0	0.0334 0.0013	0.4801 0.0029
148 76	-AB	77.0	0.0170 0.0010	0.3481 0.0022
148 76	-CD	77.0	0.0156 0.0009	0.3303 0.0022
148 76	-GG	77.0	0.0151 0.0010	0.2952 0.0021
149 76	GH	77.0	0.0140 0.0009	0.2999 0.0020
249 76	IJ	77.0	0.0159 0.0010	0.2985 0.0019
148 76	-HI	77.0	0.0159 0.0010	0.2911 0.0020
148 76	-JJ	77.0	0.0152 0.0012	0.2787 0.0020
148 76	-MN	77.0	0.0117 0.0009	0.2876 0.0020
148 76	-OP	77.0	0.0111 0.0009	0.2843 0.0021

TABLE 8.3 (contd)

Matrix	Loc ^a	z, mm ^b	²³⁸ U(n, f) ^c	²³⁸ U(n, γ) ^c
148 78	-AB	77.0	0.0061 0.0009	0.2041 0.0016
148 78	-CD	77.0	0.0060 0.0010	0.1906 0.0016
148 78	-GG	77.0	0.0066 0.0010	0.1712 0.0015
149 78	GH	77.0	0.0067 0.0009	0.1746 0.0014
249 78	IJ	77.0	0.0077 0.0011	0.1720 0.0013
148 78	-HI	77.0	0.0058 0.0011	0.1690 0.0015
148 78	-JJ	77.0	0.0036 0.0010	0.1635 0.0015
148 78	-MN	77.0	0.0068 0.0010	0.1833 0.0017
148 78	-OP	77.0	0.0059 0.0008	0.2006 0.0016

^aIn-drawer column which designates the foil location in the drawer. The ²³⁸U foils were centered on the mid-height of the drawer. A negative sign designates a plate-spanning averaging foil.

^bDistance from the reactor interface to the center of the foil.

^cExperimental results in units of 10⁻¹⁸ fissions or captures per sec per atom at a reactor power of approximately one watt. The second number is one standard deviation uncertainty. See text for details.

TABLE 8.4 Cell-Averaging Factors for ZPPR-17A

$^{239}\text{Pu}(n,f)^a$		$^{235}\text{U}(n,f)^a$		$^{238}\text{U}(n,f)^a$		$^{238}\text{U}(n,\gamma)^a$		REG./ENV. ^b	z, mm^c
1.0	.006	.9988	.0051	.998	.022	1.0664	.0078	IC F/SC/F	0-51.6
.9772	.0046	.9996	.0069	.938	.013	.8858	.0057	IC F/SC/F	178.6
.9916	.0058	.9998	.0052	.953	.012	.9172	.0061	IC F/SC/F	280.2
.9890	.0061	.9975	.0059	.957	.011	.9272	.0054	OC F/SC/F	0-280.2
.9850	.0059	1.0020	.0057	.978	.019	.9020	.0051	OC F/SC/RB	0-280.2
1.0	.006	.9988	.0051	.998	.022	1.0664	.0078	IC SC/DC/SC	0-51.6
.9888	.0060	.9974	.0050	.980	.014	.8640	.0055	IC SC/DC/SC	178.6
.9895	.0055	.9961	.0055	.985	.013	.8799	.0059	IC SC/DC/SC	280.2
.9929	.0047	.9926	.0042	.962	.013	.8762	.0048	OC CB/DC/SC	0-51.6
.9903	.0057	.9984	.0049	.974	.013	.8935	.0061	OC SC/DC/SC	0-280.2
1.0	.008	1.0022	.0063	.912	.026	1.0229	.0058	RB SC/RB/RB	ALL
1.0	.008	.9949	.0074	.988	.071	1.0170	.0071	RB RB/RB/RB	ALL
1.0	.008	.9791	.0085	.838	.100	1.0508	.0090	RB RB/RB/RR	ALL
.	.	1.0	.010	.	.	.	.	RR, AR	ALL
1.0	.006	.9988	.0051	.998	.022	1.0694	.0063	148-50	26.2
1.0	.006	.9988	.0051	.998	.022	1.0664	.0078	148-50	49.6
1.0	.006	.9988	.0051	.998	.022	1.0634	.0093	148-50	77.0
1.0	.006	.9988	.0051	1.000	.026	1.0610	.0089	148-50	100.4
1.0	.006	.9988	.0051	1.003	.030	1.0586	.0085	148-50	127.8
.9772	.0046	.9996	.0069	.938	.013	.8858	.0057	148-50	178.6
.9844	.0052	.9997	.0059	.946	.013	.9015	.0059	148-50	229.4
.9916	.0058	.9998	.0052	.953	.013	.9172	.0061	148-50	280.2
.9890	.0059	.9975	.0055	.955	.012	.9222	.0058	148-50	331.0
.9863	.0063	.9952	.0058	.957	.011	.9272	.0054	148-50	381.8
.9892	.0064	.9980	.0067	.955	.013	.9224	.0054	148-50	432.6
.9920	.0065	1.0007	.0076	.953	.014	.9175	.0054	148-50	483.4
1.0	.008	1.0005	.0059	1.081	.031	.8815	.0061	148-50	534.2
1.0	.008	1.0005	.0059	1.081	.053	.8521	.0064	148-50	585.0
1.0	.008	1.0005	.0070	1.081	.077	.8340	.0060	148-50	635.8
1.0	.008	1.0005	.0073	1.081	.16	.8053	.0058	148-50	686.6
1.0	.008	1.0005	.0074	1.081	.14	.7817	.0064	148-50	734.4
.9929	.0047	.9926	.0042	.962	.013	.8762	.0048	148-66	51.6
.9929	.0047	.9926	.0044	.977	.009	.8745	.0050	148-66	102.4
.9888	.0060	.9974	.0050	.980	.014	.8640	.0055	148-66	178.6
.9892	.0058	.9968	.0053	.982	.014	.8720	.0057	148-66	229.4
.9895	.0055	.9961	.0055	.985	.013	.8799	.0059	148-66	280.2
.9903	.0057	.9984	.0049	.980	.013	.8867	.0060	148-66	331.0
.9911	.0059	1.0007	.0043	.974	.013	.8935	.0061	148-66	381.8
.9870	.0072	.9982	.0043	.958	.015	.8822	.0067	148-66	432.6
.9829	.0086	.9957	.0042	.942	.017	.8709	.0073	148-66	483.4

TABLE 8.4 (contd)

$^{239}\text{Pu}(n,f)^a$		$^{235}\text{U}(n,f)^a$		$^{238}\text{U}(n,f)^a$		$^{238}\text{U}(n,\gamma)^a$		REG./ENV. ^b	z, mm ^c
1.0	.008	.9986	.0059	1.064	.052	.8627	.0057	148-66	534.2
1.0	.008	1.0005	.0059	1.081	.053	.8361	.0064	148-66	585.0
1.0	.008	1.0005	.0070	1.081	.077	.8340	.0060	148-66	635.8
1.0	.008	1.0005	.0073	1.081	.16	.8053	.0058	148-66	686.6
1.0	.008	1.0005	.0074	1.081	.14	.7817	.0064	148-66	734.4
.9890	.0061	.9975	.0059	.957	.011	.9272	.0054	148-70	0-381.8
.9892	.0064	.9980	.0067	.955	.013	.9224	.0054	148-70	432.6
.9920	.0065	1.0007	.0076	.953	.014	.9175	.0054	148-70	483.4
1.0	.008	1.0005	.0059	1.081	.031	.8815	.0061	148-70	534.2
1.0	.008	1.0005	.0059	1.081	.053	.8521	.0064	148-70	585.0
1.0	.008	1.0005	.0070	1.081	.077	.8340	.0060	148-70	635.8
1.0	.008	1.0005	.0073	1.081	.16	.8053	.0058	148-70	686.6
1.0	.008	1.0005	.0074	1.081	.14	.7817	.0064	148-70	734.4

^aThe second number for each cell factor is a one standard deviation uncertainty. See text for details.

^bReactor region and local environment. See text for key and discussion.

^cAxial position to which this cell factor is useable.

9. IMPROVED CROSS SECTIONS FOR ZPPR-17 (R. W. Schaefer)

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

Some theoretical considerations suggested that improved cross sections might help remedy the C/E problems. The original cross sections accounted for the close proximity of different cell types only at the stage of collapsing from 230 to 21 energy groups; in the resonance calculations and the cell homogenization the cells were treated as asymptotic. In the case of blanket cells the zero buckling eigenvalue approach used for the homogenization leads to a substantially distorted in-cell flux distribution. In addition, the particular models used for two blanket cells resulted in excessive ^{238}U resonance self shielding by equivalence theory.

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

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

Additional steps were taken to improve the cross sections. A 230 group base library was created for the SDX blanket cell calculations. This was

done using the internal blanket composition and bucklings in the MC²-2 code. (The original base library was still considered appropriate for the core cells.) Also the blanket cell models were redefined to minimize the equivalence theory resonance self shielding errors. In addition a heterogeneous resonance self shielding treatment was used for sodium in the core and blanket cells. (Originally it was homogeneous.)

Cell average, plate and detector cross sections were saved for each of the cells. The cell average cross sections have the same names as their counterparts in the original set. The first two characters of the name identify the isotope and the next two identify the cell. For example, cell average ²³⁸U in the internal blanket is called U8IB. Detector cross section names have H as a fifth character (e.g., U8IBH) and plate cross section names have a number identifying the plate as a fifth character (e.g., U8IB2). Cell average cross sections are used with homogenized cell models. Plate cross sections are used for sodium and heavy metal isotopes in plate-by-plate cell models. Detector cross sections are used for the remaining isotopes in plate cell models, and also are often the best choice available for small-sample worths and foil reaction rates.

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

There were two attempts to generate cross sections for PU-30. The first followed the same procedure used for the activation foils, yielding cross sections for ²³⁹Pu, ²⁴⁰Pu and ²⁴¹Pu whose names end in IBW. When used with a broad group sample size correction factor (from the SARCASM code) they gave worths that appear to be overshielded. To overcome this, cross sections were generated that have all the size effects built into them; they

are the cell average cross sections from a cell that had PU-30 represented as an infinite cylinder at the center, surrounded by a large annulus of homogeneous blanket and with the inner blanket bucklings imposed (names end in IC).

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

9.1 Effect of New Cross Sections

The effect of the new cross sections on eigenvalue is shown in Table 9.1 for three models of ZPPR-17A. The first model includes only the central 3x3 array of drawers, with reflective boundary conditions at X and Y boundaries. This is an economical testbed. The other two models use a full assembly representation, one with diffusion theory and the other with transport theory. With all three models it is seen that the new region average cross sections lower the eigenvalue by a little more than 0.1%. When the boundary region cross sections are also included in the first model, the effect is cut in half. The boundary cross sections are cumbersome to use in full assembly models, and their impact does not appear to be large enough to be worth the effort. In any case the cross section effect on eigenvalue is small.

Axial reaction rate traverses were computed for the three cross section options with the first model. The results are given in Table 9.2. Except for ^{239}Pu fission (F9) there are modest changes in the inner blanket and almost no change elsewhere. For F9 there is a large change in the inner blanket, which is due to the resonance shielding treatment discussed earlier. This is illustrated further by Table 9.3, which shows the sensitivity to the reaction cross section type used in the inner blanket.

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

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

In summary, the new cross sections generally have removed only a fraction of the C/E problems. One conjecture as to why the improvements were not greater has to do with neutron leakage between different cells. Although the region-averaged, group-dependent bucklings should produce a realistic collapsing spectrum and, at least for the blanket, an improved in-cell flux distribution, they do not force preservation of leakage between unlike cells. As currently implemented, the multidrawer cell option in the SDX code does not do this either. This is an area that probably warrants some investigation.

TABLE 9.1 Effect of New Cross Sections on ZPPR-17A Eigenvalue

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

TABLE 9.2 Axial Reaction Rate Traverses with Old and New Cross Sections^a

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

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

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

TABLE 9.3 Sensitivity of ^{239}Pu Fission in the Inner Blanket to Cross Section Type

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

^aSame flux used for all cases.

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

Contribution to P9IBR f^{49} at $z = 0$ to 7.6 cm

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

58.7%

10. BOWING, EXPANSION AND SMALL-SAMPLE WORTH MEASUREMENTS IN ZPPR-17A
(R. W. Schaefer and R. W. Goin)

10.1 Introduction

The purpose of these measurements was to test the accuracy of reactivity feedback calculations in reactor safety analyses. There currently is strong interest in reactivity predictions related to power reactor inherent safety mechanisms. These mechanisms include bowing, radial expansion, axial expansion, sodium density change, and control driveline expansion. The experiments were designed to simulate the power reactor phenomena as closely as feasible and to be analyzable by design methods. In addition to inherent safety phenomena, there is interest in reactivities related to core disruption. There was no time available to build disrupted core configurations; instead this issue was addressed by measuring the worth of fuel, structure, control and coolant samples at various locations.

There was one static experiment and a large number of material oscillation experiments. The static experiment simulated bowing by rearranging plates in a zone. The oscillators used were a new bowing oscillator, the axial expansion oscillator, plate-column oscillators, the axial tube oscillator and the radial tube oscillator. Table 10.1 and Fig. 10.1 give an overview of what oscillator experiments were done.

In the remaining sections the reactor configurations and experiments are described and the experimental results are presented. Sufficient information is provided to allow a thoroughly detailed analysis of each experiment. However, to make this report more readable, we have tried to isolate details at the end of each section. The last section is a brief summary. Calculations of these experiments have not yet been completed and will be reported separately.

10.2 All-Plate Shifting in a Zone

The purpose of this experiment was to simulate bowing of some core subassemblies. The motion of the duct and all its contents radially

outward was simulated. There was a corresponding inward movement of inter-subassembly sodium due to changes in the intersubassembly gap width.

This was accomplished by rearranging the plate cells in a zone. A sodium plate column, 0.64 cm-wide and as long as the core, was removed from the outside cell edge, shifting the rest of the core region plate columns toward the outside edge, and reinstalling the sodium column at the inside edge. Thus the motion corresponds to a radial displacement that is uniform over the axial core length and is the same in every cell in the zone. However, the magnitude of the displacement is large compared to what would occur in power reactor bowing (about 0.1 cm).

The size and location of the zone are indicated in Fig. 10.1. The zone had the normal mix of single-fuel-column (SFC) and double-fuel-column (DFC) drawers. It is equivalent in volume and composition to 8 power reactor subassemblies.

The experimental worth for the plate shifting is -6.02 cents with an uncertainty of 3.1%. The reactivity was determined by the subcritical source multiplication technique calibrated by a rod drop measurement. The uncertainty was obtained by adding (in quadrature) the 1.2% uncertainty from the subcritical source multiplication analysis and a 2.8% configuration reproducibility uncertainty. The latter was estimated by measuring the change in apparent subcriticality when the initial reactor configuration was restored.

Details

The zone was 1/8 core symmetric with 12 drawers per octant. The location was rows 1,246 through 1,251 and columns 27 through 30 and 69 through 72.

Because the standard cell loadings did not have 0.64 cm-wide sodium columns at the edge, the plate columns had to be rearranged in the zone before the desired plate shifting could be done. For SFC drawers it also

was necessary to replace each 1.27 cm-wide sodium column present in standard loadings with two 0.64 cm-wide sodium columns. The SFC and DFC cell arrangements are shown in Figs. 10.2 and 10.3, respectively, for the pre-shift state. Figures 10.4 and 10.5 show the post-shift arrangements for the drawers specified in the figure titles; the remaining drawers were the mirror images of the ones shown. The actual drawer master numbers are 138 through 142, 200 and 201 for the pre-shift state, and 143 through 152 and 222 through 225 for the post-shift state.

The experiment consisted of measuring the subcriticality of four reactor configurations. For Step 1 the reactor was in nearly the standard subcritical configuration. The only difference was the replacement of detector drawers in matrix positions 150-69 (detector # 26) and 250-47 (# 40) with normal SFC drawers. It was in this step that the rod drop was done, producing inverse kinetics file number 114. For Step 2 the pre-shift drawer loadings were in the zone. For Step 3 the plate columns were shifted in the zone. For Step 4 the reactor was restored to the configuration of Step 1.

Data for each step are shown in Table 10.2. Reactivities were obtained using the MCRUNCH processing code. Unity was used for detector efficiency ratios and source ratios, an approximation that is justified by two pieces of evidence. One is an examination of the change in the 62 detector signals, which indicates that the flux distribution changed only a few tenths of one percent due to the plate shifting. The other is that the chi-squared for the distribution of reactivity estimates from the detectors is reasonably close to unity.

10.3 Axial Tube Oscillator

Small-sample worths were measured in the traditional manner with the axial tube oscillator (ATO). It should be possible to relate the sample worths to both inherent safety and core disruption reactivity quantities of interest to designers.

The reactor configurations for these measurements were essentially the same as the ZPPR-17A critical reference configuration. Measurements were made with the tube installed in three different matrix positions, which are indicated in Fig. 10.1. Measurement ATO-1 was in position 159-49, which is well inside the inner core radius. Measurement ATO-2 was in position 163-41, which is in the outer core but next to the inner core. Measurement ATO-3 was in position 171-49, which is in the outer core one drawer away from the radial blanket. All of these positions had modified DFC core loadings.

Up to two five sample materials (plus the empty capsule or dummy, D-14) were oscillated in each measurement. They are ^{239}Pu (PU-30), ^{238}U (DU-6), ^{10}B (B-1), stainless steel (SS-1), and ^{235}U (U-6). The samples are described in Table 10.3. All were oscillated in Measurements 1 and 2, and all but U-6 were oscillated in Measurement 3.

The experimental results are given in Tables 10.4, 10.5 and 10.6. There Z is the axial distance from the matrix interface to the center of the sample.

It should be noted that the statistical precision is poor in many cases. This is attributable, at least in part, to the unusually large core size, which leads to small absolute worths. Worths with a statistical uncertainty in excess of 10% provide only a a loose test of calculations. The measurements that have an uncertainty greater than 10% are: SS-1, DU-6 and the last few points for the other samples in ATO-1; SS-1, the last 12 points for DU-6 and the last few points for the other samples in ATO-2; SS-1, DU-6 and the last few points for the other samples in ATO-3.

Details

Some details about the measurements are given in Table 10.1, where the axial tube measurements are referred to as ATO-1, ATO-2 and ATO-3.

The tube was in a 1.27 cm-wide (by 5.24 cm-tall) cavity at the center of a drawer. The cavity was created in the core section by removing

the sodium carbonate column. In the internal blanket section, the two 1.27 cm-wide sodium columns were replaced with 0.635 cm-wide sodium columns and the depleted uranium and Fe_2O_3 columns were shifted away from the drawer center. In the external blanket section, this same sodium replacement was made. In addition the 0.635 cm-wide steel was replaced by two 0.3175 cm-wide steel columns, with each placed between a sodium and depleted uranium column.

As noted above, the reactor configurations were similar to the ZPPR-17A critical reference. They differed only by the presence of a drawer modified to accommodate the tube and, in one case, by the presence of a plate column oscillator drawer (Section 10.7). The 8 symmetric operational control rods were banked, with the distance from matrix interface to rod tips ranging from 50.0 to 59.2 cm, depending on the measurement.

10.4 Radial Tube Oscillator

The other traditional approach, the radial tube oscillator (RTO), also was used to measure small-sample worths. All the samples used in the axial tube, except U-6, were oscillated. These are referred to as RTO-1 in Table 10.1 and Fig. 10.1. In addition, a neutron importance measurement (RTO-2 in Table 10.1 and Fig. 10.1) was made by oscillating a ^{252}Cf source in the radial tube at two different power levels, 3 watts and 80 watts.

The experimental results for both RTO-1 and RTO-2 are shown in Table 10.7. As was the case for the axial tube measurements, the statistical uncertainty exceeds 10% in a number of cases: SS-1, the last 10 points for DU-6, and the last few points for the other two samples.

There are some interesting differences between the axial tube and radial tube worths at what should be nearly equivalent locations. This is of particular interest because C/Es (not shown) for the two kinds of tube measurements are noticeably different for some samples. In Table 10.8 we display ratios of sample worth from the RTO to worth from the ATO. There are differences in the two measurement situations - in-cell location, exact axial location, and symmetrically equivalent (except for streaming) rather

than identical matrix positions. In the case of the second column of ratios the matrix positions are not even symmetrically equivalent, just equivalent in radius. Thus only unexpectedly large worth differences are of interest. The first set of ratios, from the inner blanket, indicates that worths from the RTO are about 5% higher, which is more than might be anticipated but not unreasonable. The ratios in the second column, just beyond the internal blanket, are all reasonably close to unity except for SS-1. There is as yet no explanation for the SS-1 ratio. The third column, from the outer core, shows nothing unexpected.

Details

Two modifications were made to the ZPPR-17A critical reference configuration for these measurements. One was to push the drawers back 0.635 cm from the matrix interface in rows 1,248, columns 18 through 50. This created a 1.27 cm by 5.32 cm channel in which the tube was centered. It required using tabless drawers in these positions. The reactivity loss due to this change necessitated the second change - a net shift of fuel to a higher worth location. This was accomplished by swapping the 8 SFC drawers at 159-32 and symmetrically equivalent positions with 8 DFC drawers at 161-30 and equivalent positions. The 8 symmetric operational control rods were banked, with the distance from matrix interface to rod tips being 28.2 cm for the 3 watt ^{252}Cf measurement, 41.9 cm for the 80 watt ^{252}Cf measurement, and in the range 38.1 to 40.9 for the small-sample measurements. This configuration is the only one in the oscillator experiment series that had enough reactivity excess to require control rods protruding into the core region. It turns out that these configuration differences are unimportant; data from the 64 in-core fission chambers show that the fission rate along the x-axis near the axial midplane was affected by less than 1%.

10.5 Axial Expansion Oscillator

The axial expansion oscillator (AEO) is a device used to simulate axial expansion in a small portion of the reactor (one drawer, which is about 1/6 of a power reactor subassembly). This oscillator is a special

drawer composed of segments, between which small gaps can be opened and closed. Thus uniform expansion is approximated by a few discrete gaps.

In the measurements here, three 0.635 cm-wide gaps were created, resulting in a total expansion of 1.905 cm. The gaps were created by pulling on the back end of the drawer while the front end was anchored. With all the gaps closed, the axial distances from the matrix interface to the points where the drawer segments separate were 15.2 cm, 30.5 cm and 45.7 cm.

Three measurements were made with this oscillator, which are referred to as AEO-1, AEO-2 and AEO-3. Their locations are shown in Fig. 10.1. AEO-1 and AEO-2 were in the same matrix positions as the first two axial tube measurements, inside the inner core and just beyond the inner core, AEO-3 was in the outer core two drawers from the inner core, a location where the internal blanket influence should be small and material worths should be relatively large. All of these locations had DFC core cells.

The experimental worths are -0.04977 cents $\pm 0.8\%$ for AEO-1, -0.10437 cents $\pm 0.7\%$ for AEO-2, and -0.11061 cents $\pm 0.6\%$ for AEO-3, where the uncertainties are statistical only. Measurements done in ZPPR-15D to check the experimental reproducibility showed that, in addition to statistics, there was a nonreproducibility uncertainty of about 3% (Ref. ZPR-TM-471, pg. 43). This uncertainty probably is also appropriate to these ZPPR-17 measurements.

The first experiment should be more challenging to calculate than the others. The expansion worth is about half as large for AEO-1 even though the material motion was the same in all three experiments. This is because of the power flattening effect of the internal blanket, which leads to a more delicate balance of opposing reactivity components. Another difficulty in AEO-1 is that one of the gaps is at the core/internal blanket interface.

Details

A number of details about these measurements are given in Table 10.1.

The last drawer segment of the AEO in the core region was 5.08 cm long. Because ZPPR fuel and sodium carbonate this short are not normally used, they are not in the Aden plate inventory description. The sodium carbonate plate was fabricated especially for this experiment by removing a sodium carbonate block from a standard, longer plate and cladding it with the same kind of stainless steel jacket as is on a standard plate. Thus the masses from a standard, longer plate, scaled down by the appropriate length ratio is an adequate description of this plate. The compositions of the two special ZPPR fuel plates are given in Table 10.9. They are nominally the same as standard ZPPR fuel plates.

The width of each gap was limited by attaching the drawer segments together with mylar tape ($C_{10}H_8O_4$). No gap was allowed at the core-external axial blanket interface, where the last two drawer segments meet. Two pieces of tape, each about 5 cm square (about 0.14 g), were used at the junction of each segment. A 0.14 g piece of mylar tape was used to help anchor the front of the drawer to the matrix tube.

The drive used here is a new mechanism, a double-acting air cylinder with a connecting rod that attaches to the back of the drawer. A linear potentiometer measures the total expansion of the drawer. Because the drive fits inside the matrix tube, the oscillator could be used at almost any matrix position. The previous mechanism was the axial tube drive, which could be mounted at only a few locations.

The reactor configurations for these measurements were essentially the same as the ZPPR-17A critical reference configuration. They differed only by the presence of the axial expansion oscillator, two or three plate column oscillators (Section 10.7) and, in one case, the bowing oscillator (Section 10.6). There were no steel blocks behind the oscillator drawers. The 8 symmetric operational control rods were banked, with the distance from

matrix interface to rod tips ranging from 52.3 to 55.6 cm, depending on the measurement.

10.6 Bowing Oscillator

The bowing oscillator (BO) is a new mechanism. (It should not be confused with the pin tilting oscillator used in ZPPR-15, which also has been called a bowing oscillator.) This device simulates bowing with one drawer by shifting the core section about 1.4 mm within the matrix tube. The device is also referred to as the air gap oscillator because the drawer section moves up and down in the space allowed by the cooling air gap that normally is present between the top of a drawer and a matrix tube.

As in the bowing of a power reactor subassembly, the oscillator shifts a nearly complete unit cell along a radial flux gradient a distance comparable to the intersubassembly gap. There are some obvious differences between this simulation and actual bowing, but they appear to be sufficiently unimportant that the C/E from this experiment should be a good indication of the accuracy of power reactor bowing calculations.

The first, 53.3 cm-long section of the oscillator is the portion that moved. It contained a plate loading that is similar to a DFC cell; the most important difference is that it had only 48.26 cm of core material distributed over the core half-height.

The bowing oscillator was located one drawer from the radial blanket, as shown in Fig. 10.1. This is about at the peak of the radial core worth gradient, and corresponds to bowing in part of the outermost core subassembly. This position also is symmetrically equivalent to the location of the ATO-3 measurements.

The bowing measurement was done twice in order to check reproducibility. To make this a more meaningful check, the oscillator was removed from the reactor and the plate loading was loosened and reclamped between the measurements. Unfortunately the movement indicator at the front of the oscillator in the first measurement failed before it could be

calibrated. As a result, the motion during the first measurement is not known precisely. The most precise conclusion that can be drawn from this check is that the reproducibility uncertainty is not more than 5%.

The motion of the oscillator during the second measurement is displayed in Table 10.10. These values come from both potentiometer readings and in situ feeler gauge measurements. The motion at each of the four monitoring points was different because the moving section did not behave as a completely rigid body. It is legitimate to average the left and right motions because there is no significant worth gradient across the drawer width. It also turns out that the axial worth gradient is sufficiently linear that simplifying averaging the front and back motions, which yields a motion of 0.132 cm, gives an accurate approximation to the actual effective average motion, 0.133 cm. The latter was obtained from calculations that treated the axial tilt explicitly. For purposes of deriving a C/E it is sufficient to represent the motion as a uniform displacement of 0.133 cm.

The experimental reactivity resulting from this motion is -0.01392 cents. The statistical uncertainty from the inverse kinetics processing of the data is 1.9%. In addition the values of the motions described in the previous paragraph are uncertain by about 0.004 cm (2.9%) due to calibration uncertainty. Combining these two yields an experimental uncertainty of 3.5%.

Details

Some details for these measurements are given in Table 10.1.

The plate loading in the oscillator is depicted in Figure 10.6. The front, moving section is loaded with core material. The second, stationary section contained axial blanket and some axial reflector. Cams at each lower corner of the front section can rotate to raise the drawer as far as the air gap allows. The cams are driven by an air cylinder, located in the third section, that is connected to the cams by thin-gauge steel airplane cable. The motion is measured by three linear potentiometers, one near each back corner of the first section and one at a front corner.

The front section loading was different from a normal outer core DFC cell loading in a number of ways. The axial length of core material was 48.26 cm instead of 50.80 cm. However, this material extended to 50.00 cm because there were gaps at every axial plate boundary. The gap at the front was 0.46 cm thick and contained approximately 8 g of stainless steel and 1.7 g of plastic (from the potentiometer). The three axial gaps between plates were each about 0.41 cm thick and contained about 4 g of mild steel (screws) each. The gap at the back was about 3.3 cm thick and contained about 36 g of aluminum, 9 g of stainless steel, 40 g of mild steel and 5 g of plastic. The first 2.54 cm axially of the 0.635 cm-wide U308 column was missing because the front potentiometer protruded slightly into this space. This gap had about 1 g of crushed Al foil to prevent plates from shifting. The U308 column at the other side of the drawer had to be 0.3175 cm wide, instead of the usual 0.635 cm width, to accommodate the cables, wires and a clamping bar. The resulting 0.3175 cm-wide gap spanning the length of the front section contained about 477 g of stainless steel, 3 g of copper wire and 2 g of teflon wire insulation. The plate loading was kept rigid by squeezing it between the clamping bar and the drawer side using screws that passed through the axial gaps between plates. The drawer section containing this loading was made from a standard drawer that was shortened to 53.54 cm and had the standard 0.079 cm-thick bottom replaced with a 0.025 cm-thick bottom. The drawer is stainless steel and weighs approximately 414 g.

The axial blanket loading was normal except for replacing one 5.08 cm-tall 0.635 cm-wide U308 column with 2.54 cm-tall stainless steel (to make room for cables and wires. The axial reflector was all stainless steel and was not as thick as normal.

The reactor configuration was essentially the same as the ZPPR-17A critical reference configuration. The only difference was the presence of the bowing oscillator and three other oscillators (three plate column oscillators in one measurement and two of these plus the axial expansion oscillator in the other measurement).

10.7 Plate Column Oscillators

A plate column oscillator (PCO) is a device that moves a plate column axially. It can be used to measure the reactivity due to removing a plate column from a unit cell. These oscillators were used previously in ZPPR-17A to measure sodium voiding worth.

In the current experiments they were used to measure the worth of removing Pu-U fuel, U_3O_8 , Fe_2O_3 , sodium-filled and stainless steel void can columns. There were 10 plate column oscillator experiments, which are referred to as PCO-1 through PCO-10. The locations of the oscillators are indicated in Fig. 10.1. The experimental worths are shown in Tables 10.11 through 10.21 and Figures 10.7 through 10.17. The figures show "on-the-fly" data as well as stop-point data, while the tables contain only stop-point data. The curve in each figure is simply an interpolation through the data points, not a calculated reactivity. The worths are for withdrawing the plate column the distance indicated from the full-in position, except for PCO-5 and PCO-6 as noted below.

The purpose of recording data for a partially withdrawn column was to get axial profile information and, in some cases, to look for nonlinearities in worth as a function of gap size. The latter is related to the validity of using discrete gaps to simulate axial expansion. Most of the partial withdrawal data are useful but there are two problems. One is that for low worth materials, such as sodium, the reactivity for some withdrawal positions is too uncertain to be of interest.

The second problem is with small withdrawals. Data were taken for 0.25 cm withdrawal of fuel in PCO-5 and PCO-6. Later it was determined that the oscillator is not capable of positioning a column with high percentage accuracy for such short motions. It became clear that the distance traveled in the first outward step is poorly known for PCO-6. Accordingly the inner most position was dropped in creating Table 10.16. The zero withdrawal position shown there is for the front of the column approximately 0.14 cm from the front of the oscillator, rather than flush with it. It is estimated that the withdrawal from full in is uncertain by about 0.04cm, but

the distance between other positions is known to about 0.004 cm. This uncertainty is not accounted for in the tables. It should be unimportant except for small withdrawals.

For the earlier, sodium void worth measurements and for the first 3 plate column worth measurements here, the moving column's length was 66.04 cm. For the last 7 measurements the length was increased to 101.60 cm because of concern about the feasibility of calculating worths in the drive portion of the drawer (beyond 66 cm). Material worths do not drop to effectively zero by 66 cm from the axial midplane. For example the worth of ^{239}Pu there is about 5% of the worth at the axial midplane. Thus, if the moving column is only 66 cm long and high accuracy is desired, it is necessary to model the drive portion accurately in the calculation, which probably is difficult. In contrast, adding material at the back of a 100 cm long column should have a negligible worth compared to the worth of material removal at the front of the column. (Calculations indicate that it is much less than 1%.)

PCO-1 and PCO-2 were done at an outer core SFC matrix position adjacent to the inner core. Worths at this position may be of particular interest in connection with hypothetical core disruption accident analysis. In PCO-1 the moving column was Pu-U fuel (standard ZPPR fuel) for the first 50.80 cm and 0.635 cm-wide stainless steel from there to the end of the column (66.04 cm). In PCO-2 a 0.635 cm-wide, 66.04 cm-long U308 column was oscillated.

PCO-3 and PCO-4 were done at an inner core SFC matrix position. In PCO-3 the moving column was Pu-U fuel for the first 50.80 cm and 0.635 cm-wide stainless steel from there to the end of the column (66.04 cm). Note that with this moving column fully inserted, the drawer looks like an outer core SFC cell. In PCO-4 a 0.635 cm-wide 101.60 cm-long U308 column was oscillated. (The drawer for PCO-4 had a nearly normal internal blanket.)

PCO-5 was designed to look at how fuel gap worth varies with gap width in the presence of a flux gradient. The measurement was done in the

same outer core position as in the second axial expansion measurement. Only the last 66.04 cm of the 101.60 cm-long Pu-U fuel column was attached to the drive mechanism. Consequently the withdrawal in Table 10.15 is for the portion of the column starting 35.56 cm from the front. Calculations indicate that the reactivity from the Pu-U added at the back is about 1% as large as from the withdrawal at the front of the moving segment.

The worth gradients shown in Table 10.15 and Fig. 10.11 indicate how linear the worth variation is. The gradient for the first interval may appear to disagree with the next few values, but considering the quoted uncertainty plus the position uncertainty mentioned above, there is no clear discrepancy. For intervals 2 through 5 the gradient agrees to 1%. Beyond there the changing flux gradient would be expected to change the worth gradient. Thus there appears to be linearity over the range of interest for the axial expansion simulation.

PCO-6 through PCO-10 looked at the worth of each plate column in a SFC core cell in the mid outer core. In each case a 101.60 cm-long column was moved. The sequence of many stop points near the fully inserted position provides more data on the behavior of gap worth as function of gap width. In the case of the sodium column these data should be related not only to the axial expansion experiment, but also to a sodium density reactivity coefficient. Unfortunately, the uncertainties are too large for small withdrawals of sodium. In PCO-6 the Pu-U fuel column was moved. In PCO-7 and PCO-8 a 0.635 cm-wide U_3O_8 column and a 1.27 cm-wide sodium column, respectively, were oscillated. A void can column was oscillated in place of sodium in PCO-9. Each void can mass closely matched the clad mass of the corresponding sodium plate (Table 10.22). By assuming worth separability and differencing the results of PCO-8 and PCO-9, the worth of sodium in Table 10.20 was deduced. PCO-9 by itself gives the worth of stainless steel. In PCO-10 a 0.556 cm-wide Fe_2O_3 column was oscillated.

In inferring all the worths except the worth of removing the sodium core (PCO-8 minus PCO-9) it was assumed that there was a negligible reactivity signal from moving the drive mechanism. This assumption might be questioned because the aluminum block attached to the moving column acts

like a moving reflector. To test this assumption a "dummy" measurement was done in ZPPR-17B; no column was attached to the drive, but the drive was oscillated and reactivity data were taken. The results (given with the details below) show that the drive motion reactivity is totally negligible compared to the signals from all but PCO-8, PCO-9 and PCO-10. Even for these exceptions the effect is at most a few percent.

Details

Some details about each plate column oscillator measurement are given in Table 10.1. The drawer masters for the oscillators are shown in Figures 10.18 through 10.27. Masses or serial numbers for the moving plates are given in Table 10.22; compositions are available in the ADEN materials library.

A plate column oscillator drawer can be loaded almost normally over the first 66 cm of its length. Two deviations are the introduction of a tray for the column to slide in and the omission of a 0.3175 cm-wide plate column to allow the moving column to slide easily. The tray is made from a 0.0127 cm-thick by 5 cm wide strip of stainless steel weighing 0.503 g per cm of length. The strip is bent into a channel shape whose width is slightly greater than the sliding column's width. One additional deviation is the use of mylar tape to join the individual plates of the sliding column (see below).

Beyond 66 cm axially is the driving apparatus depicted in Fig. 10.30 - metal (aluminum or steel) blocks and rods, a motor and an encoder. Of particular note is the drive block (5.08 x 5.08 x 1.91 cm aluminum). Between the drive block and the sliding plates is a 4.4 cm-tall by 2.2 cm-long aluminum block whose width was a little less than that of the sliding plates. This connecting block is taped to the plate column and screwed to the drive block.

The maximum possible axial travel (stroke) of the plate column is about 66 cm if the sliding column is 66 cm long. The maximum stroke is reduced by whatever amount the sliding column length exceeds 66 cm.

The reactor configurations for the plate column oscillator measurements were essentially the same as the ZPPR-17A critical reference configuration. They differed only by the presence of various oscillators - plate column, bowing, axial expansion or axial tube. The 8 symmetric operational control rods were banked, with the distance from matrix interface to rod tips ranging from 52.1 to 56.6 cm, depending on the measurement.

Mylar tape was used to hold the moving plate columns together. Previous experience with mylar tape in axial expansion oscillators suggests that the presence of the tape can be ignored in calculations (Ref. ZPR-TM-471, p. 43). However, because this is hydrogenous material ($C_{10}H_8O_4$), there is some reason for concern. In case it is of interest, the tape used in each experiment is described here. In PCO-1, PCO-3, PCO-5, PCO-6, PCO-8 and PCO-9 a piece of mylar tape approximately 5 cm square (about 0.14 g) was used at each plate junction. In PCO-2, PCO-4 and PCO-7 the plates were joined using two strips of mylar tape that ran the entire length of the column. The combined width of the strips was 3.49 cm, resulting in 0.020 g of tape per cm of column length. In PCO-10 a 1.3 by 1.5 cm piece of mylar tape (0.011 g) was used at each of the 25 joints.

The experiment in ZPPR-17B to determine the effect of the moving drive mechanism was done on May 28, 1987 in reactor run number 133. The reactor loading number was 122, which is equivalent to the critical reference configuration. The oscillator was in matrix position 148-31. It had a normal DFC drawer loading for the first 66 cm and was empty except for the drive mechanism beyond there (master number 851).

Two datasets were taken. In the first (IK File 30) there was an unexpectedly large (factor of 2) reactor power drift. To avoid possible difficulties in correcting for drift, a second dataset (IK File 31) was taken with a small drift. From the plots of the results, Figures 10.28 and 10.29, it can be seen that the two files are essentially consistent. In Tables 10.23 and 10.24 the data have been structured in a form that gives a clearer indication of how large the drive motion reactivity was in the ZPPR-17A experiments. The data from IK File 31 are the recommended values

and the difference between the two files is some measure of the uncertainty. Comparing the drive mechanism worths to the worths from PCO-1 through PCO-10 it is seen that the drive motion effect is totally negligible except for PCO-8, PCO-9 and PCO-10, where it is at most a few percent. The drive motion worth results cannot be used in a rigorous way without accounting for the fact that they came from ZPPR-17B. Still they show that the drive effect is small.

10.8 Summary

Generally the experiment goals were met.

The plate shifting experiment gave a reasonable representation of bowing or localized radial expansion. The experimental precision of 3% is more than adequate.

The radial and axial tube oscillator experiments gave small-sample worths through all the assembly regions. How well the effect of the large internal blanket can be calculated will be of particular interest. The worth uncertainty is adequate at most locations for the plutonium, enriched uranium and boron samples, but is too large for steel at most points and for depleted uranium at many points.

The worth of expanding a double-fuel-column element was measured with the axial expansion oscillator at three locations. The worth at the location that included the internal blanket is half as large as at the other locations; this presents a calculational challenge.

A new bowing oscillator was used for the first time. It made the most realistic simulation of bowing motion of any ZPPR experiment. As is typical of actual bowing, the motion was only 1.4 mm. This produced a very small signal (0.01 cents), yet the experimental precision was good (3.5%).

Ten experiments were done with another new device, the plate column oscillator. It was used to determine the worth of removing a plate column from a unit cell. This was done for fuel and for depleted uranium at three

matrix locations. At one outer core location it was done for all the cell constituents. Data from partial withdrawal of a column provided some information related to axial expansion. For complete withdrawal the measurement precision is very good, but the uncertainty is too large for some partial withdrawal results.

TABLE 10.1 Description of ZPPR-17A Oscillator Measurements

Name	Oscillator	Sample	Drawer Master	Matrix ^a Position	Reactor Loading	Reactor Run	Date	I. K. File
ATO-1	Axial Tube	PU-30	834	159-49 (D)	64	70	4/9/87	79
		DU-6						80
		B-1						81
		D-14						82
		SS-1						83
		U-6						84
ATO-2	Axial Tube	PU-30	835	163-41 (E)	65	71	4/10/87	86
		DU-6						87
		B-1						88
		D-14						89
		SS-1						90
		U-6						91
ATO-3	Axial Tube	SS-1	850	171-49 (G)	76	84	4/27/87	120
		DU-6						121
		D-14						122
		PU-30						123
		B-1						124
RTO-1	Radial Tube	PU-30	---	1,248 (.)	67	73	4/14/87	95
		DU-6						96,100
		B-1						97
		D-14						98
		SS-1						99
RTO-2	Radial Tube	Cf @ 3 W Cf @ 80 W	---	1,248 (.)	66	72	4/13/87	93
AEO-1	Axial Expan.	I.C. DFC	838	138-49 (D)	68	74	4/15/87	101
AEO-2	Axial Expan.	O.C. DFC	845	163-41 (E)	70	76	4/17/87	110
AEO-3	Axial Expan.	O.C. DFC	845	166-55 (F)	75	82	4/24/87	119
BO	Bowling	O.C. DFC	841	126-49 (G)	69	75	4/16/87	105
		repeat			75	82	4/24/87	118
PCO-1	Plate Column	Pu-U + SS	840	147-33 (B)	68	74	4/15/87	103
PCO-2	Plate Column	U308	842	147-33 (B)	69	75	4/16/87	107
PCO-3	Plate Column	Pu-U + SS	836	149-40 (A)	65	71	4/10/87	92
PCO-4	Plate Column	U308	843	149-40 (A)	70	76	4/17/87	112
PCO-5	Plate Column	Pu-U	839	163-41 (E)	68	74	4/15/87	102
PCO-6	Plate Column	Pu-U	844	148-31 (C)	69	75	4/16/87	106
PCO-7	Plate Column	U308	846	148-31 (C)	70	76	4/17/87	113
PCO-8	Plate Column	Na	847	148-68 (C)	70	76	4/17/87	111
PCO-9	Plate Column	Void Cans	848	148-68 (C)	75	82	4/24/87	116
PCO-10	Plate Column	Fe203	849	148-31 (C)	75	82	4/24/87	117

^aLocation symbol for Figure 10.1 is in parentheses.

TABLE 10.2 ZPPR-17A All-plate Shifting Experiment Description

Step	Reactor Loading	Reactor Run	Date	SIXTY4 File	Reactivity (cents)	Reactivity Change (cents)		χ^2
1	71	77	4/20	78	-28.75 $\pm$ 0.28	-----		
2	72	78	4/21	79	-28.56 $\pm$ 0.28	0.1	$\pm$ 0.03	0.83
3	73	79	4/22	80	-34.59 $\pm$ 0.34	-5.8	$\pm$ 0.07	1.47
4	74	80	4/23	81	-28.57 $\pm$ 0.28	0.1	$\pm$ 0.03	0.99

TABLE 10.3 Description of the Tube-type Samples Used in ZPPR-17A

Sample	Sample Dimensions, mm		Sample Mass, g	Capsule Mass, g ^a	Principal Composition	
	Length	O.D.			Component	wt. % ^b
U-6	55.19	7.62	46.89	11.463	²³⁴ U	0.95
					²³⁵ U	93.19
					²³⁶ U	0.26
					²³⁸ U	5.60
B-1	55.22	10.19	4.193	10.521	¹⁰ B	87.12
					¹¹ B	7.38
					O	1.43
					C	0.96
					Si	0.26
					Al	0.05
					H	0.09
Pu-30 ^c	55.19	7.62	38.091	11.600	²³⁹ Pu	97.20
					²⁴⁰ Pu	1.00
					²⁴¹ Pu	0.02
					²⁴¹ Am	0.03
					Al	0.95
SS-1					Fe	70.92
					Cr	19.20
					Ni	8.70
					Mn	1.42
					Si	0.30
DU-6	55.19	7.62	47.427	11.417	Cu	0.10
					²³⁵ U	0.21
					²³⁸ U	99.78

^aMaterial is stainless steel.

^bTotal composition less than 100% means that some impurities are not identified.

^c²⁴¹Pu decay adjusted to April, 1987.

TABLE 10.4 Experimental Worths From Axial Tube Measurement ATO-1

Position Region Z (cm)	Worth (cents) For Each Sample				
	PU-30	DU-6	B-1	SS-1	U-6
1 IBKT 3.99	0.2864 ± 0.0023	-0.0104 ± 0.0021	-0.2486 ± 0.0024	-0.0030 ± 0.0025	0.3138 ± 0.0024
2 IBKT 7.62	0.2872 ± 0.0024	-0.0135 ± 0.0022	-0.2718 ± 0.0026	-0.0034 ± 0.0025	0.3108 ± 0.0023
3 IBKT 12.70	0.2966 ± 0.0025	-0.0113 ± 0.0025	-0.3213 ± 0.0028	-0.0040 ± 0.0026	0.3025 ± 0.0024
4 CORE 17.78	0.3146 ± 0.0025	-0.0156 ± 0.0024	-0.3810 ± 0.0026	-0.0054 ± 0.0026	0.2920 ± 0.0026
5 CORE 22.87	0.3246 ± 0.0024	-0.0186 ± 0.0023	-0.3971 ± 0.0027	-0.0097 ± 0.0025	0.2860 ± 0.0026
6 CORE 27.95	0.3277 ± 0.0025	-0.0157 ± 0.0025	-0.3954 ± 0.0027	-0.0075 ± 0.0025	0.2813 ± 0.0027
7 CORE 33.02	0.3088 ± 0.0026	-0.0137 ± 0.0024	-0.3720 ± 0.0028	-0.0075 ± 0.0027	0.2670 ± 0.0027
8 CORE 38.10	0.2726 ± 0.0024	-0.0129 ± 0.0023	-0.3301 ± 0.0027	-0.0065 ± 0.0024	0.2335 ± 0.0026
9 CORE 43.18	0.2295 ± 0.0024	-0.0067 ± 0.0025	-0.2653 ± 0.0028	0.0035 ± 0.0027	0.2031 ± 0.0027
10 CORE 48.26	0.1782 ± 0.0029	-0.0043 ± 0.0025	-0.2023 ± 0.0029	0.0058 ± 0.0026	0.1617 ± 0.0028
11 ABKT 53.34	0.1286 ± 0.0022	0.0049 ± 0.0020	-0.1281 ± 0.0024	0.0078 ± 0.0023	0.1298 ± 0.0023
12 ABKT 58.42	0.0977 ± 0.0027	0.0021 ± 0.0024	-0.0762 ± 0.0029	0.0078 ± 0.0025	0.1010 ± 0.0026
13 ABKT 63.50	0.0664 ± 0.0026	0.0053 ± 0.0023	-0.0407 ± 0.0027	0.0060 ± 0.0024	0.0739 ± 0.0026
14 ABKT 68.58	0.0423 ± 0.0025	0.0027 ± 0.0023	-0.0272 ± 0.0027	0.0019 ± 0.0026	0.0491 ± 0.0027
15 ABKT 73.66	0.0346 ± 0.0023	0.0045 ± 0.0023	-0.0123 ± 0.0027	0.0025 ± 0.0023	0.0366 ± 0.0023
16 ABKT 78.75	0.0216 ± 0.0027	-0.0009 ± 0.0024	-0.0079 ± 0.0030	0.0036 ± 0.0027	0.0258 ± 0.0027
17 AREF 83.82	0.0149 ± 0.0023	-0.0011 ± 0.0021	-0.0031 ± 0.0025	-0.0001 ± 0.0022	0.0149 ± -0.0026

TABLE 10.5 Experimental Worths From Axial Tube Measurement ATO-2

Position		Worth (cents) For Each Sample				
Region Z (cm)		PU-30	DU-6	B-1	SS-1	U-6
1	CORE 3.99	0.4271 $\pm$ 0.0018	-0.0258 $\pm$ 0.0019	-0.5334 $\pm$ 0.0021	-0.0185 $\pm$ 0.0020	0.3713 $\pm$ 0.0021
2	CORE 7.62	0.4257 $\pm$ 0.0025	-0.0282 $\pm$ 0.0024	-0.5329 $\pm$ 0.0026	-0.0159 $\pm$ 0.0025	0.3720 $\pm$ 0.0025
3	CORE 12.70	0.4256 $\pm$ 0.0022	-0.0237 $\pm$ 0.0022	-0.5219 $\pm$ 0.0025	-0.0127 $\pm$ 0.0024	0.3682 $\pm$ 0.0024
4	CORE 17.78	0.4120 $\pm$ 0.0022	-0.0230 $\pm$ 0.0022	-0.5052 $\pm$ 0.0027	-0.0124 $\pm$ 0.0023	0.3523 $\pm$ 0.0023
5	CORE 22.86	0.3896 $\pm$ 0.0021	-0.0220 $\pm$ 0.0022	-0.4781 $\pm$ 0.0024	-0.0117 $\pm$ 0.0024	0.3304 $\pm$ 0.0023
6	CORE 27.94	0.3585 $\pm$ 0.0025	-0.0184 $\pm$ 0.0024	-0.4358 $\pm$ 0.0031	-0.0113 $\pm$ 0.0028	0.3015 $\pm$ 0.0026
7	CORE 33.02	0.3165 $\pm$ 0.0023	-0.0168 $\pm$ 0.0023	-0.3795 $\pm$ 0.0026	-0.0054 $\pm$ 0.0023	0.2703 $\pm$ 0.0025
8	CORE 38.10	0.2622 $\pm$ 0.0024	-0.0097 $\pm$ 0.0023	-0.3147 $\pm$ 0.0029	-0.0068 $\pm$ 0.0024	0.2249 $\pm$ 0.0023
9	CORE 43.18	0.2111 $\pm$ 0.0021	-0.0048 $\pm$ 0.0020	-0.2454 $\pm$ 0.0027	0.0023 $\pm$ 0.0024	0.1857 $\pm$ 0.0023
10	CORE 48.26	0.1535 $\pm$ 0.0024	-0.0011 $\pm$ 0.0021	-0.1754 $\pm$ 0.0028	0.0030 $\pm$ 0.0025	0.1397 $\pm$ 0.0023
11	ABKT 53.34	0.1059 $\pm$ 0.0024	0.0007 $\pm$ 0.0025	-0.1114 $\pm$ 0.0026	0.0045 $\pm$ 0.0026	0.1060 $\pm$ 0.0025
12	ABKT 58.42	0.0692 $\pm$ 0.0021	-0.0022 $\pm$ 0.0021	-0.0706 $\pm$ 0.0025	-0.0005 $\pm$ 0.0022	0.0749 $\pm$ 0.0023
13	ABKT 63.51	0.0466 $\pm$ 0.0023	-0.0034 $\pm$ 0.0021	-0.0449 $\pm$ 0.0024	-0.0026 $\pm$ 0.0022	0.0479 $\pm$ 0.0024
14	ABKT 68.58	0.0296 $\pm$ 0.0020	-0.0044 $\pm$ 0.0021	-0.0240 $\pm$ 0.0025	-0.0009 $\pm$ 0.0021	0.0357 $\pm$ 0.0023
15	ABKT 73.66	0.0175 $\pm$ 0.0019	-0.0024 $\pm$ 0.0020	-0.0142 $\pm$ 0.0024	-0.0026 $\pm$ 0.0021	0.0251 $\pm$ 0.0023
16	ABKT 78.75	0.0130 $\pm$ 0.0022	-0.0003 $\pm$ 0.0023	-0.0063 $\pm$ 0.0028	-0.0005 $\pm$ 0.0027	0.0192 $\pm$ 0.0025
17	AREF 83.82	0.0074 $\pm$ 0.0021	0.0019 $\pm$ 0.0021	-0.0020 $\pm$ 0.0023	0.0010 $\pm$ 0.0022	0.0093 $\pm$ 0.0022

TABLE 10.6 Experimental Worths From Axial Tube Measurement ATO-3

Position Region Z (cm)	Worth (cents) For Each Sample			
	PU-30	DU-6	B-1	SS-1
1 CORE 3.99	0.1965 ± 0.0013	-0.0032 ± 0.0013	-0.2210 ± 0.0014	0.0021 ± 0.0013
2 CORE 7.62	0.1926 ± 0.0014	-0.0043 ± 0.0013	-0.2183 ± 0.0015	0.0008 ± 0.0013
3 CORE 12.70	0.1847 ± 0.0013	-0.0025 ± 0.0014	-0.2067 ± 0.0013	0.0036 ± 0.0013
4 CORE 17.78	0.1712 ± 0.0014	-0.0026 ± 0.0013	-0.1930 ± 0.0016	0.0030 ± 0.0013
5 CORE 22.86	0.1559 ± 0.0014	-0.0013 ± 0.0014	-0.1739 ± 0.0014	0.0042 ± 0.0014
6 CORE 27.94	0.1357 ± 0.0015	-0.0015 ± 0.0014	-0.1539 ± 0.0014	0.0018 ± 0.0014
7 CORE 33.02	0.1155 ± 0.0015	-0.0008 ± 0.0016	-0.1283 ± 0.0014	0.0024 ± 0.0013
8 CORE 38.10	0.0931 ± 0.0016	0.0019 ± 0.0015	-0.1035 ± 0.0016	0.0036 ± 0.0014
9 CORE 43.18	0.0720 ± 0.0014	0.0001 ± 0.0014	-0.0761 ± 0.0015	0.0030 ± 0.0014
10 CORE 48.26	0.0523 ± 0.0015	0.0008 ± 0.0015	-0.0537 ± 0.0015	0.0028 ± 0.0015
11 ABKT 53.34	0.0349 ± 0.0014	0.0000 ± 0.0014	-0.0329 ± 0.0015	0.0043 ± 0.0014
12 ABKT 58.42	0.0274 ± 0.0015	0.0024 ± 0.0016	-0.0173 ± 0.0015	0.0042 ± 0.0015
13 ABKT 63.50	0.0151 ± 0.0014	0.0009 ± 0.0014	-0.0100 ± 0.0014	0.0018 ± 0.0013
14 ABKT 68.58	0.0110 ± 0.0016	-0.0007 ± 0.0016	-0.0057 ± 0.0015	0.0009 ± 0.0015
15 ABKT 73.66	0.0081 ± 0.0015	-0.0005 ± 0.0014	-0.0026 ± 0.0015	-0.0001 ± 0.0015
16 ABKT 78.74	0.0086 ± 0.0014	0.0007 ± 0.0014	0.0017 ± 0.0015	0.0023 ± 0.0015
17 AREF 83.82	0.0005 ± 0.0013	-0.0010 ± 0.0014	-0.0037 ± 0.0013	0.0002 ± 0.0012

TABLE 10.7 Experimental Results From The Radial Tube Measurements

Position		Worth (cents) For Each Sample				Normalized 252Cf Importance
Region X (cm)		PU-30	DU-6	B-1	SS-1	
1 IBKT 2.77		0.2195 ± 0.0020	-0.0121 ± 0.0009	-0.1875 ± 0 0019	-0.0059 ± 0.0010	0.631 ± 0.023
2 IBKT 8.29		0.2210 ± 0.0018	-0.0107 ± 0.0010	-0.1877 ± 0 0022	-0.0046 ± 0.0010	0.652 ± 0.027
3 IBKT 13.82		0.2259 ± 0.0018	-0.0128 ± 0.0012	-0.1898 ± 0 0025	-0.0044 ± 0.0011	0.610 ± 0.027
4 IBKT 19.34		0.2263 ± 0.0022	-0.0122 ± 0.0009	-0.1915 ± 0 0019	-0.0058 ± 0.0010	0.611 ± 0.027
5 IBKT 24.86		0.2330 ± 0.0021	-0.0107 ± 0.0011	-0.1918 ± 0 0020	-0.0064 ± 0.0011	0.633 ± 0.027
6 IBKT 30.39		0.2386 ± 0.0021	-0.0114 ± 0.0010	-0.2024 ± 0 0021	-0.0057 ± 0.0010	0.623 ± 0.027
7 IBKT 35.91		0.2512 ± 0.0022	-0.0128 ± 0.0010	-0.2084 ± 0 0019	-0.0049 ± 0.0010	0.645 ± 0.027
8 IBKT 41.44		0.2541 ± 0.0021	-0.0140 ± 0.0009	-0.2185 ± 0 0022	-0.0055 ± 0.0010	0.653 ± 0.027
9 IBKT 46.96		0.2716 ± 0.0019	-0.0142 ± 0.0011	-0.2246 ± 0 0019	-0.0059 ± 0.0010	0.688 ± 0.027
10 IBKT 52.49		0.2871 ± 0.0021	-0.0120 ± 0.0010	-0.2386 ± 0 0021	-0.0063 ± 0.0010	0.675 ± 0.027
11 IBKT 58.01		0.3007 ± 0.0017	-0.0154 ± 0.0010	-0.2597 ± 0 0024	-0.0067 ± 0.0010	0.759 ± 0.027
12 IBKT 63.53		0.3186 ± 0.0020	-0.0167 ± 0.0010	-0.2809 ± 0 0022	-0.0069 ± 0.0012	0.761 ± 0.027
13 IBKT 69.05		0.3319 ± 0.0021	-0.0174 ± 0.0011	-0.3158 ± 0 0026	-0.0086 ± 0.0010	0.722 ± 0.027
14 IBKT 74.59		0.3527 ± 0.0019	-0.0202 ± 0.0010	-0.3568 ± 0 0021	-0.0098 ± 0.0011	0.824 ± 0.027
15 IBKT 80.11		0.3728 ± 0.0021	-0.0203 ± 0.0010	-0.4054 ± 0 0019	-0.0068 ± 0.0010	0.866 ± 0.027
16 IBKT 85.63		0.3914 ± 0.0022	-0.0229 ± 0.0011	-0.4764 ± 0 0018	-0.0094 ± 0.0011	0.892 ± 0.029
17 CORE 91.15		0.4067 ± 0.0017	-0.0257 ± 0.0010	-0.5242 ± 0 0021	-0.0098 ± 0.0010	0.969 ± 0.027
18 CORE 96.68		0.4090 ± 0.0024	-0.0270 ± 0.0010	-0.5410 ± 0 0024	-0.0121 ± 0.0011	0.997 ± 0.027
19 CORE 102.21		0.3974 ± 0.0021	-0.0257 ± 0.0011	-0.5151 ± 0 0025	-0.0106 ± 0.0011	1.000 ± 0.027
20 CORE 107.73		0.3666 ± 0.0020	-0.0213 ± 0.0010	-0.4630 ± 0 0026	-0.0072 ± 0.0010	0.963 ± 0.027
21 CORE 113.26		0.3089 ± 0.0024	-0.0169 ± 0.0011	-0.3932 ± 0 0024	-0.0030 ± 0.0011	0.839 ± 0.027
22 CORE 118.78		0.2526 ± 0.0026	-0.0086 ± 0.0011	-0.3120 ± 0 0023	0.0003 ± 0.0009	0.742 ± 0.027
23 CORE 124.30		0.1903 ± 0.0022	-0.0058 ± 0.0010	-0.2292 ± 0 0022	0.0032 ± 0.0009	0.656 ± 0.027
24 CORE 129.83		0.1370 ± 0.0020	0.0015 ± 0.0010	-0.1482 ± 0 0023	0.0081 ± 0.0010	0.469 ± 0.027
25 RBKT 135.35		0.0875 ± 0.0020	0.0026 ± 0.0010	-0.0802 ± 0 0021	0.0070 ± 0.0011	0.424 ± 0.027
26 RBKT 140.88		0.0559 ± 0.0022	0.0027 ± 0.0010	-0.0337 ± 0 0021	0.0070 ± 0.0011	0.263 ± 0.027
27 RBKT 146.40		0.0312 ± 0.0021	0.0006 ± 0.0009	-0.0161 ± 0 0021	0.0014 ± 0.0011	0.203 ± 0.027
28 RBKT 151.92		0.0178 ± 0.0023	-0.0016 ± 0.0011	-0.0064 ± 0 0022	0.0016 ± 0.0011	0.081 ± 0.027
29 RBKT 157.45		0.0072 ± 0.0020	-0.0019 ± 0.0011	-0.0010 ± 0 0024	-0.0014 ± 0.0011	0.117 ± 0.027
30 RREF 162.97		0.0071 ± 0.0021	0.0006 ± 0.0011	-0.0015 ± 0 0023	0.0009 ± 0.0010	0.085 ± 0.027

TABLE 10.8 Ratio of RTO to ATO Worths at
Nearly Equivalent Locations

Sample	RTO, X=58.01 / ATO-1, Z=3.99	RTO, X=91.15 / ATO-2, Z=3.99	RTO, X=124.30 / ATO-3, Z=3.99
PU-30	1.050 $\pm$ 0.010	0.952 $\pm$ 0.006	0.968 $\pm$ 0.013
DU-6	-----	0.996 $\pm$ 0.083	-----
B-1	1.045 $\pm$ 0.014	0.983 $\pm$ 0.006	1.037 $\pm$ 0.012
SS-1	-----	0.530 $\pm$ 0.079	-----

TABLE 10.9 Description of the Special Fuel Plates in the AEO

Serial Num.	66-8-3972-039-13	66-8-4972-002-15
SS Clad Mass (g)	26.167	26.218
Core Mass (g)	193.238	193.663
Mo	4.83	4.84
^{238}Pu	0.02	0.01
^{239}Pu	47.48	47.67
^{240}Pu	6.36	6.48
$^{241}\text{Pu}^a$	0.80	0.84
^{242}Pu	0.07	0.08
^{235}U	0.29	0.29
^{238}U	133.39	133.45

^aMass in 1970.

TABLE 10.10 Radial Motion of The Bowing Oscillator
in the Second Measurement

<u>Axial Location</u>	<u>Motion (cm)</u>		
	<u>Left</u>	<u>Right</u>	<u>Average</u>
front (0.33 cm)	0.147	0.133	0.140
back (51.03 cm)	0.122	0.127	0.125

TABLE 10.11 Experimental Worths From PCO-1, Pu-U + SS

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
2.539	-0.16343 $\pm$ 0.00267 ($\pm$ 1.6%)
12.698	-0.94930 $\pm$ 0.00281 ($\pm$ 0.3%)
15.239	-1.16530 $\pm$ 0.00289 ($\pm$ 0.2%)
17.779	-1.38052 $\pm$ 0.00260 ($\pm$ 0.2%)
48.259	-3.49558 $\pm$ 0.00181 ($\pm$ 0.1%)
65.412	-3.94417 $\pm$ 0.00179 ($\pm$ 0.0%)

TABLE 10.12 Experimental Worths From PCO-2, U_3O_8

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 ± 0.00000 ($\pm 0.0\%$)
2.546	0.03686 ± 0.00086 ($\pm 2.3\%$)
12.706	0.17834 ± 0.00085 ($\pm 0.5\%$)
15.246	0.21546 ± 0.00100 ($\pm 0.5\%$)
17.786	0.25146 ± 0.00097 ($\pm 0.4\%$)
48.266	0.49441 ± 0.00096 ($\pm 0.2\%$)
62.871	0.47861 ± 0.00087 ($\pm 0.2\%$)

TABLE 10.13 Experimental Worths From PCO-3, Pu-U + SS

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 ± 0.00000 ($\pm 0.0\%$)
2.540	-0.10088 ± 0.00295 ($\pm 2.9\%$)
12.699	-0.59346 ± 0.00285 ($\pm 0.5\%$)
15.240	-0.73734 ± 0.00353 ($\pm 0.5\%$)
17.780	-0.88299 ± 0.00286 ($\pm 0.3\%$)
48.260	-2.72093 ± 0.00301 ($\pm 0.1\%$)
65.412	-3.23761 ± 0.00282 ($\pm 0.1\%$)

TABLE 10.14 Experimental Worths From PCO-4, U_3O_8

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 ± 0.00000 ($\pm 0.0\%$)
2.550	0.02710 ± 0.00046 ($\pm 1.7\%$)
12.710	0.12713 ± 0.00050 ($\pm 0.4\%$)
15.250	0.15187 ± 0.00053 ($\pm 0.4\%$)
17.790	0.17595 ± 0.00052 ($\pm 0.3\%$)
30.490	0.30859 ± 0.00048 ($\pm 0.2\%$)

TABLE 10.15 Experimental Worths From PCO-5, Pu-U @ 35.6 cm

Withdrawal (cm)	Reactivity (cents)	Gradient (cents/cm)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)	
0.252	-0.01572 $\pm$ 0.00075 ($\pm$ 4.8%)	-0.06249 $\pm$ 0.00300
0.634	-0.04417 $\pm$ 0.00081 ($\pm$ 1.8%)	-0.06964 $\pm$ 0.00128
1.270	-0.08814 $\pm$ 0.00077 ($\pm$ 0.9%)	-0.06940 $\pm$ 0.00061
1.904	-0.13191 $\pm$ 0.00075 ($\pm$ 0.6%)	-0.06927 $\pm$ 0.00039
2.539	-0.17509 $\pm$ 0.00086 ($\pm$ 0.5%)	-0.06896 $\pm$ 0.00034
3.175	-0.21521 $\pm$ 0.00082 ($\pm$ 0.4%)	-0.06778 $\pm$ 0.00026
3.810	-0.25710 $\pm$ 0.00077 ($\pm$ 0.3%)	-0.06748 $\pm$ 0.00020
5.091	-0.33528 $\pm$ 0.00071 ($\pm$ 0.2%)	-0.06586 $\pm$ 0.00014
7.626	-0.48187 $\pm$ 0.00077 ($\pm$ 0.2%)	-0.06318 $\pm$ 0.00010

TABLE 10.16 Experimental Worths From PCO-6, Pu-U

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 ± 0.00000 ($\pm 0.0\%$)
0.381	-0.03489 ± 0.00296 ($\pm 8.5\%$)
1.015	-0.09919 ± 0.00266 ($\pm 2.7\%$)
1.651	-0.16187 ± 0.00292 ($\pm 1.8\%$)
2.285	-0.21904 ± 0.00305 ($\pm 1.4\%$)
4.826	-0.47124 ± 0.00300 ($\pm 0.6\%$)
14.986	-1.42977 ± 0.00309 ($\pm 0.2\%$)
29.788	-2.63774 ± 0.00212 ($\pm 0.1\%$)

TABLE 10.17 Experimental Worths From PCO-7, U_3O_8

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
0.645	0.00858 $\pm$ 0.00059 ($\pm$ 6.9%)
1.279	0.01769 $\pm$ 0.00063 ($\pm$ 3.6%)
2.550	0.03537 $\pm$ 0.00058 ($\pm$ 1.6%)
5.089	0.07148 $\pm$ 0.00057 ($\pm$ 0.8%)
15.250	0.20647 $\pm$ 0.00065 ($\pm$ 0.3%)
30.012	0.36187 $\pm$ 0.00062 ($\pm$ 0.2%)

TABLE 10.18 Experimental Worths From PCO-8, Clad Na

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
0.667	0.00220 $\pm$ 0.00056 ($\pm$ 25.4%)
1.302	0.00501 $\pm$ 0.00057 ($\pm$ 11.4%)
2.572	0.00871 $\pm$ 0.00056 ($\pm$ 6.4%)
5.112	0.01917 $\pm$ 0.00057 ($\pm$ 2.9%)
15.272	0.05510 $\pm$ 0.00058 ($\pm$ 1.1%)
30.039	0.08655 $\pm$ 0.00049 ($\pm$ 0.6%)

TABLE 10.19 Experimental Worths From PCO-9, Void Cans

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
0.632	0.00078 $\pm$ 0.00060 ($\pm$ 77.2%)
1.266	0.00138 $\pm$ 0.00069 ($\pm$ 50.0%)
2.537	0.00308 $\pm$ 0.00063 ($\pm$ 20.4%)
5.077	0.00572 $\pm$ 0.00062 ($\pm$ 10.9%)
15.238	0.01719 $\pm$ 0.00065 ($\pm$ 3.8%)
30.485	0.03219 $\pm$ 0.00061 ($\pm$ 1.9%)

TABLE 10.20 Experimental Worths From PCO-8 Minus PCO-9, Na

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
0.667	0.00142 $\pm$ 0.00082 ($\pm$ 58.0%)
1.302	0.00364 $\pm$ 0.00089 ($\pm$ 24.6%)
2.572	0.00563 $\pm$ 0.00084 ($\pm$ 14.9%)
5.112	0.01346 $\pm$ 0.00084 ($\pm$ 6.2%)
15.272	0.03790 $\pm$ 0.00087 ($\pm$ 2.3%)
30.039	0.05483 $\pm$ 0.00078 ($\pm$ 1.4%)

TABLE 10.21 Experimental Worths From PCO-10, Fe_2O_3

Withdrawal (cm)	Reactivity (cents)
0.000	0.00000 $\pm$ 0.00000 ($\pm$ 0.0%)
0.645	0.00418 $\pm$ 0.00049 ($\pm$ 11.8%)
1.280	0.00689 $\pm$ 0.00048 ($\pm$ 7.0%)
2.550	0.01446 $\pm$ 0.00045 ($\pm$ 3.1%)
5.090	0.03118 $\pm$ 0.00040 ($\pm$ 1.3%)
15.250	0.09257 $\pm$ 0.00040 ($\pm$ 0.4%)
30.490	0.15896 $\pm$ 0.00050 ($\pm$ 0.3%)

TABLE 10.22 Description of Moving Plates in the Plate Column Oscillator Experiments^a

Pu-U in PCO-1,3 Serial #	U ³ O ₈ in PCO-2,4,7 Mass (g)	Pu-U in PCO-5,6 Serial #	Na in PCO-8 Mass (g)	Clad in PCO-8 Mass (g)	Void Cans in PCO-9 Mass (g)	Fe ² O ₃ in PCO-10 Mass (g)	
						left	right
370-23	119.55	416-21 ^b	110.34	79.21	79.34	34.40	34.75
273-22	121.65	427-32 ^b	111.56	80.39	80.28	51.88	33.60
336-22	116.22	333-10	54.84	43.39	43.04	50.61	51.35
	119.86	211-22	110.84	79.21	79.25	50.50	50.90
	120.77	208-24	108.32	80.74	80.79	51.18	51.20
	118.45	403-06	54.51	43.64	43.66	51.39	51.88
	119.69					51.16	49.66
	120.60					51.36	51.40
	117.36					51.26	51.59
	118.75					52.28	49.31
	119.82					50.63	51.31
	119.96					52.02	51.61
	119.98					51.66	50.19
	121.00					34.15	51.50
	119.16						
	119.35						
	118.70						
	121.44						
	117.94						
	117.42						

^aListed in order from the front of the column.^bStationary in PCO-5.

TABLE 10.23 PCO Drive Reactivity For 66.0 cm-long Column

From IK File 30		From IK File 31	
Withdrawal (cm)	Reactivity (cents)	Withdrawal (cm)	Reactivity (cents)
0.000	0.00000	0.000	0.00000
2.538	-0.00128	2.548	-0.00114
12.698	-0.00522	12.708	-0.00486
15.238	-0.00594	15.248	-0.00560
17.779	-0.00656	17.788	-0.00627
35.564	-0.00869	35.568	-0.00930
35.817	-0.00869	35.822	-0.00933
36.199	-0.00870	36.203	-0.00937
36.834	-0.00872	36.838	-0.00943
38.104	-0.00874	38.108	-0.00954
40.644	-0.00876	40.648	-0.00974
50.804	-0.00850	50.808	-0.01021
65.408	-0.00780	65.412	-0.01033

TABLE 10.24 PCO Drive Reactivity For 101.6 cm-long Column

From IK File 30		From IK File 31	
Withdrawal (cm)	Reactivity (cents)	Withdrawal (cm)	Reactivity (cents)
0.000	0.00000	0.000	0.00000
0.253	-0.00001	0.254	-0.00003
0.635	-0.00002	0.635	-0.00006
1.270	-0.00004	1.270	-0.00012
2.540	-0.00006	2.540	-0.00024
5.080	-0.00007	5.080	-0.00044
15.240	0.00019	15.240	-0.00091
29.844	0.00089	29.844	-0.00103

A PCO-3, PCO-4	E ATO-2, AEO-2, PCO-5
B PCO-1, PCO-2	F AEO-3
C PCO-6 --- PCO-10	G ATO-3, BO
D ATO-1, AEO-1	PLATE SHIFTING ZONE
	RTO-1, RTO-2

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

Fig. 10.2 Pre-shift Loading Pattern for SFC Drawers

Fig. 10.3 Pre-shift Loading Pattern for DFC Drawers

Fig. 10.4 Post-shift Loading Pattern for SFC Drawers in Half-1 Columns 69-72 and Half-2 Columns 27-30

Fig. 10.5 Post-shift Loading Pattern for DFC Drawers in Half-1 Columns 69-72 and Half-2 Columns 27-30

Fig. 10.7 Experimental Worths from PCO-1, Pu-U + SS.

Fig. 10.8 Experimental Worths from PCO-2, U308

Fig. 10.9 Experimental Worths from PCO-3, Pu-U + SS

Fig. 10.10 Experimental Worths from PCO-4, U308

Fig. 10.11 Experimental Worths from PCO-5, Pu-U @ 35.6 cm

Fig. 10.12 Experimental Worths from PCO-6, Pu-U

Fig. 10.13 Experimental Worths from PCO-7, U308

Fig. 10.14 Experimental Worths from PCO-8, Clad Na

Fig. 10.15 Experimental Worths from PCO-9, Void Cans

Fig. 10.16 Experimental Worths from PCO-8 Minus PCO-9, Na

Fig. 10.17 Experimental Worths from PCO-10, Fe203

Fig. 10.18 Oscillator Plate Loading in PCO-1 (Master 17-0-840)

Fig. 10.19 Oscillator Plate Loading in PCO-2 (Master 17-0-842)

Fig. 10.20 Oscillator Plate Loading in PCO-3 (Master 17-0-836)

Fig. 10.21 Oscillator Plate Loading in PCO-4 (Master 17-0-843)

Fig. 10.22 Oscillator Plate Loading in PC0-5 (Master 17-0-839)

Fig. 10.23 Oscillator Plate Loading in PCO-6 (Master 17-0-844)

Fig. 10.24 Oscillator Plate Loading in PC0-7 (Master 17-0-846)

Fig. 10.25 Oscillator Plate Loading in PC0-8 (Master 17-0-847)

Fig. 10.26 Oscillator Plate Loading in PCO-9 (Master 17-0-848)

Fig. 10.27 Oscillator Plate Loading in PCO-10 (Master 17-0-849)

Fig. 10.28 PCO Drive Motion Reactivity from ZPPR-17B IK File 30

Fig. 10.29 PCO Drive Motion Reactivity from ZPPR-17B IK File 31

Fig. 10.30. Plate Column Oscillator Drive Mechanism.

11. REVISIONS TO EXPERIMENTAL CONTROL ROD WORTHS IN ZPPR-15D
(P. J. Collins and D. M. Smith)

Following publication of the control rod worths for ZPPR-15D in ANL-ZPR-473, p. 68 et seq., it was discovered that the DIF3D code had developed an error in processing the energy distribution of the source input. The source calculations are used to calculate fission rate distributions in subcritical states for processing experimental countrates (calculation of detector efficiencies) and for calculation of "effective source ratios" required by the McCRUNCH processing. The code error has now been corrected and the source-driven calculations were repeated. The revised experimental worths are given in Table 11.1.

The experimental control rod worths are increased over the previously reported values by 0.3% to 0.6% for the central rods, by 1.2% to 1.4% for the banks of 5, 6, or 7 primary rods, and by 4.1% when all 13 rods are inserted.

The calculated efficiency ratios show much improved agreement with experimental countrate ratios. In ZPPR-15D, 63 fission chambers were used for data reduction since one data channel (for detector number 21) was not operating. Counting times were 1800 seconds for the farthest subcritical cases. Because the core contained only 10% plutonium out of the total fissile mass, the total source was lower than in the all-plutonium fuelled cores. Thus, the average statistical uncertainty was about 2% for the measurements with 5, 6, or 7 rods inserted and about 3% for all 13 rods inserted. At this level, the McCRUNCH code rejected no more than one detector and even the efficiencies calculated for detectors adjacent to control rods were acceptable. Note that given an acceptable statistical fit to the experimental countrate ratios, the statistical uncertainty on the mean reactivity is the standard deviation of the distribution of reactivities divided by $(\text{number of detectors})^{1/2}$. Thus in the present case with 62 or 63 detectors retained, the statistical uncertainties are approximately 0.2% for single rods, 0.3% for banks of 5, 6 or 7 rods and 0.4% for 13 rods.

The control rod worths are compared with calculations using nodal diffusion theory in xyz geometry and 21 energy groups in Table 11.2. The results show good consistency for the 50% B₄C/50% sodium-steel reference rods with C/E values ranging between 0.96 and 0.95 and merely a hint of a radial variation. However, the C/E results for ZPPR-15D are several percent lower than those for ZPPR-15B (also given in Table 11.2). The lower predictions in ZPPR-15D for the central rods, of 5% to 6% are particularly disturbing.

TABLE 11.1 Measured Control Rod Worths in ZPPR-15D - Revised

Configuration	Data File	No. of Detectors	Source Ratio	Worth, \$ ^a	σ_s , % ^b	σ_t , % ^b
Central CRP	182	63	1.0008	0.158	0.206	0.870
Central CR (50% B ₄ C)	183	63	1.0261	1.392	0.191	0.801
5 Primary CRs (1,13 missing)	185	63	0.9831	6.201	0.266	0.821
6 Primary CRs (13 missing)	184	63	1.0043	7.816	0.289	0.828
7 Primary CRs	186	62	1.0297	9.726	0.325	0.838
All 13 CRs	187	62	1.0775	19.979	0.449	0.896
Repeat						
Reference	188	63	1.000	0.001	---	---
Central CR (100% B ₄ C)	196	63	1.0321	1.953	0.139	0.554
Central CR ^c (Segmented)	195	63	1.0321	1.406	0.179	0.572

^aFirst seven worths relative to reference $\rho = 7.55\phi$, data file 179. Last two worths relative to reference $\rho = 4.04\phi$, data file 194.

^b σ_s is the total statistical uncertainty including contributions from the least-squares fitting, corrections to temperature, interface separation and ²⁴¹Pu decay. σ_t is the total uncertainty including correlated components for reactivity calibration and relative source ratios.

^cUsing efficiencies and initial source ratios calculated for the 100% B₄C rod.

TABLE 11.2 Comparison of Calculated and Measured Control
Rod Worths in ZPPR-15D - Revised

<u>Rods</u>	<u>Experiment, \$</u>	<u>Calculation, \$</u>	<u>C/E</u>	<u>C/E in ZPPR-15B</u>
Central CRP	0.158	0.186	1.18	1.17
Central CR	1.392	1.337	0.960	1.018
5 Primary	6.201	5.940	0.952	0.965
6 Primary	7.816	7.456	0.953	---
7 Primary	9.726	9.257	0.952	0.980
All 13 CRs	19.979	18.971	0.950	0.953
Central 100% B ₄ C	1.953	1.930	0.988	1.043
Central Segmented	1.406	1.390	0.989	---

12. MEASUREMENT AND ANALYSIS OF ^{238}U DOPPLER REACTIVITY IN ZPPR-15
 (R. E. Kaiser, J. M. Gasidlo and R. W. Goin)

Reactivity Doppler measurements were performed in phases A, B and D of ZPPR-15, at matrix position 163-51, 284 mm from core center. The fuel composition in ZPPR-15A was plutonium only; zirconium was introduced in 15B, and ^{235}U fuel was substituted for most of the plutonium in 15D. The measurements from ZPPR-15A were originally reported in ZPR-TM-469, p. 84, along with some analysis, and the final calculated values were reported in ZPR-TM-471, p. 55. All of the measurements were performed using the standard technique of oscillating the sample in and out of the core at different sample temperatures.* The sample reactivity was inferred from inverse kinetics analysis of the output of two ex-core BF_3 chambers as the sample oscillated between positions at the core center and beyond the axial reflector. The net reactivity of the sample material alone was determined from a separate empty capsule measurement. Samples used in the various experiments included natural and enriched UO_2 , depleted U metal and depleted U metal alloyed with 10% Zr. Specifications of the samples, including the phases of ZPPR-15 which they were measured, are given in Table 12.1. The measured data for phases B and D are included in Table 12.2 through 12.4. A refined expansion correction, applied to the metal samples, results in some slight variation from previously quoted results, particularly for the depleted U sample in phase A.

As described for the 15A measurements, all metal sample data were corrected for axial thermal expansion based upon an axial worth profile for depleted uranium using an estimate of the mass shift from a position of average worth to one with a worth corresponding to the end of the sample. The expansion corrections amounted to between one and two percent of the total signal. Data for each sample were then fit to the function CT^{-Y} . The fitting procedure allowed determination of the effective measured reactivity at the nominal temperatures shown in Table 12.5 through 12.7 which show

*R. E. Kaiser et al., "Extrapolation of Small Sample Doppler Reactivity Measurements," Proc. of the Conference on Advances in Reactor Physics and Core Thermal Hydraulics, NUREG/CP-0034, Vol. I (1982).

comparison to calculation for phases A, B and D. The reactivity values are not taken from the fitted curve, but represent temperature adjusted, measured values. The higher temperatures for the metal sample, 900 K and 1000 K, were chosen to bracket the lower phase change at 941 K, while avoiding the additional expansion at the second phase change. The results of the fitting calculation for the expansion corrected metal samples, were not significantly affected by the phase change. The parameter γ was very nearly independent of whether or not the final data point was included. Data from the fitting calculation are presented in Table 12.8.

The reference temperature (300 K) data for the depleted U sample in phase B was remarkably inconsistent with the data at elevated temperatures, and gave anomalous results from the $CT^{-\gamma}$ fit. By omitting that data point and performing the fit for the elevated temperatures only, results were obtained that were more consistent with other measurements of the UZr and depleted U samples. Results quoted here are therefore based on a reference temperature of 500 K for the depleted U sample in phase B.

Analysis of the Doppler measurements in ZPPR-15 was performed using SDX/MC² for generation of cross sections for the samples at the reference and elevated temperatures, the finite difference diffusion theory option of DIF3D for real and adjoint flux calculations, and VARI3D for first-order perturbation calculations of Doppler reactivity. The sample cross-sections were based on ENDF/B Version 5.2 data and were processed using equivalence theory, with a 230 group intermediate library. The SDX model included the Doppler sample surrounded by a homogenized steel-void region, representing the Doppler oscillator structure and a region of the inner core composition. The data for the sample and structure were collapsed to the 21-group structure using the SDX fluxes. Cross sections for the fuel zones around the sample used the data generated for the various ZPPR-15 reference cores.

The flux calculations were done using one-fourth xy plane, half z symmetry, including the Doppler sample at reference temperature. The Doppler reactivities were determined from first-order perturbation theory by replacing the reference temperature sample cross sections with cross

sections evaluated at the various elevated temperatures. Total sample worth was inferred from a small perturbation of the mass of the sample at reference temperature.

Calculations for phases B and D used a 21 energy group structure, as opposed to the 28 group set used in the ZPPR-15A calculations. Comparison of calculated reactivities for the DU metal sample using both group structures indicated comparable results and the same fraction of total reactivity (54.9%) from the resolved resonance region in both cases.

Cross sections for the different samples were generated with a variety of core environments, corresponding to the different phases of ZPPR-15. Comparisons of calculations using cross sections from different environments indicate that the results are essentially independent of the spectrum used to collapse to 21 groups. For instance, the UZr sample was measured in phases B (Pu fuel) and D (U fuel). Cross sections were generated for the sample in both environments and both sets were used to analyze the phase D experiments. The resulting C/Es were 0.754 ± 0.006 using the phase B cross sections and 0.744 ± 0.006 using those from the appropriate phase (D). Similar differences were found in analyzing the depleted uranium sample measurements in phases B and D, where different cross sections were used.

Table 12.9 illustrates the variation in average C/E and in the percent of total reactivity arising from the resolved resonance range for the non-fissile Doppler measurements. The value for depleted U in phase B is subject to question because of difficulty with the data, but for all of the samples, a significant reduction in the fraction of reactivity from the resolved resonance region is accompanied by a reduction in C/E. Data from the U-fuelled phase D exhibit lower C/E's than in any of the Pu-fuelled phases, as well as having more reactivity coming from the unresolved resonance region.

The fissile UO_2 sample was measured only in the ^{235}U fuelled phase D. The average C/E, determined as an uncertainty weighted average of the C/Es at the various elevated temperatures, was 0.569 ± 0.018 , substantially less than the 0.772 ± 0.011 measured for the natural uranium oxide. The

calculated contribution from ^{238}U in the fissile sample was 10% lower in specific worth than the calculation for the natural UO_2 sample, but this may be accounted for by greater dilution in the fissile sample. Further investigation of the accuracy of the ^{235}U contribution is planned.

In summary, the C/E values for the ZPPR-15 Doppler measurements are reasonably consistent, with a tendency to slightly lower values as the spectrum hardens. The exception to this is in the fissile UO_2 sample, which is remarkably lower in C/E for reasons not completely understood at this time. For any given fertile sample, the nature of the environment specified for group collapse in the generation of sample cross sections appears to have a negligible effect on C/E, even to the extent of plutonium vs. uranium fuel.

TABLE 12.1 Reactivity Doppler Sample Specifications and Use in ZPPR-15

Sample	Length, ^a mm	Total Mass kg ²³⁸ U	Atom Densities (atoms/barn-cm)				Measured in Phases
			²³⁸ U	²³⁵ U	¹⁶ O	Zr	
Natural UO ₂ (N-3)	305	1.086	0.01827	0.00013	0.03680	--	A, B, D
Depleted U Metal (N-11)	254	2.386	0.04736	0.00019	--	--	A, B, D
Depleted U Metal, 10 w/o Zr (N-24)	305	2.375	0.03562	0.00009	--	0.01068	B, D
33% Enriched UO ₂ (E-33-A)	305	0.9896 ^b	0.01081	0.00548	0.03905	--	D

^aAll samples are 25.4 mm in diameter.

^bTotal uranium mass.

TABLE 12.2 ZPPR-15A Doppler Reactivity Measurements

Natural UO ₂ Sample		Depleted U Metal Sample			
		Uncorrected		Expansion Corrected ^a	
Temp., K ^b	$\rho, \phi/\text{kg } ^{238}\text{U}^c$	Temp., K ^b	$\rho, \phi/\text{kg } ^{238}\text{U}^d$	Temp., K ^b	$\rho, \phi/\text{kg } ^{238}\text{U}^d$
543	-0.0350 ± 0.0013^e	503	-0.0255 ± 0.0008^e	503	-0.0253 ± 0.0008^e
685	-0.0491 ± 0.0017	640	-0.0377 ± 0.0008	640	-0.0374 ± 0.0008
800	-0.0570 ± 0.0012	784	-0.0487 ± 0.0008	784	-0.0483 ± 0.0008
954	-0.0690 ± 0.0013	892	-0.0563 ± 0.0008	892	-0.0558 ± 0.0008
1100	-0.0784 ± 0.0012	1023	-0.0632 ± 0.0008	1023	-0.0624 ± 0.0008^d
Sample worth	$-1.574 \pm 0.002\phi/\text{kg}$	Sample worth	$-1.169 \pm 0.0014\phi/\text{kg}$		

^aCalculated correction based on a calculated (FOP) axial worth profile for ^{238}U .

^bReference temperature was 300K.

^cUO₂ sample (N-3) contains 1.086 kg ^{238}U .

^dU-metal sample (N-11) contains 2.386 kg ^{238}U .

^eUncertainties include effect of $\pm 5\text{K}$ temperature uncertainty.

TABLE 12.3 Measured Reactivity Doppler Values from ZPPR-15B

Depleted Uranium Metal Sample		
Temp., K ^b	Uncorrected $\rho, \phi/\text{kg } ^{238}\text{U}^c$	Expansion Corrected ^a $\rho c, \phi/\text{kg } ^{238}\text{U}^c$
490	-0.0280 ± 0.0007^d	-0.0278 ± 0.0007^d
659	-0.0442 ± 0.0007	-0.0439 ± 0.0007
802	-0.0551 ± 0.0006	-0.0547 ± 0.0006
913	-0.0615 ± 0.0006	-0.0609 ± 0.0006
1016	-0.0673 ± 0.0005	-0.0665 ± 0.0005
Sample	-1.227 ± 0.0001	
UZr Metal Sample		
Temp., K ^b	Uncorrected ^a $\rho, \phi/\text{kg } ^{238}\text{U}^c$	Expansion Corrected ^a $\rho c, \phi/\text{kg } ^{238}\text{U}^c$
505	-0.0268 ± 0.0005^d	-0.0266 ± 0.0005^d
655	-0.0406 ± 0.0005	-0.0402 ± 0.0005
806	-0.0509 ± 0.0005	-0.0503 ± 0.0005
904	-0.0556 ± 0.0005	-0.0550 ± 0.0005
1047	-0.0648 ± 0.0004	-0.0637 ± 0.0005
Sample	-1.310 ± 0.001	
Natural UO ₂ Sample		
Temp., K ^b	$\rho, \phi/\text{kg U-238}^c$	
490	-0.0262 ± 0.0009^d	
642	-0.0412 ± 0.0009	
777	-0.0526 ± 0.0008	
914	-0.0610 ± 0.0008	
1013	-0.0712 ± 0.0007	
Sample	-1.945 ± 0.005	

^aCorrection based on a calculated (FOP) axial worth profile for ^{238}U .

^bReference temperature was 300K.

^cSample masses are listed in Table I.

^dUncertainties include effect of $\pm 5\text{K}$ temperature uncertainty.

TABLE 12.4 Measured Reactivity Doppler Values from ZPPR-15D

Natural UO ₂ Sample		Enriched UO ₂ Sample	
Temp., K ^b	ρ , ϕ /kg ²³⁸ U ^c	Temp., K ^b	ρ , ϕ /kg U ^c
531	-0.0145 ± 0.0006 ^d	500	-0.0080 ± 0.0008 ^d
651	-0.0195 ± 0.0006	649	-0.0130 ± 0.0008
790	-0.0246 ± 0.0006	786	-0.0172 ± 0.0007
936	-0.0300 ± 0.0006	940	-0.0194 ± 0.0007
1081	-0.0329 ± 0.0005	1083	-0.0235 ± 0.0006
Sample	-0.641 ± 0.002	Sample	+2.393 ± 0.001

Depleted Uranium Metal Sample		
Temp., K ^b	Uncorrected ρ , ϕ /kg ²³⁸ U ^c	Expansion Corrected ^a ρ_c , ϕ /kg ²³⁸ U ^c
503	-0.0131 ± 0.0003 ^d	-0.0130 ± 0.0003 ^d
650	-0.0204 ± 0.0003	-0.0203 ± 0.0003
797	-0.0255 ± 0.0003	-0.0253 ± 0.0003
896	-0.0284 ± 0.0003	-0.0281 ± 0.0003
1011	-0.0314 ± 0.0003	-0.0310 ± 0.0003
Sample	-0.584 ± 0.001	

UZr Metal Sample		
Temp., K ^b	Uncorrected ρ , ϕ /kg ²³⁸ U ^c	Expansion Corrected ^a ρ_c , ϕ /kg ²³⁸ U ^c
532	-0.0147 ± 0.0003 ^d	-0.0146 ± 0.0003 ^d
656	-0.0201 ± 0.0003	-0.0199 ± 0.0003
809	-0.0257 ± 0.0003	-0.0254 ± 0.0003
904	-0.0288 ± 0.0003	-0.0285 ± 0.0003
1032	-0.0323 ± 0.0002	-0.0318 ± 0.0003
Sample	-0.618 ± 0.001	

^aCorrection based on a calculated (FOP) axial worth profile for ²³⁸U.^bReference temperature was 300K.^cSample masses are listed in Table I.^dUncertainties include effect of ±5K temperature uncertainty.

TABLE 12.5 Comparison of Corrected Calculation and Experiment for ZPPR-15A Doppler Reactivity Measurements

Natural UO_2 Sample ^a				Depleted U Metal Sample ^b			
Nominal Temp., K ^c	Reactivity, $\phi/\text{kg } ^{238}\text{U}$		C/E	Nominal Temp., K ^c	Reactivity, $\phi/\text{kg } ^{238}\text{U}$		C/E
	C	E			C	E	
500	-0.0246	-0.0301 $\pm$ 0.0013	0.817 $\pm$ 0.035	500	-0.0202	-0.0250 $\pm$ 0.0008	0.808 $\pm$ 0.026
650	-0.0389	-0.0459 $\pm$ 0.0017	0.867 $\pm$ 0.032	650	-0.0333	-0.0382 $\pm$ 0.0008	0.872 $\pm$ 0.018
800	-0.0495	-0.0570 $\pm$ 0.0012	0.868 $\pm$ 0.018	800	-0.0416	-0.0494 $\pm$ 0.0008	0.842 $\pm$ 0.014
950	-0.0564	-0.0687 $\pm$ 0.0013	0.821 $\pm$ 0.016	900	-0.0480	-0.0563 $\pm$ 0.0008	0.852 $\pm$ 0.012
1100	-0.0642 ^d	-0.0784 $\pm$ 0.0012	0.819 $\pm$ 0.012	1000	-0.0527 ^d	-0.0612 $\pm$ 0.0008	0.861 $\pm$ 0.011
Sample Worth	-1.723 ^d	-1.574 $\pm$ 0.002	1.095 $\pm$ 0.002		-1.167 ^d	-1.169 $\pm$ 0.002	0.998 $\pm$ 0.002

^aNatural UO_2 sample is 305 mm long by 25.4 mm diameter, and contains 1.086 kg of ^{238}U .

^bDepleted U metal sample is 254 mm long by 25.4 mm diameter, and contains 2.396 kg of ^{238}U .

^cReference temperature was 300 K.

^dRecalculated values.

TABLE 12.6 Comparison of Calculated and Experimental Results for
Small-Sample Reactivity Doppler Measurements in ZPPR-15B

Nominal Temp., K ^a	Reactivity, ρ /kg ²³⁸ U ^a		
	C	E	C/E
Natural UO ₂ Sample			
500	-0.0232	-0.0273 ± 0.0009	0.850 ± 0.028
650	-0.0356	-0.0419 ± 0.0009	0.849 ± 0.018
800	-0.0430	-0.0542 ± 0.0008	0.838 ± 0.012
950	-0.0540	-0.0632 ± 0.0008	0.854 ± 0.010
1100	-0.0604	-0.0727 ± 0.0007	0.831 ± 0.008
Sample Worth	-1.833	-1.945 ± 0.005	0.942 ± 0.002
Depleted U Metal Sample ^b			
650	-0.0112	-0.0154 ± 0.0008	0.727 ± 0.038
800	-0.0203	-0.0267 ± 0.0007	0.760 ± 0.020
900	-0.0253	-0.0324 ± 0.0007	0.781 ± 0.017
1000	-0.0300	-0.0379 ± 0.0006	0.792 ± 0.012
Sample Worth	-1.194	-1.227 ± 0.001	0.973 ± 0.001
UZr Metal Sample			
500	-0.0217	-0.0261 ± 0.0005	0.831 ± 0.016
650	-0.0326	-0.0398 ± 0.0005	0.819 ± 0.010
800	-0.0408	-0.0499 ± 0.0005	0.818 ± 0.008
900	-0.0470	-0.0548 ± 0.0005	0.858 ± 0.008
1000	-0.0517	-0.0614 ± 0.0005	0.842 ± 0.006
Sample Worth	-1.318	-1.310 ± 0.001	1.006 ± 0.001

^aReactivities corrected to nominal temperatures according to $\rho = CT^{-\gamma}$.
E values are not points on the fitted curve, but are measured values
with a correction applied.

^bE values for the depleted Metal sample are based on a reference
temperature of 500K because the 300K data were inconsistent.

TABLE 12.7 Comparison of Calculated and Experimental Results for
Small-Sample Reactivity Doppler Measurements in ZPPR 15D

Nominal Temp., (K) ^a	Reactivity, ρ /kg ^a		
	C	E	C/E
Depleted U Metal			
500	-0.0097 ^b	-0.0129 $\pm$ 0.0003	0.752 $\pm$ 0.017
650	-0.0148	-0.0203 $\pm$ 0.0003	0.730 $\pm$ 0.011
800	-0.0189	-0.0254 $\pm$ 0.0003	0.743 $\pm$ 0.009
900	-0.0211	-0.0282 $\pm$ 0.0003	0.750 $\pm$ 0.008
1000	-0.0232	-0.0307 $\pm$ 0.0003	0.757 $\pm$ 0.007
Sample Worth	-0.541	-0.584 $\pm$ 0.001	0.926 $\pm$ 0.002
UZr Metal			
500	-0.0094 ^c	-0.0130 $\pm$ 0.0003	0.723 $\pm$ 0.017
650	-0.0143	-0.0197 $\pm$ 0.0003	0.726 $\pm$ 0.011
800	-0.0184	-0.0251 $\pm$ 0.0003	0.733 $\pm$ 0.009
900	-0.0207	-0.0284 $\pm$ 0.0003	0.729 $\pm$ 0.008
1000	-0.0227	-0.0310 $\pm$ 0.0003	0.732 $\pm$ 0.008
Sample Worth	-0.584	-0.618 $\pm$ 0.001	0.945 $\pm$ 0.001
Natural UO ₂			
500	-0.0101 ^b	-0.0130 $\pm$ 0.0006	0.773 $\pm$ 0.036
650	-0.0153	-0.0195 $\pm$ 0.0006	0.784 $\pm$ 0.024
800	-0.0194	-0.0249 $\pm$ 0.0006	0.780 $\pm$ 0.019
950	-0.0230	-0.0304 $\pm$ 0.0006	0.756 $\pm$ 0.015
1100	-0.0259	-0.0334 $\pm$ 0.0005	0.776 $\pm$ 0.012
Sample Worth	-0.662	-0.641 $\pm$ 0.002	1.033 $\pm$ 0.003
Enriched UO ₂			
500	-0.0051 ^c	-0.0080 $\pm$ 0.0008	0.638 $\pm$ 0.064
650	-0.0077	-0.0130 $\pm$ 0.0008	0.592 $\pm$ 0.036
800	-0.0098	-0.0175 $\pm$ 0.0007	0.560 $\pm$ 0.022
950	-0.0116	-0.0196 $\pm$ 0.0007	0.592 $\pm$ 0.021
1100	-0.0132	-0.0238 $\pm$ 0.0006	0.555 $\pm$ 0.014
Sample Worth	+2.313	+2.393 $\pm$ 0.001	0.967 $\pm$ 0.001

^aReactivity corrected to nominal temperatures according to $\rho = CT^{\gamma}$.
E values are not points on the fitted curve but are measured values
with a correction applied. Specific worths relative to kg ²³⁵U except
for enriched sample, which is relative to kg U.

^bCalculated using cross sections based on ZPPR-15A spectrum.

^cCalculated using cross sections based on ZPPR-15D spectrum.

TABLE 12.8 Reactivity Doppler Fitting Parameters for
ZPPR-15 Phases A, B, and D

Sample	Fit Parameter γ^a		
	Phase A	Phase B	Phase D
Natural UO_2	0.901 ± 0.100	0.895 ± 0.074	0.938 ± 0.106
Enriched UO_2	-	-	0.713 ± 0.197
Depleted U Metal ^b	0.879 ± 0.084	1.151 ± 0.221^c	1.043 ± 0.068
UZr Metal ^b	-	1.024 ± 0.066	0.960 ± 0.056

^aObtained from fit to form $\text{CT}^{-\gamma}$ of the measured values.

^bData corrected for expansion.

^cFit performed without 300K value, which was suspect.

TABLE 12.9 Average C/E's and Fraction of Reactivity for ^{238}U
Doppler from the Resolved Resonance Range in ZPPR-15

Sample	ZPPR-15 Phase		
	A	B	D
<u>Natural UO_2</u>			
C/E ^a	0.832 ± 0.012	0.841 ± 0.008	0.772 ± 0.011
% Resolved	73.44	71.25	63.99
<u>Depleted U Metal</u>			
C/E ^a	0.853 ± 0.008	0.780 ± 0.014^b	0.748 ± 0.005
% Resolved	54.90	52.37	44.41
<u>UZr Metal</u>			
C/E ^a	-	0.836 ± 0.005	0.730 ± 0.006
% Resolved	-	58.63	50.72

^aC/E's are uncertainty weighted averages of measurements at all elevated temperatures.

^bBased on 500K data as reference temperature.