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A COMPARISON BETWEEN PHYSICS PARAMETERS IN CONVENTIONAL AND HETEROGENEOUS LMFBRS USING RESULTS FROM ZPPR

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ABSTRACT

The analysis of several ZPPR experiments has been made using consistent methods and data. Results for conventional and heterogeneous LMFBR designs are compared in some detail.

1. INTRODUCTION

Studies of conventional two-zone LMFBR cores in ZPPR have ranged from clean benchmarks to detailed engineering mock-up designs. In ZPPR-7, an alternative heterogeneous design was studied which contained three internal blanket subassembly rings. Results from ZPPR-7 prompted comparisons with the analysis of conventional cores. Improvements in analytical methods during the sequence of ZPPR assemblies and revisions to ENDF/B data necessitated re-analysis of earlier assemblies. The paper summarizes the principal results from the comparisons.

2. ASSEMBLY DESCRIPTIONS

ZPPR assemblies 2, 3, and 4 were designed to provide basic data for conventional two-zone fast reactors of about 350 MWe. The configurations were relatively simple, but assemblies 3 and 4 contained nineteen control rod positions (CRPs). Each had a core height of 916 mm and 458 mm axial blankets. The midplane sections of ZPPR-2 and ZPPR-4 are shown in Figure 1.

The first three assemblies of the ZPPR-7 program, 7A, 7B, and 7C, provided benchmark data for the heterogeneous design. Each contained three internal blanket rings and a central blanket zone. To provide an analytical benchmark, ZPPR-7A had continuous blanket rings and no control rod positions. In 7B and 7C, six inner ring and six outer ring CRP's were included. 7A and 7B had plutonium fuel in core subassembly regions with none in the internal blankets. In 7C some plutonium was removed from core regions and put into the internal blankets, resulting in a more uniform fuel distribution. The midplane views of the 7A and 7B (or 7C) cores are also shown in Figure 1. Later assemblies in the ZPPR-7 program were

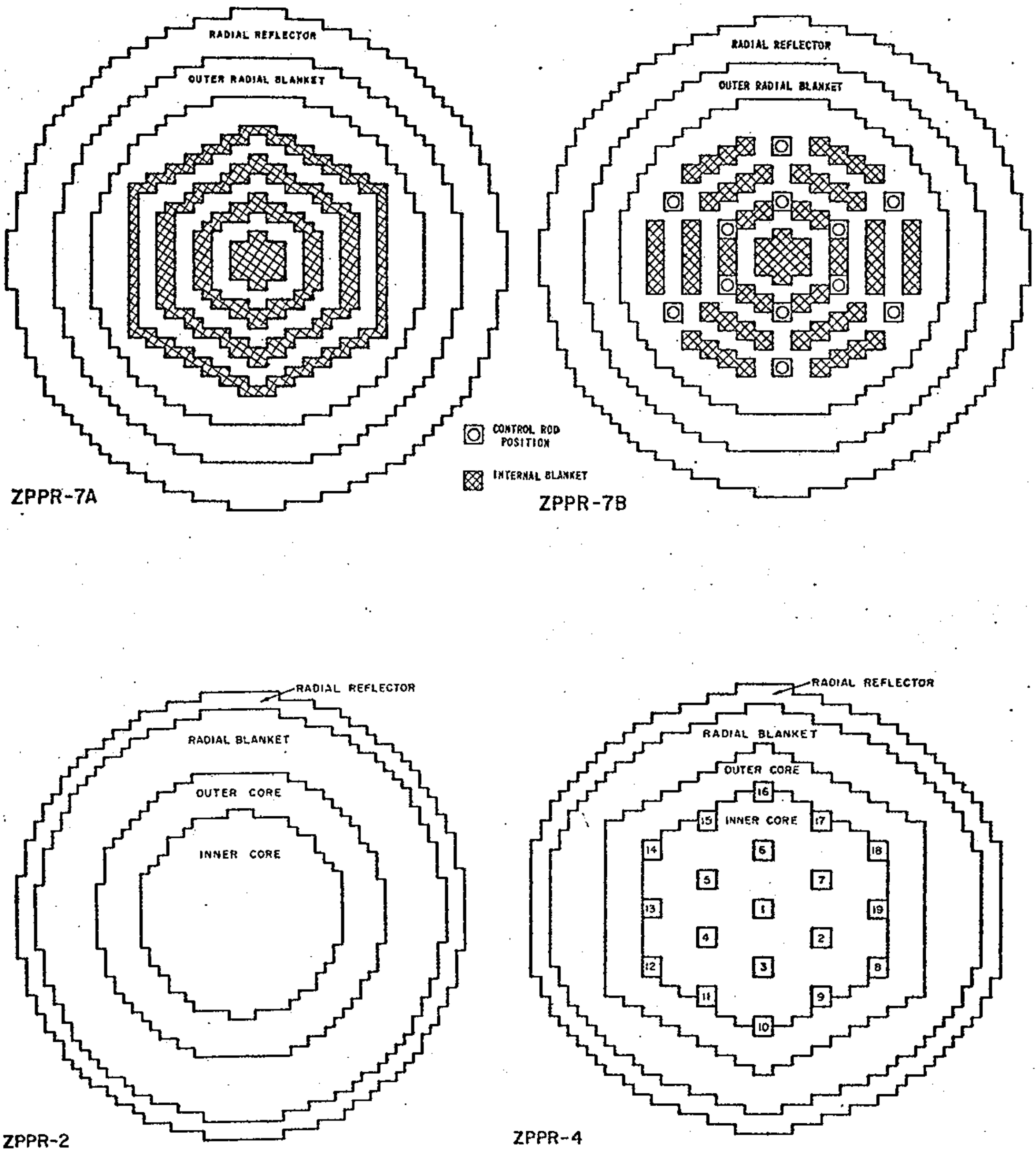

Fig. 1. Heterogeneous and Homogeneous ZPPR Assemblies

built to study variations of the blanket and CRP arrangements and to provide more detailed design information.

3. CALCULATION MODELS AND EIGENVALUES

Experience with ZPPR analysis has shown that an xyz description of the reactor is necessary. However, for axially symmetric cores, at least, the judicious use of zone- and group-dependent bucklings to represent the z dimension has been shown to give negligible errors for k_{eff} and midplane reaction rates. The reference analytical model for the present comparison used xy geometry with 4 mesh points per ZPPR matrix (equivalent to 16 mesh points per subassembly in the CRBR core). ENDF/B Version IV data were used in 28 energy groups. The use of this relatively fine mesh and group description was prompted by the increased sensitivity in the heterogeneous cores.

Multigroup data were processed through the MC^2-II/SDX system to treat cell heterogeneity. An intermediate library in 156 groups was used to collapse data to 28 groups for core and blanket regions individually. Zone- and group-dependent bucklings were obtained from the midplane fluxes of an rz calculation for each assembly. Some axial corrections, principally for transport and streaming effects, were also derived from these rz models.

TABLE 1. Comparison of Calculated k_{eff} Results

	ZPPR-3/1B	ZPPR-4/1	ZPPR-7A	ZPPR-7B	ZPPR-7C
Experiment (E) k_{eff}:	1.0015	1.0008	1.0003	1.0006	1.0015
Calculation (C) k_{eff}:					
rz diffusion	0.9841	0.9862	0.9792	0.9772	0.9859
xy diffusion	0.9843	0.9823	0.9801	0.9808	0.9864
xy transport S_4	0.9878	0.9853	0.9851	0.9862	0.9880
Corrections					
plate streaming	-0.0038	-0.0038	-0.0046	-0.0048	-0.0046
axial transport	+0.0008	+0.0008	+0.0014	+0.0014	+0.0014
others[a]	-0.0000	-0.0000	+0.0003	+0.0003	+0.0003
C/E:					
xy transport S_4 corrected	0.9833	0.9815	0.9819	0.9831	0.9836

[a] Net result of compensating corrections, each less than 0.05%, for transport mesh size, buckling approximation and improved steel reflector cross sections.

The calculated k_{eff} values are compared in Table 1. The diffusion theory results are appreciably lower for assemblies 7A and 7B compared with assemblies 3/1B, 4/1, and 7C. Thus "design-level" calculations would show larger bias factors for the initial loadings of heterogeneous cores.

The "best" values with the current analysis, using xy transport calculations with corrections applied, gave agreement in k_{eff} for the five assemblies to within 0.2%. The improvement was largely due to increased transport effects in 7A and 7B. Uncertainties in the analysis, principally treatment of microscopic and macroscopic heterogeneities, are estimated to represent 0.2% in k_{eff}. The calculated k_{eff} values for these assemblies are consistent with those from other fast-assembly data-testing benchmarks and are correlated with the over estimation of the ^{238}U(n,γ)/^{239}Pu(n,f) ratio with ENDF/B-IV data[1].

4. REACTION RATE RATIOS AND DISTRIBUTIONS

Extensive reaction rate distributions of ^{239}Pu(n,f), ^{235}U(n,f), ^{238}U(n,f), and ^{238}U(n,γ) were measured in all assemblies. Analysis of the non-threshold reaction rates in 7A and 7B showed a radial discrepancy in calculations; the calculation-to-experimental (C/E) ratios were up to 5% higher in the outer fuel ring relative to those in the inner fuel ring. This discrepancy was not present in assemblies of conventional design or in 7C, which had a more homogeneous distribution of fuel. This characteristic is illustrated in Table 2, where the C/E ratios for ^{235}U(n,f) in ZPPR-7A have been averaged through each radial zone.

Investigations were made to study the errors in calculating radial power distributions in 7A and 7B. Table 3 shows the effect of refinements to the calculational model. The largest correction was due to streaming effects. The sum of the corrections reduced the discrepancy between inner and outer positions by 2%.

TABLE 2. Analysis of Calculations for ^{235}U(n,f) in Annular Zones[a] in ZPPR-7A

Zone	No. of Positions	Average C/E	RMS Deviation
Center Blanket	5	0.999	0.005
Core ring 1	5	0.994	0.013
Blanket ring 1	6	1.016	0.005
Core ring 2	7	1.010	0.004
Blanket ring 2	6	1.025	0.008
Core ring 3	7	1.028	0.008
Blanket ring 3	4	1.039	0.009
Core ring 4	13	1.037	0.010
Radial blanket	14	1.031	0.019

[a] Transport S_4 calculation.

The sensitivity of the power distributions to several of the principal cross-sections was derived for 7A. As shown in Table 4, the shape was especially sensitive to variations in ^{238}U capture and inelastic scattering. The same variations had a much smaller effect in the conventional core (ZPPR-2). Reasonable changes in these data could thus account for the residual discrepancy after modelling corrections. These same data alterations were shown to give similar changes to k_{eff} for both ZPPR-7A and ZPPR-2.

TABLE 3. Corrections to the ^{235}U(n,f)
Reaction Rate at the x-axis of ZPPR-7A

	First Core Ring	Outer Core Ring	Difference
Reference C/E with xy transport S_4-P_1[a]	1.004	1.050	+4.6%
Correction factors:			
Streaming	1.008	0.997	-1.1%
$(S_8$-$P_1)/(S_4$-$P_1)$	1.002	0.997	-0.5%
$(S_8$-$P_3)/(S_8$-$P_1)$	0.999	1.002	+0.3%
Mesh Size $(S_8$-$P_3)$	1.000	1.000	0.0
Buckling Approximation	1.002	0.999	-0.3%
Space-dependent group collapse	1.003	0.999	-0.4%
Total Correction	1.014	0.994	-2.0%
Corrected C/E	1.018	1.044	+2.6%

[a] Scattering was treated with a P_0 expansion, corrected for transport effects.

TABLE 4. Effect of Cross Section
Alterations on Power Density Shape

		Effect on Power Density Tilt[a], %	
Cross Section	Alteration, %	ZPPR-7A	ZPPR-2
^{238}U(n,γ)	-5	+1.6	+0.5
^{238}U(n,f)	+5	+0.2	+0.1
^{238}U(n,n$'$)	-10	+0.8	∿0
^{239}Pu(n,γ)	+10	-0.1	-0.2
^{239}Pu(n,f)	+1	∿0	∿0
Fe(n,γ)	-10	+0.1	+0.1
Σ_{tr}	-5	+2.2	+0.4
Σ_{tr} (core only)	-5	+0.9	—

[a] Ratio of C/E near the core center to that near the core edge.

TABLE 5. ZPPR-7A Comparison of Calculations for ^{238}U(n,f)

Calculation Method	Average C/E		Difference between Core and Blankets
	Core Drawers	Internal Blanket Drawers	
Diffusion Theory	0.860	1.079	25%
Transport S_4	0.891	0.989	11%
Transport S_4 with coupled core/blanket cell data	0.929	0.949	2%

TABLE 6. Summary of C/E Results for the Ratio ^{238}U(n,γ)/^{239}Pu(n,f) at the Midplane

Assembly/ Calculation[a]	Average C/E				
	Double Fuel Column	Single Fuel Column	Spiked Internal blankets	Normal Internal blankets	Radial blankets
ZPPR-7A: DT	1.111	—	—	1.068	1.066
S_4	1.104	—	—	1.075	1.073
ZPPR-7B: DT	1.103	—	—	1.059	1.063
S_4	1.096	—	—	1.066	1.070
ZPPR-7C: DT	1.113	1.073	1.075	—	1.068
S_4	1.107	1.072	1.079	—	1.074
ZPPR-4/1: DT					
Inner core	1.054	1.041	—	—	—
Outer core	1.081	1.078	—	—	—
Radial blanket	—	—	—	—	1.027

[a] DT: diffusion theory; S_4: transport S_4 calculation.

In ZPPR-7A and 7B, the microscopic ^{238}U fission rate varied by as much as a factor of two between adjacent fuel and blanket subassemblies. Diffusion calculations gave relative errors of 25% as shown in Table 5. A transport analysis reduced the differences to 11%, but the final resolution of this problem required improved multigroup cross-section processing which treated coupled core and blanket cells. Experiments with a pin sector in 7B showed that this effect was not unique to the ZPPR plate cells, and would also be present in the power reactor configuration. Similar problems, but reduced in magnitude, were also observed in conventional reactors across the core/blanket interfaces.

Comparison of reaction rate ratios gave C/E values within a few percent of those in conventional cores. In particular results for ^{238}U(n,γ)/^{239}Pu(n,f) shown in Table 6 confirmed the substantial increase in breeding gain calculated for the heterogeneous core. Differences in C/E between core and internal blanket zones of several percent indicated the need for more refined analysis.

5. CONTROL ROD WORTHS

Many control rod worth measurements were made throughout the ZPPR programs. An analysis has been completed, using consistent methods and data, for ZPPR-3/1B, four phases of ZPPR-4, and ZPPR-7B, 7C, and 7G. The calculations used diffusion theory, xy geometry, nine-group data with zone- and group-dependent bucklings for the full core height. The mean C/E ratios for each phase are compared in Table 7. More detail of individual rod worths can be found in References 2 and 3. A significant improvement in the experimental techniques was achieved for the ZPPR-7 measurements. In this core, 16 in-core fission chambers were used to monitor the subcritical reactivity, resulting in smaller experimental errors than for the ZPPR-3 and 4 measurements.

TABLE 7. Summary of ZPPR Control Rod C/E's

Assembly	Rods Included	Number of Measurements	Mean C/E	RMS Deviation
3/1B	All	22	1.096	0.025
4/1	"	8	1.092	0.021
4/2	"	5	1.074	0.037
4/3	"	5	1.073	0.027
4/4	"	8	1.088	0.018
7B	Inner ring	4	0.983	0.012
	Outer ring	6	1.031	0.016
7C	Inner ring	4	0.981	0.011
	Outer ring	6	0.997	0.010
7G	Inner ring	4	0.978	0.002
	Outer ring	20	1.042	0.019

The main feature of the control rod analysis was that significantly lower C/E values were obtained for the heterogeneous core. Additionally for 7B and 7G, C/E's for the inner ring were 5 to 6% lower than for the outer ring positions. This result is consistent with the analysis of the radial power distributions.

Large changes in rod worth, up to 60%, occured with redistribution of plutonium (7B→7C). These were well predicted by calculation. Experiments in ZPPR-4, which simulated build-up of plutonium in the radial blanket with depletion in the core, gave smaller change in rod worth. Control rod interactions were stronger in the heterogeneous core. For the six outer ring corner rods the interaction was +55% in 7B and +31% in 7C compared to 21% in ZPPR-3/1B.

TABLE 8. Corrections to Calculated Control Rod Worths

	4/1 Central Rod	7B 6 Inner Ring Rods	7B 6 Outer Ring Rods	7C 6 Inner Ring Rods	Uncertainty %
Reference C/E	1.087	0.965	1.078	0.972	2.0
Corrections, %					
Group condensation	-1.0	+0.9	-2.5	-0.7	0.5
Mesh size	+1.1	+2.4	+2.4	+2.3	0.5
Transport theory	-5.5	-4.6	-3.2	-3.2	0.5
Bucklings[a]	-2.5	-1.0	-1.0	-1.0	1.0
Plate streaming	-0.1	+2.6	-0.1	+1.3	0.5
Rod heterogeneity	-1.5	0.0	0.0	0.0	1.0
CRP streaming[a]	+1.8	+4.3	3.0	+3.9	0.5
Total correction	-7.5	+4.6	-1.4	+2.6	1.8
C/E after correction	1.012	1.011	1.064	0.998	2.7

[a] Estimated from results for a single rod at the center.

The control rod analysis (Table 7) indicated substantially different bias factors between conventional and heterogeneous cores. (Note, however, that the LMFBR design methods are not necessarily the same as used for the present ZPPR analysis, so that the actual design biases could be different from those in the table). An understanding of these results is essential before biases can be applied with confidence. Consequently, a detailed investigation of the approximations made in the analysis was started. The results obtained are shown in Table 8 for a few selected cases. Different corrections to the reference model for each case combine so as to reduce the initial discrepancies. As was the case for the power distribution, differences in C/E for the inner and outer positions in 7B are reduced by these refinements. Some studies of data sensitivities have also been made; a reduction 5% in ^{238}U capture was shown to give a further improvement of 2½% between the 7B inner and outer positions[3]. These studies are being extended.

6. SODIUM VOID REACTIVITY

Sodium void measurements, ranging from subassembly-sized regions to zones occupying a substantial fraction of the core volume, were made throughout the ZPPR program. A detailed analysis with current techniques was made for ZPPR-5. This showed the necessity of treating streaming effects in the ZPPR plate-type cells. Simple two component bias factors were shown to be an effective method for extrapolation of ZPPR results to LMFBR designs[4]. This technique was less accurate in regions near zone boundaries.

Experimental results for zones near the center of ZPPR-7A demonstrated reductions in the positive component of sodium worth compared to homogeneous ZPPR cores (Table 9). Calculations for ZPPR-7 gave less consistent comparisons with experiment than had been obtained with comparable calculations of ZPPR-5 measurements. Difficulties in the analysis resulted from modelling the complex internal geometry of the core with cylindrical models.

TABLE 9. Comparison of Sodium Void Reactivities

Zone	Experiment, ¢/kg Na	Calculation, ¢/kg Na		
		Non-Leakage	Leakage	C-E
Midplane to 305 mm				
ZPPR-2, 93 drawers	0.997 ± 0.006	1.736	−0.487	0.252
ZPPR-5A Zone 1C[a]	0.751 ± 0.008	1.611	−0.770	0.089
ZPPR-7A Fuel Ring 1	0.865 ± 0.009	1.129	−0.286	−0.022
305 mm to 457 mm				
ZPPR-5A Zone 1B[a]	−1.162 ± 0.010	0.861	−2.119	−0.096
ZPPR-7A Fuel Ring 1	−0.361 ± 0.123	0.499	−1.026	−0.166

[a] The zones are shown in Reference 4.

7. SUMMARY

The experiments in ZPPR-7 confirmed the principal benefits predicted for the heterogeneous core: lower sodium void coefficient and enhanced breeding ratio. The initial analysis showed substantially different C/E ratios than had been obtained in conventional cores. A more refined analysis was able to resolve many of these discrepancies, but also indicated a different sensitivity of several parameters to basic cross-section data.

REFERENCES

1. P.J. Collins et al., "Consistency of Fast Reactor Integral Measurements Using Cross-Section Adjustment," Trans. Am. Nucl. Soc. 27, 884 (1977).

2. H. McFarlane et al., "Measurement and Calculation of Control Worths in ZPPR Assembly-4," Trans. Am. Nucl. Soc., 27, 906 (1977).

3. M.J. Lineberry et al., "Physics Studies of a Heterogeneous LMFBR," Nuclear Technology, to be published (1978).

4. C.L. Beck et al., "On the Extrapolation of ZPR Sodium Void Measurements to the Power Reactor," Fast Reactor Safety and Related Physics, Chicago, CONF-761001, 512 (1976).