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ROD AND PLATE HETEROGENEITY STUDIES
IN ZPPR-2

by

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TABLE OF CONTENTS

<u>No.</u>	<u>Title</u>	<u>Page</u>
ABSTRACT		9
1. INTRODUCTION.		9
2. ASSEMBLY DESCRIPTION.		12
3. ANALYTICAL TECHNIQUES		18
3.1 Cross-section Preparation and Heterogeneity Treatment. . .		18
3.2 Reactor Calculation Models		19
3.3 Small-sample Worths		21
3.4 Reaction-rate Ratios and Scans		21
4. LARGE-ZONE ROD SUBSTITUTION AND REACTOR CRITICALITY		23
5. CELL REACTIVITY WORTHS.		28
6. SMALL-SAMPLE REACTIVITY WORTHS.		33
7. NEUTRON SPECTRUM		36
8. FISSION-CHAMBER RATIOS		42
9. IN-CELL REACTION RATES		44
9.1 CALHET Comparisons in the Plate Core.		46
9.2 RABID and S_n Calculations of ^{238}U Capture in the Plate Cell. .		46
9.3 Cell-averaged Reaction Rates in Normal and Voided Rod and Plate Environments.		48
10. REACTION RATES ACROSS AXIAL AND RADIAL BOUNDARIES. .		50
10.1 Foil/Fission Chamber Comparisons in the Plate Core.		50
10.2 Axial Foil Measurements in Plate and Rod Environments. . .		53
10.3 Radial Foil Measurements in Plate and Rod Environments. . .		58
11. SODIUM REACTIVITY COEFFICIENT		62

TABLE OF CONTENTS

<u>No.</u>	<u>Title</u>	<u>Page</u>
11.1	Large-scale Central Voiding	62
11.2	Large-scale, Offcenter Voiding	63
11.3	Sample Variation and Environmental Effects at Core Center .	63
11.4	Plate-rearrangement and Rod-mixing Studies	64
12.	^{238}U DOPPLER REACTIVITY COEFFICIENTS	65
13.	SUMMARY OF CONCLUSIONS	67
13.1	Large-zone Substitution and Reactor Criticality	67
13.2	Cell Reactivity Worths	67
13.3	Small-sample Reactivity Worths	67
13.4	Neutron Spectrum	68
13.5	Fission-chamber Ratios	68
13.6	In-cell Reaction Rates	68
13.7	Reaction Rates across Axial and Radial Boundaries	68
13.8	Sodium Reactivity Coefficients	69
13.9	^{238}U Doppler Reactivity Coefficients	69
14.	CONCLUDING REMARKS	70
	ACKNOWLEDGMENTS	71
	REFERENCES	72

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Assembly 2: Reference Loading with Equal-zone Volumes	14
2.	As-built ZPPR Assembly-2 Equal-zone Configuration: Half 1 . . .	14
3.	As-built ZPPR Assembly-2 Equal-zone Configuration: Half 2 . . .	15
4.	ZPPR Assembly-2 Plate-cell Configurations.	15
5.	ZPPR Matrix Configuration with Inner-core Drawer Loading	16
6.	ZPPR Assembly-2 Rod-cell Configurations.	17
7.	Typical Drawer and Calandria Loadings for ZPPR Assembly 2. . .	17
8.	Rod-cell Substitution Zones in ZPPR Assembly 2.	24
9.	Front Views of Drawer Loadings Used in Rearranged Plate-cell Zone Experiments in ZPPR Assembly 2.	29
10.	Comparison of Neutron Spectra Measured at Center of Plate Core and Rod Zone.	38
11.	Measured and Calculated Spectra at Center of Plate Core	39
12.	Measured and Calculated Spectra at Center of 69-position Rod. Zone	40
13.	Comparison of ^{238}U Measured Capture Rates in the ZPPR-2 Inner-core Plate Cell with RABID and S_n Calculations	48

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Compositions of Final Equal-zone Configuration of ZPPR Assembly 2	13
II.	Average Compositions of 69-drawer Calandria Regions and Matching Plate Region.	16
III.	Compositional Correction Terms and Associated Uncertainties for Central 69 Matrix Locations	26
IV.	Summary of Central Calandria-drawer Substitutions.	26
V.	Plate Measurements in Inner Core	29
VI.	Rod Measurements in Inner Core	30
VII.	Comparison of Cell Worths in Inner Core	30
VIII.	Plate Measurements in Outer Core	31
IX.	Rod Measurements in Outer Core	31
X.	Ratio of Experimental Specific Reactivities at Center of Inner Core in Plate and Rod Environments	33
XI.	Ratios of Calculated and Measured Specific Reactivities at Center of Inner Core in Plate and Rod Environments	34
XII.	Comparison of Measured and Calculated Neutron Spectra in Plate Core and Rod Zone of ZPPR-2	36
XIII.	Comparison of Calculated and Measured Ratios for Neutron Spectra in Plate Core and Rod Zone of ZPPR-2	37
XIV.	Calculated and Measured Fission Ratios in Plate and Rod Environments	43
XV.	Calculated and Measured Reaction-rate Ratios in Normal and Voided Plate Cells	45
XVI.	Calculated and Measured Cell-averaged Reaction-rate Ratios in Normal and Voided Plate and Rod Cells	45
XVII.	Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses Measured in Plate Core with Foils and Counters	51
XVIII.	Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses Measured in Plate Core with Foils and Counters	51
XIX.	Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core with Foils and Counters	52
XX.	Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core with Foils and Counters	53

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
XXI.	Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones	54
XXII.	Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones	54
XXIII.	Comparison of $^{238}\text{U}(n,\gamma)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones	55
XXIV.	Comparison of Measured and Calculated $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones	55
XXV.	Comparison of Measured and Calculated $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones	56
XXVI.	Comparison of Measured and Calculated $^{238}\text{U}(n,\gamma)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones	56
XXVII.	Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector	58
XXVIII.	Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector	58
XXIX.	Comparison of $^{238}\text{U}(n,\gamma)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector	59
XXX.	Comparison of Calculated and Measured $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses in Plate Core and Rod Sector.	59
XXXI.	Comparison of Calculated and Measured $^{238}\text{U}(n,f)$ Reaction-rate Radial Traverses in Plate Core and Rod Sector.	60
XXXII.	Comparison of Calculated and Measured $^{238}\text{U}(n,\gamma)$ Reaction-rate Radial Traverses in Plate Core and Rod Sector.	60
XXXIII.	Summary of C/E Values for Sodium Reactivities near Center of Inner Core.	64
XXXIV.	Specific Sodium-reactivity Worths in Rearranged Plate and Mixed-rod Zones	64
XXXV.	Comparisons of Experimental and Calculated Values for Natural- UO_2 Doppler Experiments in ZPPR Assembly 2	66
XXXVI.	Comparison of Natural- UO_2 Doppler Measurements in Inner-core Plate and Rod Configurations of ZPPR Assembly 2	66

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ABSTRACT

Measurements have been made in the Demonstration Reactor Benchmark, ZPPR Assembly 2, to provide physics data necessary for LMFBR design. An important objective of the ZPPR program was to test the applicability of data obtained in the plate-fueled critical to a power-reactor design with a more homogeneous composition. Sufficient fuel inventory was obtained in the form of rods which were used, within sodium-filled calandria, to build large zones in which direct comparisons of parameters could be made with those in the plate zones. A variety of quantities have been compared in the two environments. In addition to the direct reactivity worth of rod-for-plate substitution, comparisons are given for small-sample and cell-reactivity worths, neutron spectra, reaction-rate ratios, in-cell reaction rates, reaction-rate scans, sodium-void coefficient, and ^{238}U Doppler coefficient. The experiments are compared with calculations using the ARC system and ENDFB/Version-I data. Many parameters of interest can be adequately studied in the plate geometry, and the calculation methods, in general, give a good representation of the heterogeneity effects. Areas are identified in which further experimental and analytical study is needed.

1. INTRODUCTION

Most fast-reactor critical assemblies currently used to establish the major physics characteristics of large fast power reactors differ from the power reactors in a rather distinctive way. Whereas the power reactors consist of bundles of uniform-composition rods or pins (usually mixed plutonium and uranium dioxide) clad in stainless steel and cooled with sodium, the critical assemblies may contain, for example, plates of metallic fuel, plutonium metal, uranium metal, or plutonium-uranium alloy, interspersed with plates of Fe_2O_3 , U_3O_8 , stainless steel, and sodium-filled steel cans. Thus, although the average compositions of the power reactor and its zero-power simulation may be identical, there are significant differences in the internal arrangement of the component elements.

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Since the power reactor contains the important fissile and fertile atoms uniformly mixed with each other and also with the oxygen present in the core, the power reactor is close to homogeneous in a neutronic sense. In contradistinction, the critical facility has been termed "heterogeneous," and any transformations needed to convert critical-facility data to the appropriate homogeneous or power-reactor configuration have been described as "heterogeneity problems" of fast critical assemblies.

We should state at the outset that the expression "heterogeneity problems" carries a wrong connotation in that the consequences of heterogeneity, more frequently than not, result in rather small corrections to the measured, "heterogeneous" data, and that the term "problem" is truly applicable to only some parameters, such as the sodium-reactivity coefficient, which are quite sensitive to local environment. Nevertheless, a justifiable concern has persisted for many years, since the transformation of experimental data to the power-reactor condition has been based upon semiempirical measurements made with different degrees of heterogeneity, together with often-sophisticated calculations whose accuracy, unfortunately, was difficult to assess.

The information we shall present here, on heterogeneity studies in the Zero Power Plutonium Reactor Assembly 2 (ZPPR-2), represents a major advance in that, for the first time, an extensive series of comparative experiments has been performed in both the heterogeneous plate geometry and in "homogeneous" rod zones of carefully matched composition in a realistic simulation of a mixed plutonium/uranium oxide reactor of Demonstration size (350 to 500 MWe) and geometry. These experiments have not only used the plate or rod configurations in a gross sense, but have included detailed, in-cell reaction rates and reactivities in the plate and rod environments in order to provide sensitive tests of the calculations and guard against fortuitous cancellation of effects that could obscure inaccuracies.

The experiments we shall present are:

- a. Heterogeneity effects upon the critical size as demonstrated by large-zone rod substitutions in the plate core, and the following series of measurements in both plate and rod configurations.
- b. Reactivity worths of the reactor constituents in the "as-built," in-cell environments.
- c. Small-sample reactivity worths.
- d. Neutron spectra.
- e. Fission ratios measured with chambers.
- f. In-cell measurements of ^{239}Pu and ^{238}U reaction rates.
- g. ^{238}U capture, and ^{238}U and ^{239}Pu fission rates across both axial and radial boundaries.

- h. Sodium-reactivity coefficients.
- i. ^{238}U and ^{239}Pu Doppler effects.

Where possible, calculated comparisons will also be given, although the principal purpose is to present all the ZPPR Assembly-2 experimental data that relate directly to heterogeneity effects. Furthermore, in a number of cases, reliable calculations cannot yet be performed, and the comparative experimental data must be used as an illustration of the magnitude of heterogeneity effects. The calculated data presented are those obtained during the experiments using the early Version I of the Evaluated Nuclear Data File B (ENDF/B1). This is not believed to be a significant factor, since the magnitude of most heterogeneity effects should not be sensitive to the exact choice of data and the conclusions drawn should be of general applicability. Calculations with the latest Version III of ENDF/B are in progress.

In comparison with calculations, the emphasis here is properly not upon the ability to calculate a quantity either in a plate or rod environment, but upon the ability to calculate the change in the ratio of calculation to experiment when changing from plate to rod configurations.

2. ASSEMBLY DESCRIPTION

ZPPR is a large split-table machine by which two matrices of horizontally laid, rectangular steel tubes may be brought together remotely; one table is stationary, and the other is movable. Each separate matrix is 10 ft wide, 10 ft high, and 4 ft (the tube length) deep, so that the complete matrix is 10 x 10 x 8 ft. Open-topped steel drawers, normally filled with vertically placed plates, may be placed in the matrices to form a wide variety of reactor assemblies. Stainless steel clad Pu/U/Mo alloy is the principal fuel; similarly clad sodium simulates the coolant; and unclad U_3O_8 , uranium metal, and Fe_2O_3 are added to give appropriate compositions.

A detailed description of ZPPK Assembly 2 is given by Amundson et al.,¹ but since this assembly is the first that reproduces many characteristics of a true Demonstration-sized power reactor, we list below the main characteristics appropriate to the Demonstration Reactor. The most important features of ZPPR-2 are:

- a. Appropriate fuel and critical mass. It contains more than 1000 kg of plutonium.
- b. Appropriate composition. The assembly regions closely simulate the mixed PuO_2/UO_2 fuel, stainless steel structure, sodium coolant, and blanket compositions of a true power reactor.
- c. Appropriate geometry. The core is a flattened cylinder (height/diameter ratio ≈ 0.5) with two equal-volume zones. To provide power flattening, the plutonium concentration in the outer zone is 50% higher than in the inner one. The axial and radial blankets are of suitable thickness and are bounded by an external reflector (steel and sodium).
- d. Appropriate fuel geometry. Although most of the ZPPR inventory is necessarily in plate form, a significant quantity (about 150 kg of plutonium) of mixed PuO_2/UO_2 rods and corresponding sodium-filled calandrias was used to check data in both plate and rod configurations. Plate and rod compositions were carefully matched, and the effect of mixing rods of different enrichments (plutonium content) was studied.
- e. Completeness of program. An extensive series of sodium-reactivity, Doppler-effect, neutron-spectrum, reactivity, and reaction-rate experiments was performed in both normal and sodium-voided rod and plate-cell environments.

Among important features not incorporated in ZPPR-2 are the presence of large numbers of massive control rods and sodium-filled control-rod positions. These features are present in the closely related ZPPR Assembly 3 now being studied. Table I and Figs. 1-3 show the composition, a view of the interface, and two sections of the assembly. Note that the axis of symmetry is horizontal in ZPPR-2.

TABLE 1. Compositions of Final Equal-zone Configuration of ZPPR Assembly 2
(loading No. 90). ANL Neg. No. 103-B11280 Rev. 1.

Material	Region Average Compositions, $10^{24} \times \text{atoms/cm}^3$								
	Inner Core Zone ^a	Outer Core Zone ^a	Inner Radial Blanket ^b	Outer Radial Blanket ^b	Radial Reflector	Axial Blankets ^b of Inner Core	Axial Blankets ^b of Outer Core	Na-Steel Axial Reflector (Half No. 1)	Steel Axial Reflector (Half No. 2)
²³⁹ Pu	0.0008433	0.0012741	--	--	--	--	--	--	--
²⁴⁰ Pu	0.0001117	0.0001687	--	--	--	--	--	--	--
²⁴¹ Pu	0.0000154	0.0000232	--	--	--	--	--	--	--
²⁴² Pu	0.0000018	0.0000028	--	--	--	--	--	--	--
²³⁸ Pu	0.0000006	0.0000009	--	--	--	--	--	--	--
²⁴¹ Am	0.0000029	0.0000044	--	--	--	--	--	--	--
²³⁵ U	0.0000123	0.0000115	0.0000245	0.0000245	--	0.0000156	0.0000156	--	--
²³⁸ U	0.0055503	0.0051915	0.0110855	0.0110855	--	0.0070356	0.0070570	--	--
Na	0.0087964	0.0085643	0.0063981	0.0059632	--	0.0087386	0.0088083	0.0089657	--
O	0.0131158	0.0117613	0.0201324	0.0201334	--	0.0138946	0.0140083	--	--
Fe	0.0125763	0.0138521	0.0069233	0.0075411	0.0715610	0.0107508	0.0093550	0.0357128	0.0726809
Cr	0.0027018	0.0025229	0.0019915	0.0021715	0.0012051	0.0028351	0.0024180	0.0053473	0.0016391
Ni	0.0012210	0.0011601	0.0008978	0.0009874	0.0005133	0.0012753	0.0010954	0.0024120	0.0007057
Mn	0.0002095	0.0002020	0.0001574	0.0001743	0.0005981	0.0002297	0.0002054	0.0006113	0.0006225
Si	0.0001307	0.0001130	0.0000889	0.0000967	0.0000503	0.0001410	0.0001116	0.0002757	0.0000727
Cu	0.0000190	0.0000203	0.0000169	0.0000181	0.0000127	0.0000174	0.0000173	0.0000171	0.0000142
Mo	0.0002306	0.0003410	0.0000143	0.0000147	0.0000118	0.0000144	0.0000142	0.0000142	0.0000129
C	0.0000295	0.0000233	0.0010128	0.0010132	0.0005575	0.0000359	0.0000296	0.0002136	0.0005603
Al	0.0000034	0.0000043	0.0000020	0.0000027	--	0.0000024	0.0000024	0.0000021	--
P	0.0000050	0.0000041	0.0000041	0.0000041	0.0000155	0.0000065	0.0000055	0.0000192	0.0000165
S	0.0000017	0.0000014	0.0000014	0.0000014	0.0000249	0.0000022	0.0000018	0.0000097	0.0000250
H	--	--	0.0000083	0.0000083	--	--	--	--	--

^a Does not include impurities in fuel plates.

^b For total length in front and back drawers, excluding spring gap.

Fig. 1. Assembly 2: Reference Loading with Equal-zone Volumes. ANL Neg. No. 103-A11520.

Fig. 2. As-built ZPPR Assembly-2 Equal-zone Configuration: Half 1. ANL Neg. No. 103-A11441.

Fig. 3

As-built ZPPR Assembly-2 Equal-zone Configuration: Half 2. ANL Neg. No. 103-A11240.

Figures 4 and 5 show the plate-cell configurations of the inner- and outer-core zones of ZPPR-2. Each drawer is of similar composition in the

CORE ZONE 1

CORE ZONE 2

TYPE A

TYPE B

Fig. 4

ZPPR Assembly-2 Plate-cell Configurations. ANL Neg. No. 103-A11278.

BLANKET

RADIAL

AXIAL

Fe_2O_3 - 1/8"

DEPLETED U - 1/8"

Fig. 5

ZPPR Matrix Configuration with Inner-core
Drawer Loading. ANL Neg. No. 103-B1172.

inner core (one-drawer cell), but repeatability occurs every two drawers in the outer core (two-drawer cell). The number of fuel plates per drawer are 1 and $1\frac{1}{2}$ respectively, in the inner and outer core.

Rod cells are constructed by using stainless steel-clad oxide rods loaded into calandrias, which are then placed directly in the matrix tubes. The calandrias are 2 x 2 x 12-in.-long stainless steel boxes, each containing 16 sealed stainless steel through-tubes in which the fuel rods are placed. The volume between the tubes and the box is either sodium-filled or left void to simulate normal or sodium-voided core compositions. The rods are each 6 in. long and nominally $\frac{3}{8}$ in. in diameter. Three types of rods--depleted UO_2 , a 15% PuO_2 mix with UO_2 , and a similar 30% mix--may be used alone or mixed to simulate blanket and different core compositions.

Rod equivalents of the inner- and outer-core plate configurations are shown in Fig. 6, loaded drawers and calandrias in Fig. 7, and rod and matched-plate compositions in Table II.

TABLE II. Average Compositions of 69-drawer Calandria Regions and Matching Plate Region

Region Compositions, 10^{22} atoms/cm ³					Region Compositions, 10^{22} atoms/cm ³				
Material	Inner Core (0 to 18 in. Axially in Both Halves)		Axial Blanket (18- to 24-in. Axial Section in Both Halves)		Material	Inner Core (0 to 18 in. Axially in Both Halves)		Axial Blanket (18- to 24-in. Axial Section in Both Halves)	
	PuO ₂ -UO ₂ Rods in Calandria	Matching Plate Loading	UO ₂ Rods in Calandria	Matching Plate Loading		PuO ₂ -UO ₂ Rods in Calandria	Matching Plate Loading	UO ₂ Rods in Calandria	Matching Plate Loading
²³⁸ Pu	0.00005	0.00006	-	-	Mn	0.02510	0.02186	0.02507	0.02569
²³⁹ Pu	0.08438	0.08439	-	-	Si	0.01604	0.01301	0.01604	0.01532
²⁴⁰ Pu	0.01126	0.01118	-	-	Mo	0.02312	0.02356	0.00150	0.00240
²⁴¹ Pu	0.00162 ^a	0.00148 ^a	-	-	Cu	0.00245	0.00287	0.00245	0.00362
²⁴² Pu	0.00019	0.00018	-	-	Co	0.00078	0.00036	0.00078	0.00069
²⁴¹ Am	0.00025 ^a	0.00035 ^a	-	-	Al	0.00029	0.00034	0.00029	0.00024
²³⁵ U	0.00126	0.00123	0.00135	0.00153	Ta	0.00002	-	0.00002	-
²³⁸ U	0.55636	0.55530	0.65630	0.69326	Ti	0.00017	-	0.00012	-
O	1.30821	1.31287	1.31650	1.26518	Nb	0.00053	-	0.00053	-
Na	0.88779	0.89116	0.88779	0.88486	C	0.00297	0.00292	0.00297	0.00405
Fe	1.16899 ^b	1.22672 ^b	1.16601 ^b	1.11237 ^b	P	0.00061	0.00045	0.00061	0.00064
Cr	0.33592	0.25996	0.33542	0.31088	S	0.00030	0.00016	0.00030	0.00027
Ni	0.15300	0.11847	0.15277	0.13968					

^aCorrected for ²⁴¹Pu decay to date of July 1, 1971.

^bIncludes minor impurities in claddings, rods, sodium and unaccountables in steel analyses.

INNER CORE

0-16-0

OUTER CORE

8-8-0

NORMAL ROD CELL CONFIGURATIONS

INNER CORE

4-8-4

OUTER CORE

12-0-4

8-0-8

REARRANGED ROD CELL CONFIGURATIONS

ROD COMPOSITION KEY:
 G = 30% PuO₂ / DEPLETED UO₂
 F = 15% PuO₂ / DEPLETED UO₂
 D = DEPLETED UO₂

Fig. 6

ZPPR Assembly-2 Rod-cell Configurations.
 ANL Neg. No. 103-B11165.

Fig. 7

Typical Drawer and Calandria
 Loadings for ZPPR Assembly 2.
 ANL Neg. No. 103-B11191.

3. ANALYTICAL TECHNIQUES

3.1 Cross-section Preparation and Heterogeneity Treatment

All reactor calculations were made with a basic 27-energy-group set of data. The preparation of the broad-group set involved two steps for a given reactor zone. First, the ENDF/B Version-I data were reduced to the 27-group structure through a fundamental-mode calculation for the zone composition. This stage also involved treatment of self-shielding for uranium and plutonium in the plate or rod cells. Second, the broad-group flux distribution through the cells was computed using integral-transport perturbation theory, and a "homogenized" set of isotopic cross sections was obtained by flux-volume weighting. This procedure was carried out for each principal zone of the reactor: inner core, outer core, radial breeder, and axial breeder, both for the normal cells and for the sodium-voided cells where required. Data for axial- and radial-reflector materials were taken from the breeder-zone calculations.

The fundamental-mode calculations were made with the MC² module of the ARC system,² using the ultrafine-group option with the consistent B₁ neutronics calculation. Both homogeneous- and heterogeneous-cell calculations were performed. The homogeneous cell calculations were done for each reactor region (1) to provide data for a reactor calculation to estimate the heterogeneity effect on k_{eff} by comparison with calculations using the heterogeneous data, and (2) to provide homogeneously shielded data for calculation of reaction rates and perturbation-sample worths.

The first step in the preparation of the "heterogeneous" data was to perform heterogeneous resonance self-shielding calculations. Since the MC² code is limited to a two-region equivalence relation, the cell must consist of alternate fuel and diluent regions. This means that for uranium in the core zones, two calculations were required: one for uranium in the fuel (Pu-U-Mo) plate and one for uranium in the U₃O₈ plate. In each case, the neighboring uranium plate had to be assumed to be of the same type, thus producing some error in the mutual-shielding effect. An additional calculation was required to treat the plutonium in the fuel plate.

Since the MC² calculations (and subsequent transport calculations) were only one-dimensional, several descriptions of the material distribution in the cell are possible for the heterogeneity calculations. The approach taken was to perform the calculations with material densities and plate thicknesses determined from a horizontal section at the midplane of the cell. In addition, the drawer and matrix structures at the top and bottom of the cell, as well as the cladding material, were homogenized into the diluent region. This procedure did not account for the void at the top of the cell or the different heights of the plates in the cell, but it should provide representative optical path lengths and σ_p values for the equivalence relationships.

The second step was to use the 27-group data from the MC² calculations appropriate to each plate as input for the CALHET code.³ This code calculates the fine structure of the flux within the cell by the integral-transport perturbation method of Storrer et al.⁴ The entire cell is treated by the code within the approximations of one space dimension. The flux advantage factors for each plate from CALHET are used to weight the cross sections for each isotope in the cell and finally to provide the so-called heterogeneous data for the zone.

A limitation of the present heterogeneity method is that each zone is treated in isolation. Some error is to be expected, for example, near the boundary of a rod zone and a plate zone. Thus, the data for rod cells will be more applicable in the interior of the rod zones. Some improvement in this respect would be expected in calculations that will be made with the SDX code⁵ using ENDF/B Version-III data. This will enable the MC² and CALHET calculations to be made in up to 156 groups. The 156-group data for each zone can be input into a one-dimensional diffusion calculation for the reactor and the data then collapsed to 27 groups appropriately for each reactor zone desired. Thus some level of zone interaction will be possible. However, the treatment of self-shielding effects for resonant materials in boundary cells will still remain a problem.

3.2 Reactor Calculation Models

Most of the calculations were made with a basic R-Z model of ZPPR-2 loading 90. Additional calculations were made with an X-Y representation of the reactor center plane for off-center-zone voiding cases and for reaction-rate and reactivity-sample scans. A one-dimensional cylindrical (R) model was also used for a study of geometrical effects by comparison with the X-Y model and for calculations of transport-versus-diffusion-theory effects.

The reactor zones and dimensions for the R-Z model are those shown in Fig. 2. The model was made symmetric about the center plane and thus neglected the relatively unimportant differences in the top and bottom axial-reflector compositions. The axial-zone dimensions were the same as for the as-built reactor, and radial-zone boundaries were determined so as to preserve the zone volumes.

The R-Z calculations were made with the 27-energy-group data using the DARC2D diffusion module.⁶ The number of (R,Z) mesh intervals was limited to a maximum of about 30 x 20, giving an average mesh spacing of about 5 cm, in order to avoid the relatively slow channel-ordering solution method in DARC2D. Several spatial mesh structures were used within the basic model in order to define different experimental configurations:

- a. For central-plate-zone voiding cases, the radial mesh defined cylindrical zones equivalent to 1, 9, 21, and 93 matrix positions and the axial mesh gave boundaries at 6.036 and 12.036 in. from the midplane.

b. For the central rod zone, a radial mesh was used that described the 69-matrix-position zone.

c. For the reaction-rate and perturbation-sample scans, a radial mesh was used that gave the same number of equal intervals across each zone as were required along the experimental scan line. The axial mesh was constructed so as to define the traverse-tube positions at 3.036, 7.036, 11.036, 14.036, and 22.036 in. from the midplane. This model was also used for calculations of the off-center voided zones in an annular representation.

d. Other mesh assignments were used for the analysis of particular experiments such as the Doppler-effect measurements.

An X-Y representation of the reactor was necessary for two main reasons. The first was the asymmetric geometry of the outer-core zone in ZPPR-2. The outer core was five drawers thick in the "X direction" and four drawers thick in the "Y direction." This results in an approximately cylindrical outer-core boundary, but at the expense of an asymmetric flux distribution in the X and Y directions. The resulting outer core in the R-Z model is about $4\frac{1}{2}$ drawers thick and has errors of several percent in the fluxes, by comparison with a given X or Y direction in the actual reactor, although the total integrated power is closely reproduced.

The second reason is that the correspondence between matrix positions in the reactor and radii in the R-Z model is ambiguous due to the cylindricalization, and an accurate calculation of properties of off-center positions requires a detailed representation of the actual geometry. A second X-Y model was required to represent the radial rod sector that was built for plate/rod comparisons.

The X-Y models were restricted to a quadrant of the reactor in order to avoid condensing the 27-group data to fewer groups and consequent problems of the effect of group condensation. Because of the quadrant symmetry, the numbers of inner- and outer-core drawers was not quite the same as in the as-built reactor, and the rod sector was reflected on the opposite side of the core.

The mesh structure in the X and Y directions corresponded exactly to the actual matrix pitch with one mesh point per drawer, so that, apart from the approximations noted above, an accurate map of the midplane of the reactor was obtained. Zone- and group-dependent bucklings were used to represent axial leakage in the model. These were included in the nuclear data as DB^2 absorption terms. The zone- and group-dependent bucklings were obtained by analyzing the axial leakage from a 0- to 12-in.-high zone in the R-Z calculation corresponding to the height of the voided zones.

3.3 Small-sample Worths

Small-sample reactivity worths were calculated by first-order perturbation theory. The fluxes and adjoint fluxes were obtained for the normal reactor loading and for the 69-position rod core. For central worths, the values were obtained directly from the R-Z model. For the sample scans, a correction was necessary to take into account the detailed X-Y geometry of the reactor. For each sample, the worth at a position (x,y,z) was "synthesized" by combining the worths calculated from RZ, XY, and one-dimensional R models as follows:

$$W(x,y,z) \approx W_{RZ}(r,z) \frac{W_{XY}(x,y,Ba^2)}{W_R(r,Ba^2)},$$

where r is the radius on the R-Z model assumed to correspond to the true position (x,y). The R model had the same radial mesh as the R-Z model and the same axial bucklings as the X-Y model.

For scattering materials such as sodium, iron, and carbon, for which the axial-leakage component of the worth is large away from the center plane, a further modification was necessary. For these materials, the axial-leakage component was first subtracted from the total worth, the "X-Y correction" (applicable to nonleakage and radial-leakage components) was applied, and then the axial-leakage component was added back.

These geometrical correction factors were normalized to unity at the center of the reactor, where the R-Z calculations are the most valid. Significant corrections were obtained in the outer-core and radial-blanket regions.

A transport/diffusion-theory correction was also applied to the scans. This was obtained, as a function of radius, from the ratio of worths from an S4 transport calculation using SNARC1D to the one-dimensional (R) diffusion calculation above. The transport and diffusion models used identical mesh structure and nuclear data. Generally, corrections of up to a few percent were obtained.

The small-sample worths were calculated using cross sections obtained from homogeneous MC² calculations for the respective zones. The experimental worths were reduced to "zero size" in a consistent manner, using the same data as for the SARCASM code.⁷ Thus, for resonant materials present in the zone, both calculated and experimental worths correspond to self-shielding for the homogeneous composition rather than for infinite dilution.

3.4 Reaction-rate Ratios and Scans

Reaction-rate ratios and reaction-rate scans were calculated using the same models as for the sample worths. For the scans, corresponding

geometrical and transport corrections were applied. For the reaction rates measured with fission chambers, shielded data appropriate to the homogeneous zone composition were used. For the foil measurements, data appropriate to the plate in which the measurement was made were used. These data were obtained from the CALHET calculations for the cell and thus included the correct self-shielding and flux advantage factors within the limitations of the cell-calculation method.

4. LARGE-ZONE ROD SUBSTITUTION AND REACTOR CRITICALITY

The long-standing lack of direct experimental checks upon heterogeneity effects in fast reactors led to the procurement of sufficient steel-jacketed oxide rods and both voided and sodium-filled steel calandrias to match certain plate compositions quite precisely. The number of calandrias and amount of plutonium available in rods were sufficient to construct a pseudocylindrical zone about 2 ft in diameter and 4 ft high.

The single-drawer plate cell of the inner core of ZPPR-2 was chosen to match the rod-calandria compositions. A close match was achieved by filling the entire 4 x 4 array of through-tubes in each calandria with a single type of rod, the 15% PuO_2/UO_2 mix. One small discrepancy existed in that molybdenum was present in the standard Pu/U/Mo plate fuel, but not in the rods or calandria. This lack was corrected by laying appropriate thin sheets of molybdenum metal in each matrix tube beneath the calandrias.

The principal experiment consisted of replacing plate-filled drawers in pseudocylindrical regions at the center of the inner core with matching rod calandrias and measuring the reactivity change by means of the calibrated control rods. The substitution was made over the entire core height, and since the calandrias are 12 in. long and the core half-height is 18 in., the inner 6 in. of the axial blanket was also replaced by a matched, depleted- UO_2 rod-calandria combination. Normal plate regions lie outside the rodded zone, both axially and radially.

The rod substitution was made in four progressively larger diameter zones, 21 positions (of five-drawers diameter), 41 positions (seven-drawers diameter), 61 positions, and 69 positions (both of nine-drawers diameter). The outlines of the zones are shown in Fig. 8a.

Since the composition was designed for the best practical match, the reactivity change is exceedingly small (maximum $7 \times 10^{-4} \Delta k/k$) and a very careful study of material differences was necessary to measure this change with reasonable accuracy. The problems were principally those arising from the different plate lengths that must be used in a critical assembly. The match was made by carefully selecting and weighing plate components to obtain, drawer by drawer, as close a material match to the calandrias as possible. The procedure followed was to select fuel plates on the basis of fissile plutonium content to match the plutonium in the preselected calandria elements. U_3O_8 plates were then selected to complete the uranium match. The oxygen match was completed by weighing and loading Fe_2O_3 . This procedure was followed in matching material compositions in each of three spatial zones for each drawer. These zones were:

- a. The front 12 in. of the inner-core composition.
- b. The rear 6 in. of the inner-core composition.
- c. The first 6 in. of the axial blanket.

a. CYLINDRICAL ZONES AT THE CENTER OF THE INNER CORE

b. RADIAL SECTOR IN THE INNER AND OUTER CORE REGIONS

Fig. 8. Rod-cell Substitution Zones in ZPPR Assembly 2. ANL Neg. No. 103-B11169.

The rest of the axial blanket (beyond 24 in. in each half) was used for both plates and rods so that no material balance was necessary.

In this manner, 42 matching calandria drawers were obtained, and the reactivity effect of the 69 matrix-size zone was evaluated by successive placements of these matched calandria drawers. Reference control-rod positions were established with the plate drawers in core. The plate drawers were then replaced with the matched calandrias, and the reactivity changes were then measured by comparing calibrated control-rod positions. The resulting compositions are given in Table II.

The above matching procedure was designed to minimize the mismatch in fissile plutonium, ^{238}U , and oxygen. However, certain compositional differences inevitably remained, primarily in the stainless steel constituents. The correction for these zonal material imbalances was made zone by zone for all four matching zones using measured and calculated radial and axial small-sample reactivities averaged over each matching zone. Average material worths were determined for each subzone using measured small-sample reactivity traverses. An exception to this was the manganese worth, which was calculated. This correction term is dominated by the inherent mismatch in stainless steel and by the fissile-material differences due to ^{241}Pu decay. Additionally, a significant correction was also found to be necessary for the slightly different axial distributions of materials (principally plutonium and uranium) in the rod and plate configurations (i.e., inside a zone). This effect occurs because of the different physical designs of the clad PuO_2/UO_2 rods and the $\text{Pu}/\text{U}/\text{Mo}$ fuel plates, plus the fact that the U_3O_8 plates are unclad and thus form continuous columns.

The uncertainty in the correction term was also calculated. This uncertainty is due to (1) errors in the measured reactivities, (2) the error in material matching due to imprecise knowledge of the actual mass of each material involved, and (3) half-closure errors, i.e., the uncertainty in the reactivity associated with the reproducibility of the closure position.

To illustrate, Table III presents the results for the 69-position zone. In Table III, ΔM is the material mismatch, σ_1 is the error due to imprecise knowledge of the mass of each material, σ_2 is the error due to uncertainties in the material-worth measurements, and σ is the overall error on the correction term and is equal to $(\sigma_1^2 + \sigma_2^2)^{1/2}$. Table IV summarizes the experimental results, corrections, and errors, and lists the final reactivity and uncertainty for each of the four calandria-for-drawer zone substitutions.

For the large-zone substitution, first-order perturbation-theory calculation is expected to be inaccurate. Thus, calculations for the perturbed condition of the reactor were made. In addition to taking the difference of

two calculated k_{eff} values, a more attractive approach was to make an "exact" perturbation calculation. By this, we mean that the flux was calculated for the normal condition and the adjoint flux for the perturbed condition; the data perturbation was the difference between the macroscopic data for the plate and rod cells. (Alternatively, the normal adjoint and the perturbed real flux could be used; this results in the same total reactivity change, but with different components.) This method has the advantage that the reactivity change can be broken down into a number of components (e.g., absorption, spectrum, fission source, and leakage) to permit some insight into the effects taking place.

TABLE III. Compositional Correction Terms and Associated Uncertainties for Central 69 Matrix Locations

Material	ΔM^a (Plate-Rod), kg	ρ , Ih	σ_1 , Ih	σ_2 , Ih	σ , Ih
$^{239}\text{Pu} + ^{241}\text{Pu}$	-0.098	-8.24	3.59	0.023	3.59
^{235}U	0.035	-1.08	0.0	0.033	0.033
^{238}U	1.80	2.34	3.28	0.71	3.35
Mo	-0.037	0.11	0.021	0.01	0.023
Fe, Ni, Cr, Mn and impurities	-17.98	15.29	0.49	4.49	4.52
		8.42	4.89	4.55	6.67

^aThese values were derived from measured masses of the actual material loadings which were not necessarily identical to the zone average compositions given in Table II.

TABLE IV. Summary of Central Calandria-drawer Substitutions

Number of Positions	Measured Reactivity Change, Ih	Correction for Compositional Mismatch, Ih	Fuel Displacement Correction, Ih	Half- Closure Error, Ih	Corrected Reactivity Change, Ih
21	-22.8	2.68 ± 1.95	-3.47 ± 0.69	0.8	-23.6 ± 2.2
41	-44.1	5.16 ± 4.08	-6.63 ± 1.33	1.13	-45.6 ± 4.4
61	-67.2	7.49 ± 6.22	-9.68 ± 1.94	1.38	-69.4 ± 6.7
69	-76.1	8.42 ± 6.67	-10.85 ± 2.17	1.60	-78.5 ± 7.2^c

^aWhen rods are substituted for plates, there is an axial movement of core material caused by differences in piece lengths and cladding structure. The corrections were determined from the calculated axial shape normalized to the measured central worths for the plutonium and uranium components only.

^bThe half-closure uncertainties were cumulative, since the incremental zone enlargements were done sequentially.

^cAn exact perturbation calculation gives a result of -74.3 Ih for a C/E value of 0.946 ± 0.087 .

The calculation was made only for the largest 69-position zone. The result was 74.3 Ih (998.49 Ih/% $\Delta k/k$ conversion factor). Combined with the experimental value of 78.5 ± 7.2 Ih, this gives a ratio of calculation to experiment of 0.946 ± 0.087 .

This value of C/E indicates that the effects of heterogeneity upon critical size may be calculated with some confidence. The heterogeneity effect for the entire reactor was obtained from two R-Z calculations; one used the "heterogeneous" data, and the other used the homogeneous zone data as described in Sec. 3.1 above. The difference in k_{eff} calculated was 1.2%. This value is consistent with that obtained from calculations with the VIM Monte Carlo code,⁸ which predicted a heterogeneity effect of $(1.4 \pm 0.5)\%$. If the uncertainty in C/E obtained from the central-zone substitution is assumed to apply to the entire reactor, this uncertainty leads to one of only 0.11% in the calculated k_{eff} due to heterogeneity.

Finally, a rod substitution in a representative pseudosector of the reactor was attempted to derive a heterogeneity correction for the entire reactor core. In the outer core, each calandria contained eight 15% and eight 30% PuO_2/UO_2 rods. This gave the required 1.5/1 ratio of outer- to inner-core fuel concentrations. The cross section of this rod substitution is shown in Fig. 8b. This experiment presented far greater difficulties than the central substitution, and, although the reactivity changes on rod insertion were successfully measured, no reliable result has yet been derived. The difficulties lie in the fact that the outer-core plate and rod compositions were not designed as exact matches. The composition mismatches are therefore greater. Also, there is the additional complication that the reactivity worths of all materials vary rapidly across the outer core, and those of the scattering materials may even change sign. The result is a very difficult, and currently unreliable, assessment of the quite large composition corrections.

5. CELL REACTIVITY WORTHS

The worths of the cell components and also of the full cell have been measured (a) in the inner core with the normal plate arrangement and two rearranged plate cells, (b) in the inner-core central rod zone with the standard rod arrangement and two different rod combinations of the same average composition, (c) in the outer, two-drawer-cell plate core with the normal arrangement only, and (d) in the outer-core region of the rod sector with the normal rod composition and one different rod mixture of the same average composition.

In all cases, except for the standard compositions, a small zone was constructed of the same structure as the cell to be measured. The measurement was made by axial oscillation of the drawer (or in the case of the outer plate cell, two drawers) containing the cell and cell components to be studied, or the full cell (excluding any cans) was removed from the front 6 in. ($Z = 0$ to 6 in.) and the worth of the change was measured.

There are limitations upon the cell components that may be removed and thus upon those whose worths may be measured. In the plate cell, the sodium worth was measured by replacing a sodium-filled can with an empty one; the same procedure was used for the Pu/U/Mo fuel. Each of the uncanned plates, Fe_2O_3 and U_3O_8 , was completely removed, and the remaining plates were held in place with wire spacers. Neither the actual drawer nor the front 6 in. of the matrix tube is removable. The worth of these plus that of the steel cans was calculated and added to the measured worths to give the full-cell worth. In the rod cell, the sodium worth was again measured by substituting a calandria empty of sodium for the first 6 in. in place of the filled one, and the worths of the fuel rods were measured by replacing them with unfilled rods. The worths of the calandria itself ($Z = 0$ to 6 in.), the matrix tube, and the empty rod cans were calculated and added to the measured values to give the full-cell worth.

The reactivity changes involved in rearranging plate cells or mixing rods are small, and care was taken to ensure the identical replacement of the remaining components after a change had been made. For rod mixing, the standard (0-16-0) mixture in the inner core was replaced by (4-8-4) and (8-0-8) mixtures and the average compositions were matched closely. Calculated corrections were applied for the residual differences. Here the three numbers denote the number of 30% PuO_2/UO_2 , 15% PuO_2/UO_2 , and depleted- UO_2 rods present in a section of a calandria.

The inner-core measurements were all made in the central position, 137-37. The rearranged plate region was 3 x 3 matrix positions in cross section for the full core height, ± 18 in. The drawer loadings used are shown in Fig. 9. The central rod measurements were all made in a smaller, 3 x 3 zone at the center of the major zone, and the mixing was carried out over a height of $Z = \pm 12$ in.

Fig. 9. Front Views of Drawer Loadings Used in Rearranged Plate-cell Zone Experiments in ZPPR Assembly 2. ANL Neg. No. 103-B11171.

The outer-core plate measurement was made in two matrix positions, 124-37 and 124-38, located horizontally at the top of the matrix array. The outer core was only four drawers thick in this position, and the cell is therefore two drawers inside the outer core (from the reactor center) and not located at the midpoint of the outer core. This location was necessary to avoid flux differences between the two drawers making up the cell.

The outer-core rod measurements were made in position 136-23 at the center of the 5 x 5 outer-core portion of the rodded sector. The standard rod composition of the outer core is (8-8-0), and a (12-0-4) rod mix experiment was conducted, in position 136-23, at the center of a similar mixed-rod zone of dimensions 5 x 5 and $Z = \pm 12$ in.

The physical stroke of the oscillated drawer was not identical for all conditions. Calculated corrections were made where necessary to give the worth corresponding to complete removal of the material being measured from the reactor.

The rod loadings in the inner and outer core are shown in Fig. 6. The experimental data are presented in Tables V-IX.

TABLE V. Plate Measurements in Inner Core ($Z = 0$ to 6 in.)

Component Type (Number) (Mass, g)	Reactivity Worth, Δk		
	Normal	Rearranged 1	Rearranged 2
Na (163.70 g) (2)	-0.736 ± 0.125	-0.766 ± 0.006	-0.714 ± 0.006
Pu/U/Mo alloy (669.1 g) (1)	16.688 ± 0.071	--	--
U_3O_8 (726.2 g) (2)	-4.66 ± 0.068	--	--
Fe_2O_3 (204.32 g) (1)	-0.817 ± 0.060	--	--
(Sum, All Plates)	10.475 ± 0.159	--	--
Direct Measurement Full Cell	10.462 ± 0.069	--	--
Nonremoved Steel ^a (405.46 g)	-2.114 ± 0.11	--	--
Total Cell Worth	8.348 ± 0.130	--	--

^aMatrix tubes, drawer, and cans; calculated by integration of the measured small worths.

The technique of determining component worths and full-cell worths of cells of differing plate or rod configurations inside a relatively small zone of that configuration is potentially very valuable. But the full value of the technique can only be realized if it is possible to control extraneous perturbations of the experimental configuration and also obtain similar calculated data against which the experiments can be compared. These criteria are not really satisfied today, and thus

TABLE VI. Rod Measurements in Inner Core (Z = 0 to 6 in.)

Component (mass, g)	Reactivity Worth, I_h		
	0-16-0	4-8-4	8-0-8
Na (165.0 g)	-0.784 ± 0.013	-0.770 ± 0.015	-0.792 ± 0.015
All Rods (1630.4 g Inc. SS)	10.582 ± 0.016	10.464 ± 0.016	10.682 ± 0.016
Total Measured	9.798 ± 0.021	9.694 ± 0.022	9.890 ± 0.022
Nonremoved Steel ^a (760.8 g)	-2.704 ± 0.135	-2.704 ± 0.135	-2.704 ± 0.135
Stroke Correction ^b	0.335 ± 0.053	0.335 ± 0.053	0.335 ± 0.053
Total Cell Worth	7.53 ± 0.20	7.54 ± 0.20	7.62 ± 0.20

^aMatrix tube, calandria and rod cladding; calculated by integration of the measured small-sample worths.

^bCorrection for partial stroke based on the full-stroke measurements.

TABLE VII. Comparison of Cell Worths in Inner Core (Z = 0 to 6 in.)

Cell Type	Reactivity Worth, I_h	Cell Type	Reactivity Worth, I_h
Plate	8.348 ± 0.130	4-8-4	7.62 ± 0.20
0-16-0	7.53 ± 0.20	8-0-8	7.54 ± 0.20

TABLE VIII. Plate Measurements in Outer Core (Z = 0 to 6 in.)

Component Type (mass, g)	(Number)	Reactivity Worth, Ih
Na (3x½ in; 2x½ in.) (315.87 g)		+0.057 ± 0.006
Pu/U/Mo alloy (1959.33 g)	(3)	+19.760 ± 0.009
U ₃ O ₈ (714.3 g)	(2)	-0.950 ± 0.024
Fe ₂ O ₃ (646.6 g)	(6)	-0.211 ± 0.019
(Sum, All Plates)		18.656 ± 0.032
Direct Measurement Full Cell		19.063 ± 0.035
Nonremoved Steel ^a (942.04 g)		-0.754 ± 0.109
Stroke Correction ^b		1.619 ± 0.053
Total Cell Worth		19.928 ± 0.127

^aMatrix tube, drawers, and cladding calculated by integration of the measured small-sample worths.

^bIncludes correction for partial stroke based on the full-stroke measurements in the inner core.

TABLE IX. Rod Measurements in Outer Core (Z = 0 to 6 in.)

Component Type (Mass, g)	Reactivity Worth, Ih	
	8-8-0	12-0-4
Na (165.0 g)	0.1129 ± 0.0040	0.1129 ± 0.0035
All Rods (1628.8 g SS Inc.)	10.1346 ± 0.0056	9.7445 ± 0.0047
Total Measured	10.2475 ± 0.0040	9.8574 ± 0.0031
Nonremoved Steel ^a	-2.704 ± 0.135	-2.704 ± 0.135
Stroke Correction ^b	+0.148 ± 0.025	+0.144 ± 0.025
Total Cell Worth	7.688 ± 0.137	7.297 ± 0.137

^aMatrix tube, calandria, and rod cladding; calculated by integration of the measured small-sample worths.

^bCorrection for partial stroke based on the full-stroke measurements.

we present the experimental data to show the magnitudes of the heterogeneity effects and the availability of experimental data.

The results of the inner-core studies are summarized in Table VII. Note that the variation in the rod-cell worth is well within the experimental error, indicating that only the average cell composition is significant from the criticality viewpoint. The sensitive, in-cell sodium worths in the rod cells are also identical within errors (see Table VI). The very important conclusion can therefore be reached that it is possible to simulate a specified composition by mixing the rod types in appropriate numbers and be reasonably confident that the measurements made with the mixture are close to those made with a uniform rod type. This conclusion must be treated with caution when considering compositions significantly different from the present one until calculations are available that establish the sensitivity of measured parameters to the average composition. The approximate 10% difference between the plate and rod cell worths is about a factor of 3 or 4 larger than expected from the rod/plate zone substitution experiments described in Sec. 4. Since these zone substitutions are well supported by calculations, there can be no doubt that the present single-drawer studies do not give a reliable indication of the effects of plate/rod substitution upon critical size or reactivity. The probable explanation lies in undefined systematic errors connected with the different fuel types. It appears that very careful control of the experimental conditions is

necessary to ensure that only heterogeneity effects and not, for example, material-displacement effects are being measured. There is, however, no present reason to doubt the validity of the relative worths of the different rod-cell types.

The outer-core rod-cell-worth data given in Table IX support the rod-cell conclusions reached in the inner core quite well, indicating that the ability to use rod mixing is valid over the entire reactor core. The rod data cannot be directly compared with the plate-cell worths given in Table VIII because of the different locations in the outer core (note that the plate cell is twice the mass of the rod cells), and each must be separately compared with the appropriate calculations.

6. SMALL-SAMPLE REACTIVITY WORTHS

A range of small-sample reactivity worths was measured in the "slot" at $Z = 0$ in. at the center of the plate core and at the center of the 69-position rod zone located at the core center. The results of these measurements, corrected for finite sample size using the SARCASM code,⁷ are given in Tables X and XI.

Before these results are discussed, some brief comments on the experimental technique would be appropriate. First, the reactivity worths of these small samples are measured by repeated oscillation of the samples between the position of measurement and a point well outside the reactor, where their worths are negligible. The reactivity worths are determined either from an analysis of the resulting power trace (inverse-kinetics method) or by recording the change in position of a previously calibrated control rod, which maintains the reactor at a constant power level automatically (autorod method). These techniques are relatively standard and will not be described further here. The samples are oscillated in a thin-walled steel tube, which penetrates the reactor radially at right angles to the matrix tubes and drawers or calandrias. Such a penetration can be made in the rod zone only by pushing back a row of calandrias approximately 0.25 in. in each half to form a "slot" about 0.5 x 2 in. in

TABLE X. Ratio of Experimental Specific Reactivities at Center of Inner Core in Plate and Rod (69-position) Environments

Sample	Specific Reactivity, Ih/kg		Worth Ratios	
	Plate, P	Rod, R	P/R ^a	P/R Normalized ^b
²³⁹ Pu	118.20 ± 0.40	114.77 ± 0.40	1.030 ± 0.005	1.000
²⁴¹ Pu	170.9 ± 6.3	162.4 ± 6.1	1.052 ± 0.055	1.021 ± 0.055
²³⁵ U	95.26 ± 0.29	92.00 ± 0.11	1.035 ± 0.003	1.005 ± 0.006
²³⁸ U	-7.06 ± 0.08	-7.10 ± 0.09	0.994 ± 0.017	0.965 ± 0.018
¹⁰ B	-2265.7 ± 30.8	-2145.5 ± 24.5	1.056 ± 0.019	1.025 ± 0.020
Ta	-48.23 ± 0.84	-44.09 ± 0.69	1.094 ± 0.026	1.062 ± 0.026
Fe	-3.37 ± 0.08	-2.87 ± 0.12	1.174 ± 0.056	1.140 ± 0.056
Fe ₂ O ₃	-4.34 ± 0.94	-3.70 ± 0.73	1.173 ± 0.344	1.139 ± 0.344
SS	-3.41 ± 0.05	c	-	-
Ni	-4.36 ± 0.13	-4.32 ± 0.11	1.009 ± 0.040	0.980 ± 0.040
C	-10.88 ± 0.65	-10.24 ± 0.46	1.063 ± 0.079	1.032 ± 0.079
Na	-4.59 ± 0.12	-5.60 ± 0.31	0.820 ± 0.054	0.796 ± 0.054
Cr	-3.09 ± 0.18	-3.13 ± 0.15	0.987 ± 0.074	0.958 ± 0.074

^aWeighted mean of all P/R values = 1.034 ± 0.0025.

^bNormalized to P/R for ²³⁹Pu of 1.000. Weighted mean of all P/R normalized values = 1.004 ± 0.005.

^cNot measured.

TABLE XI. Ratios of Calculated and Measured Specific Reactivities (1h/kg)
at Center of Inner Core in Plate and Rod (69-position) Environments

Sample	Plate			Rod			$R = \frac{(C/E)_P}{(C/E)_R}$ ^a
	Experimental Value (E)	Calc. Value (C)	$(C/E)_P$	Experimental Value (E)	Calc. Value (C)	$(C/E)_R$	
²³⁹ Pu	118.20 ± 0.40	139.27	1.178 ± 0.004	114.77 ±	133.36	1.162 ±	1.014 ± 0.005
²⁴¹ Pu	170.9 ± 6.3	224.0	1.311 ± 0.048	162.4 ±	212.2	1.307 ±	1.004 ± 0.052
²³⁵ U	95.26 ± 0.29	118.32	1.242 ± 0.004	92.00 ± 0.11	112.26	1.220 ± 0.001	1.012 ± 0.003
²³⁸ U	-7.06 ± 0.08	-9.79	1.387 ± 0.016	-7.10 ± 0.09	-9.35	1.317 ± 0.017	1.060 ± 0.018
¹⁰ B	-2265.7 ± 30.8	-2665.4	1.176 ± 0.016	-2145.5 ± 24.5	-2519.0	1.174 ± 0.013	1.002 ± 0.018
Ta	-48.23 ± 0.84	-54.68	1.134 ± 0.020	-44.09 ± 0.69	-49.79	1.129 ± 0.018	1.004 ± 0.024
Fe	-3.37 ± 0.08 ^b	-3.81	1.131 ± 0.027	-2.87 ± 0.12	-3.56	1.240 ± 0.052	0.912 ± 0.044
Fe ₂ O ₃	-4.34 ± 0.94	-4.94 ^b	1.138 ± 0.249	-3.70 ± 0.73	-4.55 ^c	1.230 ± 0.243	0.926 ± 0.272
SS	-3.41 ± 0.05	-4.19 ^b	1.229 ± 0.018	--	--	--	--
Ni	-4.36 ± 0.13	-4.30	0.986 ± 0.029	-4.32 ± 0.11	-4.06	0.940 ± 0.024	1.050 ± 0.042
C	-10.88 ± 0.65	-11.40	1.048 ± 0.063	-10.24 ± 0.46	-10.28	1.004 ± 0.045	1.043 ± 0.078
Na	-4.59 ± 0.12	-4.32	0.941 ± 0.025	-5.34 ± 0.31	-3.83	0.717 ± 0.041	1.376 ± 0.091
Cr	-3.09 ± 0.18	-5.35	1.731 ± 0.100	-3.13 ± 0.15	-4.97	1.588 ± 0.076	1.090 ± 0.082

^aWeighted mean $R = \frac{(C/E)_P}{(C/E)_R} = 1.013 \pm 0.0025$.

^bCalculated from sum of parts.

^cThis value is derived by combining the steel, nickel, and chromium measurements, since the directly measured value is believed to be in error.

section. To obtain a closely comparable series of measurements in the plate environment, a nominally identical "slot" measurement was made in the plate core. The differences that arise are those due to the different locations and quantities of steel present at the ends of the drawers and plates in one instance and the calandrias and rods in the other. Additionally, the slot environment is believed to permit neutron streaming. This complicates off-center measurements in particular and, in the case of low-worth scattering materials such as sodium, off-center measurements in the slot in large flux gradients are believed to be in error by up to a factor of two.

The streaming effects at the core center, although not well known, should be small and also the same for plate and rod conditions. The effects of the differing quantities of steel around the sample are similarly not well known, but calculations indicate effects from about 0.3 to 3% for ²³⁹Pu and sodium, respectively. Since the steel quantities in the rod and plate cells are nearly the same, the relative effects in plate and rod configurations must be closely similar.

We therefore have not attempted to correct the experimental data given in Tables X and XI, since we are considering only the effects of changing from plate to rod environments.

Table X presents a straightforward comparison of the experimentally measured worths. The unnormalized plate/rod-worth ratios for nearly all the materials are close to unity, and the ratios when normalized to unity for ²³⁹Pu (to take account of the small changes in the perturbation denominator caused by insertion of the rod zone) are almost all within two standard deviations of unity. The weighted mean is 1.004 ± 0.005 .

The normalized P/R ratio for sodium is significantly different from unity. A detailed discussion of sodium reactivities by Davey et al.⁹ indicates, but not conclusively, that the sodium measurement in the rod zone may be in error.

Table XI gives a more useful comparison of worths, since both sets of measurements are separately compared with calculated values. As described in Sec. 3, these calculations are derived from two-dimensional, R-Z, diffusion-theory models of the reactor and assume that the small samples measure "cell-averaged" reactivity worths. Inclusion of the calculated values should allow for changes in the real and adjoint spectra as well as for changes in the perturbation denominator. The last column, which gives the ratio of C/E's for plates and rods, should clearly be unity (within experimental errors) if the calculations are completely correct; but, for example, the ²³⁹Pu ratio is 1.014 ± 0.005 , and the weighted mean for all samples is 1.013 ± 0.0025 .

However, again with the exception of the possibly erroneous sodium value, nearly all values are within two standard deviations of unity.

We therefore conclude that, at least for this particular composition:

- a. The ratios of normalized experimental worths in plate and rod environments are close to unity (weighted mean = 1.004 ± 0.005).
- b. Close agreement is also obtained when calculated corrections are applied for differences between rod and plate environments (weighted mean = 1.013 ± 0.0025).
- c. For both plates and rods, the assumption that the small cylindrical samples do measure cell-averaged worths is not contradicted by these studies.

7. NEUTRON SPECTRUM

The neutron spectrum between about 1 keV and 1-2 MeV was measured at the centers of the plate inner core and the 69-position rod zone. The method is the well-known technique of analyzing the energy distribution of proton-recoil pulses in hydrogen and methane proportional counters. The ZPPR-2 spectrum measurements are described in detail by Simons et al.¹⁰ so that only a brief description is needed here.

The counters were cylindrical with diameters of 0.375-0.625 in. and active lengths of about 1.0 in. and were placed, together with some associated electronics, directly inside the reactor. A cylindrical lead shield was placed around the counter to reduce the gamma-ray background, and the entire package displaced a volume of about $2 \times 2 \times 10$ in. of core material. Thus, the counter was loaded in a normal drawer with the necessary plates removed, or, in the rod environment, a calandria was pushed back in the matrix tube to provide the needed volume. Experiments and calculations have shown that the lead shield produces no significant distortion over the measured energy range.

As can be seen, the measured spectrum is some form of region average, more clearly so in the rod case where the environment is closer to homogeneous.

The results of the experiments and calculations are shown in Tables XII and XIII and Figs. 10-12. The calculated spectra were derived from the appropriate R-Z models for the plate and rod zones (see Sec. 3).

TABLE XII. Comparison of Measured and Calculated Neutron Spectra in Plate Core and Rod Zone of ZPPR-2

Group No.	Lower Limit		Experimental ^a			Calculated ^b			$\frac{C_P/C_R}{E_P/E_R}$
	Lethargy	Energy	Plate E_P	Rod E_R	E_P/E_R	Plate C_P	Rod C_R	C_P/C_R	
1	0.5	6065. keV				0.279	0.283	0.9859	
2	1.0	3679.				1.122	1.141	0.9833	
3	1.5	2231.				2.732	2.764	0.9884	
4	2.0	1353.				3.878	3.910	0.9918	
5	2.5	820.8	3.713 ± 0.042	4.589 ± 0.026	0.8091 ± 0.0102	4.839	4.900	0.9876	1.2258 ± 0.0155
6	3.0	497.9	5.620 ± 0.044	5.957 ± 0.031	0.9434 ± 0.0089	9.460	9.547	0.9909	1.0029 ± 0.0077
7	3.5	302.0	8.632 ± 0.054	8.737 ± 0.038	0.9880 ± 0.0075	9.021	9.079	0.9936	0.9581 ± 0.0076
8	4.0	183.2	8.813 ± 0.059	8.498 ± 0.035	1.0371 ± 0.0082	11.818	11.879	0.9949	1.0114 ± 0.0082
9	4.5	111.1	10.957 ± 0.069	11.139 ± 0.057	0.9837 ± 0.0080	11.240	11.300	0.9960	0.9959 ± 0.0081
10	5.0	67.38	11.874 ± 0.084	11.889 ± 0.049	0.9987 ± 0.0082	10.282	10.310	0.9973	0.9992 ± 0.0114
11	5.5	40.87	11.324 ± 0.103	11.347 ± 0.077	0.9980 ± 0.0113	8.502	8.591	0.9899	0.9477 ± 0.0097
12	6.0	24.79	9.117 ± 0.077	8.728 ± 0.050	1.0446 ± 0.0107	6.938	6.890	1.0070	0.9972 ± 0.0187
13	6.5	15.03	6.207 ± 0.097	6.147 ± 0.063	1.010 ± 0.0189	6.174	6.089	1.0140	0.9185 ± 0.0132
14	7.0	9.119	6.001 ± 0.070	5.436 ± 0.045	1.1039 ± 0.0158	4.422	4.423	0.9998	0.9773 ± 0.0199
15	7.5	5.531	4.372 ± 0.073	4.274 ± 0.050	1.0229 ± 0.0209	2.665	2.636	1.0110	0.9445 ± 0.0230
16	8.0	3.355	2.705 ± 0.055	2.527 ± 0.034	1.0704 ± 0.0261	1.647	1.597	1.0313	0.8485 ± 0.0379
17	8.5	2.035	1.596 ± 0.057	1.313 ± 0.035	1.2155 ± 0.0542	0.573	0.579	0.9896	1.2175 ± 0.0579
18	9.0	1.234	0.828 ± 0.035	1.019 ± 0.022	0.8126 ± 0.0386	1.728	1.690	1.0225	1.3006 ± 0.0315
19	9.5	748.5 eV	1.430 ± 0.030	1.819 ± 0.022	0.7861 ± 0.0190	1.194	1.137	1.0501	
20	10.0	454.0				0.760	0.690	1.1014	
21	10.5	275.4				0.354	0.294	1.2041	
22	11.5	101.3				0.319	0.235	1.3574	
23	12.5	37.27				0.049	0.035	1.4000	
24	13.5	13.71				0.00?	0.001	2.000	
25	14.5	4.043				0.000	0.000		
26	16.5	0.683				0.000	0.000		
27	Thermal	Thermal	($\Sigma = 93.189$)	($\Sigma = 93.419$)		0.000	0.000		

^aExperimental flux normalized relative to the calculated flux over group numbers 4-18.

^bCalculated flux normalized to $100 \text{ n/cm}^2\text{-sec}$ over group numbers 1-27.

TABLE XIII. Comparison of Calculated and Measured Ratios for Neutron Spectra in Plate Core and Rod Zone of ZPPR-2

Group No.	Lower Limit		Normal Plate Core Flux			Rod Zone Flux			$\frac{C_P/E_P}{C_R/E_R}$
	Lethargy	Energy	Experimental E_P^a	Calc. $C_P^{b,c}$	C_P/E_P	Experimental E_R^a	Calc. $C_R^{b,d}$	C_R/E_R	
1	0.5	6065. keV		0.279			0.283		
2	1.0	3679.		1.122			1.141		
3	1.5	2231.		2.732			2.764		
4	2.0	1353.	3.713 ± 0.042	3.878	1.0444 ± 0.0118	4.589 ± 0.026	3.910	0.8520 ± 0.0048	1.2258 ± 0.0155
5	2.5	820.8	5.620 ± 0.044	4.839	0.8610 ± 0.0067	5.957 ± 0.031	4.900	0.8226 ± 0.0043	1.0467 ± 0.0098
6	3.0	497.9	8.632 ± 0.054	9.460	1.0959 ± 0.0069	8.737 ± 0.038	9.547	1.0927 ± 0.0048	1.0029 ± 0.0077
7	3.5	302.0	8.813 ± 0.059	9.021	1.0236 ± 0.0069	8.498 ± 0.035	9.079	1.0684 ± 0.0044	0.9581 ± 0.0076
8	4.0	183.2	10.957 ± 0.069	11.878	1.0786 ± 0.0068	11.139 ± 0.057	11.879	1.0664 ± 0.0055	1.0114 ± 0.0082
9	4.5	111.1	11.874 ± 0.084	11.240	0.9466 ± 0.0067	11.889 ± 0.049	11.300	0.9505 ± 0.0039	0.9959 ± 0.0081
10	5.0	67.38	11.324 ± 0.103	10.282	0.9080 ± 0.0083	11.347 ± 0.077	10.310	0.9087 ± 0.0062	0.9992 ± 0.0114
11	5.5	40.87	9.117 ± 0.077	8.504	0.9328 ± 0.0079	8.728 ± 0.050	8.591	0.9843 ± 0.0056	0.9477 ± 0.0097
12	6.0	24.79	6.207 ± 0.097	6.938	1.1178 ± 0.0175	6.147 ± 0.063	6.890	1.1209 ± 0.0115	0.9972 ± 0.0187
13	6.5	15.03	6.001 ± 0.070	6.174	1.0288 ± 0.0120	5.436 ± 0.045	6.089	1.1201 ± 0.0093	0.9185 ± 0.0132
14	7.0	9.119	4.372 ± 0.073	4.422	1.0114 ± 0.0169	4.274 ± 0.050	4.423	1.0349 ± 0.0121	0.9773 ± 0.0199
15	7.5	5.531	2.705 ± 0.055	2.665	0.9852 ± 0.0200	2.527 ± 0.034	2.636	1.0431 ± 0.0140	0.9445 ± 0.0230
16	8.0	3.355	1.596 ± 0.057	1.647	1.0320 ± 0.0369	1.313 ± 0.035	1.597	1.2163 ± 0.0324	0.8485 ± 0.0378
17	8.5	2.035	0.828 ± 0.035	0.573	0.6920 ± 0.0293	1.019 ± 0.022	0.579	0.5684 ± 0.0123	1.2175 ± 0.0579
18	9.0	1.234	1.430 ± 0.030	1.728	1.2084 ± 0.0254	1.819 ± 0.022	1.690	0.9291 ± 0.0112	1.3006 ± 0.0315
19	9.5	748.5 eV		1.194			1.137		
20	10.0	454.0		0.760			0.690		
21	10.5	275.4		0.354			0.294		
22	11.5	101.3		0.319			0.235		
23	12.5	37.27		0.049			0.035		
24	13.5	13.71		0.002			0.001		
25	14.5	5.043		0.000			0.000		
26	16.5	0.683	($\Sigma = 93.189$)	0.000		($\Sigma = 93.419$)	0.000		
27	Thermal	Thermal		0.000			0.000		

^aExperimental flux normalized relative to the calculated flux over group numbers 4-18.

^bCalculated flux normalized to 100 n/cm²-sec over group numbers 1-27.

^cDIF-2D Code, ENDF/B-1, CALHET-weighted, plutonium and uranium self-shielded, plate-zone cross sections and densities in Assembly 2, Z = 0.5, R = 1.595 cm.

^dDIF-2D Code, ENDF/B-1, CALHET-weighted, plutonium and uranium self-shielded, rod-zone cross sections and densities for a 26.5-cm-radius inner-core zone, Z = 0.5, R = 1.595 cm.

Fig. 10. Comparison of Neutron Spectra Measured at Center of Plate Core and Rod Zone (normalized to same area). ANL Neg. No. 103-A11914.

Fig. 11. Measured and Calculated (Versions-I and -II) Spectra at Center of Plate Core. ANL Neg. No. 103-A11739.

Fig. 12. Measured and Calculated (Version-I) Spectra at Center of 69-position Rod Zone. ANL Neg. No. 103-A11912.

Table XII shows the ratio of the measured and calculated fluxes in the rod and plate environments, group by group. Figure 10 shows the experimental data normalized to the same total flux, together with percentage differences as a function of energy. The calculations predict changes in group fluxes of less than 1% over nearly all groups. The maximum change predicted is only 3%, whereas the experiments indicate much larger changes: 5-10% in a number of groups, and 20% or more at the highest and lowest energies.

Table XIII and Figs. 11 and 12 lay emphasis upon comparisons of the measurements in each environment with calculations. In many respects there is excellent general agreement between calculation and experiment particularly if some relatively minor displacements in the energy scale were allowed.

Returning to Table XII and Fig. 10, we can discern that the largest deviations between the rod and plate measurements appear to be associated with energy regions where the flux is changing more rapidly. If an energy displacement between the two measurements were permitted, many of the discrepancies could be eliminated. As a further illustration, the sums of the measured fluxes in Groups 15-18 for plate and rod, respectively, are 7.039 and 7.149%, and the corresponding calculated figures are 7.087 and 6.961%. All these figures lie within 3% of each other and indicate that the very large discrepancies disappear on a coarser energy scale.

The evidence therefore points to the conclusion that the observed, quite significant discrepancies between the calculated and measured flux differences in plate and rod geometry are false. Although it cannot be proven conclusively, it is possible that the calculations predict the effects of heterogeneity upon spectrum quite well. Certainly, if a coarser energy grouping (which minimizes effects of errors in the energy scales) is chosen, excellent agreement is obtained between calculation and experiment in regions where major discrepancies previously existed. However, further theoretical study of self-shielding in the sodium resonances in the heterogeneous situations is required, since these effects are not well understood at present.

In passing, note the rather small effect of the use of Version-I or -II cross sections upon the calculated spectrum (Fig. 11). We wish to point out that the one region, near 50 keV, where Version II overtly gives much better agreement with experiment has been found to be erroneous, due to an incorrect output of the ETOE code, which resulted in erroneous assignment of a large scattering width to a minor resonance in this region (see Simons et al.¹⁰).

8. FISSION-CHAMBER RATIOS

The fission rates of ^{233}U , ^{234}U , ^{235}U , ^{236}U , ^{238}U , and ^{240}Pu were measured relative to that of ^{239}Pu in cavities of about $2 \times 2 \times 2.5$ in. at the center of the inner core in both the plate environment and the 69-position rod environment. Additionally, the $^{241}\text{Pu}/^{239}\text{Pu}$ fission ratio was measured in the rod zone only.

The fission chambers used were ionization chambers of overall spherical geometry, each separate chamber being a hemisphere and the plate fissile materials being back-to-back at the equator. The chambers were specially constructed for some studies of inelastic neutron scattering, and the spherical geometry is a consequence of this original need. The chambers were of the continuous-flow type, and the pulses from each separate chamber were collected in multichannel analyzers. The chambers were basically intercalibrated by irradiation in a thermal flux, but these relative calibrations have been checked extensively against chambers calibrated by other techniques, and the results showed excellent consistency. The limiting accuracy in fission-ratio measurements is believed to be the calibration accuracy, which is 1-2%. Full details of the chamber design and calibration are given in Refs. 11 and 12.

In the plate configuration, the drawer was loaded to form a void to provide space for the counter from $Z = 2$ to 4 in. The gas-flow tubes, connectors, and cables were laid in place of one of the 1/2-in.-thick sodium cans to exit axially at the rear of the reactor. In the rod zone, a special calandria was pushed back about 2.5 in., so that the fueled region projected by 2.5 in. into the axial blanket; this should cause a negligible error in the central fission ratios. The special calandria had a 1-in.-dia hole in place of the four central rod locations. The connectors and gas-flow tubes exited through this hole.

The calculated ratios were derived from 27-group, R-Z, diffusion-theory calculations using shielded data appropriate to the homogeneous composition (see Sec. 3.4).

The results of calculations and experiments are shown in Table XIV. Although the ratio C/E for plate or rod environments may be significantly different from unity, the change in the C/E ratio when comparing plate and rod environment is well predicted. The ratio $R \equiv (C_p/E_p)/(C_r/E_r)$ is unity to within one standard deviation for five of the six cases, and within two standard deviations for the sixth case.

We therefore conclude that the differences between cell-averaged fission ratios for plates and rods is well predicted for six ratios of widely different spectral response. The weighted mean value of R for the six fission ratios is 1.019 ± 0.012 .

TABLE XIV. Calculated and Measured Fission Ratios in Plate and Rod Environments

Fission Ratio	Plate			Rod			$R \equiv \left(\frac{C_P}{E_P} \right) / \left(\frac{C_R}{E_R} \right)^a$
	Experiment E_P	Calc. C_P	$\frac{C_P}{E_P}$	Experiment E_R	Calc. C_R	$\frac{C_R}{E_R}$	
$\frac{^{238}\text{U}}{^{239}\text{Pu}}$	0.0214 ± 0.0005	0.0218	1.019 ± 0.024	0.0227 ± 0.0005	0.0225	0.991 ± 0.022	1.028 ± 0.033
$\frac{^{236}\text{U}}{^{239}\text{Pu}}$	0.0473 ± 0.0010	0.0473	1.000 ± 0.021	0.0509 ± 0.0011	0.0486	0.955 ± 0.021	1.047 ± 0.030
$\frac{^{234}\text{U}}{^{239}\text{Pu}}$	0.1592 ± 0.0034	0.1529	0.960 ± 0.021	0.1623 ± 0.0034	0.1568	0.966 ± 0.020	0.994 ± 0.029
$\frac{^{240}\text{Pu}}{^{239}\text{Pu}}$	0.1818 ± 0.0039	0.1850	1.018 ± 0.026	0.1901 ± 0.0041	0.1894	0.996 ± 0.021	1.022 ± 0.033
$\frac{^{233}\text{U}}{^{239}\text{Pu}}$	1.543 ± 0.033	1.606	1.041 ± 0.022	1.556 ± 0.034	1.602	1.030 ± 0.023	1.011 ± 0.032
$\frac{^{235}\text{U}}{^{239}\text{Pu}}$	1.067 ± 0.016	1.159	1.086 ± 0.016	1.079 ± 0.016	1.153	1.069 ± 0.016	1.016 ± 0.023
$\frac{^{241}\text{Pu}}{^{239}\text{Pu}}$	Not measured	--	--	1.385 ± 0.034	1.488	1.074 ± 0.026	--

^aWeighted mean $(C_P/E_P)/(C_R/E_R) = 1.019 \pm 0.012$.

9. IN-CELL REACTION RATES

Fission rates in ^{239}Pu and ^{238}U and capture rates in ^{238}U were measured near the inner-core center of the normal plate-fueled core, the 93-drawer-plate voided region, and the 69-position normal and voided rod zone. This was accomplished by irradiating foils placed between plates or between special rods with thin ends and subsequently counting their activities using Ge(Li) gamma counters. The gamma counters were calibrated, both absolutely and relatively:

- a. By foil irradiations in a thermal flux, where some fission and capture cross sections are known to high accuracy.
- b. By the use of calibrated gamma sources obtained from the National Bureau of Standards and the International Atomic Energy Agency.
- c. By back-to-back irradiation of fissile foils with fission chambers of known mass and efficiency in both thermal and fast fluxes.
- d. By counting ^{239}Np in equilibrium with a calibrated ^{243}Am source.

By a combination of such techniques, absolute activities may be measured to about 2% accuracy or better. Full details of the detector calibrations and foil-counting techniques are given by Maddison.¹³ In general, these foil activities were then combined to form ratios of the ^{238}U activities to the ^{239}Pu fission rate.

Plate-averaged reaction rates were derived from the foil measurements. For uranium oxide, special plates were used to give the average through the thickness of the plate directly. For the fuel plate, this technique could not be used. Standard foil plates were replaced with half-thickness fuel plates, and a foil irradiation was made between the two halves in addition to those at the two outside edges. The details of the methods used are given by Gasidlo et al.¹⁴ In addition to the statistical errors quoted in Tables XV and XVI, uncertainties on the ratios of about 1% are estimated for the detector calibration and about 1% for deriving the plate-averaged values.

Here we will examine the effects of heterogeneity in two ways. First, we will examine the ability to calculate the variation in activities within the plate cell. Comparisons with calculations will mostly be made using the plate multigroup cross sections generated by MC²/CALHET, together with the fluxes from the RZ model. These will show the spatial variations only as the differences in the averages over the Pu/U/Mo fuel plate and the U_3O_8 plates. This procedure is inappropriate for a foil of a strong-resonance-absorber material positioned between the plates of the cell. One test case was made, comparing experimental ^{238}U capture rates with an ultrafine-group integral transport code, RABID,¹⁵ and with S_n transport-theory calculations. The CALHET calculations use ENDF/B Version-I data, and the RABID and S_n calculations use ENDF/B Version II (modified).

TABLE XV. Calculated and Measured Reaction-rate Ratios
in Normal and Voided Plate Cells

Reaction	Sodium Condition	Region in Cell	Calc. C	Experiment E	C/E
$\frac{^{238}\text{U}(n,f)}{^{239}\text{Pu}(n,f)}$	Normal	Fuel	0.02569	0.02667 ± 0.00028	0.9633 ± 0.0101
		U_3O_8	0.02104	0.02239 ± 0.00023	0.9397 ± 0.0097
		Cell Avg.	0.02305	0.02424 ± 0.00018	0.9509 ± 0.0071
	Voided	Fuel	0.02791	0.03025 ± 0.00039	0.9226 ± 0.0119
		U_3O_8	0.02393	0.02657 ± 0.00038	0.9006 ± 0.0129
		Cell Avg.	0.02565	0.02816 ± 0.00027	0.9109 ± 0.0087
$\frac{^{238}\text{U}(n,\gamma)}{^{239}\text{Pu}(n,f)}$	Normal	Fuel	0.15763	0.14120 ± 0.00060	1.1164 ± 0.0047
		U_3O_8	0.16523	0.14390 ± 0.00070	1.1482 ± 0.0056
		Cell Avg.	0.16195	0.14274 ± 0.00047	1.1346 ± 0.0037
	Voided	Fuel	0.15355	0.13620 ± 0.00120	1.1274 ± 0.0099
		U_3O_8	0.15922	0.13800 ± 0.00140	1.1538 ± 0.0117
		Cell Avg.	0.15677	0.13722 ± 0.00095	1.1425 ± 0.0079

TABLE XVI. Calculated and Measured Cell-averaged Reaction-rate Ratios
in Normal and Voided Plate and Rod Cells

Reaction	Sodium Condition	Plate or Rod	Calculation (C)	Experiment (E)	C/E
$\frac{^{238}\text{U}(n,f)}{^{239}\text{Pu}(n,f)}$	Normal	Plate	0.02305	0.02424 ± 0.00018	0.9509 ± 0.0071
		Rod	0.02270	0.02517 ± 0.00012	0.9019 ± 0.0043
	Voided	Plate	0.02565	0.02816 ± 0.00027	0.9109 ± 0.0087
		Rod	0.02523	0.02545 ± 0.00019	0.9914 ± 0.0074
$\frac{^{238}\text{U}(n,\gamma)}{^{239}\text{Pu}(n,f)}$	Normal	Plate	0.16195	0.14274 ± 0.00047	1.1346 ± 0.0037
		Rod	0.16291	0.14648 ± 0.00035	1.1122 ± 0.0027
	Voided	Plate	0.15677	0.13722 ± 0.00095	1.1425 ± 0.0079
		Rod	0.15859	0.13888 ± 0.00051	1.1419 ± 0.0042

The experimental rod-cell data show that reaction rates vary slightly with position of the rod in a calandria. The effect is not large, and, since current calculations cannot take this variation into account, only cell-averaged comparisons can be made. Our second comparison will therefore be of cell-averaged data for normal and voided rod and plate zones.

9.1 CALHET Comparisons in the Plate Core

Table XV shows the results of the comparisons with calculations within the normal and voided plate cells. With all reaction rates in both normal and voided conditions, the calculations follow the measured trends quite well. For ^{238}U capture, the in-cell variation is only about 5% and the C/E ratios are almost identical within the experimental error, the total range being about 1.12-1.15. The in-cell ^{238}U fission rates vary by about 20%. However, the C/E's are in agreement with each other within errors for each separate condition, normal or voided, but in about 4% disagreement between the two conditions. This disagreement could be due to an error in the change in the gross spectrum in going from the normal to voided condition.

We conclude that the plate calculations give good confidence in being able to predict heterogeneity effects.

9.2 RABID and S_n Calculations of ^{238}U Capture in the Plate Cell

The RABID integral-transport code¹⁵ provides a rigorous treatment of the reaction rate of a resonant material in a plate cell within the limitations of its description by a one-dimensional slab geometry. It is, however, time-consuming and expensive and has been used in the proof-testing sense, not as a code for routine generation of reaction-rate distributions. In RABID, materials are designated as either resonant or nonresonant. For the former, the code is given the explicit resonance parameters (generated by sampling techniques in the unresolved resonance region) as well as flat background cross sections. For the latter, the code is given thermal capture and fission cross sections that vary with a $1/v$ dependence.

The calculations quoted here are described in detail by Plummer.¹⁶ All the resonance data used, including the parameters necessary to generate ladders of ^{238}U resonances in the unresolved region, were taken from the ANL-revised ENDF/B Version-II library. In the energy range 3.35-40.9 keV, through which the ^{238}U resonances are unresolved, the procedure used was to generate a sequence of 20 ^{238}U resonances covering a subrange of a few hundred eV located at the midpoint of each quarter-lethargy MC^2 fine group. The foil reaction rates generated by RABID were then weighted by the MC^2 fine-group flux. For these RABID cases, only ^{238}U was treated as a resonant material. It was found that the proximity of the RABID broad group to a large iron resonance, for example, could cause scattering from iron atoms to dominate the ^{238}U capture in determining the shape of the ^{238}U capture rate across the cell. This effect was, of course, a real one for the few hundred eV spanned

by the RABID group. However, this effect was far from representative of the entire quarter-lethargy range being sampled by the RABID case. For this reason, all materials except ^{238}U were given smooth-cross-section data. For iron, chromium, nickel, manganese, and sodium, smooth cross sections were generated from the Version-II revised resonance data by running homogeneous RABID cases. These cases covered the entire unresolved energy range and yet took little computer time because they were single-region problems with relatively few resonances. Smooth cross sections for the remaining isotopes were obtained from Version-I MC² broad-group cross sections, as were ^{238}U cross sections for the homogeneous RABID cases.

Another refinement to the previous RABID foil-analysis technique was to precede each RABID group in the unresolved range by an initial broad group covering about 0.125 lethargy unit. The purpose of this group was to smooth the slowing-down source to the following broad group into a shape more realistic than that which results from RABID's initial flat-flux assumption. This had a nonnegligible effect on the reaction-rate profile.

The energy range from 101 eV to 3.55 keV, throughout which the ^{238}U resonances are resolved, was covered in its entirety by a series of RABID cases. Below 101 eV, there is negligible contribution to the ^{238}U capture rate. Resonance data were supplied not only for ^{238}U , but also for ^{240}Pu and sodium. Where they were measured (below 275 eV), the ^{239}Pu resonances were also included.

Above 40.9 keV, the ^{238}U -capture cross section is treated as a continuum, with negligible self-shielding effects. The contribution to the ^{238}U capture rate was calculated simply from MC² broad-group cross sections and fluxes.

In this manner, the total ^{238}U -foil capture rate was calculated at six different positions in the cell. These points are plotted in Fig. 13. Because there are only six points, the dashed line connecting them should be considered as little more than a guide to their location. For comparison, the experimental data points are plotted with their estimated error bars. The experimental points are normalized by a simple least-squares fit at those cell positions for which there are both calculated and experimental data.

Also plotted are results obtained from the inventory module of the ARC system in conjunction with a 1D transport S-20 cell calculation in 27 groups. Neutron leakage was simulated by group-dependent DB² values calculated from 2D R-Z geometry diffusion-theory results. The ^{238}U and ^{239}Pu cross sections used in the cell calculation were properly self-shielded for their environments by MC². The ^{238}U cross sections used in the reaction-rate edit were the values appropriate to the U_3O_8 plate. The problem in this type of approach lies in the fact that no single position-independent set of ^{238}U capture cross sections can reflect the varying resonance self-shielding the ^{238}U foil experiences at the different foil locations in the cell. The RABID results

and the S-20 transport results are normalized so that the reaction rate is unity at the interface between the sodium plate and the Fe_2O_3 plate.

Fig. 13. Comparison of ^{238}U Measured Capture Rates in ZPPR-2 Inner-core Plate Cell with RABID and S_n Calculations. ANL Neg. No. 103-B11168.

We conclude that the in-cell ^{238}U capture rates can be well calculated by use of the sophisticated RABID technique, but that a straightforward use of the broad-group transport codes can give meaningful results only if the data used are appropriately shielded for the foil at different positions within the cell.

9.3 Cell-averaged Reaction Rates in Normal and Voided Rod and Plate Environments

Cell-averaged reaction rates for normal and voided, rod and plate cells are compared with calculations in Table XVI. Here the major question is the consistency of C/E's between rod and plate for a given condition and reaction rate. For ^{238}U , capture the C/E's for the two voided conditions, plate and rod, are in excellent agreement. The C/E's for the normal cells are in poorer, but not bad, agreement. For ^{238}U fission, the range of C/E's is quite large, about 4% for the normal conditions and about 8% in the other direction for the voided conditions.

We conclude that the change in ^{238}U capture between plate and rod environments is reasonably well calculated, but that there are disturbing differences of up to 8% in the case of ^{238}U fission. The reasonable prediction of the variation of ^{238}U fission rates in the plate cell (see Sec. 9.1 above) would indicate problems in the rod-cell calculations.

10. REACTION RATES ACROSS AXIAL AND RADIAL BOUNDARIES

This section describes a series of comparative measurements made in both rod and plate environments in the axial and radial directions.

For the axial experiments, directly comparable plate and rod zones were constructed for both the core and axial blanket on the core centerline. Since the rods are all 6 in. long and the calandria are 12 in. long, the rod axial blanket was necessarily 18 in. long. To obtain direct comparison, therefore, an 18-in.-long plate axial blanket was constructed in place of the normal 16-in. blanket over the same zone volume as that occupied by the rods. The zone with the 18-in. axial blanket had a cross section of 37 matrix positions.

For the radial experiments, the rod pseudosector shown in Fig. 8b was constructed where the calandrias directly replaced plate-filled drawers. The calandrias extended for 24 in. into each half of the reactor.

In both the axial and radial directions, experiments were made in which the responses of ^{238}U and ^{239}Pu fission chambers were checked against those of foil detectors. These experiments were only performed in the plate configurations; thus the results are not connected with the heterogeneity directly, but they will be briefly described here because they are relevant to the applicability of various techniques.

Most of the work presented here will consist of comparisons of foil measurements in plate and rod environments with each other and with calculations.

10.1 Foil/Fission Chamber Comparisons in the Plate Core

When measurements are made in an axial direction with a fission chamber, some plates within a drawer must be removed to accommodate the approximately 1/2-in.-dia traverse tube, chambers, remote-drive mechanism, and cables. This was accomplished in the center of the inner core by omitting one of the two 1/2-in.-thick, sodium-filled cans in the central drawer. The channel so created raises the possibility of neutron streaming in the axial direction. Foil measurements in the plate drawer were made using foils placed against both the Pu/U/Mo fuel plate and one of the U_3O_8 plates in the core and on the surface of the uranium and U_3O_8 plates in the blanket. Clearly, even excluding streaming effects, the chambers and foils do not, in general, measure the same quantities, because of in-cell variations in reaction rates. For ^{239}Pu , however, the variation between the two foil locations is about 3% in the core and the blanket. Both foils and fission chambers should therefore be closely comparable. Table XVII shows the comparative results of foil and chamber measurements. Although the shapes given by both detectors are in good agreement in the core (up to 40.640 cm), there is a slight tendency for the counter data to be higher as the blanket is approached. In the axial blanket

itself, the counter is 5-25% higher. Streaming is probably present in the counter technique, and this invalidates the counter measurements in the axial blanket.

TABLE XVII. Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses Measured in Plate Core with Foils and Counters

Axial Position, cm	Relative Reaction Rate $\pm \sigma$		
	Foil Avg. ^a	Counter	Counter/Foil Avg.
7.711	0.9857 $\pm$ 0.0085	0.9844 $\pm$ 0.0015	0.9987 $\pm$ 0.0087
17.780	0.9183 $\pm$ 0.0083	0.9240 $\pm$ 0.0042	1.0062 $\pm$ 0.0102
27.940	0.8075 $\pm$ 0.0072	0.8049 $\pm$ 0.0035	0.9968 $\pm$ 0.0099
35.560	0.7032 $\pm$ 0.0072	0.7022 $\pm$ 0.0030	0.9986 $\pm$ 0.0111
35.657	0.7017 $\pm$ 0.0071	0.7009 $\pm$ 0.0027	0.9989 $\pm$ 0.0108
40.640	0.6275 $\pm$ 0.0051	0.6289 $\pm$ 0.0031	1.0022 $\pm$ 0.0095
45.720	0.5624 $\pm$ 0.0060	0.5879 $\pm$ 0.0026	1.0453 $\pm$ 0.0121
50.800	0.5240 $\pm$ 0.0030	0.5483 $\pm$ 0.0026	1.0464 $\pm$ 0.0078
55.880	0.4630 $\pm$ 0.0041	0.4901 $\pm$ 0.0018	1.0585 $\pm$ 0.0101
55.971	0.4619 $\pm$ 0.0042	0.4891 $\pm$ 0.0018	1.0589 $\pm$ 0.0104
66.040	0.3356 $\pm$ 0.0030	0.3834 $\pm$ 0.0021	1.1424 $\pm$ 0.0120
76.200	0.2377 $\pm$ 0.0022	0.2928 $\pm$ 0.0018	1.2318 $\pm$ 0.0137

^aCell averaged by using only the foil data adjacent to the fuel plates in the core and a linear average in the axial blanket. Foil data were normalized to the calculated results by averaging the first four C/E values to unity before interpolating to the counter positions.

The ^{238}U fission rate is higher at the surface of the Pu/U/Mo fuel than at the U_3O_8 plate, in the core; but deep within the blanket the rates are equal. In the transition region at the inner portion of the axial blanket, the blanket cell is being "driven" by the core cell, and an intermediate condition exists. We have chosen to adopt the cell-averaged ^{238}U fission rates in the plate cell to represent the foil data; these are compared with the chamber results in Table XVIII. Again the evidence is that streaming invalidates the counter results.

TABLE XVIII. Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses Measured in Plate Core with Foils and Counters

Axial Position, cm	Relative Reaction Rate $\pm \sigma$		
	Foil Avg. ^a	Counter	Counter/Foil Avg.
7.711	0.9831 $\pm$ 0.0071	0.9840 $\pm$ 0.0015	1.0009 $\pm$ 0.0074
17.780	0.9050 $\pm$ 0.0059	0.8986 $\pm$ 0.0032	0.9929 $\pm$ 0.0074
27.940	0.7780 $\pm$ 0.0071	0.7771 $\pm$ 0.0029	0.9988 $\pm$ 0.0098
35.560	0.6524 $\pm$ 0.0071	0.6478 $\pm$ 0.0026	0.9929 $\pm$ 0.0115
35.657	0.6508 $\pm$ 0.0072	0.6460 $\pm$ 0.0026	0.9926 $\pm$ 0.0117
40.640	0.5268 $\pm$ 0.0045	0.5320 $\pm$ 0.0028	1.0099 $\pm$ 0.0101
45.720	0.3505 $\pm$ 0.0033	0.3659 $\pm$ 0.0020	1.0439 $\pm$ 0.0114
50.800	0.1934 $\pm$ 0.0026	0.2130 $\pm$ 0.0012	1.1013 $\pm$ 0.0161
55.880	0.1211 $\pm$ 0.0021	0.1355 $\pm$ 0.0009	1.1189 $\pm$ 0.0208
55.971	0.1201 $\pm$ 0.0021	0.1344 $\pm$ 0.0008	1.1191 $\pm$ 0.0207
66.040	0.0542 $\pm$ 0.0026	0.0612 $\pm$ 0.0006	1.1292 $\pm$ 0.0553
76.200	0.0259 $\pm$ 0.0039	0.0282 $\pm$ 0.0003	1.0888 $\pm$ 0.1644

^aCell averaged by using the relative mass of the adjacent plates in both the core and axial blanket. Foil data were normalized to the calculated results by averaging the first four C/E values to unity before interpolating to the counter positions.

In the radial direction, streaming in the direction of the access tube is minimized as far as possible in the plate core by accommodating the 1/2-in.-dia guide tube in a close-fitting "tunnel" formed by using plates, each with a nominal 1/2-in.-dia hole, so that the 2 x 1/2-in. slot formed in the axial direction is not present. Also, the drive rod and cables reduce streaming down the tube itself. As in the axial direction, the ^{239}Pu foil distributions are little affected by their position within the cell, and the ^{238}U fissions show a significant variation. The ^{238}U foil measurements might then be expected to show effects related to changing cell structure in the radial direction.

The results of the ^{239}Pu and ^{238}U radial fission measurements are shown in Tables XIX and XX. For ^{239}Pu , the two techniques give good agreement over a large portion of the inner core, but they begin to diverge as the outer core is approached and disagree by about 5% in the outer core itself. In the radial blanket, the counter measurement is about 3% low at the inner portion, and the ratio increases smoothly to the outer part, where it is 10% high. The ^{238}U results show good agreement between both techniques throughout the inner core, but there are significant discrepancies in the outer core and radial blanket. The different trends shown for ^{239}Pu and ^{238}U fission could be attributed to the strong differences in their spectral response.

We conclude that, with the counter measurements in the radial direction, streaming is present, and this produces significant effects in the outer portions of the core and blanket.

TABLE XIX. Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core with Foils and Counters

Matrix Location	Radial Position, cm	Relative Reaction Rate $\pm \sigma$		
		Foils ^a	Counter	Counter/Foils
137-37	0.	0.9864 $\pm$ 0.0121	0.9844 $\pm$ 0.0015	0.9978 $\pm$ 0.0123
137-36	5.525	0.9815 $\pm$ 0.0096	0.9862 $\pm$ 0.0053	1.0048 $\pm$ 0.0112
137-35	11.049	0.9744 $\pm$ 0.0062	0.9783 $\pm$ 0.0053	1.0040 $\pm$ 0.0084
137-34	16.574	0.9671 $\pm$ 0.0076	0.9684 $\pm$ 0.0054	1.0013 $\pm$ 0.0096
137-33	22.098	0.9547 $\pm$ 0.0064	0.9537 $\pm$ 0.0052	0.9990 $\pm$ 0.0086
137-32	27.623	0.9420 $\pm$ 0.0096	0.9348 $\pm$ 0.0051	0.9924 $\pm$ 0.0115
137-31	33.147	0.9254 $\pm$ 0.0060	0.9181 $\pm$ 0.0051	0.9921 $\pm$ 0.0085
137-30	38.672	0.9086 $\pm$ 0.0069	0.8977 $\pm$ 0.0050	0.9880 $\pm$ 0.0093
137-29	44.196	0.8874 $\pm$ 0.0050	0.8737 $\pm$ 0.0049	0.9846 $\pm$ 0.0078
137-28	49.721	0.8652 $\pm$ 0.0067	0.8411 $\pm$ 0.0048	0.9721 $\pm$ 0.0094
137-27	55.245	0.8242 $\pm$ 0.0080	0.8040 $\pm$ 0.0047	0.9755 $\pm$ 0.0111
137-26	60.770	0.7734 $\pm$ 0.0059	0.7552 $\pm$ 0.0045	0.9765 $\pm$ 0.0095
137-25	66.294	0.7283 $\pm$ 0.0044	0.6999 $\pm$ 0.0043	0.9610 $\pm$ 0.0083
137-24	71.819	0.6768 $\pm$ 0.0055	0.6388 $\pm$ 0.0041	0.9439 $\pm$ 0.0098
137-23	77.343	0.6076 $\pm$ 0.0038	0.5762 $\pm$ 0.0038	0.9483 $\pm$ 0.0086
137-22	82.868	0.5347 $\pm$ 0.0046	0.5047 $\pm$ 0.0031	0.9439 $\pm$ 0.0100
137-21	88.392	0.4618 $\pm$ 0.0027	0.4399 $\pm$ 0.0027	0.9526 $\pm$ 0.0081
137-20	93.917	0.3769 $\pm$ 0.0044	0.3644 $\pm$ 0.0022	0.9668 $\pm$ 0.0127
137-19	99.441	0.3101 $\pm$ 0.0025	0.3039 $\pm$ 0.0018	0.9800 $\pm$ 0.0098
137-18	104.966	0.2474 $\pm$ 0.0023	0.2453 $\pm$ 0.0015	0.9915 $\pm$ 0.0110
137-17	110.490	0.1936 $\pm$ 0.0019	0.1956 $\pm$ 0.0012	1.0103 $\pm$ 0.0117
137-16	116.015	0.1484 $\pm$ 0.0016	0.1552 $\pm$ 0.0009	1.0458 $\pm$ 0.0156
137-15	121.539	0.1148 $\pm$ 0.0022	0.1240 $\pm$ 0.0009	1.0801 $\pm$ 0.0221
137-14	127.064	0.0958 $\pm$ 0.0018	0.1076 $\pm$ 0.0008	1.1232 $\pm$ 0.0227

^aFoil data were normalized to the calculated results by averaging the first four C/E values to unity before interpolating to the counter positions.

TABLE XX. Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core with Foils and Counters

Matrix Location	Radial Position, cm	Relative Reaction Rate to		
		Foils ^a	Counter	Counter/Foils
137-37	0.	0.9930 ± 0.0120	0.9840 ± 0.0015	0.9909 ± 0.0121
137-36	5.525	0.9696 ± 0.0141	0.9758 ± 0.0060	1.0064 ± 0.0159
137-35	11.049	0.9748 ± 0.0105	0.9775 ± 0.0061	1.0028 ± 0.0125
137-34	16.574	0.9784 ± 0.0149	0.9589 ± 0.0060	0.9801 ± 0.0161
137-33	22.098	0.9508 ± 0.0108	0.9568 ± 0.0060	1.0063 ± 0.0131
137-32	27.623	0.9244 ± 0.0149	0.9320 ± 0.0059	1.0082 ± 0.0175
137-31	33.147	0.9189 ± 0.0094	0.9289 ± 0.0058	1.0109 ± 0.0121
137-30	38.672	0.9124 ± 0.0105	0.9049 ± 0.0058	0.9918 ± 0.0131
137-29	44.196	0.8869 ± 0.0070	0.8830 ± 0.0057	0.9956 ± 0.0102
137-28	49.721	0.8626 ± 0.0082	0.8650 ± 0.0056	1.0028 ± 0.0115
137-27	55.245	0.8591 ± 0.0070	0.8632 ± 0.0056	1.0048 ± 0.0105
137-26	60.770	0.8790 ± 0.0103	0.8820 ± 0.0057	1.0034 ± 0.0134
137-25	66.294	0.9309 ± 0.0073	0.8911 ± 0.0057	0.9572 ± 0.0097
137-24	71.819	0.9198 ± 0.0059	0.8467 ± 0.0056	0.9205 ± 0.0085
137-23	77.343	0.8072 ± 0.0073	0.7627 ± 0.0045	0.9449 ± 0.0102
137-22	82.868	0.7152 ± 0.0088	0.6386 ± 0.0041	0.8929 ± 0.0124
137-21	88.392	0.5412 ± 0.0044	0.4907 ± 0.0031	0.9067 ± 0.0093
137-20	93.917	0.2581 ± 0.0026	0.2718 ± 0.0019	1.0531 ± 0.0129
137-19	99.441	0.1321 ± 0.0026	0.1443 ± 0.0011	1.092 ± 0.023
137-18	104.966	0.0765 ± 0.0026	0.0800 ± 0.0006	1.046 ± 0.036
137-17	110.490	0.0431 ± 0.0029	0.0468 ± 0.0004	1.086 ± 0.074
137-16	116.015	0.0255 ± 0.0018	0.0274 ± 0.0003	1.075 ± 0.077
137-15	121.539	0.0132 ± 0.0026	0.0169 ± 0.0002	1.28 ± 0.25
137-14	127.064	0.0076 ± 0.0018	0.0100 ± 0.0002	1.32 ± 0.31

^aFoil data were normalized to the calculated results by averaging the first three C/E values to unity before interpolating to the counter positions.

10.2 Axial Foil Measurements in Plate and Rod Environments

In the axial direction, foil measurements and calculations in both plate and rod configurations are complicated by several factors that make comparisons between experiments in the different environments and comparisons between calculation and experiment very difficult. The experimental comparisons of reaction rates in rods and plates are shown in Tables XXI-XXIII. Comparisons of calculation and experiment are shown in Tables XXIV-XXVI.

In the plate configuration, as has already been mentioned, the different in-cell reaction-rate distributions in the core and blanket complicate any simple comparison between measurements in the plate and rod zones. Additionally, there is no currently available technique to calculate the axial plate distributions, including the in-cell behavior. Although the Monte Carlo code VIM could, in principle, describe the geometry with precision, we must exclude it, since it would be exceedingly expensive to obtain adequate statistical precision.

In the rod configuration, the in-cell heterogeneity is clearly less than in a plate cell, but significant axial perturbations still exist, due to the presence of substantial (about 0.1 in.) steel end caps on the 6-in.-long oxide rods. The effects of the end caps are reduced as far as possible in the core by the use of special 3-in.-long rods with thin (about 0.005 in.), flat, steel end caps between which foils can be placed. In the blanket, since the hazard of plutonium is not present, it is feasible to place foils inside a rod between the pellets of UO_2 .

TABLE XXI. Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones

Axial Position, cm	Relative Reaction Rate $\pm \sigma$				
	Rod	Position I ^a	Position II ^a	Plate Avg. ^a	Plate Avg./Rod
7.620 ^b	0.9869 $\pm$ 0.0065	1.0	1.0321 $\pm$ 0.0064	0.9862 $\pm$ 0.0086	0.9993 $\pm$ 0.0109
15.240 ^c	0.9559 $\pm$ 0.0081	0.9500 $\pm$ 0.0079	0.9822 $\pm$ 0.0057	0.9374 $\pm$ 0.0076	0.9806 $\pm$ 0.0115
22.860 ^d	0.8593 $\pm$ 0.0107	0.8794 $\pm$ 0.0071	0.8986 $\pm$ 0.0057	0.8675 $\pm$ 0.0070	1.0095 $\pm$ 0.0150
30.404 ^b	0.7941 $\pm$ 0.0069	0.7844 $\pm$ 0.0057	0.7980 $\pm$ 0.0050	0.7740 $\pm$ 0.0056	0.9747 $\pm$ 0.0110
38.100 ^b	0.6594 $\pm$ 0.0063	0.6744 $\pm$ 0.0053	0.6827 $\pm$ 0.0044	0.6654 $\pm$ 0.0053	1.0091 $\pm$ 0.0126
45.720 ^c	0.5992 $\pm$ 0.0100	0.5683 $\pm$ 0.0061	0.5869 $\pm$ 0.0057	0.5624 $\pm$ 0.0060	0.9386 $\pm$ 0.0186
53.340 ^b	0.5099 $\pm$ 0.0054	0.4919 $\pm$ 0.0041	0.5074 $\pm$ 0.0064	0.4929 $\pm$ 0.0037	0.9667 $\pm$ 0.0125
60.884 ^d	0.4239 $\pm$ 0.0051	0.4009 $\pm$ 0.0041	0.4153 $\pm$ 0.0041	0.4026 $\pm$ 0.0028	0.9498 $\pm$ 0.0132
68.580 ^b	0.3362 $\pm$ 0.0026	0.3049 $\pm$ 0.0031	0.3131 $\pm$ 0.0035	0.3049 $\pm$ 0.0023	0.9069 $\pm$ 0.0098
76.200 ^c	0.2515 $\pm$ 0.0042	0.2363 $\pm$ 0.0021	0.2455 $\pm$ 0.0041	0.2377 $\pm$ 0.0022	0.9451 $\pm$ 0.0180
83.820 ^b	0.1980 $\pm$ 0.0053	0.1852 $\pm$ 0.0023	0.1895 $\pm$ 0.0017	0.1848 $\pm$ 0.0014	0.9333 $\pm$ 0.0260
91.364 ^d	0.1824 $\pm$ 0.0023	0.1577 $\pm$ 0.0036 ^e	0.1618 $\pm$ 0.0035 ^e	0.1576 $\pm$ 0.0024 ^e	0.8640 $\pm$ 0.0171 ^e

^aData in the two cell positions, included to show heterogeneity effects, were arbitrarily normalized to 1.0 at $Z = 7.620$ cm. The cell average was calculated by using only the foil data adjacent to the fuel plate in the core and a linear average in the axial blanket and normalizing to 1.0 at the core center.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil data were extrapolated from the two nearest positions.

TABLE XXII. Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones

Axial Position, cm	Relative Reaction Rate $\pm \sigma$				
	Rod	Position I ^a	Position II ^a	Plate Avg. ^a	Plate Avg./Rod
7.620 ^b	0.9917 $\pm$ 0.0089	1.0	0.8764 $\pm$ 0.0094	0.9836 $\pm$ 0.0071	0.9918 $\pm$ 0.0114
15.240 ^c	0.8372 $\pm$ 0.0153	0.9386 $\pm$ 0.0092	0.8373 $\pm$ 0.0083	0.9319 $\pm$ 0.0067	1.1131 $\pm$ 0.0219
22.860 ^b	0.8477 $\pm$ 0.0076	0.8527 $\pm$ 0.0086	0.7598 $\pm$ 0.0081	0.8461 $\pm$ 0.0063	0.9981 $\pm$ 0.0116
30.404 ^b	0.6842 $\pm$ 0.0115	0.7447 $\pm$ 0.0092	0.6633 $\pm$ 0.0075	0.7389 $\pm$ 0.0061	1.0799 $\pm$ 0.0202
38.100 ^c	0.5371 $\pm$ 0.0062	0.6095 $\pm$ 0.0081	0.5230 $\pm$ 0.0078	0.5926 $\pm$ 0.0059	1.1033 $\pm$ 0.0168
45.720 ^c	0.3278 $\pm$ 0.0095	0.3461 $\pm$ 0.0040	0.3194 $\pm$ 0.0051	0.3505 $\pm$ 0.0033	1.0692 $\pm$ 0.0326
48.590 ^e	0.2234 $\pm$ 0.0023	0.2383 $\pm$ 0.0028	0.2371 $\pm$ 0.0038	0.2514 $\pm$ 0.0025	1.1253 $\pm$ 0.0161
51.511 ^e	0.1603 $\pm$ 0.0138	0.1716 $\pm$ 0.0027	0.1724 $\pm$ 0.0033	0.1819 $\pm$ 0.0022	1.1347 $\pm$ 0.0986
54.432 ^e	0.1329 $\pm$ 0.0069	0.1290 $\pm$ 0.0031	0.1301 $\pm$ 0.0038	0.1369 $\pm$ 0.0025	1.0301 $\pm$ 0.0567
57.506 ^e	0.0986 $\pm$ 0.0023	0.0959 $\pm$ 0.0035	0.0997 $\pm$ 0.0043	0.1033 $\pm$ 0.0029	1.0477 $\pm$ 0.0382
60.884 ^d	0.0710 $\pm$ 0.0051	0.0765 $\pm$ 0.0032	0.0783 $\pm$ 0.0036	0.0818 $\pm$ 0.0026	1.152 $\pm$ 0.091
68.580 ^b	0.0387 $\pm$ 0.0031	0.0394 $\pm$ 0.0030	0.0391 $\pm$ 0.0039	0.0416 $\pm$ 0.0024	1.075 $\pm$ 0.106
76.200 ^c	0.0205 $\pm$ 0.0015	0.0247 $\pm$ 0.0057	0.0241 $\pm$ 0.0037	0.0259 $\pm$ 0.0039	1.263 $\pm$ 0.212
83.820 ^b	0.0118 $\pm$ 0.0012	0.0165 $\pm$ 0.0055 ^f	0.0146 $\pm$ 0.0029 ^f	0.0175 $\pm$ 0.0057 ^f	1.48 $\pm$ 0.51 ^f
91.364 ^d	0.0050 $\pm$ 0.0008	0.0042 $\pm$ 0.0058 ^f	0.0063 $\pm$ 0.0059 ^f	0.0049 $\pm$ 0.0060 ^f	0.98 $\pm$ 1.21 ^f

^aData in the two cell positions, included to show heterogeneity effects, were arbitrarily normalized to 1.0 at $Z = 7.620$ cm. The cell average was calculated by multiplying the foil data with the relative ^{238}U masses in the adjacent plates and normalizing to 1.0 at the core center.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil was located between bare pellets inside the rod cladding.

^fFoil data were extrapolated from the two nearest positions.

TABLE XXIII. Comparison of $^{238}\text{U}(n,\gamma)$ Reaction-rate Axial Traverses Measured in Rod and Matched Plate Zones

Axial Position, cm	Relative Reaction Rate $\pm \sigma$				
	Rod	Position I ^a	Position II ^a	Plate Avg. ^a	Plate Avg./Rod
7.620 ^b	0.9817 $\pm$ 0.0039	1.0	1.0010 $\pm$ 0.0057	0.9819 $\pm$ 0.0044	1.0002 $\pm$ 0.0060
15.240 ^c	1.0494 $\pm$ 0.0040	0.9511 $\pm$ 0.0082	0.9598 $\pm$ 0.0052	0.9381 $\pm$ 0.0044	0.8939 $\pm$ 0.0054
22.860 ^b	0.8671 $\pm$ 0.0032	0.8789 $\pm$ 0.0067	0.8856 $\pm$ 0.0052	0.8664 $\pm$ 0.0040	0.9992 $\pm$ 0.0059
30.404 ^d	0.9004 $\pm$ 0.0035	0.7929 $\pm$ 0.0067	0.7991 $\pm$ 0.0046	0.7818 $\pm$ 0.0040	0.8683 $\pm$ 0.0056
38.100 ^b	0.6843 $\pm$ 0.0027	0.6929 $\pm$ 0.0057	0.7012 $\pm$ 0.0041	0.6851 $\pm$ 0.0032	1.0012 $\pm$ 0.0061
45.720 ^c	0.6974 $\pm$ 0.0029	0.6033 $\pm$ 0.0031	0.6162 $\pm$ 0.0046	0.5983 $\pm$ 0.0028	0.8579 $\pm$ 0.0054
48.590 ^e	0.5505 $\pm$ 0.0023	0.5466 $\pm$ 0.0021	0.5832 $\pm$ 0.0046	0.5527 $\pm$ 0.0023	1.0040 $\pm$ 0.0059
51.511 ^e	0.5267 $\pm$ 0.0026	0.4955 $\pm$ 0.0018	0.5502 $\pm$ 0.0046	0.5105 $\pm$ 0.0022	0.9692 $\pm$ 0.0063
54.432 ^e	0.4838 $\pm$ 0.0021	0.4598 $\pm$ 0.0024	0.5134 $\pm$ 0.0055	0.4750 $\pm$ 0.0027	0.9818 $\pm$ 0.0070
57.506 ^e	0.4508 $\pm$ 0.0019	0.4278 $\pm$ 0.0023	0.4699 $\pm$ 0.0053	0.4385 $\pm$ 0.0026	0.9727 $\pm$ 0.0071
60.884 ^d	0.5828 $\pm$ 0.0024	0.3852 $\pm$ 0.0016	0.4266 $\pm$ 0.0044	0.3963 $\pm$ 0.0021	0.6800 $\pm$ 0.0046
68.580 ^b	0.3280 $\pm$ 0.0016	0.3236 $\pm$ 0.0016	0.3623 $\pm$ 0.0046	0.3033 $\pm$ 0.0019	0.9247 $\pm$ 0.0073
76.200 ^c	0.3263 $\pm$ 0.0017	0.2196 $\pm$ 0.0011	0.2435 $\pm$ 0.0031	0.2261 $\pm$ 0.0015	0.6929 $\pm$ 0.0058
83.820 ^b	0.1773 $\pm$ 0.0010	0.1618 $\pm$ 0.0009	0.1813 $\pm$ 0.0026	0.1674 $\pm$ 0.0013	0.9442 $\pm$ 0.0091
91.364 ^d	0.3304 $\pm$ 0.0014	0.1265 $\pm$ 0.0016	0.1854 $\pm$ 0.0060	0.1502 $\pm$ 0.0027 ^f	0.4546 $\pm$ 0.0084 ^f

^aData in the two cell positions are plate-averaged reaction rates arbitrarily normalized to 1.0 at $Z = 7.620$ cm. The cell average was calculated by multiplying by the relative plate masses in both the core and axial blanket and normalizing to 1.0 at the core center.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil was located between bare pellets inside the rod cladding.

^fFoil data were extrapolated from the two nearest positions.

TABLE XXIV. Comparison of Measured and Calculated $^{239}\text{Pu}(n,f)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones

Axial Position, cm	0-16-0 Rod Zone			Plate Core		
	C	E	C/E	C	E ^a	C/E
7.620 ^b	0.9848	0.9869 $\pm$ 0.0065	0.9979 $\pm$ 0.0066	0.9848	0.9862 $\pm$ 0.0086	0.9986 $\pm$ 0.0087
15.240 ^c	0.9373	0.9559 $\pm$ 0.0081	0.9805 $\pm$ 0.0083	0.9372	0.9374 $\pm$ 0.0076	0.9998 $\pm$ 0.0081
22.860 ^b	0.8612	0.8593 $\pm$ 0.0107	1.0022 $\pm$ 0.0125	0.8608	0.8675 $\pm$ 0.0070	0.9923 $\pm$ 0.0080
30.404 ^d	0.7603	0.7941 $\pm$ 0.0069	0.9574 $\pm$ 0.0083	0.7590	0.7740 $\pm$ 0.0056	0.9806 $\pm$ 0.0071
38.100 ^b	0.6451	0.6594 $\pm$ 0.0063	0.9783 $\pm$ 0.0093	0.6414	0.6654 $\pm$ 0.0053	0.9639 $\pm$ 0.0077
45.720 ^c	0.5665	0.5992 $\pm$ 0.0100	0.9454 $\pm$ 0.0158	0.5632	0.5624 $\pm$ 0.0060	1.0014 $\pm$ 0.0107
53.340 ^b	0.5057	0.5099 $\pm$ 0.0054	0.9918 $\pm$ 0.0105	0.5122	0.4929 $\pm$ 0.0037	1.0392 $\pm$ 0.0078
60.884 ^d	0.4139	0.4239 $\pm$ 0.0051	0.9764 $\pm$ 0.0117	0.4175	0.4026 $\pm$ 0.0028	1.0370 $\pm$ 0.0072
68.580 ^b	0.3239	0.3362 $\pm$ 0.0026	0.9634 $\pm$ 0.0075	0.3259	0.3049 $\pm$ 0.0023	1.0689 $\pm$ 0.0081
76.200 ^c	0.2492	0.2515 $\pm$ 0.0042	0.9909 $\pm$ 0.0165	0.2509	0.2377 $\pm$ 0.0022	1.0555 $\pm$ 0.0098
83.820 ^b	0.1967	0.1980 $\pm$ 0.0053	0.9934 $\pm$ 0.0266	0.1979	0.1848 $\pm$ 0.0014	1.0709 $\pm$ 0.0081
91.364 ^c	0.1765	0.1824 $\pm$ 0.0023	0.9677 $\pm$ 0.0122	0.1760	0.1576 $\pm$ 0.0024 ^e	1.1168 $\pm$ 0.0170 ^e

^aData are the cell-averaged values of two sets of foils.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil data were extrapolated from the two nearest positions.

TABLE XXV. Comparison of Measured and Calculated $^{238}\text{U}(n,f)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones

Axial Position, cm	0-16-0 Rod Zone			Plate Core		
	C	E	C/E	C	E ^a	C/E
7.620 ^b	0.9844	0.9917 ± 0.0089	0.9926 ± 0.0089	0.9844	0.9836 ± 0.0071	1.0008 ± 0.0072
15.240 ^c	0.9352	0.8372 ± 0.0153	1.1171 ± 0.0204	0.9350	0.9319 ± 0.0067	1.0033 ± 0.0072
22.860 ^b	0.8545	0.8477 ± 0.0076	1.0080 ± 0.0090	0.8538	0.8461 ± 0.0063	1.0091 ± 0.0075
30.404 ^d	0.7380	0.6842 ± 0.0115	1.0786 ± 0.0181	0.7366	0.7389 ± 0.0061	0.9969 ± 0.0082
38.100 ^b	0.5887	0.5371 ± 0.0062	1.0961 ± 0.0127	0.5858	0.5766 ± 0.0059	1.0160 ± 0.0104
45.720 ^c	0.3398	0.3278 ± 0.0095	1.0366 ± 0.0300	0.3335	0.3505 ± 0.0033	0.9515 ± 0.0090
48.590 ^e	0.2504	0.2234 ± 0.0023	1.1209 ± 0.0115	0.2430	0.2514 ± 0.0025	0.9666 ± 0.0096
51.511 ^e	0.1937	0.1603 ± 0.0138	1.208 ± 0.104	0.1883	0.1819 ± 0.0022	1.0352 ± 0.0125
54.432 ^e	0.1478	0.1329 ± 0.0069	1.112 ± 0.058	0.1440	0.1369 ± 0.0025	1.0519 ± 0.0192
57.506 ^e	0.1112	0.0986 ± 0.0023	1.128 ± 0.026	0.1088	0.1033 ± 0.0029	1.053 ± 0.030
60.884 ^d	0.0808	0.0710 ± 0.0051	1.138 ± 0.082	0.0793	0.0818 ± 0.0026	0.969 ± 0.031
68.580 ^b	0.0359	0.0387 ± 0.0031	0.928 ± 0.074	0.0356	0.0416 ± 0.0024	0.856 ± 0.049
76.200 ^c	0.0189	0.0205 ± 0.0015	0.922 ± 0.067	0.0189	0.0259 ± 0.0039	0.730 ± 0.110
83.820 ^b	0.0100	0.0118 ± 0.0012	0.847 ± 0.086	0.0100	0.0175 ± 0.0057 ^f	0.57 ± 0.19 ^f
91.364 ^d	0.0055	0.0050 ± 0.0008	1.100 ± 0.176	0.0057	0.0049 ± 0.0060 ^f	1.16 ± 1.42 ^f

^aData are the cell-averaged values of two sets of foils.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil was located between bare pellets inside the rod cladding.

^fFoil data were extrapolated from the two nearest positions.

TABLE XXVI. Comparison of Measured and Calculated $^{238}\text{U}(n,\gamma)$ Reaction-rate Axial Traverses in Rod and Matched Plate Zones

Axial Position, cm	0-16-0 Rod Zone			Plate Core		
	C	E	C/E	C	E ^a	C/E
7.620 ^b	0.9849	0.9817 ± 0.0039	1.0033 ± 0.0040	0.9849	0.9819 ± 0.0044	1.0031 ± 0.0045
15.240 ^c	0.9381	1.0494 ± 0.0040	0.8939 ± 0.0034	0.9382	0.9381 ± 0.0044	1.0001 ± 0.0047
22.860 ^b	0.8635	0.8671 ± 0.0032	0.9958 ± 0.0037	0.8637	0.8664 ± 0.0040	0.9969 ± 0.0046
30.404 ^d	0.7662	0.9004 ± 0.0035	0.8510 ± 0.0033	0.7662	0.7818 ± 0.0040	0.9800 ± 0.0050
38.100 ^b	0.6567	0.6843 ± 0.0027	0.9597 ± 0.0038	0.6562	0.6851 ± 0.0032	0.9578 ± 0.0045
45.720 ^c	0.5677	0.6974 ± 0.0029	0.8140 ± 0.0034	0.5582	0.5983 ± 0.0028	0.9330 ± 0.0044
48.590 ^e	0.5333	0.5505 ± 0.0023	0.9688 ± 0.0040	0.5195	0.5527 ± 0.0023	0.9399 ± 0.0039
51.511 ^e	0.4978	0.5267 ± 0.0026	0.9451 ± 0.0047	0.4825	0.5105 ± 0.0022	0.9452 ± 0.0041
54.432 ^e	0.4597	0.4838 ± 0.0021	0.9502 ± 0.0041	0.4438	0.4750 ± 0.0027	0.9343 ± 0.0053
57.506 ^e	0.4188	0.4508 ± 0.0019	0.9290 ± 0.0039	0.4028	0.4385 ± 0.0026	0.9186 ± 0.0054
60.884 ^d	0.3737	0.5828 ± 0.0024	0.6412 ± 0.0026	0.3580	0.3963 ± 0.0021	0.9034 ± 0.0048
68.580 ^b	0.2789	0.3280 ± 0.0016	0.8503 ± 0.0041	0.2654	0.3033 ± 0.0019	0.8750 ± 0.0055
76.200 ^c	0.2029	0.3263 ± 0.0017	0.6218 ± 0.0032	0.1926	0.2261 ± 0.0015	0.8518 ± 0.0057
83.820 ^b	0.1475	0.1773 ± 0.0010	0.8319 ± 0.0047	0.1389	0.1674 ± 0.0013 ^f	0.8297 ± 0.0064 ^f
91.364 ^d	0.1161	0.3304 ± 0.0014	0.3514 ± 0.0015	0.1084	0.1502 ± 0.0027 ^f	0.7217 ± 0.0130 ^f

^aData are the cell-averaged values of two sets of foils.

^bFoil was located between two thin-ended rods.

^cFoil was located between two normal-ended rods.

^dFoil was located on the end of a normal rod at the end of a calandria.

^eFoil was located between bare pellets inside the rod cladding.

^fFoil data were extrapolated from the two nearest positions.

The effects of these local environments upon the measurements are clear in Tables XXI-XXIII. The effects are smallest for ^{239}Pu fission, but the ratio of plate to rod-cell activity is clearly 3-6% different for foils placed between normal-ended rods (footnote c, Table XXI) and between thin-ended special rods (footnote b). Here we must emphasize that variations in the plate/rod ratio cannot be considered to be exclusively due to the variations in the rod environment. The placement of the foils in the plate condition probably results in a more uniform local environment (within a given region, core or blanket) than with rods. The effects of local environment are expected to be larger for ^{238}U fission (due to inelastic scattering in the steel) and ^{238}U capture (due to changes in the shielding of the resonances), and this is apparent in Tables XXII and XXIII. With regard to ^{238}U fission, the rod measurements between the normal-ended rods (footnotes c and d) show an expected strong depression (about 10%) in the ^{238}U fission rate relative to those between the thin-ended rods (in the core) and between pellets (in the blanket). Exclusion of such measurements (at $Z = 15.240, 30.404, 45.720, 60.884, 76.200, \text{ and } 91.364 \text{ cm}$) gives good agreement between rod and plate measurements in the inner part of the core, but quite significant disagreements in the blanket. Exclusion of exactly the same points produces an even closer uniformity for ^{238}U capture, with again the same pattern of good plate/rod agreement in the core but increasing disagreement (up to 8%) in the blanket.

Because of the complicated nature of the reactions in both plate and rod environments, it would be unwise to draw any sweeping conclusions. Provisionally, we may conclude that:

- a. Better consistency is obtained when the rod measurements made between normal rods are excluded.
- b. The resulting plate/rod comparisons for all reactions are in good agreement in the core, but significant disagreements (about 10%) exist in comparisons in the axial blanket.

Turning to the comparisons with calculation (see Tables XXIV-XXVI), we note that:

- a. For ^{239}Pu fission, calculation and experiment are in good agreement in both core and axial blanket for the rod zone when the measurements between the normal rods are excluded as suggested above, but disagreements approaching 10% are noted in the plate case in the axial blanket.
- b. For ^{238}U fission, disagreements approaching 15% are noted in the axial blanket in the rod zone, even when the experimental data at some points are omitted as suggested above. The agreement with calculation is actually somewhat better in the inner region with the plate environment.
- c. For ^{238}U capture, a much-improved agreement between calculation and experiment is obtained by excluding the foils placed between normal rods. Disagreements up to about 15% are obtained at deep penetration in the blanket for both plate and rod environments.

10.3 Radial Foil Measurements in Plate and Rod Environments

Here we will first compare the experimental data obtained with foils in the rod sector and the plate core (Tables XXVII-XXIX) and then compare these with calculations (Tables XXX-XXXII).

TABLE XXVII. Comparison of $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Normalized Reaction Rate to		
		Plate	Rod	Plate/Rod
137-37	0.620	0.9862 $\pm$ 0.0106	0.9986 $\pm$ 0.0092	0.9876 $\pm$ 0.0140
137-36	4.905	0.9820 $\pm$ 0.0092	0.9823 $\pm$ 0.0099	0.9997 $\pm$ 0.0138
137-32	27.003	0.9439 $\pm$ 0.0099	0.9327 $\pm$ 0.0085	1.0120 $\pm$ 0.0141
137-30	38.052	0.9107 $\pm$ 0.0071	0.8889 $\pm$ 0.0092	1.0245 $\pm$ 0.0133
137-28	49.101	0.8690 $\pm$ 0.0071	0.8252 $\pm$ 0.0071	1.0531 $\pm$ 0.0125
137-27	54.625	0.8294 $\pm$ 0.0078	0.7947 $\pm$ 0.0071	1.0437 $\pm$ 0.0135
137-26	60.150	0.7785 $\pm$ 0.0064	0.7516 $\pm$ 0.0071	1.0358 $\pm$ 0.0130
137-25	64.435	0.7475 $\pm$ 0.0057	0.7151 $\pm$ 0.0071	1.0453 $\pm$ 0.0131
137-25	68.153	0.7100 $\pm$ 0.0057	0.6790 $\pm$ 0.0067	1.0457 $\pm$ 0.0133
137-24	72.439	0.6700 $\pm$ 0.0054	0.5346 $\pm$ 0.0061	1.0558 $\pm$ 0.0132
137-23	75.484	0.6302 $\pm$ 0.0047	0.6020 $\pm$ 0.0065	1.0468 $\pm$ 0.0137
137-23	79.202	0.5848 $\pm$ 0.0051	0.5511 $\pm$ 0.0056	1.0612 $\pm$ 0.0142
137-22	83.488	0.5269 $\pm$ 0.0045	0.4969 $\pm$ 0.0051	1.0604 $\pm$ 0.0142
137-21	86.533	0.4899 $\pm$ 0.0037	0.4513 $\pm$ 0.0046	1.0855 $\pm$ 0.0138
137-21	90.251	0.4336 $\pm$ 0.0032	0.4074 $\pm$ 0.0049	1.0643 $\pm$ 0.0150
137-20	92.329	0.4009 $\pm$ 0.0038	0.3857 $\pm$ 0.0054	1.0394 $\pm$ 0.0176
137-20	95.187	0.3672 $\pm$ 0.0041	0.3519 $\pm$ 0.0038	1.0435 $\pm$ 0.0162
137-19	97.854	0.3302 $\pm$ 0.0030	0.3233 $\pm$ 0.0032	1.0213 $\pm$ 0.0137
137-19	100.711	0.2940 $\pm$ 0.0039	0.2926 $\pm$ 0.0042	1.0048 $\pm$ 0.0196
137-18	106.236	0.2336 $\pm$ 0.0028	0.2316 $\pm$ 0.0045	1.0086 $\pm$ 0.0230
137-17	111.760	0.1817 $\pm$ 0.0023	0.1842 $\pm$ 0.0064	0.986 $\pm$ 0.036
137-16	117.285	0.1385 $\pm$ 0.0019	0.1344 $\pm$ 0.0052	1.031 $\pm$ 0.042
137-15	122.809	0.1077 $\pm$ 0.0028	0.1156 $\pm$ 0.0044	0.932 $\pm$ 0.043
137-14	128.334	0.0922 $\pm$ 0.0022	0.0844 $\pm$ 0.0031	1.092 $\pm$ 0.048

TABLE XXVIII. Comparison of $^{238}\text{U}(n,f)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Normalized Reaction Rate to		
		Plate	Rod	Plate/Rod
137-37	0.620	0.9968 $\pm$ 0.0106	0.9830 $\pm$ 0.0166	1.0140 $\pm$ 0.0202
137-36	4.905	0.9773 $\pm$ 0.0136	0.9797 $\pm$ 0.0160	0.9976 $\pm$ 0.0214
137-32	27.003	0.9325 $\pm$ 0.0153	0.9616 $\pm$ 0.0133	0.9697 $\pm$ 0.0208
137-30	38.052	0.9204 $\pm$ 0.0106	0.9155 $\pm$ 0.0148	1.0054 $\pm$ 0.0200
137-28	49.101	0.8703 $\pm$ 0.0086	0.8664 $\pm$ 0.0148	1.0045 $\pm$ 0.0198
137-27	54.625	0.8644 $\pm$ 0.0071	0.8537 $\pm$ 0.0148	1.0125 $\pm$ 0.0194
137-26	60.150	0.8773 $\pm$ 0.0106	0.8411 $\pm$ 0.0136	1.0430 $\pm$ 0.0211
137-25	64.435	0.9517 $\pm$ 0.0086	0.8796 $\pm$ 0.0133	1.0820 $\pm$ 0.0191
137-25	68.153	0.9248 $\pm$ 0.0103	0.8715 $\pm$ 0.0172	1.0612 $\pm$ 0.0240
137-24	72.439	0.9201 $\pm$ 0.0118	0.8453 $\pm$ 0.0142	1.0885 $\pm$ 0.0230
137-23	75.484	0.8596 $\pm$ 0.0106	0.7877 $\pm$ 0.0133	1.0913 $\pm$ 0.0228
137-23	79.202	0.7691 $\pm$ 0.0086	0.7115 $\pm$ 0.0130	1.0810 $\pm$ 0.0232
137-22	83.488	0.7068 $\pm$ 0.0086	0.6307 $\pm$ 0.0121	1.1207 $\pm$ 0.0255
137-21	86.533	0.6118 $\pm$ 0.0056	0.5590 $\pm$ 0.0127	1.0945 $\pm$ 0.0268
137-21	90.251	0.4673 $\pm$ 0.0053	0.4199 $\pm$ 0.0096	1.1129 $\pm$ 0.0284
137-20	92.329	0.3098 $\pm$ 0.0041	0.2944 $\pm$ 0.0163	1.0523 $\pm$ 0.0599
137-20	95.187	0.2201 $\pm$ 0.0035	0.2128 $\pm$ 0.0066	1.0343 $\pm$ 0.0360
137-19	97.854	0.1558 $\pm$ 0.0050	0.1498 $\pm$ 0.0093	1.040 $\pm$ 0.073
137-19	100.711	0.1148 $\pm$ 0.0024	0.1151 $\pm$ 0.0054	0.997 $\pm$ 0.051
137-18	106.236	0.0658 $\pm$ 0.0032	0.0603 $\pm$ 0.0102	1.091 $\pm$ 0.192
137-17	111.760	0.0366 $\pm$ 0.0038	0.0365 $\pm$ 0.0090	1.00 $\pm$ 0.27
137-16	117.285	0.0225 $\pm$ 0.0019	0.0219 $\pm$ 0.0036	1.03 $\pm$ 0.19
137-15	122.809	0.0105 $\pm$ 0.0036	0.0111 $\pm$ 0.0033	0.95 $\pm$ 0.43
137-14	128.334	0.0069 $\pm$ 0.0020	0.0093 $\pm$ 0.0030	0.74 $\pm$ 0.32

TABLE XXIX. Comparison of $^{238}\text{U}(n,\gamma)$ Reaction-rate Radial Traverses Measured in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Normalized Reaction Rate to		
		Plate	Rod	Plate/Rod
137-37	0.620	0.9764 $\pm$ 0.0035	0.9857 $\pm$ 0.0041	0.9906 $\pm$ 0.0054
137-36	4.905	0.9926 $\pm$ 0.0040	0.9823 $\pm$ 0.0042	1.0105 $\pm$ 0.0059
137-32	27.003	0.9486 $\pm$ 0.0040	0.9246 $\pm$ 0.0036	1.0260 $\pm$ 0.0059
137-30	38.052	0.9015 $\pm$ 0.0030	0.8782 $\pm$ 0.0054	1.0265 $\pm$ 0.0072
137-28	49.101	0.8514 $\pm$ 0.0035	0.8018 $\pm$ 0.0041	1.0619 $\pm$ 0.0070
137-27	54.625	0.7877 $\pm$ 0.0030	0.7717 $\pm$ 0.0033	1.0207 $\pm$ 0.0058
137-26	60.150	0.7558 $\pm$ 0.0030	0.7273 $\pm$ 0.0039	1.0392 $\pm$ 0.0069
137-25	64.435	0.7062 $\pm$ 0.0035	0.6879 $\pm$ 0.0043	1.0266 $\pm$ 0.0082
137-25	68.153	0.6946 $\pm$ 0.0030	0.6445 $\pm$ 0.0038	1.0777 $\pm$ 0.0079
137-24	72.439	0.6243 $\pm$ 0.0030	0.5971 $\pm$ 0.0029	1.0464 $\pm$ 0.0071
137-23	75.484	0.5833 $\pm$ 0.0025	0.5572 $\pm$ 0.0038	1.0468 $\pm$ 0.0084
137-23	79.202	0.5499 $\pm$ 0.0030	0.5158 $\pm$ 0.0035	1.0661 $\pm$ 0.0093
137-22	83.488	0.5170 $\pm$ 0.0025	0.4748 $\pm$ 0.0042	1.0889 $\pm$ 0.0110
137-21	86.533	0.4567 $\pm$ 0.0023	0.4498 $\pm$ 0.0023	1.0153 $\pm$ 0.0073
137-21	90.251	0.4340 $\pm$ 0.0022	0.4115 $\pm$ 0.0023	1.0547 $\pm$ 0.0080
137-20	92.329	0.3836 $\pm$ 0.0017	0.3666 $\pm$ 0.0016	1.0464 $\pm$ 0.0065
137-20	95.187	0.3595 $\pm$ 0.0016	0.3330 $\pm$ 0.0017	1.0796 $\pm$ 0.0073
137-19	97.854	0.3253 $\pm$ 0.0015	0.3005 $\pm$ 0.0017	1.0825 $\pm$ 0.0079
137-19	100.711	0.2907 $\pm$ 0.0013	0.2735 $\pm$ 0.0013	1.0438 $\pm$ 0.0067
137-18	106.236	0.2319 $\pm$ 0.0017	0.2140 $\pm$ 0.0012	1.0836 $\pm$ 0.0100
137-17	111.760	0.1785 $\pm$ 0.0013	0.1646 $\pm$ 0.0009	1.084 $\pm$ 0.010
137-16	117.285	0.1331 $\pm$ 0.0008	0.1217 $\pm$ 0.0009	1.094 $\pm$ 0.010
137-15	122.809	0.0967 $\pm$ 0.0015	0.0891 $\pm$ 0.0007	1.085 $\pm$ 0.019
137-14	128.334	0.0727 $\pm$ 0.0014	0.0665 $\pm$ 0.0005	1.093 $\pm$ 0.023

TABLE XXX. Comparison of Calculated and Measured $^{239}\text{Pu}(n,f)$ Reaction-rate Radial Traverses in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Rod Sector			Plate Core		
		C	E	C/E	C	E	C/E
137-37	0.620	0.9846	0.9986 $\pm$ 0.0092	0.9860 $\pm$ 0.0091	0.9846	0.9862 $\pm$ 0.0106	0.9984 $\pm$ 0.0107
137-36	4.905	0.9833	0.9823 $\pm$ 0.0099	1.0010 $\pm$ 0.0101	0.9829	0.9820 $\pm$ 0.0092	1.0009 $\pm$ 0.0094
137-32	27.003	0.9430	0.9327 $\pm$ 0.0085	1.0110 $\pm$ 0.0092	0.9468	0.9439 $\pm$ 0.0099	1.0031 $\pm$ 0.0105
137-30	38.052	0.9006	0.8889 $\pm$ 0.0092	1.0132 $\pm$ 0.0105	0.9085	0.9107 $\pm$ 0.0071	0.9976 $\pm$ 0.0078
137-28	49.101	0.8411	0.8252 $\pm$ 0.0071	1.0193 $\pm$ 0.0088	0.8534	0.8690 $\pm$ 0.0071	0.9820 $\pm$ 0.0080
137-27	54.625	0.8034	0.7947 $\pm$ 0.0071	1.0109 $\pm$ 0.0090	0.8179	0.8294 $\pm$ 0.0078	0.9861 $\pm$ 0.0093
137-26	60.150	0.7597	0.7516 $\pm$ 0.0071	1.0108 $\pm$ 0.0095	0.7769	0.7785 $\pm$ 0.0064	0.9979 $\pm$ 0.0082
137-25	64.435	0.7184	0.7151 $\pm$ 0.0071	1.0046 $\pm$ 0.0100	0.7380	0.7475 $\pm$ 0.0057	0.9873 $\pm$ 0.0075
137-25	68.153	0.6797	0.6790 $\pm$ 0.0067	1.0010 $\pm$ 0.0099	0.7010	0.7100 $\pm$ 0.0057	0.9873 $\pm$ 0.0079
137-24	72.439	0.6314	0.6346 $\pm$ 0.0061	0.9950 $\pm$ 0.0096	0.6541	0.6700 $\pm$ 0.0054	0.9763 $\pm$ 0.0079
137-23	75.484	0.5939	0.6020 $\pm$ 0.0065	0.9865 $\pm$ 0.0107	0.6173	0.6302 $\pm$ 0.0047	0.9795 $\pm$ 0.0073
137-23	79.202	0.5452	0.5511 $\pm$ 0.0056	0.9893 $\pm$ 0.0101	0.5693	0.5848 $\pm$ 0.0051	0.9735 $\pm$ 0.0085
137-22	83.488	0.4851	0.4969 $\pm$ 0.0051	0.9763 $\pm$ 0.0100	0.5093	0.5269 $\pm$ 0.0045	0.9666 $\pm$ 0.0083
137-21	86.533	0.4417	0.4513 $\pm$ 0.0046	0.9787 $\pm$ 0.0100	0.4655	0.4899 $\pm$ 0.0037	0.9502 $\pm$ 0.0072
137-21	90.251	0.4009	0.4074 $\pm$ 0.0049	0.9840 $\pm$ 0.0118	0.4228	0.4336 $\pm$ 0.0032	0.9751 $\pm$ 0.0072
137-20	92.329	0.3808	0.3857 $\pm$ 0.0054	0.9873 $\pm$ 0.0138	0.4012	0.4009 $\pm$ 0.0038	1.0007 $\pm$ 0.0095
137-20	95.187	0.3483	0.3519 $\pm$ 0.0038	0.9898 $\pm$ 0.0107	0.3670	0.3672 $\pm$ 0.0041	0.9995 $\pm$ 0.0112
137-19	97.854	0.3146	0.3233 $\pm$ 0.0032	0.9731 $\pm$ 0.0096	0.3319	0.3302 $\pm$ 0.0030	1.0051 $\pm$ 0.0091
137-19	100.711	0.2810	0.2926 $\pm$ 0.0042	0.9604 $\pm$ 0.0138	0.2967	0.2940 $\pm$ 0.0039	1.0092 $\pm$ 0.0134
137-18	106.236	0.2233	0.2316 $\pm$ 0.0045	0.9642 $\pm$ 0.0187	0.2358	0.2336 $\pm$ 0.0028	1.0094 $\pm$ 0.0121
137-17	111.760	0.1744	0.1842 $\pm$ 0.0064	0.947 $\pm$ 0.033	0.1834	0.1817 $\pm$ 0.0023	1.009 $\pm$ 0.013
137-16	117.285	0.1378	0.1344 $\pm$ 0.0052	1.025 $\pm$ 0.040	0.1432	0.1385 $\pm$ 0.0019	1.034 $\pm$ 0.014
137-15	122.809	0.1125	0.1156 $\pm$ 0.0044	0.973 $\pm$ 0.037	0.1150	0.1077 $\pm$ 0.0028	1.068 $\pm$ 0.028
137-14	128.334	0.0987	0.0844 $\pm$ 0.0031	1.169 $\pm$ 0.043	0.0996	0.0922 $\pm$ 0.0022	1.080 $\pm$ 0.026

TABLE XXXI. Comparison of Calculated and Measured $^{238}\text{U}(n,f)$ Reaction-rate
Radial Traverses in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Rod Sector			Plate Core		
		C	E	C/E	C	E	C/E
137-37	0.620	0.9844	0.9830 ± 0.0166	1.0014 ± 0.0169	0.9844	0.9968 ± 0.0106	0.9876 ± 0.0105
137-36	4.905	0.9835	0.9797 ± 0.0160	1.0039 ± 0.0164	0.9843	0.9773 ± 0.0136	1.0072 ± 0.0140
137-32	27.003	0.9477	0.9616 ± 0.0133	0.9855 ± 0.0136	0.9482	0.9325 ± 0.0153	1.0168 ± 0.0167
137-30	38.052	0.9141	0.9155 ± 0.0148	0.9985 ± 0.0161	0.9148	0.9204 ± 0.0106	0.9939 ± 0.0114
137-28	49.101	0.8738	0.8664 ± 0.0148	1.0085 ± 0.0172	0.8741	0.8702 ± 0.0086	1.0044 ± 0.0099
137-27	54.625	0.8544	0.8537 ± 0.0148	1.0008 ± 0.0174	0.8555	0.8644 ± 0.0071	0.9897 ± 0.0081
137-26	60.150	0.8585	0.8411 ± 0.0136	1.0207 ± 0.0165	0.8635	0.8773 ± 0.0106	0.9843 ± 0.0119
137-25	64.435	0.8755	0.8796 ± 0.0133	0.9953 ± 0.0151	0.8869	0.9517 ± 0.0086	0.9319 ± 0.0084
137-25	68.153	0.8729	0.8715 ± 0.0172	1.0016 ± 0.0198	0.8914	0.9248 ± 0.0103	0.9639 ± 0.0107
137-24	72.439	0.8357	0.8453 ± 0.0142	0.9886 ± 0.0166	0.8620	0.9201 ± 0.0118	0.9369 ± 0.0120
137-23	75.484	0.7871	0.7877 ± 0.0133	0.9992 ± 0.0169	0.8176	0.8596 ± 0.0106	0.9511 ± 0.0117
137-23	79.202	0.7160	0.7115 ± 0.0130	1.0063 ± 0.0184	0.7509	0.7691 ± 0.0086	0.9763 ± 0.0109
137-22	83.488	0.6081	0.6307 ± 0.0121	0.9642 ± 0.0185	0.6459	0.7068 ± 0.0086	0.9138 ± 0.0111
137-21	86.533	0.5098	0.5590 ± 0.0127	0.9120 ± 0.0207	0.5469	0.6118 ± 0.0056	0.8939 ± 0.0082
137-21	90.251	0.3727	0.4199 ± 0.0096	0.8876 ± 0.0203	0.4046	0.4673 ± 0.0053	0.8658 ± 0.0098
137-20	92.329	0.2966	0.2944 ± 0.0163	1.0075 ± 0.0558	0.3240	0.3098 ± 0.0041	1.0458 ± 0.0138
137-20	95.187	0.2046	0.2128 ± 0.0066	0.9615 ± 0.0298	0.2252	0.2201 ± 0.0035	1.0232 ± 0.0163
137-19	97.854	0.1382	0.1498 ± 0.0093	0.923 ± 0.057	0.1528	0.1558 ± 0.0050	0.981 ± 0.031
137-19	100.711	0.0937	0.1151 ± 0.0054	0.814 ± 0.038	0.1041	0.1148 ± 0.0024	0.907 ± 0.019
137-18	106.236	0.0528	0.0603 ± 0.0102	0.876 ± 0.148	0.0589	0.0658 ± 0.0032	0.895 ± 0.044
137-17	111.760	0.0290	0.0365 ± 0.0090	0.795 ± 0.196	0.0323	0.0366 ± 0.0038	0.883 ± 0.092
137-16	117.285	0.0169	0.0219 ± 0.0036	0.772 ± 0.127	0.0188	0.0225 ± 0.0019	0.836 ± 0.071
137-15	122.809	0.0100	0.0111 ± 0.0033	0.90 ± 0.27	0.0112	0.0105 ± 0.0036	1.07 ± 0.37
137-14	128.334	0.0058	0.0093 ± 0.0030	0.62 ± 0.20	0.0055	0.0069 ± 0.0020	0.94 ± 0.27

TABLE XXXII. Comparison of Calculated and Measured $^{238}\text{U}(n,\gamma)$ Reaction-rate
Radial Traverses in Plate Core and Rod Sector

Matrix Location	Radial Position, cm	Rod Sector			Plate Core		
		C	E	C/E	C	E	C/E
137-37	0.620	0.9846	0.9857 ± 0.0041	0.9989 ± 0.0042	0.9846	0.9764 ± 0.0035	1.0084 ± 0.0036
137-36	4.905	0.9833	0.9823 ± 0.0042	1.0010 ± 0.0043	0.9832	0.9926 ± 0.0040	0.9905 ± 0.0040
137-32	27.003	0.9425	0.9246 ± 0.0036	1.0194 ± 0.0040	0.9471	0.9486 ± 0.0040	0.9984 ± 0.0042
137-30	38.052	0.8982	0.8782 ± 0.0054	1.0228 ± 0.0063	0.9077	0.9015 ± 0.0030	1.0069 ± 0.0034
137-28	49.101	0.8328	0.8018 ± 0.0041	1.0387 ± 0.0053	0.8480	0.8514 ± 0.0035	0.9960 ± 0.0041
137-27	54.625	0.7900	0.7717 ± 0.0033	1.0237 ± 0.0044	0.8081	0.7877 ± 0.0030	1.0259 ± 0.0039
137-26	60.150	0.7364	0.7273 ± 0.0039	1.0125 ± 0.0054	0.7579	0.7558 ± 0.0030	1.0028 ± 0.0040
137-25	64.435	0.6913	0.6879 ± 0.0043	1.0049 ± 0.0063	0.7116	0.7062 ± 0.0035	1.0076 ± 0.0050
137-25	68.153	0.6487	0.6445 ± 0.0038	1.0065 ± 0.0059	0.6689	0.6946 ± 0.0030	0.9630 ± 0.0042
137-24	72.439	0.5977	0.5971 ± 0.0029	1.0010 ± 0.0049	0.6188	0.6248 ± 0.0030	0.9904 ± 0.0048
137-23	75.484	0.5620	0.5572 ± 0.0038	1.0086 ± 0.0069	0.5831	0.5833 ± 0.0025	0.9997 ± 0.0043
137-23	79.202	0.5174	0.5158 ± 0.0035	1.0031 ± 0.0068	0.5379	0.5499 ± 0.0030	0.9782 ± 0.0053
137-22	83.488	0.4698	0.4748 ± 0.0042	0.9895 ± 0.0088	0.4890	0.5170 ± 0.0025	0.9458 ± 0.0046
137-21	86.533	0.4393	0.4498 ± 0.0023	0.9767 ± 0.0050	0.4573	0.4567 ± 0.0023	1.0013 ± 0.0050
137-21	90.251	0.3914	0.4115 ± 0.0023	0.9512 ± 0.0053	0.4076	0.4340 ± 0.0022	0.9392 ± 0.0048
137-20	92.329	0.3622	0.3666 ± 0.0016	0.9880 ± 0.0043	0.3773	0.3836 ± 0.0017	0.9836 ± 0.0044
137-20	95.187	0.3265	0.3330 ± 0.0017	0.9805 ± 0.0050	0.3399	0.3595 ± 0.0016	0.9455 ± 0.0042
137-19	97.854	0.2969	0.3005 ± 0.0017	0.9880 ± 0.0056	0.3087	0.3253 ± 0.0015	0.9490 ± 0.0044
137-19	100.711	0.2654	0.2785 ± 0.0013	0.9530 ± 0.0044	0.2756	0.2907 ± 0.0013	0.9481 ± 0.0042
137-18	106.236	0.2061	0.2140 ± 0.0012	0.9631 ± 0.0054	0.2135	0.2319 ± 0.0017	0.9207 ± 0.0067
137-17	111.760	0.1550	0.1646 ± 0.0009	0.9417 ± 0.0051	0.1605	0.1785 ± 0.0013	0.8992 ± 0.0065
137-16	117.285	0.1153	0.1217 ± 0.0009	0.947 ± 0.007	0.1193	0.1331 ± 0.0008	0.896 ± 0.005
137-15	122.809	0.0860	0.0891 ± 0.0007	0.965 ± 0.008	0.0887	0.0967 ± 0.0015	0.917 ± 0.014
137-14	128.334	0.0662	0.0665 ± 0.0005	0.996 ± 0.008	0.0686	0.0727 ± 0.0014	0.944 ± 0.018

The experimental comparisons for the three reaction rates show that the measurements are in general agreement over the inner core, but differ by up to about 10% in the outer core. Consideration of the geometry and neutronics of the rod zone indicates that the differences might be reduced considerably by using a modified zone shape. The reactivity of a rod cell in the sector is less than that of a plate cell of the same composition (see Sec. 4). It is therefore clear that the average fluxes will be slightly lower in the rod sector than in the plate core, all other things being equal. Near the inner-core center, however, the rod sector is only one matrix position wide (see Fig. 8b); thus the flux will be closer to that of the plate core. Thus, progressing from the core center to the outer core, we expect a progressively decreasing flux level in the rod sector. This trend is apparent in the $^{239}\text{Pu}(n,f)$ and $^{238}\text{U}(n,\gamma)$ reactions that are not spectrum-sensitive (Tables XXVII and XXIX), but is less evident in the $^{238}\text{U}(n,f)$ case, presumably because of compensation due to spectral differences between the two zones.

It would appear then, that if a spatially varying distribution is needed in a rod zone, provision of a suitable thickness of rod "buffer" around the entire measuring region would be beneficial (for example, a "slab" rather than a pseudosector). As a corollary, we see that such an experiment would give close agreement in relative reaction rates in plate and rod environments and that, in general, excellent spatially varying measurements may be obtained in the plate configuration alone.

The calculated data given in Tables XXX-XXXII were obtained with X-Y calculations of the as-built geometry with axial leakage simulated by pseudo-absorption cross sections. From these data we conclude that:

- a. For ^{239}Pu fission, there is excellent agreement over the entire inner core, outer core, and radial blanket for both rod and plate environments, with a tendency to C/E lying a few percent below unity in the outer regions.
- b. For ^{238}U fission, there is good agreement in the rod sector, except for the extreme outer core, where the calculations are about 10% low, and in the blanket. In the plate environment, the calculations are in worse agreement in the outer core.
- c. For ^{238}U capture in both rod and plate environments, the agreement is generally excellent, with again a tendency to low calculated values in the extreme outer core.

11. SODIUM REACTIVITY COEFFICIENT

This section summarizes that part of the sodium-reactivity-coefficient studies that related to heterogeneity. Due to both experimental and computational difficulties, the neutronics of the sodium reactivity coefficient is very complex and the full study (Davey et al.⁹) must be consulted for complete details.

In brief, the heterogeneity-related sodium-coefficient studies consisted of:

- a. Sodium-voiding, large-scale reactivity-worth measurements made by voiding pseudocylindrical zones at the center of the inner core in both the normal plate environment and in the 69-position rod zone.
- b. Similar offcenter, large voiding experiments in the normal plate core and in the rod sector. The voiding was in both the outer part of the inner core and a section of the outer core.
- c. Measurements of small cylindrical worths, plate-voiding in-cell, and calandria voiding in-cell, at the center of the inner core in the plate configuration, the voided-plate configuration, and the normal rod zone. Worths of sodium, in-cell, were measured with rearranged plate distributions and with different combinations of rods of different compositions.

The comparisons made are between calculated and measured values of the total sodium worth (including any leakage component), between calculated and "measured" values of the nonleakage component (after subtraction of a calculated leakage component from the total measured and calculated values), and of different measurements where the data show experimentally the effect of different types of heterogeneity.

11.1 Large-scale Central Voiding

These experiments consist simply of measuring the reactivity change upon voiding pseudocylindrical regions at the center core. In all cases considered here, the cylindrical voided regions were 24 in. high ($Z = \pm 12$ in.). In the plate case, the maximum voided zone was 93 positions; in the rod case, the maximum voiding was of the full rod zone of 69 positions. The precision that is possible with the largest zones is excellent, approximately 1%, and considerable confidence can be placed in the validity of the calculations since the cross-section generation techniques for zones are believed to be most applicable to large zones (see Sec. 3). For both these reasons, these central measurements are the most reliable test of heterogeneity effects.

The measured sodium-reactivity worths in plate and rod configurations are similar (4-10% differences, depending on zone size), and the differences are well predicted.

The ratios of calculation and experiment (C/E) for the total sodium worth for plates and rods are 0.782 ± 0.002 and 0.790 ± 0.005 , respectively, in excellent agreement. Subtraction of the calculated leakage components gives even closer agreement, the plate and rod nonleakage C/E's being 0.846 ± 0.002 and 0.847 ± 0.004 .

We conclude, therefore, that the differences between rod and plate heterogeneity are well calculated for large-scale voiding at the core center.

11.2 Large-scale, Offcenter Voiding

The offcenter, large-scale voiding was identical in type with the central voiding described above. The voiding was all made over an axial height of 24 in. ($Z = \pm 12$ in.). The outer-core voiding was of the entire 5×5 region of the rod sector in the outer core and also of the adjacent 5×5 region in the inner core (see Fig. 8b). In these outer regions, radial leakage effects are much stronger than at the core center, particularly in the outer core itself where the magnitude of the leakage is sufficient to change the sign of the sodium worth.

The calculation of the worths of these outer-core voidings is exceedingly difficult, since it requires a three-dimension representation and only two-dimensional synthesis techniques are currently available. Consequently, the present best use of these data is as an experimental indication of the magnitude of heterogeneity effects. It was found that, in all cases (including tests in which subregions were voided), the measured worths in rods and plates were identical within experimental error, and the weighted mean ratio of sodium worths, rod/plate, was 0.955 ± 0.018 .

We conclude that the offcenter, leakage-dominated sodium worths are essentially identical in rod and plate configurations.

11.3 Sample Variation and Environmental Effects at Core Center

Sodium worths have been measured at the core center with small, cell-averaging cylinders in the "tunnel" environment at $Z = 3.036$ in. in the normal plate configuration, and in the "slot" environment ($Z = 0.0$ in.) in the normal plate and rod and the voided plate configurations. Additionally, the worth of "in-cell" voiding from $Z = 0$ to 6 in. has been measured (by use of empty sodium cans and calandrias) in the normal plate and rod environments. Also an "inverse-voiding" worth was measured in one drawer of the voided plate zone by inserting sodium-filled cans.

These measurements provide stringent tests of heterogeneity. Unfortunately, however, they also appear to provide overstringent tests of our ability to describe the experimental conditions adequately in calculations. The comparisons with calculation, shown in Table XXXIII, show a distressingly large variation in C/E's, and we cannot gain confidence in our ability to

compute heterogeneity effects from these data. To avoid overemphasizing the implications of these results, we should note that, as stated above, the test of computational ability provided by these sodium-voiding experiments is indeed severe and failure here does not imply that quantities other than the sodium worth cannot be calculated adequately.

TABLE XXXIII. Summary of C/E Values for Sodium Reactivities near Center of Inner Core

Environment	Tunnel	Slot	In-Cell
Normal Plate Core	0.828 ± 0.032	0.911 ± 0.025	0.856 ± 0.008
Voided Plate Zone		0.929 ± 0.050	0.535 ± 0.033
Normal Rod Zone		0.695 ± 0.040	0.769 ± 0.007

11.4 Plate-rearrangement and Rod-mixing Studies

The worths of sodium voiding in-cell were measured at the reactor center in the nonvoided plate and rod environments with a rearrangement of plates and different mixes of rods (which gave the same average composition for the different cells). The measurements were made by axial oscillation of a single long drawer, located at the center of a 3 x 3 zone of the changed cell. The rearranged rod and plate configurations are shown in Figs. 6 and 9.

No calculated values are currently available, but the experimental specific worths, shown in Table XXXIV, show that the variations between all the rod and plate configurations are small.

TABLE XXXIV. Specific Sodium-reactivity Worths in Rearranged Plate and Mixed-rod Zones (normal sodium content)

Environment ^a	Sodium Worth, lh/kg	Environment ^a	Sodium Worth, lh/kg
Normal Plate Cell	-4.425 ± 0.041	Normal Rod (0-16-0)	-4.89 ± 0.04
Rearranged Plate I	-4.679 ± 0.045	Mixed Rod I (4-8-4)	-4.67 ± 0.08
Rearranged Plate II	-4.362 ± 0.045	Mixed Rod II (8-0-8)	-4.80 ± 0.10

^aThe normal and rearranged plate and rod cells are shown in Figs. 6 and 9. The numbers in parentheses for the rod cases are the number of 30% PuO₂/UO₂, 15% PuO₂/UO₂, and depleted UO₂ rods in a calandria, respectively.

12. ^{238}U DOPPLER REACTIVITY COEFFICIENTS

The ^{238}U Doppler reactivity coefficient was measured at the center of the inner core in the normal and voided plate core and also in the normal and voided, 69-position rod zone. The sample, of natural UO_2 , is about 1 in. in diameter and 12 in. long and penetrates the zone axially, so that it is well within the rod and voided zones and the measurements are characteristic of the zones. The sample is electrically heated from room temperature ($\sim 300^\circ\text{K}$) up to about 1100°K . The reactivity change is measured either by analyzing the power trace as the sample is moved from the center to the outside of the reactor (inverse-kinetics method) or by following the movement of a previously calibrated control rod, which automatically holds the power constant (autorod method).

Full details of all Doppler experiments and calculations are given by Kaiser et al.¹⁷ Here we will consider the changes associated only with heterogeneity.

Table XXXV compares the results of each separate experiment calculations. Table XXXVI compares the values of the plate/rod experimental ratios to the calculated ratios. The two tables show the same data in different ways, but from the viewpoint of heterogeneity, Table XXXVI is more meaningful.

Examination of the next to the last column (of Table XXXVI) which gives the calculated to measured ratios for the relative Doppler effects in rods and plates, shows that for each of the six measurements, the relative rod and plate Doppler effects are predicted excellently. In all cases, the ratio of calculation and experiment is within two standard deviations of unity.

The actual sample-worth change between the rod and plate environments is also very well predicted for the sodium-voided case ($C/E = 1.023 \pm 0.004$), but not quite so well for the normal case ($C/E = 0.938 \pm 0.003$). Study of the small-sample ^{238}U reactivity-worth calculations and experiments (Sec. 6) shows that the C/E 's for rod and plate for those samples are in good agreement (1.317 ± 0.017 and 1.387 ± 0.016 for rod and plate, respectively) and that the experimental specific reactivities in rod and plate are closely similar (-7.10 ± 0.09 and -7.06 ± 0.08 , respectively). It would appear, therefore, that one of the four Doppler sample worths is a few percent in error, and the calculated value for the rod case is possibly most suspect. The single discrepancy noted here should therefore not be regarded with concern.

We conclude that the evidence of the ^{238}U Doppler studies is that the effects of heterogeneity upon the Doppler temperature coefficient of reactivity, and thus upon the low-energy spectrum, are predicted with confidence.

TABLE XXXV. Comparisons of Experimental and Calculated Values for Natural-UO₂ Doppler Experiments in ZPPR Assembly 2

Environment	Sample Temp., °K ^a	Specific Sample Worth at 300°K, or Specific Worth Change, Δh /g of ²³⁸ U ^b			Comments
		Experiment	Calculation	C/E ^c	
Normal Plate	300	-6.61 ± 0.02	-8.62 ^d	1.304 ± 0.004	Reference Worth $\Delta \rho$ due to sample heating
Inner Core	500	-0.222 ± 0.008	-0.232	1.045 ± 0.037	
z=0 cm	800	-0.453 ± 0.009	-0.462	1.020 ± 0.020	
r=5.8 cm	1100	-0.621 ± 0.009	-0.624 ^d	1.005 ± 0.014	
Normal Rod	300	-6.68 ± 0.01	-8.16	1.222 ± 0.002	Reference Worth $\Delta \rho$ due to sample heating
Inner Core	500	-0.194 ± 0.009	-0.212	1.093 ± 0.051	
z=0 cm	800	-0.419 ± 0.009	-0.421	1.005 ± 0.022	
r=5.8 cm	1100	-0.551 ± 0.008	-0.568	1.031 ± 0.015	
Sodium-voided Plate Inner Core	300	-6.44 ± 0.02	-8.13	1.262 ± 0.004	Reference Worth $\Delta \rho$ due to sample heating
z=0 cm	500	-0.150 ± 0.009	-0.152	1.013 ± 0.061	
r=5.8 cm	800	-0.303 ± 0.012	-0.296	0.977 ± 0.039	
	1100	-0.415 ± 0.011	-0.395	0.952 ± 0.025	
Sodium-voided Rod Inner Core	300	-5.93 ± 0.01	-7.66	1.292 ± 0.002	Reference Worth $\Delta \rho$ due to sample heating
z=0 cm	500	-0.142 ± 0.011	-0.143	1.007 ± 0.078	
r=5.8 cm	800	-0.287 ± 0.011	-0.278	0.969 ± 0.037	
	1100	-0.417 ± 0.011	-0.368	0.882 ± 0.023	

^aAll experimental values are adjusted to the nominal temperatures using an experimentally derived power law, CT^{-Y} .

^bANL Sample N-3 (1086.15 g ²³⁸U, 7.83 g ²³⁵U, 140.16 g O), 12 in. long and 1-in. OD.

^cUncertainties on C/E values are based solely on experimental uncertainties.

^dDenotes exact calculations, others based on approximations.

TABLE XXXVI. Comparison of Natural-UO₂ Doppler Measurements in Inner-core Plate and Rod Configurations of ZPPR Assembly 2

Sample Temperature, T_K^a	Specific Sample Worth at 300°K or Specific Worth Change, $\Delta h/kg$ $^{238}U^b$						$R = \frac{C_P/C_R}{E_P/E_R}$	Comments
	Experiment			Calculation				
	E_R	E_P	E_P/E_R	C_R	C_P	C_P/C_R		
Normal Core								
300	-6.68 ± 0.01	-6.61 ± 0.02	0.990 ± 0.003	-8.16	-8.62	1.056	1.067 ± 0.003	Reference Worth } $\Delta\rho$ due to sample heating
500	-0.194 ± 0.009	-0.222 ± 0.008	1.144 ± 0.067	-0.212	-0.232	1.094	0.956 ± 0.056	
800	-0.418 ± 0.009	-0.453 ± 0.009	1.084 ± 0.032	-0.421	-0.462	1.097	1.012 ± 0.030	
1100	-0.551 ± 0.008	-0.621 ± 0.009	1.117 ± 0.023	-0.568	-0.624	1.098	0.974 ± 0.020	
Na-voided Core ^c								
300	-5.93 ± 0.01	-6.44 ± 0.02	1.086 ± 0.004	-7.66	-8.13	1.061	0.977 ± 0.004	Reference Worth } $\Delta\rho$ due to sample heating
500	-0.142 ± 0.011	-0.150 ± 0.009	1.056 ± 0.104	-0.143	-0.152	1.063	1.007 ± 0.099	
800	-0.287 ± 0.011	-0.303 ± 0.012	1.056 ± 0.058	-0.278	-0.296	1.065	1.008 ± 0.055	
1100	-0.417 ± 0.011	-0.415 ± 0.011	0.995 ± 0.037	-0.368	-0.395	1.073	1.078 ± 0.040	

^aAll experimental values are adjusted to the nominal temperatures using an experimentally derived power law, CT^{-Y} .

^bANL Sample N-3 (1086.15 g ²³⁸U, 7.83 g ²³⁵U, 140.16 g O), 12 in. long and 1-in. OD.

^cSodium-voided plate zone consists of 93 matrix positions, rod sodium-voided zone of 69 matrix positions, all voided 12 in. in each half.

13. SUMMARY OF CONCLUSIONS

13.1 Large-zone Substitution and Reactor Criticality (Sec. 4)

(1) A good experimental determination (to about 10% accuracy) was feasible for an inner-core, pseudocylindrical, rod-for-plate substitution. The C/E for the reactivity change of the largest zone substituted is 0.946 ± 0.087 . This indicates that the effect of heterogeneity upon criticality may be calculated with good confidence.

(2) A sector, rod-for-plate substitution involved large reactivity corrections for composition mismatches in the outer-core zone. This resulted in an unreliable measurement of the reactivity change.

13.2 Cell Reactivity Worths (Sec. 5)

(3) The full-cell and in-cell sodium worths for the composition of the normal (0-16-0) inner-core rod cell and two alternate rod cells of the same average composition [(4-8-4) and (8-0-8)] are identical within experimental errors. This indicates that reactivities equivalent to those in a uniform rod composition may be obtained by using mixtures of rod types if the average composition is held constant. No calculations are yet feasible, and this conclusion should be considered to be provisional, except for the particular composition studied.

(4) The inner-core full-cell worths for plate and rod cells differ by about 10%. This is a factor of 3 or 4 greater than that expected from the large-zone substitutions and calculation (Sec. 4). Unidentified systematic experimental errors, which affect the plate/rod comparison, are believed to be present, but there is no reason to believe that the rod/rod comparisons (noted above) are invalid.

(5) The outer-core full-cell and sodium worths in the normal (8-0-8) cell and a (12-0-4) cell of the same average composition are also identical, supporting item 3 above.

(6) The outer-core plate and rod cell worths were not measured in identical locations. Comparisons can therefore only be made with calculated values that have not yet been obtained.

13.3 Small-sample Reactivity Worths (Sec. 6)

(7) The ratios of experimental, small-sample reactivities at the center of the plate core and a central rod zone when normalized using the experimental ^{239}Pu worth is close to unity for all types of material: fissile, fertile, structural, control, and coolant. The weighted mean is 1.004 ± 0.005 .

(8) Close agreement is also obtained when calculated corrections are applied for differences in the rod and plate environments (weighted mean: 1.013 ± 0.0025).

(9) These studies do not contradict the assumption that the small cylindrical samples measure a "cell-averaged" worth in both plate and rod environments.

13.4 Neutron Spectrum (Sec. 7)

(10) The experimental spectra in rod and plate environments indicate differences that are not shown in the calculations. But these discrepancies are probably false and due to energy-scale problems, since the discrepancies disappear when a coarse energy scale is adopted.

13.5 Fission-chamber Ratios (Sec. 8)

(11) The measured differences between cell-averaged fission ratio (measured with chambers) for plate and rod environments are very well predicted for six ratios of widely different spectral response. The weighted mean of C/E for rod and plate environments is 1.019 ± 0.012 .

13.6 In-cell Reaction Rates (Sec. 9)

13.6.1 Comparisons in the Plate Core (Sec. 9.1)

(12) Comparisons of ^{238}U fission and capture rates and ^{239}Pu fission rates averaged over plates with MC²/CALHET/RZ diffusion calculations are good, indicating that these in-cell heterogeneity effects can be calculated.

13.6.2 RABID and S_n Calculations of ^{238}U Capture in the Plate Cell (Sec. 9.2)

(13) The heterogeneous, in-cell ^{238}U capture rates are well calculated using the sophisticated RABID technique, but broad-group S_n calculations require position-dependent cross sections for the foil.

13.6.3 Cell-averaged Reaction Rates in Normal and Voided Plate Environments (Sec. 9.3)

(14) The change in ^{238}U capture between rod and plate environments is reasonably well calculated for both normal and voided cells, but ^{238}U fission rates show discrepancies. The rod-cell calculations may be in error.

13.7 Reaction Rates across Axial and Radial Boundaries (Sec. 10)

13.7.1 Foil/Fission Chamber Comparisons in the Plate Core (Sec. 10.1)

(15) In the axial direction, streaming is present in the counter technique. This invalidates these measurements in the axial blanket but not in the core.

(16) In the radial direction, streaming is also present in the counter technique. This produces 5-10% discrepancies in the outer portion of the core and in the blanket.

13.7.2 Axial Foil Measurements in Plate and Rod Environments (Sec. 10.2)

(17) Some rod measurements (made with foils placed between normal rods) should be excluded, because of the effects of cladding upon effective cross sections in the detecting foils. After exclusion of these results, the measurements in rod and plate environments are in good agreement (for all reactions) in the core, but disagreements up to about 10% exist in the axial blanket. In general, the calculations and experiments are in good agreement for ^{239}Pu fission, but there are disagreements of up to about 15% in the axial blanket.

13.7.3 Radial Foil Measurements in Plate and Rod Environments (Sec. 10.3)

(18) Good agreement between plate- and rod-environment data is obtained in both environments, except near the core center, where the rod "sector" is probably too narrow to provide a true rod environment.

(19) Comparisons between calculation and experiment are generally in excellent agreement, except for the extreme outer core and in the blanket for the rod environment. In the plate environment, the calculated ^{238}U fission rate is about 10-15% too low in the outer core and radial blanket. The calculated ^{238}U capture rate in the radial blanket is too low in both rod and plate environments.

13.8 Sodium Reactivity Coefficients (Sec. 11)

13.8.1 Large-scale Central Voiding (Sec. 11.1)

(20) The differences between the effects of rod and plate heterogeneity and large-scale central voiding are calculated with excellent accuracy.

13.8.2 Large-scale Offcenter Voiding (Sec. 11.2)

(21) The offcenter, leakage-dominated sodium worths are essentially identical in rod and plate environments.

13.8.3 Sample Variation and Environmental Effects at the Core Center (Sec. 11.3)

(22) Central sodium worths with different types of samples show a disturbingly large variation of C/E's, which cannot be explained at present.

13.8.4 Plate Rearrangement and Rod Mixing Studies (Sec. 11.4)

(23) The variation in in-cell sodium worths in all these environments is small.

13.9 ^{238}U Doppler Reactivity Coefficients (Sec. 12)

(24) The differences in the ^{238}U Doppler coefficient in rod and plate environments, normal and voided, in the inner and outer core, are well calculated.

14. CONCLUDING REMARKS

Ideally, the questions of heterogeneity are those of determining to what degree the measurements made in a plate-fueled critical assembly were equivalent to those that would be obtained in a rod-fueled, power-reactor geometry, and also, where necessary, with what confidence the plate-fueled measurements could be corrected to be equivalent to rod-fueled data. The answers to these questions are not given explicitly, either in the detailed discussions or in the summary of conclusions that form the previous sections; and in point of fact, the questions cannot be addressed properly without knowledge of the accuracy to which data are needed. Clearly the questions cannot be answered without vital input from the power-reactor designer. Indeed it must be true that degree of success will vary with the specific parameter and specific reactor design. Nevertheless, some general statements can be made as a result of the present work.

First, and most important, there is no area in which there is evidence that the general question of heterogeneity is not understood. Where discrepancies exist, it is currently reasonable to attribute these to experimental and computational difficulties and inaccuracies.

Second, for many parameters, our present knowledge of heterogeneity effects is probably quite satisfactory. Indeed it is encouraging how many measurements made in the plate-fueled environment require no correction to be applicable to the power-reactor environment, although this may be particularly true for the present compositions and not applicable for quite different reactors.

Third, there are important areas in which further experimental and analytical work is needed to refine our knowledge and remove discrepancies. This is true with the potentially powerful technique of small-zone measurements.

Finally, the experimental technique of substitution of matched rod regions, probably using mixed rods, will continue to be very valuable both in the reactor core and, perhaps particularly, in blanket design.

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REFERENCES

1. P. I. Amundson et al., "Spatially Dependent Benchmark Parameters in the Initial Demonstration Plant Critical Assembly," *Proc. Conference New Developments in Reactor Physics and Shielding* (Sept 1972).
2. B. J. Toppel, A. L. Rago, and D. M. O'Shea, *MC², A Code to Calculate Multigroup Cross Sections*, ANL-7318 (June 1967).
3. F. L. Fillmore, *The CALHET-2 Heterogeneous Perturbation Code and Application to ZPR-3-48*, AI-69-13 (Mar 1, 1969).
4. F. Storrer et al., *Heterogeneity Calculation for Fast Reactors by a Perturbation Method*, Nucl. Sci. Eng. 24, 153 (1966).
5. W. M. Stacey et al., *New Space-Dependent Fast Neutron Multigroup Cross Section Preparation Capability*, Trans. Am. Nucl. Soc. 15, 292 (June 1972); and, W. M. Stacey et al., "Advances in Methods for Fast Neutron Multigroup Cross Section Calculations and Their Effect Upon the Neutronics Properties of LMFBR Critical Assemblies," *Proc. Conference New Developments in Reactor Physics and Shielding* (Sept 1972).
6. T. A. Daly, G. K. Leaf, and A. S. Kennedy, *The ARC System Two-dimensional Diffusion Theory Capability*, DARC2D, ANL-7716 (May 1972).
7. P. J. Collins and R. G. Palmer, "Calculated Size Effects for Reactivity Perturbation Samples in ZPPR," *Applied Physics Division Annual Report: July 1, 1970, to June 30, 1971*, ANL-7910, pp. 247-249 (Jan 1972).
8. F. L. Fillmore, *Results of Monte Carlo Calculations for ZPPR Assembly 2*, ANL-7928 (Mar 1972).
9. W. G. Davey, R. G. Palmer, and P. J. Collins, *Sodium-voiding Studies in a Plutonium-fueled Fast Assembly (ZPPR-2) of Demonstration-reactor-Size, Composition, and Geometry*, ANL-7962 (Mar 1974).
10. G. G. Simons, R. G. Palmer, and A. P. Olson, *Applications of Neutron Spectra in the Demonstration Benchmark*, Trans. Am. Nucl. Soc. 14, 834-835 (Oct 1971).
11. W. G. Davey and P. I. Amundson, *Inelastic Scattering Measurements in a Fast Reactor by the Spherical Shell Method*, Nucl. Sci. Eng. 28, 111 (Apr 1967).
12. P. I. Amundson, A. M. Bromfield, W. G. Davey, and J. M. Stevenson, "An International Comparison of Fission Detector Standards," *Proceedings of the International Conference on Fast Critical Experiments and Their Analysis: October 10-13, 1966*, ANL-7320, pp. 679-687.
13. D. W. Maddison, "Ge(Li) Detector Calibration and Data Correction for Small Source-to-Detector Distances and Absolute Standard Source Comparisons," *Applied Physics Division Annual Report: July 1, 1970, to June 30, 1971*, ANL-7910, pp. 395-396 (Jan 1972).
14. J. M. Gasidlo et al., "Reaction Rate Ratios in Plate and Rod Environments in ZPPR Assembly 2," *Applied Physics Division Annual Report: July 1, 1971, to June 30, 1972*, ANL-8010 (to be published).
15. Arne P. Olson, *RABID: An Integral Transport Theory Code for Neutron Slowing Down in Slab Cells*, ANL-7645 (Apr 1970).

16. J. P. Plummer, " ^{238}U In-Cell Capture Rates for the Inner-Core Zone of ZPPR, Assembly 2," *Reactor Development Program Progress Report: December 1971*, ANL-7900, p. 7.6 (Jan 28, 1972).
17. R. E. Kaiser and J. M. Gasidlo, "On the Effect of Core Configuration on ^{238}U Doppler Measurements in ZPPR Assembly 2," *Proc. Conference New Developments in Reactor Physics and Shielding* (Sept 1972).