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ANALYSIS OF FTR PHASE A
CONTROL ROD EXPERIMENTS
IN ZPR-III,
ASSEMBLY 48 AND 48-A

April 1969

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CONTROL ROD EXPERIMENTS IN ZPR-III
ASSEMBLY 48 AND 48A

By

R. A. Bennett
S. L. De Myer

Experimental Physics Section
Reactor and Plant Technology Department
FFTF Project

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ABSTRACT

Critical experiments in support of the design of the Fast Flux Test Reactor are to be carried out in three parts. Phase A, the first of this series, was devoted essentially to a study of control rod reactivity worths and rod interactions. This report presents the results of an analysis of the data obtained by personnel of Argonne National Laboratory on ZPR-III Assemblies 48 and 48A. Details of the experiments are to be reported by ANL.

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ANALYSIS OF FTR PHASE A
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I. INTRODUCTION

A critical experiments program is being carried out in support of the design of the Fast Test Reactor (FTR) of the Fast Flux Test Facility (FFTF). The program is two fold. First, idealized experiments are being conducted to obtain data to be used in evaluation of calculational models of FTR neutronics. Second, engineering mockup experiments are to be performed to verify the design detail of FTR. The experiments are being carried out at the Argonne National Laboratories in their "Zero Power Facilities" in Phases A, B, and C. Phases A and B are expected to include all of the idealized experiments, while the engineering mockup experiments will be done in Phase C. This report presents the results of an analysis of the Phase A experiments, which consisted of measurements of control rod worths, rod interactions, rod heterogeneities and enrichment effects, and flux perturbations induced by the control elements.

II. SUMMARY

Analyses of in-core (coaxial) and reflector control rod experiments indicate that with a relatively simple physics model and through the use of few-group theory, one can compute reactivity worths of isolated and small groups of interacting control rods to within approximately 10%. The models employed here generally underestimated experimental results by this amount or less. While transport theory has been used for nearly all calculations reported here, it has been shown (See Appendix E) that the use of diffusion theory does nearly as well.

For in-core rods with considerable internal heterogeneities and high ^{10}B content it was found necessary to simulate the actual rod geometry in a two-dimensional model. This requirement, however, can be relaxed for more dilute rods. Axial leakage effects must, of course, then be accounted for by using DB^2 , leakage cross sections, obtained from analyses of similar but simpler unrodded reactors.

For reflector rods, experimental results indicated that the rod heterogeneity effects were as large or larger than for in-core rods. Because of mesh limitations in computer codes, heterogeneity effects in peripheral rods could not be investigated. Good agreement between experiment and theory was found, however, without specific representation of internal rod heterogeneities.

Inspection of radial worth distributions and reaction rates through rod test positions at the core-reflector interface reveals a definite need for using "zoned" cross section sets. Details of how zoning should be done is a subject for additional investigation.

III. EXPERIMENT DESCRIPTION

All experiments were performed in ZPR-III.⁽¹⁾ Central rod experiments were performed on the axis of ZPR-III, Assembly 48. Peripheral rod experiments were performed at the core-reflector boundary of ZPR-III, Assembly 48A.

CENTRAL ROD EXPERIMENTS

Assembly 48⁽²⁾ has a core of plutonium, uranium, carbon, stainless steel, and sodium in the form of a right circular cylinder having an effective radius of 42.175 cm and a length of 76.02 cm. Both axially and radially the core is blanketed with approximately 30 cm of ^{238}U . The basic, unperturbed, critical loading is illustrated by the areal profiles of halves one and two as shown in Figures 1 and 2 and by the axial cross section shown in Figure 3. Eight safety rods and two control rod positions used for ZPR-III control are also shown. The central rod experiments were done in the P-row, Column-16 (P 16) matrix location.

Control rods having various configurations of B_4C , stainless steel, aluminum, and sodium were substituted into P 16 in place of a base loading of sodium and stainless steel.

Both lumped and distributed B_4C material patterns were used throughout the entire experimental series to study heterogeneity effects. They are illustrated in Figures 4 and 5. The distributed rod was used to evaluate rod worths as a function of ^{10}B enrichment.

Aluminum, used in these rods to simulate sodium, was an experimental necessity due to the limited size of platelets in the sodium inventory. It was used at 45% density. The central 1/4 by 2 in. sodium plate in Figure 4 was replaced in the distributed pattern by this aluminum for the lumped rod experiments.

Unit Cell Area $\square$ = 4.7502 in.²
 = 30.6439 cm²

- $\blacksquare$ Asymmetries in Assembly 48
- $\square$ T Control Rod Test Location
- $\times$ Safety Rods
(Spiked Fuel Drawers 1)
- $\times$ R Control Rod
(Spiked Fuel Drawer 2)

FIGURE 1. ZPR-III Assembly 48 (Half 1)

- Fuel Drawer Added between 12 in. and 19 in. Insertion Steps for Rod #1
- Asymmetries in Core 48A (FTR Step 1)
- Control Rod Test Location
- Safety Rods (Spiked Fuel Drawers 1)
- Control Rod (Spiked Fuel Drawer 2)

FIGURE 2. ZPR-III Assembly 48 (Half 2)

FIGURE 3. Axial Cross Section of ZPR-III Assembly 48

FIGURE 4. Cross Section of a "Distributed" Control Rod Drawer (Rod 1)

TABLE 1. Rod Compositions

	Rod 1	Rod 2	Rod 3, 4
Material	Distributed Enriched B ₄ C	Distributed Natural B ₄ C	Distributed, Lumped with Al
	Vol%		
B ₄ C	21.04	21.04	21.04
Na	27.12	27.12	18.08
SS	51.84	51.84	50.36
Al	—	—	10.52
MATERIAL ATOM DENSITIES			
¹⁰ B	0.073556	0.017746	0.073556
¹¹ B	0.007524	0.074746	0.007524
C	0.030162	0.024909	0.030162
Na	0.023498	0.023498	0.023498
Fe	0.051826	0.051826	0.050996
Cr	0.013915	0.013915	0.013693
Ni	0.006846	0.066846	0.006737
Al	—	—	0.021499
HOMOGENEOUS ATOM DENSITIES			
¹⁰ B	0.015486	0.003736	0.015486
¹¹ B	0.001584	0.015736	0.001584
C	0.006350	0.005244	0.006350
Na	0.006263	0.006263	0.004175
Fe	0.026775	0.026775	0.025831
Cr	0.007189	0.007189	0.006936
Ni	0.003537	0.003537	0.003413
Al	—	—	0.002635

limitations only two diametrically opposed 100° sectors of blanket were replaced by a sodium-nickel-stainless steel reflecting mixture. The azimuthal width of the reflector was shown by calculation to be sufficient to damp out the blanket-reflector interface spectral effects near all test positions. Areal profiles of the actual critical loadings of this assembly, ZPR-III Assembly 48A, are shown in Figure 6.

TABLE 2. Measured Central Control Rod Worths (P 16)

<u>ROD</u>	<u>Rod Description</u>	<u>Rod Worth, (a) % $\Delta k/k$</u>
1	91 at.% ^{10}B Enriched, Distributed, no Al	1.743
2	Natural B_4C Distributed, no Al	0.744
3	Enriched, Lumped with Al	1.526
4	Enriched, Distributed, with Al	1.734

(a) Uncertainties are approximately $\pm 2\%$

TABLE 3. Worth Versus Length of Insertion
of Central Enriched Rod 1

<u>Length of Rod Insertion from Blanket Edge, in.</u>		<u>Exp. Worth, % $\Delta k/k$</u>
Blanket	8	0.003
	12	0.027
Core	19	0.287
	27	0.892
	35	1.483
	42	1.719
Blanket	54	1.743

Various patterns of rod matrix positions were employed to investigate rod interaction between adjacent rods and cross-core rods. The matrix positions used were P 9, P 23, N 9, R 9, L 10, and T 10. This nomenclature is that used at ZPR-III. The experimental worths and rod patterns are given in Table 4.

Reaction rate distributions of ^{239}Pu fission, ^{238}U fission, and ^{10}B capture were measured in Assembly 48A. (See Section IV) The measurements were made with chambers whose physical

Lattice unit size = 2.180 in. x 2.180 in.

- SR = ^{239}Pu Enriched Safety Rod Fuel Drawer
CR = ^{239}Pu Enriched Control Rod Fuel Drawer
 = B_4C Enriched Reflector Control Rod Positions

FIGURE 6. ZPR-III Assembly 48A

TABLE 4. *Experimental Results*

<u>Case</u>	<u>Rod Location</u>	<u>% $\Delta k/k^{(a)}$</u>
1	L 10	0.392
2	T 10	0.382
3	N 9	0.350
4	R 9	0.350
5	P 9	0.417
6	P 23	0.412
7	P 9 + P 23	0.821
8	N 9 + R 9	0.674
9	N 9 + P 23 + R 9	1.092
10	N 9 + P 9 + R 9	0.939
11	L 10 + T 10	0.754
12	L 10 + P 23 + T 10	1.188
13	L 10 + P 9 + T 10	1.097

a. *Uncertainties are approximately $\pm 2\%$ of these numbers*

TABLE 5. *Neutron Counter Descriptions*

<u>Chamber</u>	<u>Effective Length</u>	<u>Composition</u>
$^{10}\text{BF}_3$	2 in.	$^{10}\text{BF}_3$
^{239}Pu fission	1 in.	94.92% ^{239}Pu 0.77 mg/cm ² 4.75% ^{240}Pu 0.315% ^{241}Pu Loading: 0.010% ^{242}Pu 6.55 mg
^{238}U fission	1 in.	Depleted 80ppm ^{235}U Loading: 4.4 mg

descriptions are given in Table 5. Small sample reactivity worth distribution measurements were made and are also discussed later.

IV. ANALYSIS

Analysis of these experiments was done with two-dimensional transport theory⁽⁵⁾ in the S-2 approximation. Percent differences between S-2 and S-4 approximations were 2% or less and are shown in Appendices C and E. Two-dimensional diffusion theory⁽⁶⁾ was also employed for a few comparisons. Results are also discussed in Appendix E. For analysis of central control rod experiments, an R-Z model was employed in which the reactor platelets and the rod platelets were homogenized and cylindricized. To investigate the lumping effect within a single rod, a detailed X-Y model was used. In the latter case and in all analyses of peripheral rod experiments, average axial bucklings were used to account for axial leakage. The bucklings were inferred from cylindricized R-Z models of the respective cores. All worths were inferred from k_{eff} differences, where the calculated k_{eff} 's were close to unity.

Most calculations were done with a five energy group model. Cross sections for these calculations were taken from the PNL-modified 26-group Bondarenko set⁽⁷⁾ and were averaged over spectra using the PNL code "FCC IV".⁽⁸⁾ Specifically, cross sections for the core materials were averaged over the fundamental mode spectrum of the core. Cross sections for the blanket were averaged over the fundamental mode spectrum of the blanket. Rod cross sections for analyses of the core rod experiments were averaged over the same core spectrum. Likewise, the cross sections for peripheral rods were averaged over the core spectrum. This latter approximation is briefly discussed in Appendix A. Reflector cross sections were averaged over the fundamental mode reflector spectrum which was calculated with a Pu-fission source and zero value for the radial buckling.

ANALYSIS - CENTRAL ROD EXPERIMENTS

Three models were used in the analysis of the central rod experiments. The first was an R-Z model in which the P 16 matrix tube was homogenized into a cylinder by conservation of area and material masses. The worths of the natural and enriched rods inferred with this model are as shown in Table 6. The calculations were converged to a k -variation of one part in 10^{-5} , which yields about $6 \times 10^{-3}\%$ $\Delta k/k$ uncertainty in the calculated difference (see Appendix D). This precision far exceeds the degree of agreement between the experimental and calculated values as shown in the E/C column of Table 6. Note the fairly good agreement between the experiment and the R-Z homogeneous calculation for the weakly absorbing natural B_4C rod (Rod 2) and the much poorer agreement for the 90% enriched B_4C rod (Rod 1). This obviously suggests a lumping or self-shielding effect. Thus, a homogenized model is simply not a good model of the distributed rod and an even worse model of the lumped rod.

Rod self-shielding was investigated further by using X-Y models in which actual rod geometries were specified in detail, as is shown in Figures 7 and 8. Axial leakage was simulated by

TABLE 6. Core 48 Central Control Rods Worths
Measurement Versus Calculation (% $\Delta k/k$)

Rod Number	Rod Description	Calculational Model ^(a)			Experiment ^(b) (E)	E/C
		a R-Z Hom.	b X-Y Hom.	c X-Y Het.		
1	Enriched, ^(c) Distributed, No Al	2.022	2.007	1.842	1.743	a. 0.862 b. 0.868 c. 0.946
2	Natural, Distributed, No Al	0.782	0.782	0.752	0.744	a. 0.951 b. 0.951 c. 0.989
3	Enriched, Lumped, with Al	—	2.006	1.649	1.526	a. — b. 0.761 c. 0.925
4	Enriched, Distributed with Al	—	2.006	1.848	1.734	a. — b. 0.864 c. 0.938

a. Calculational precision $\approx \pm 0.006\%$ $\Delta k/k$

b. Experimental uncertainty $\approx \pm 2.0\%$ of these numbers

c. Boron in enriched rods is 91 at.% ^{10}B

FIGURE 7. Lumped Control Rod 3

FIGURE 8. Distributed Control Rod 4

using the usual DB^2 approximation. The diffusion coefficient had spatial dependence in a region-wise sense, while B^2 was held constant. The appropriate value of B^2 was inferred from the above 2D R-Z calculations with a 1D cylindrical calculation. In the latter, the eigenvalue was forced to be that of the 2D analysis by adjustment of reactor height and hence B^2 . It was then assumed that the effective height of the 1D R model and an X-Y model of the same core should be the same.

Using the reactor axial buckling inferred in this fashion, the values of the enriched and natural and lumped and distributed rods were recalculated. They are listed in Table 6 also (X-Y heterogeneous column). While the improvement is significant, e.g., for the enriched distributed rod the E/C value is increased from 0.861 to 0.945, some disagreement still exists. The model still yields values that consistently overestimate the measured values. Note the very slight improvement in the E/C value for the natural distributed rod. Note also that differences between the calculated worths of the enriched distributed rods with and without aluminum are almost insignificant.

It is concluded that calculations of the reactivity worth of heterogeneous, highly enriched B_4C rods, using few-group transport theory, can be expected to overestimate worth by no more than 15%. Estimates within about 5% can be obtained with detailed heterogeneous models.

The reactivity worth of stepped control rod insertions was calculated with the two-dimensional transport code, "2DF",⁽⁴⁾ using R-Z geometry. Consistent with previous calculations, these worth values were obtained using five cross section energy groups and the S-2 transport approximation. The enriched B_4C rod was cylindricized and homogenized to conserve volume.

The results of the centerline axial stepped insertion calculations and the comparison with experimental values are listed in Table 7. The results, for larger rod worths are consistent with previous rod calculations. For smaller values of rod worth, the E/C values are rather random, as is to be expected in view of the magnitude of the worth and the comparable values of experimental and calculational error.

TABLE 7. *Worth Versus Length of Insertion of Central Enriched Control Rod*

<u>Rod Insertion, in.</u>		<u>Exp. % $\Delta k/k$</u>	<u>Calc. % $\Delta k/k$</u>	<u>E/C</u>
Blanket	8	0.003	0.002	1.5
	12	0.027	0.027	1.0
Core	19	0.287	0.225	1.28
	27	0.892	1.056	0.84
	35	1.483	1.777	0.83
	42	1.719	2.042	0.84
Blanket	54	1.738	2.061	0.84

ASSEMBLY 48A PERIPHERAL ROD ANALYSES

Inspection of Figure 6 and Table 4 reveals a number of symmetric and asymmetric arrays of rods which, for optimum analysis, necessitate the use of full-core, half-core, and quarter-core calculational models. These models are illustrated in Figures 9, 10, and 11, respectively. Positions L 10 or T 10, N 9, or R 9, and P 9 and P 23 are locations used for all peripheral rod experiments. In Figure 9, SR1 and SR2 are calculational model locations that allow either of the two sets of safety rod locations N 13 and N 19 or S 13 and S 19 to be simulated. (See Figure 6 to note asymmetry.) This full-core model with positions SR1 and SR2 was used to evaluate the effect of the asymmetric location of safety rods. The effect was less than 0.01 % $\Delta k/k$.

FIGURE 9. ZPR-III Assembly 48A, Calculational Model of Full Core

FIGURE 10. ZPR-III Assembly 48A, Calculational Model of Half Core

Zone	Material
1	Core "48A"
2	Safety Rod
3	Control Rod
4	Control Rod
5	Control Rod
6	Inconel "1"
7	Inconel "2"
8	Inconel "3"
9	^{238}U Blanket
10	Stainless Steel Mesh

FIGURE 11. ZPR-III Assembly 48A, Calculational Model Using Quarter-Core Symmetry

Worths of single rods in positions L 10 (or T 10), N 9 (or R 9), and P 9 (or P 23) have been calculated using the full-core model, shown in Figure 9. Worths of paired rods P 9 and P 23 were calculated using both the half and quarter core models shown in Figures 10 and 11, respectively. All remaining worths of sets of two and three rods were calculated using the half-core model. Calculated results are compared in Table 8 with experimental data of Table 4.

TABLE 8. Experiment-Theory Comparisons

Case	Rod Location	Exp (E) % $\Delta k/k$	Calc (C) % $\Delta k/k$	E/C	Core Size
1	L 10	0.392	0.411	0.954	Full
2	T 10	0.382	0.414	0.923	Full
3	N 9	0.350	0.394	0.888	Full
4	R 9	0.350	0.394	0.888	Full
5	P 9 or P 23	0.417	0.448	0.931	Full
6	P 9 or P 23	0.412	0.427	0.965	1/2
7	P 9 + P 23	0.821	0.831	0.988	1/4
8	N 9 + R 9	0.674	0.703	0.959	1/2
9	N 9 + P 23 + R 9	1.092	1.134	0.963	1/2
10	N 9 + P 9 + R 9	0.939	0.966	0.972	1/2
11	L 10 + T 10	0.754	0.754	1.000	1/2
12	L 10 + P 23 + T 10	1.188	1.183	1.004	1/2
13	L 10 + P 9 + T 10	1.097	1.101	0.996	1/2

All full-core calculations appear to overestimate rod worths by a larger margin than is the case for the half-core and quarter-core comparisons. The half-core calculations have been made with the maximum-allowable mesh detail with respect to computer core storage. The full-core calculation then has, at best, only half the mesh detail of the other models. As a maximum of detail is necessary in the quadrant containing the

control rods, the resultant lack of detail in the remaining quadrants decreases the accuracy of the calculation. These full-core comparisons also show that the calculations tend to indicate the relative increase in the worths of L 10 and T 10 over the worths of N 9 or R 9. Since a greater fraction of the perimeter of L 10 (or T 10) is adjacent to the core one might expect this behavior. In general, the balance of the comparisons (half-core comparisons) are quite good and consistent.

Additional information available that is of interest is the apparent interaction of these rods in the various sets or combinations listed in Table 8.

Cross-core interaction is not distinguishable from separate and combined experimental measurements on rods in positions P 9 and P 23, i.e., the sum of separate worths 0.417 plus 0.412 equals 0.829 which is only 1% greater than the measured value of 0.821. Since the experimental uncertainties are $\pm 2\%$, this difference is not considered statistically significant. This situation changes for the rod sets having closer spacing e.g., N 9 and P 9, etc.

Rod interaction as a function of separation can be inferred from worths of single rods and worths of combination of the same single rods. Without specifying the functional dependence of the interaction function f_{ij} between two rods i and j separated by a distance x_{ij} , one may write

$$f_{ij} = \frac{W_i + W_j - (W_i, W_j)}{(W_i + W_j)}$$

where W_i and W_j are single rod worths and (W_i, W_j) is the worth of both rods i and j as a pair. Note that f_{ij} is a function of x_{ij} . When three rods are involved one may write

$$(W_i, W_j, W_k) = W_i(1 - f_{ij} - f_{ik}) + W_j(1 - f_{ij} - f_{jk}) + W_k(1 - f_{ki} - f_{kj}).$$

If the system is symmetric and rod j is midway between rods i and k , $f_{ij} = f_{jk}$ and of course $f_{ij} = f_{ji}$, $f_{jk} = f_{kj}$, and $f_{ik} = f_{ki}$. Hence, one may write

$$(W_i, W_j, W_k) = (W_i + W_j + W_k) - f_{ik}(W_i + W_k) - f_{ij}(W_i + W_k + 2W_j).$$

These formulae yield interaction factors as given in Table 9 for high and intermediate enrichment B_4C rods.

While these data may not all actually be members of a single set, because of differences in surroundings, they are presented together in Figure 12.

TABLE 9. *Peripheral Control Rod Interactions*

Rods	Interaction Factor	f_{ij} Interaction Enriched (1100 g ^{10}B /Rod)	x_{ij} Separation (edge to edge) (x 2.180 in.)
P 9 and P 23	0	$f_{P\ 9, P\ 23}$	13
L 10 and T 10	0.026	f_{LT}	7
L 10 and P 9, or P 9 and T 10	0.046	f_{LP}	3.16
N 9 and R 9	0.037	f_{NR}	3
N 9 and P 9 or P 9 and R 9	0.100	f_{NP}	1
<u>Intermediate (680 g ^{10}B/rod)</u>			
N 9 and R 9	0.030	f_{NR}	3
N 9 and P 9 or P 9 and R 9	0.081	f_{NP}	1

Rod selfshielding was investigated experimentally at the core-reflector boundary of Assembly 48A. The worth of two configurations of the enriched rod, distributed and lumped, were measured in the P 9 position. The homogenized rod in the P 9 position was used as the model to calculate both

FIGURE 12. Interaction Between Rods i and j Separated by a Distance $2.18 x_{ij}$ in.

configurations. Whereas the homogenized rod calculation is a good approximation for the distributed experimental rod measurement ($E/C = 0.965$), the comparison with the lumped rod is less favorable, (E/C of 0.838).

The worth of three enrichments of distributed B_4C rods were compared experimentally in the P 9 position and two enrichments in the rods and combinations of rods N 9; N 9, R 9; N 9, R 9, P 9. Calculations have been made for intermediate and full enrichments for P 9; N 9, R 9; N 9, R 9, P 9 and are compared in Table 10. Consistent with the fully enriched peripheral rod calculations, the intermediate enriched rod worths were calculated, using a quarter-core, X-Y geometry model of 2DF with the S-2 approximation. In Figure 13, curves

TABLE 10. *Experimental and Calculated Rod Worths, % $\Delta k/k$*

Rod Position	Intermediate Enriched B_4C 680 g $^{10}B/Rod$			Fully Enriched B_4C 1100 g $^{10}B/Rod$		
	Exp.	Calc.	E/C	Exp.	Calc.	E/C
P 9	0.320	0.326	0.982	0.412	0.427	0.965
N 9, R 9	0.532	0.549	0.969	0.674	0.703	0.959
P 9, N 9, R 9	0.753	0.777	0.969	0.939	0.966	0.972

are shown of the experimental and calculated worths versus enrichment for control rod position P 9.

REACTION RATE AND SMALL SAMPLE WORTH DISTRIBUTIONS

Power peaking and gross reactivity effects can be inferred from spatial distributions of reaction rates and small sample reactivity worths. Such distributions can be predicted with essentially the same calculational tools used in rod worth calculations. To provide a test of these aspects of the calculational models, a series of radial reaction rate and small

FIGURE 13. *Worth Versus Enrichment of ^{10}B of Distributed Rods, Position P 9*

sample reactivity worth spatial distributions were measured. Analyses of these distributions are presented below. An auxiliary benefit of these analyses is the integral assessment of the space-energy cross section portion of the model. For example, in view of the rapid variation of the energy distribution of neutrons near the core boundary of a reflected (rather than a ^{238}U blanketed) fast core, good analysis may require an improved space-energy cross section model.

Distributions of ^{239}Pu and ^{238}U fission rates and ^{10}B capture rates and corresponding worth distributions have been measured and analyzed for Assembly 48A. The distributions were measured in the radial direction through the P-row and hence, through the P 9 rod test position. Measurements were made with and without the rod in place and are so labeled. Five group cross sections, fluxes, and adjoints from the quarter-core analysis described earlier were used in the comparison calculations. In all curves presented one may find one or two sets of experimental data and one or two calculated curves. The two sets of experimental data arise from traverses taken along a core diameter. Data from equal radii are different, of course, because of random statistical processes, but more importantly from the asymmetry of the loading of the fuel platelets within the drawers (Figure 14). Two calculated curves are sometimes presented to indicate the effect of using core and reflector averaged cross sections.

FIGURE 14. Normal Central Drawer of ZPR-III Assembly 48

In Figure 15, the radial worth distribution of a small sample of ^{239}Pu (4.5% ^{240}Pu) is shown. (See Table 11 for sample descriptions.) The core portion of the calculated results is the absolute worth obtained from the use of core-averaged cross sections. The overestimate in plutonium worths is consistent with that obtained by others.⁽¹¹⁾ This poor agreement persists throughout the core. As shown by the dashed line, this core cross section set yields better agreement in the reflector. The reflector curve obtained with the use of a reflector averaged cross section is in much greater disagreement.

TABLE 11. *Specifications of Reactivity Samples Used in Assembly 48A Traverses*

Sample Material	Shape	Material Dimensions, in.			Material Mass, g	Material Composition, wt%
		Length	OD	Thickness		
Plutonium	Annulus	1.86	0.34	0.020	9.187	95.05 ^{239}Pu , 4.50 ^{240}Pu , 0.45 ^{241}Pu
Enriched Uranium	Annulus	1.90	0.39	0.010	7.128	93.16 ^{235}U , 6.84 ^{238}U
Depleted Uranium	Cylinder	2.00	0.19	-	19.63	99.78 ^{238}U , 0.21 ^{235}U
Enriched Boron	Annulus	1.90	0.39	0.010	0.406	85.48 ^{10}B , 7.32 ^{11}B , 7.2 impurity ^(a)
Tantalum	Annulus	1.98	0.38	0.015	9.67	>99% Ta
Stainless Steel	Cylinder	2.00	0.42	-	35.90	Type 304, approx 72 Fe, 18 Cr, 10 Ni

a. *This composition is suspect pending confirmation of additional analyses.*

The disagreement for the core results is not understood. A reasonable partial explanation of the disagreement in the reflector is as follows. The cross sections are averaged over a reflector spectrum that not only does not account for gross leakage effects, but is assumed to be constant over the entire

FIGURE 15. ^{239}Pu Worth Traverse

reflector. Hence, the spectrum is too soft near the core and the cross sections and reactions are correspondingly too large.

The effects of introducing a distributed B_4C control rod (Rod 1) at the core boundary are illustrated in Figure 16. Cross sections for the rod region were the same as for the core. Comments made above about the unrodded distribution are also applicable here, except that the experiment theory correlation in the rod is quite good.

Similar sets of curves for ^{238}U and ^{10}B worths are shown next in Figures 17, 18, 19, and 20, respectively. The calculated reflector worth of ^{238}U appears to be quite in error with the control rod absent but in fair agreement when the rod is present.

In Figure 19 one again sees the large disagreement near the core-reflector interface. Here, as with ^{239}Pu , the reflector-averaged cross sections give results which are too large because the spectrum is too soft. From Figures 19 and 20 one readily sees the reduced reactivity value of boron near the control rod position when the control rod is present. Note also the better experiment-theory correlation near the rod as for ^{238}U and ^{239}Pu .

Stainless steel was measured because it was part of the sample carrying apparatus. Interestingly, the experiment-theory correlation shown in Figures 21 and 22 is exceptionally good for both the rods in and out situation.

Tantalum is of interest as a control material and was evaluated in the rods-out configuration. The absolute calculated spatial distribution is shown in Figure 23 by the solid line. The dashed line is the same curve normalized to the experimental data at $r = 0$. These results may be used to assess the relative merits of tantalum and boron as fast reactor control materials.

FIGURE 16. ^{239}Pu Worth Traverse Through Rod

FIGURE 17. Depleted Uranium Worth Traverse

FIGURE 18. Depleted Uranium Worth Traverse Through Rod

FIGURE 19. Enriched Boron Worth Traverse

FIGURE 20. Enriched Boron Worth Traverse Through Rod

FIGURE 21. Stainless Steel Worth Traverse

FIGURE 22. Stainless Steel Worth Traverse Through Rod

FIGURE 23. Tantalum Worth Traverse

Fission rates for ^{239}Pu with rods in and out of Assembly 48A are shown in Figures 24 and 25. Here, and in all remaining reaction rate comparisons, the calculated curves and experimental data are arbitrarily normalized at the core center.

In Figures 24 through 27 one can see that the experiment-theory correlation of fission in ^{239}Pu and ^{238}U , which is a relatively high-energy effect, is quite good both with rods in and out. This is not true for ^{10}B capture as shown in Figures 28 and 29.

For ^{10}B capture, a low energy effect, the neutron spectrum of the reflector is entirely too soft. Hence, the high capture rate calculated with reflector averaged cross sections. The core averaged cross sections are, of course, correspondingly too low, as shown.

In summary, one may conclude that space-energy problems for reflected systems are unresolved. Best solutions to experiment-theory correlations require iterative solution in which spectra are generated first from models having gross spatial detail followed by adjustments from models having finer detail. Such work is presently underway as a part of analyses of Phase B FFTF Critical Experiments.

FIGURE 24. ^{239}Pu Fission Rate Traverse

FIGURE 25. ^{239}Pu Fission Rate Traverse Through Rod

FIGURE 26. ^{238}U Fission Rate Traverse

FIGURE 27. ^{238}U Fission Rate Traverse Through Rod

FIGURE 28. ^{10}B Absorption Rate Traverse Through Rod

FIGURE 29. ^{10}B Absorption Rate Traverse

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APPENDICES

APPENDIX A

GROUP CROSS SECTIONS

Few-group cross sections used in these analyses were obtained by energy averaging (only) the PNL version of the Bondarenko 26-energy group set. For the core and reflector, the 26-group cross sections were averaged over different neutron spectra. For the core, the neutron spectrum from a fundamental mode diffusion calculation ($k_{\text{eff}} \equiv 1.00$) was used, while for the reflector the fundamental mode spectrum for the reflector was used. For the latter, a plutonium fission neutron source was used. Similarly the cross sections for the ^{238}U blanket were averaged over the fundamental mode spectrum of the blanket calculated with $B^2 = 0$.

As indicated in the main text, these methods are not completely adequate. Averaged cross sections should have spatial dependence with homogeneous zones, i.e., within the core and within the reflector. To accomplish this, one must iterate between multidimensional approximate solutions and cross section averaging schemes until spatial flux distributions as well as eigenvalues have converged. The extent of the iteration required needs to be demonstrated.

APPENDIX B

EFFECT OF AXIAL BUCKLING APPROXIMATION

Analyses of Assembly 48A experiments were done with 2DF, a two dimensional transport code. The third dimensional effects of leakage were approximated by using a "leakage cross section," DB^2 , where B^2 is the whole reactor average axial buckling. Variation of B^2 with radius is only accounted for in an integral sense. To obtain some measure of the adequacy of the approximation, one peripheral rod experiment was analyzed with the two-energy group 3D diffusion code, Whirlaway.⁽¹⁰⁾ Both 2D and 3D analyses were made and the results are given in Table B-1. The 2D transport calculation is also given. Assuming 2D and 3D diffusion and transport models have similar inadequacies, the 3D transport value has been estimated and is also given in Table B-1. The correction is approximately 4% and produces an over-estimate of the experimental worth; the E/C is 0.947.

Inspection of Table B-1 reveals disagreement between absolute values of the comparable 2D and 3D diffusion multiplication constants. No attempt has been made to resolve these differences.

TABLE B-1. *Comparison of 2D and 3D Diffusion and Transport Calculations*

Model	Rod Position		Rod Worth,
	$k_{\text{eff, Out}}$	$k_{\text{eff, In}}$	% $\Delta k/k$
2D, Diffusion	0.98160	0.97264	0.913
3D, Diffusion	0.98963	0.98204	0.949
2D, Transport	0.98294	0.97474	0.834
3D, Transport	—	—	0.867 (Estimated)
Exp.			0.821
Estimated Transport, E/C = 0.947 = 0.821/0.867			

APPENDIX C

PARTIAL EVALUATION OF ROD WORTH VERSUS SN APPROXIMATION

Multiplication constants obtained from calculations in the S-4 approximation are significantly better than those from the S-2 approximation. Since most of the rod calculations presented here were done in the S-2 approximation, the effect of using S-2 has been evaluated. Worths of enriched rods in Assembly 48 position P 16 and in Assembly 48A positions P 9 and P 23 have been calculated in both the S-2 and S-4 approximation. Data and comparisons are shown in Table C-1. The central rod effect is shown to be approximately a -1.65% difference and for the peripheral rod the effect is shown to be -2.1% difference.

TABLE C-1. *Effect of Sn Approximation on Control Rod Worth^(a)*

	S-2, <u>k_{eff}</u>	S-4, <u>k_{eff}</u>	%(S-2 - S-4), <u>% Difference</u>
<u>Assembly 48</u>			
Calculation:			
(1) Na Column	0.99129	0.99336	-0.208
(2) Enriched Rod	0.97042	0.97290	-0.255
(3) Rod Worth % $\Delta k/k$	2.096	2.060	1.75
Measurement:			
(4) Rod Worth % $\Delta k/k$	1.743	1.743	
(5) = (4)/(3)	0.832	0.846	-1.65
<u>Assembly 48A</u>			
Calculation:			
(6) No Rods	0.98312	0.98527	-0.218
(7) Rods P 9 + P 23	0.97453	0.97684	-0.236
(8) Rod Worth % $\Delta k/k$	0.874	0.856	2.10
Measurement:			
(9) Rod Worth % $\Delta k/k$	0.821	0.821	
(10) = (9)/(8)	0.939	0.959	-2.09

a. *All rods mentioned above are the enriched, distributed rods described as Type 1.*

APPENDIX D

ERRORS IN CALCULATED MULTIPLICATION CONSTANTS

Since only reactivity differences are of interest in this report, absolute precision is not discussed here. Convergence has been investigated to assess the relative uncertainty in multiplication constants. It has been shown that successive estimates of the eigenvalue that differ by an amount equal to or less than ϵ (convergence criterion) are equal to or less than 6ϵ from the "most precise answer" to the problem that can be found. For example, 2DF calculations using an ϵ of 10^{-7} (in k) approach the limits of the numerical precision of the code. Hence, values of multiplication found for 10^{-7} convergence are "most precise answers." Table D-I illustrates eigenvalues obtained for one problem using different values of ϵ . One can see that, independent of ϵ , the eigenvalue k_{eff} is less than 6ϵ from the eigenvalue corresponding to an ϵ of 10^{-7} .

Since all results reported here were obtained for an ϵ of 10^{-5} , reactivity differences are in error by less than $\pm(6\sqrt{2\epsilon})$. For P 9 and P 23, the worth would be 0.8340 ± 0.0084 or approximately $\pm 1\%$, which is, for this configuration, better than the experimental uncertainty of $\pm 2\%$.

TABLE D-I. *Eigenvalues Obtained Using Different Values of ϵ*

<u>Convergence Criterion, ϵ</u>	<u>Converged Eigenvalue, k_{eff}</u>	<u>Δk</u>	<u>Difference^(b)</u>
10^{-3}	1.012600	0.005770	5.77ϵ
10^{-4}	1.017770	0.000600	6.00ϵ
10^{-5}	1.018311	0.000059	5.9ϵ
10^{-6}	1.018365	0.000005	5ϵ
10^{-7}	1.018370 ^(a)	—	0

a. "Most precise answer"

b. Difference from "most precise answer"

APPENDIX E

TRANSPORT VERSUS DIFFUSION THEORY

The code 2DB is a diffusion theory version of the transport code 2DF. With the exception of the theory used in calculations, the codes are quite similar and can accept the same problem cases. To compare the two codes, one of these control rod calculations was revised and recalculated in 2DB. The quarter core, X-Y geometry mockup of the ZPR-III, with two control rods (P 9 and P 23) symmetrically placed on the core-reflector interface was used. The unrodded case was also calculated. The runs in 2DB were 9 times faster than the S-2 transport runs and give results which agree very well with the experiment. A comparison of these calculations is given in Table E-1.

TABLE E-1. Transport Diffusion Theory Comparison

<u>Case Description</u>	<u>k_{eff}</u>	<u>Time on 1108 Computer, min: sec</u>
<u>2DB</u>		
No Control Rods	0.98299	:59
Two Control Rods	0.97476	:54
Rod Worth % $\Delta k/k$	0.837	
<u>2DF - S-2</u>		
No Control Rods	0.98312	7:24
Two Control Rods	0.97453	7:18
Rod Worth % $\Delta k/k$	0.874	
<u>2DF - S-4</u>		
No Control Rods	0.98527	16:52
Two Control Rods	0.97684	10:56
Rod Worth % $\Delta k/k$	0.855	
<u>Experiment</u>		
Rod Worth % $\Delta k/k$	0.821	

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