

September 5, 1979

ZPR-TM-349

CONF-790933--4

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MASTER

APPLIED PHYSICS DIVISION

ZPR Technical Memorandum No. 349

Experimental Studies of Large Conventional
LMFBR Cores at ZPPR*

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*Paper presented at the IAEA Symposium on Fast Reactor Physics
Aix-en-Provence, France, September 1979. ✓

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ABSTRACT

Results of a critical experiment program for 700 MW(e) LMFBRs are reviewed. Both a clean benchmark assembly and one simulating a power reactor design were constructed. Experiments discussed include reaction rate distributions and ratios, control rod worths and interactions, and sodium coefficients. Analysis of these experiments with ENDF/B Version IV cross sections is reported. The comparison between calculated and measured parameters is not too different in these cores than in the 350 MW(e) assemblies. An exception is that the radial fission rate is calculated up to 3% too high at the edge of the inner core relative to the core center.

A series of critical experiments has been completed recently at the Zero Power Plutonium Reactor (ZPPR) which provides integral reactor parameters for conventional two-zone LMFBRs of about 700 MW(e). The program was conducted on ZPPR assemblies 9 and 10, the latter core being a cooperative study between the U.S. and Japan. Together these assemblies form an initial data base for assessment of physics issues in LMFBRs of this size. This paper discusses the most significant results: criticality, power distributions, control rod worths, and sodium-void reactivities.

Data related to the three assemblies considered here are shown in Table I, and Fig. 1. In all three systems the fuel simulated mixed-oxide with a volume fraction of about 0.40, all three had core heights of 1.018 m, and each had a 0.406 m axial blanket followed by a 0.133 m iron reflector. In the radial blankets depleted oxide was simulated with a heavy metal volume fraction of about 0.55. ZPPR-9 was a clean physics benchmark with a core volume of 4600 liters, and fulfilled much the same role that ZPPR-2 did in an earlier series of benchmark

experiments on smaller systems. ZPPR-10A and 10B had about the same core volume as ZPPR-9, but included nineteen control rod positions (CRPs) and more typical core outlines. CRPs were all sodium-filled in 10A, while in 10B seven control rods (CRs) made of natural B_4C were inserted (the center rod plus six rods on the flats of the hexagonal outer control ring). Although not discussed here, later phases of ZPPR-10 included brief experiments on systems of about 6000 liters core volume.

Sectional views of the major drawer loadings used in ZPPR-9 and 10 are shown in Fig. 2. Enrichment changes that were required in the three critical configurations were accomplished by mixing the number of single-column and double-column fuel drawers. The inner core of ZPPR-9 was particularly simple in that it was composed entirely of identical single-column fuel drawers.

All calculations were done with ENDF/B Version IV data, processed through MC²-II and SDX [1,2] to produce a multigroup library with resonance and plate heterogeneity effects treated. To produce the reference 28-group library used in most calculations discussed here, the final energy collapse was done separately for infinite media of each region of the reactor.

Criticality Calculations

The eigenvalue predictions for the three assemblies are of particular interest since differences in calculated k_{eff} are related to the accuracy of prediction of the reactivities of fuel, CRPs, and control rods.

Experimental excess reactivities were obtained after correcting for operational shim rods in the reference configuration, for temperature (to 293K), and for ^{241}Pu decay. Total uncertainties of about 0.02% Δk have been estimated for (a) measurement of shim rod worths, (b) calculated β_{eff} used to convert reactivities to Δk units, (c) interface gap of the split-table assembly, (d) uncertainty in the average core temperature, (e) uncertainty in ^{241}Pu decay constant, (f) void slots in the operational safety rod locations, and (g) uncertainties in isotopic compositions.

The reference calculations used xyz diffusion theory in 28 groups with Benoist diffusion coefficients to treat streaming in the plate cells. In the xy plane the mesh size was one ZPPR drawer (55 x 55 mm). Eigenvalues from these reference calculations are shown in Table II.

The effects of some refinements in the calculations are also shown in Table II. Mesh and transport (S_4) corrections

have been obtained from xy models. These are largest in 10B because of the inserted control rods. An axial transport correction was obtained for ZPPR-9 from comparisons of rz and xy calculations. It is well known that diffusion calculations overestimate the axial leakage in the CRPs. Corrections for this effect have been calculated for a central CRP in ZPPR-9 and extrapolated to the off-center positions in ZPPR-10A and 10B.

The diffusion theory result for ZPPR-10A is lower than that for ZPPR-9 because of errors in calculating leakage in the CRPs. The transport corrections lead to reasonably good agreement. In the conversion of core 10A to 10B, the seven control rods which were part of the 10B configuration were first inserted so that the core was subcritical by 16.6\$. Calculations overestimate this reactivity by 5 to 8% (discussed later). The core was then made critical by replacement of single column fuel drawers by double column drawers. However, this change is typically overestimated by a larger percentage (12 to 15%) with ENDF/B data. Thus the higher k_{eff} calculated for 10B is qualitatively in agreement with the respective errors in calculating reactivity worths of control rods and fuel.

Several refinements to the calculations have yet to be evaluated. For example, an alternative treatment of outer core cell heterogeneity in ZPPR-10B gave a difference of 0.05% Δk for the reference reactor. Also, it would be desirable to formulate anisotropic diffusion coefficients to treat streaming in the off-center CRPs. It is clear that it will be very difficult to calculate all necessary corrections at the 0.02% level to match the experiments.

With respect to criticality, the conclusion is that:

- Calculated results for the large cores are only 0.1% to 0.2% higher than those for a range of smaller assemblies [3]. This result is consistent with studies of variation in k_{eff} with changes in nuclear data which showed similar sensitivities for ZPPR-2 and ZPPR-9.

Reaction Rate Measurements

Detailed reaction rates were measured in ZPPR-9 for all regions of the core and blankets. In ZPPR-10A and 10B, most measurements were made at the axial midplane to characterize the distributions in the presence of control rods and CRPs. Measurements were made with foils placed between plates of the cells. Additional fine structure measurements,

including some in special cells with split fuel plates, were used to convert the foil reaction rates to cell-averaged values. The statistical uncertainty on each measurement was less than 1% (1 σ) except for $^{238}\text{U}(n,f)$ in the blanket zones. Uncertainties in calibration and foil-to-cell average conversion factors were estimated to be 1% to 2%. Calculations were identical to the reference methods described in the previous section, except that the operational shim rods used to control reactor power were included in the model.

In the IAEA/NEACRP comparison calculations for a large fast reactor [4], large differences were noted in the power shape with different cross section bases (on the order of 10% variation). Sensitivities of the ZPPR-9 fission distribution to key cross sections have been shown to approach the larger IAEA/NEACRP model [5]. Thus one of the interesting questions to be answered in the ZPPR-9 and 10 program was whether or not discrepancies exist in the radial fission rate distribution calculated with ENDF/B-IV data. In Table III, the data have been summarized to show radial effects. It was observed that essentially the same C/E information was obtained from $^{235}\text{U}(n,f)$ and for $^{239}\text{Pu}(n,f)$, within the core zones, and C/E results for these two fission rates have been averaged. In addition C/E's have been averaged in steps of three adjacent locations, corresponding to approximately one subassembly, and averaged across the outer core. Comparisons of results along the x and y axes is a test of the treatment of shim rods and plate streaming (and a core cell asymmetry which was present in ZPPR-9), although in cores 10A and 10B a basic difference along the axes existed because of the CRPs and control rods.

Results from ZPPR-9 indicate that calculated fission rates are overpredicted by between 2% and 3% at the edge of the inner core or in the outer core, relative to the core center. Values of C/E along the two axes differ by about 1% and are not as close as desirable. Results from ZPPR-10A show smaller radial disagreement than for ZPPR-9. The next stage in the analysis is to obtain fine mesh xy transport calculations, which are expected to produce some changes, particularly in ZPPR-10A and 10B.

Table IV shows C/E values for the principal reaction rate ratios averaged over positions in the inner core and outer core of the three assemblies. Each value represents the average of about 30 results in the inner core and ten in the outer core. The results are similar to those obtained in previous ZPPR assemblies with ENDF/R data. In particular, the $^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)$ ratio is overestimated by 7 to 9%. It is interesting to note that a downward revision of the ^{238}U capture cross section of 5% would reduce the discrepancy in the radial fission rate comparison by about 1.5% [5].

The conclusion of the reaction rate experiments in ZPPR-9 and 10 is that:

- Discrepancies of up to 3% exist between calculated and measured radial fission rates. This is much smaller than the variation in computed power shapes among the participants in the recent IAEA/NEACRP comparison.
- ^{238}U capture rates continue to be significantly overpredicted when ENDF-B/IV is used to interpret the foil measurements done at ZPPR.

Control Rod Worths

A large number of control rod worth measurements were done in ZPPR-9 and 10. The objectives of these experiments were to (1) measure worths of boron control rods, individually and in groups, (2) to study rod interaction effects, and (3) to examine size, heterogeneity, and composition effects, including limited use of tantalum and europium oxide control materials.

Since ZPPR-9 contained no control rod positions, these were added as needed by replacing fuel drawers with sodium-filled drawers. No more than seven of these special CRPs were inserted simultaneously, and most ZPPR-9 measurements were made with one or two CRPs. In ZPPR-9 most rods were constructed of drawers completely filled over the entire core length with natural B_4C plates, in a 3 x 3 array of matrix positions. Most of the ZPPR-10 rod measurements used drawers half-filled with B_4C , and half-filled with sodium (see Fig. 2). One worth measurement with the lighter 50/50 rod was done in ZPPR-9 for normalization.

Rod worth measurements were made by a version of the modified source multiplication technique in use at ZPPR [6,7]. There are two major elements to this well known technique: (1) calibration of an initial reference subcritical reactivity and (2) determination of subsequent subcritical states by detector responses, with corrections for changes in detector efficiencies, importance of source neutrons, and β_{eff} .

Calibration of the reference subcritical state introduces uncertainties which propagate straight through to all final reactivity values. This uncertainty is estimated at 1.5 - 2%, most of which comes from the delayed neutron parameters used to analyze the rod drop experiment which establishes the reference subcriticality. This systematic uncertainty is highly correlated among the ZPPR-9, 10A, and 10B assemblies,

since the reference subcritical states of all three were made to depend on measured delayed neutron parameters for 10A, with changes calculated for ZPPR-9 and 10B. Thus the calibration uncertainty affects absolute control rod worth, but has small impact on C/E comparison of results among the three cores.

Sixty-four fission chambers were located in the ZPPR-9 and 10 assemblies for use in source multiplication measurements. With each measurement a nine-group inhomogeneous diffusion calculation was used to provide an efficiency correction (changes in individual detector responses relative to the reactor fission integral), and an effective source correction (changes in the total importance of source neutrons relative to the average importance of a fission neutron). Each of the sixty-four detectors resulted in a reactivity prediction, and these were fitted to a linear relationship between reactivity and efficiency ratio to help eliminate any bias in calculated efficiency changes and also to improve statistics. Random errors due to count statistics and efficiency changes were reduced to the order of tenths of a percent, leaving the effective source correction as the major source of uncertainty. This was rather arbitrarily assumed to be about one-tenth of the magnitude of the correction itself, resulting in an uncertainty in the 0.1 - 3.0% range, but generally less than 1%. Changes in β_{eff} were not applied; the resultant error does not affect the comparison of calculation and experiment, but only the absolute reactivity values. The calculated change in β_{eff} was generally a few tenths of a percent.

For all cases reported, rod worths were taken relative to sodium-filled CRPs. Reference calculations were made with nine-group diffusion theory in xy geometry. The mesh area chosen was equal to the area of one ZPPR drawer. Energy and region dependent bucklings were used to account for axial leakage; these were derived from rz calculations by integrating leakage over the full core height. Bucklings applied to all CRPs and CRs came from separate calculations with central CRPs or CRs.

Results for single rods and groups of six rods are shown in Table V. Corrections have been applied where presently available for transport (from S_4 calculations), mesh, plate streaming (Benoist procedure), group condensation (twenty-eight to nine groups), buckling approximation (rz versus r or xyz versus xy calculations), and CRP streaming (S_4 calculation in rz geometry of a single, central CRP).

In ZPPR-10A the C/E from either the reference or corrected calculation is about 1% higher for the six inner ring rods than for the central rod, and 4% higher for the six outer ring rods. The increase is also noted in 10B when the available corrections are applied. The exception is ZPPR-9 where the C/E is lower in the inner ring; this is unexplained but may be tied to absence of CRPs.

The center rods have corrected C/E values of about 1.05, and these compare to values of about 1.01 for control rod experiments in CRBR-related assemblies which were analyzed with similar methods [3].

Interactions of control rods must be well known to ensure adequate reactor control margins. Potential interactions grow as reactor size increases because of an increase in flux sensitivity to material perturbation. Worths of rods in the presence or absence of other rods were part of the ZPPR-9 and 10 program.

Results for a number of different banks of rods are shown in Table VI. Interactions in excess of 50% are observed, but generally the reference method for control rod calculations predicts these interactions to within a few percent. Interaction effects between rods located in the inner ring are typically smaller than interaction effects of rods located in the outer ring.

In Table VII, rod interactions are viewed from a different perspective. Here single rods are inserted in the presence of other rods, and large changes in the single rod worth are observed. For instance, the worth of the central control rod changes by an order of magnitude when measured first relative to an inserted bank of six inner ring control rods and then relative to an inserted bank of six outer ring control rods. These interaction effects are predicted accurately with the reference methods.

A series of measurements was made at the center of ZPPR-9 and in the central CRP of ZPPR-10A to study special control rod effects. The ZPPR-9 experiments investigated rod size and composition. All C/E values were within 1.5% for (i) CRs consisting of solid natural B_4C plates in 3 x 3, 2 x 3, and 2 x 2 drawer sizes, (ii) a 3 x 3 CR of 50/50 B_4C and sodium mixture (see Fig. 2), and (iii) tantalum and europium oxide 2 x 2 CRs.

ZPPR-10A experiments were directed mainly at rod heterogeneity. Special control rods (3 x 3) were constructed of B_4C and stainless steel pins (9.5 mm o.d.) in different patterns

with both fully-enriched and natural boron. About 1% change was noted in C/E for rectangular versus circular arrangements of enriched pins, or for a rod with half as many enriched pins. About 0.5% increase in C/E was observed when natural pins were substituted for enriched pins in both a circular and rectangular arrangement. Finally, 0.4% increase in C/E was noted when the effective cross sectional area of the rod was increased with constant total number of enriched pins (rod worth increased by 14%).

In summary the control rod measurements of ZPPR-9 and 10 indicate:

- Rod worth C/E values generally increase with radius of the rod location, consistent with reaction rate results. When similar methods are applied the central rod C/E of about 1.05 is 4% higher than observed in 350 MW(e) conventional cores.
- Rod interactions are large, up to 50% in the outer ring, and are predicted to within a few percent with nine-group diffusion theory.
- Effects on C/E ratio due to rod size, boron loading, and rod heterogeneity are small, less than 1.5%.

Sodium Void Reactivities

Prediction of sodium coefficients in large LMFBRs could impact the choice of either a conventional or heterogeneous core arrangement, and several sodium void experiments were done on ZPPR-9 and 10. Here the discussion will focus on reactivities associated with voiding central zones, and on effects near a CRP (10A) and a fully-inserted CR (10B).

Two types of measurements were done. The most direct method is the familiar one of defining a subcritical reference state, and then removing all or part of the sodium from selected zones. Standard source multiplication with the sixty-four fission chambers described above is used to determine reactivity (efficiency and source corrections have been shown to be less than 1%, even for substantial voided zones). As with control rod worths, there is an uncertainty of about 1.5% in the reactivity of the reference state, but again this is made to be strongly correlated among the three assemblies.

Determining the spatial characteristics of the sodium coefficient by zone voiding involves lengthy periods for loading changes. An alternative method is sometimes used at ZPPR where the worth of sodium in a single drawer is determined

by oscillating the drawer with and without sodium. This technique gives a rapid measure of the sodium coefficient, but of course omits any effect due to spatial or spectral redistribution of the flux. The shape of the radial sodium coefficient derived by drawer oscillations, when compared to a smooth curve, implies the real uncertainty in the measurements is about $\pm 5\%$. Only about half of this value can be explained by counter statistics, drawer positioning, and temperature drift; the remainder needs further study.

Central zones voided in ZPPR-9 had radii of 94, 190, and 307 mm (9, 37, and 97 drawers respectively). For each radial zone, four axial steps of ± 203 , 406, 609, and 686 mm were voided. In ZPPR-10 the same axial increments were voided to radii of 190, 274, and 419 mm. The central CRP or CR of ZPPR-10 always retained sodium. In each of these zones, about 75% of the sodium was removed; the sodium carbonate plates shown in Fig. 2 remained. To ensure that this caused no bias, a special experiment was done in ZPPR-9 in which a central zone was constructed with sodium replacing the carbonate, and then a zone was voided. The C/E was identical to that obtained when 75% of the sodium was removed.

Results of the sodium void experiments for the center-most axial zone are shown in Table VIII. The reference calculations were with 28-group diffusion theory in rz geometry (ZPPR-9) or xyz geometry (ZPPR-10). Cross sections in the voided zones were derived from the asymptotic voided spectrum. The corrections shown in the table used methods described previously. The importance of the streaming correction is reaffirmed as is the transport correction near control rods [8].

An estimate of the effect of less rigorous modeling can be made from the C/E values in Table VIII when xy first-order diffusion-perturbation (FOP) calculations (constant transverse buckling) were done, or when rz exact diffusion-perturbation (EP) was used. These values are fairly typical for near-central zones: xy FOP calculations with constant buckling generally will be within $\pm 10\%$ if care is taken to ensure that the proper half-height is chosen. Homogenizing CRPs (and more particularly CRs) in rz calculations can result in large errors. While this last problem is widely appreciated, it appears to be of greater magnitude in large reactors where the calculated flux shape is more sensitive to modeling approximations.

Finally Table VIII shows the results of first-order diffusion perturbation calculations (xy geometry, constant buckling with streaming corrections) of the single-drawer sodium coefficients. C/E numbers quoted are averages of all values in

the inner core; uncertainties shown are the standard deviations of the mean values. Results are consistent with the zone C/E values within the errors, indicating that the drawer oscillation technique may be a useful substitute where needed and where several measurements can be made to overcome the uncertainty of a single measurement.

Similar results were obtained for other radial steps near the axial midplane, as might be expected since the maximum radius is not very large in these experiments. In the axial direction, C/E values obtained are fairly consistent through most of the core zone, but break down near and in the axial blanket where the void reactivity changes sign, as shown in Table IX. The numbers shown come from rz exact diffusion-perturbation calculations (with streaming corrections), with all entries scaled to make the centermost C/E identical to the corrected reference results of Table VIII. The fall off in C/E in the outer axial zones is consistent with the evidence that the Benoist procedure overestimates the streaming correction [2,8].

In the series of critical experiments related to CRBR, near-central zone sodium coefficients were predicted with C/E values of 1.25 for ZPPR-2 (the clean core) and about 1.10 for ZPPR-5 (nineteen CRPs) using methods similar to those employed here [8].

Conclusions for the sodium-void experiments at this stage are:

- Sodium coefficients obtained by voiding zones near the center of the assembly are predicted with C/E values of about 1.17 when refined calculations are done. Variations of about 10% can be observed with more simple methods. No appreciable bias exists in predicting sodium coefficients around withdrawn or inserted control rods.
- No substantial change in C/E is observed in comparing the ZPPR-9 and 10 results with earlier results from smaller conventional cores.

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TABLE I. Reactor Design Parameters in
ZPPR-9 and 10

	ZPPR-9	ZPPR-10A	ZPPR-10B
<u>Volume</u>			
inner core (ℓ)	2525	2522	2522
outer core	2074	2074	2074
<u>Core</u>			
critical mass (kg fissile Pu)	1956	2071	2292
Pu enrichment ^a			
inner core	0.1096	0.1181	0.1395
outer core	0.1608	0.1692	0.1893
<u>Control</u>			
No. of CRPs	none	19	19
sodium-steel	- -	19	12
B ₄ C-sodium-steel	- -	0	7

^aPu/(U+Pu), with the plutonium approximately
88% ²³⁹Pu.

TABLE II. Comparison of Calculated k_{eff} Values

	<u>ZPPR-9</u>	<u>ZPPR-10A</u>	<u>ZPPR-10B</u>
<u>Experiment (E)</u>	1.00198	1.00223	1.00158
(1 σ uncertainty)	(0.00021)	(0.00022)	(0.00024)
<u>Reference calculation:</u>			
xyz diffusion	0.98394	0.98095	0.98337
<u>Corrections:</u>			
xy mesh	-0.00040	-0.00070	-0.00303
xy transport	+0.00138	+0.00284	+0.00441
axial transport	+0.00052	+0.00316	+0.00220
<u>Corrected Calculation (C)</u>			
C/E	0.9835	0.9841	0.9854

TABLE III. Tests of Calculated Radial Fission Distributions^a

		Ratio Calculation/Experiment					
		ZPPR-9		ZPPR-10A		ZPPR-10B	
		x-axis	y-axis	x-axis	y-axis	x-axis	y-axis
Inner Core							
center	1	1.000	1.000	CRP	1.000	CR	1.000
	2	1.001	1.001	0.990	0.993	0.989	0.991
	3	1.004	1.010	0.989	0.989	0.987	0.992
	4	1.014	1.000	0.997	1.001	0.988	0.998
	5	1.023	1.016	1.003	1.007	0.998	1.014
edge	6	1.034	1.021	CRP	1.010	CR	1.020
Outer Core Average		1.027	1.016	1.010	0.993	1.015	0.995

^aC/E ratios for $^{235}\text{U}(n,f)$ and $^{239}\text{Pu}(n,f)$ have been averaged. Values in the inner core are the average for three adjacent drawers and represent approximately one subassembly.

TABLE IV. Summary of Reaction Rate Ratio C/E Values

Ratio	Zone	C/E ^a		
		ZPPR-9	ZPPR-10A	ZPPR-10B
$^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)$	Inner Core	1.086	1.071	1.072
	Outer Core	1.091	1.082	1.090
$^{235}\text{U}(n,f)/^{239}\text{Pu}(n,f)$	Inner Core	1.024	1.028	1.022
	Outer Core	1.028	1.026	1.021
$^{238}\text{U}(n,f)/^{239}\text{Pu}(n,f)$	Inner Core	0.938	0.929	0.935
	Outer Core	0.971	0.922	0.909

^aRMS deviations for the $^{238}\text{U}(n,\gamma)$ and $^{235}\text{U}(n,f)$ ratios are between 0.9 and 1.6%. For the $^{238}\text{U}(n,f)$ ratio deviations are between 1.6 and 3.0%.

TABLE V. Single and Multiple Control Rod Worths in ZPPR-9 and 10

	Center Rod		Six Inner Ring Rods			Six Outer Ring Rods		
	ZPPR-9	10A	ZPPR-9	10A	10B	ZPPR-9	10A	10B
<u>Measured Value (\$)</u>	3.34	2.67	13.75	13.54	11.65	14.96	9.75	11.22
<u>Reference Method C/E</u>	0.986	1.018	0.959	1.032	1.059	0.996	1.058	1.062
<u>Corrections (%)</u>								
Transport	-3.8	-3.6	-3.7	-4.6	-5.7	-1.0	-1.9	-1.9
Mesh	+6.1	+4.6	+5.7	+4.3	+4.2	+6.1	+3.8	+4.4
Plate streaming	+2.3	+1.9	+2.3	+2.9	+1.8	+0.7	+0.3	-0.1
Total	+4.6	+2.9	+4.3	+2.6	+0.3	+5.8	+2.2	+2.4
<u>Corrected C/E^a</u>	1.031	1.048	1.000	1.059	1.062	1.054	1.081	1.087

^aCentral rod C/E values become 1.046 and 1.048 for ZPPR-9 and 10A when further corrections for group condensation, bucklings, and CRP streaming are applied (-0.8, +1.0, and +1.3% in ZPPR-9; -0.5, -1.1, and +1.6% in ZPPR-10A).

TABLE VI.

Interaction Effects of Rod Groups

Rod Group	ZPPR-9			ZPPR-10B		
	Group Rod Worth, \$	Interaction ^a Effect, %	Calculated Interaction, %	Group Rod Worth, \$	Interaction ^a Effect, %	Calculated Interaction, %
Inner ring of 6 rods	13.75	-4.0	-3.9	11.65	+4.2	+4.5
Outer ring of 6 rods	14.96	+52.0	+49.0	11.22	+54.5	+55.3

$${}^a\text{Rod interaction effect } I = \left\{ \frac{\text{group rod worth}}{\text{sum of individual rod worths}} - 1 \right\} \times 100\%$$

TABLE VII. Worths of Single Control Rods in the Presence of Other Inserted Rods

Position of Single Rod Inserted	Rod Configuration Already in Core	ZPPR-9		ZPPR-10A		ZPPR-10B ^a	
		Measured Worth, \$	Calculated Worth, \$	Measured Worth, \$	Calculated Worth, \$	Measured Worth, \$	Calculated Worth, \$
Center rod	6 inner ring rods	0.41	0.44	0.97	0.90		
Center rod	6 outer ring rods	5.60	5.53	4.07	4.03		
Inner ring rod ^b	5 inner ring rods			2.49	2.55	2.09	2.16
Inner ring rod ^b	5 inner ring rods + 6 outer ring rods			3.63	3.67		
Outer ring rod ^b	5 outer ring rods	3.99	3.97	3.07	3.17	3.31	3.51

^aFor ZPPR-10B the rod configuration description is in addition to the reference pattern (center rod and 6 outer ring rods).

^bThe worth of a single inner or outer ring rod may be derived from Table VI.

TABLE VIII. Comparison of Central Zone and Single-Drawer Sodium Void Reactivities

	ZPPR-9	ZPPR-10A	ZPPR-10B
Zone radius (m)	0.307	0.419	0.419
Measured reactivity, ρ (E) ^a	28.43	42.50	36.18
Reference diffusion calculation, ρ (C)	33.05	49.75	39.45
correction for streaming	-2.1%	(-2.5%) ^b	(-6.5%) ^b
mesh	0	-0.5%	+3.0%
transport	-1.1%	+1.0%	+7.2%
Corrected C/E	1.13	1.18	1.20
rz - EP C/E	1.14	1.25	1.43
xy - FOP C/E	1.09	1.14	1.06
C/E, inner core average of single-drawer sodium worth	1.18 ± 0.04	1.13 ± 0.04	1.16 ± 0.05

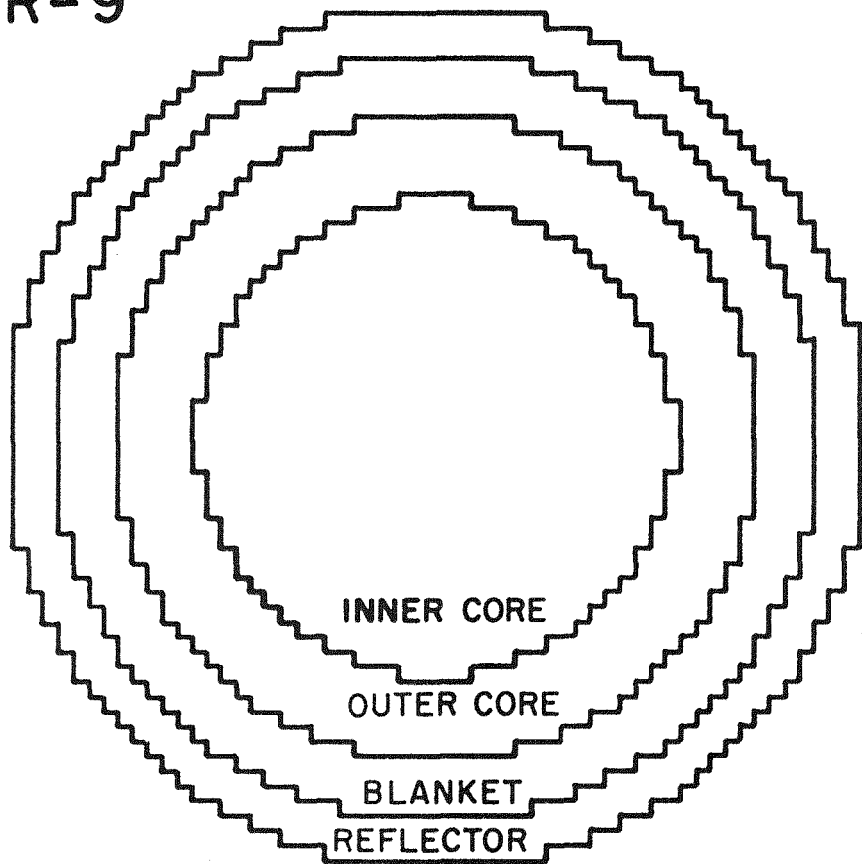
^aUncertainties are about 2%, and include estimates for errors of reference state (~ 1.5%), and random errors in the measurement (~ 1.0%).

^bThis correction is already included in the reference method and is shown for completeness in this Table.

TABLE IX. Axial Distribution of C/Es for Zone Void Worths

Void Step Description, Axial Extent, mm	C/E Values		
	ZPPR-9	ZPPR-10A	ZPPR-10B
+ 0 - 203	1.13	1.18	1.20
+ 203 - 406	1.15	1.12	1.24
+ 406 - 508	0.98	1.04	1.21
+ 508 - 686 (ax. blkt)	0.82	0.83	1.03

ZPPR-9



ZPPR-10

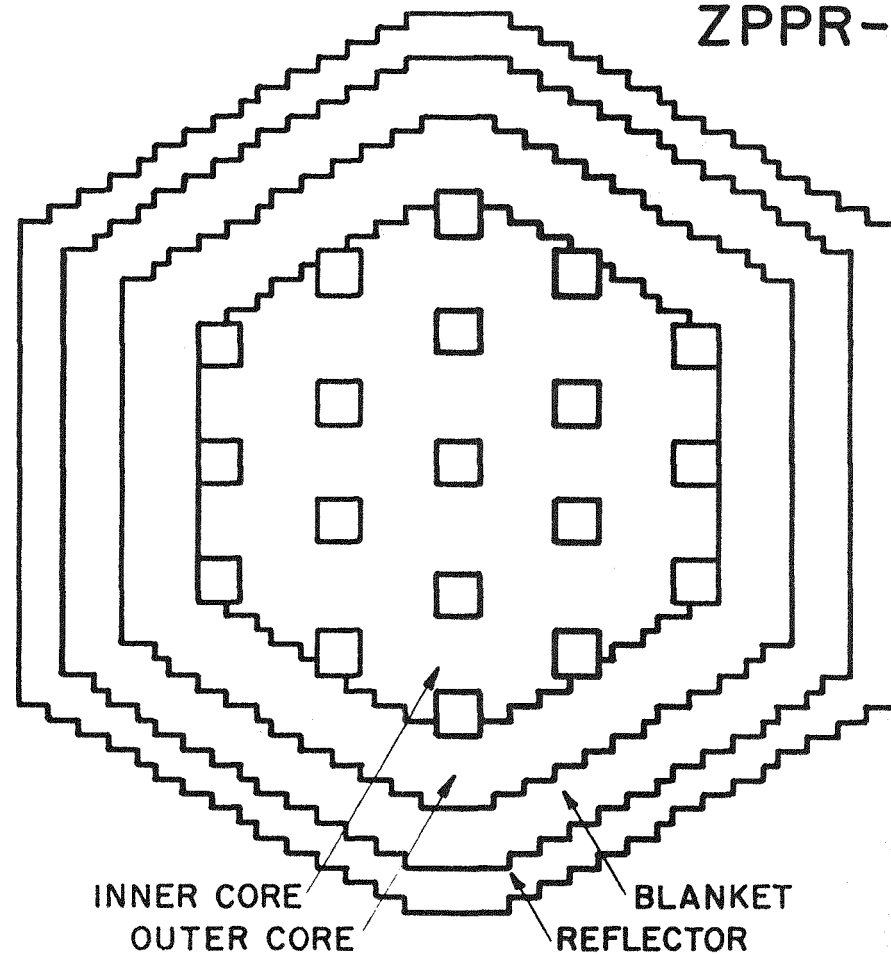
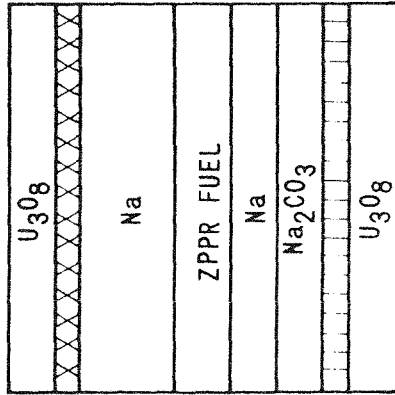
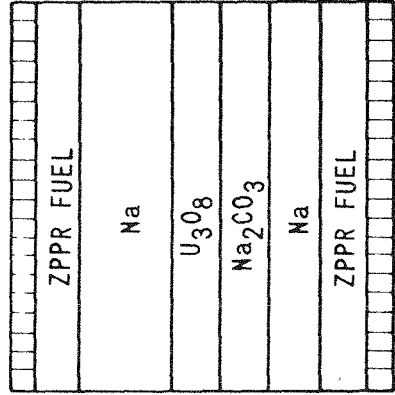


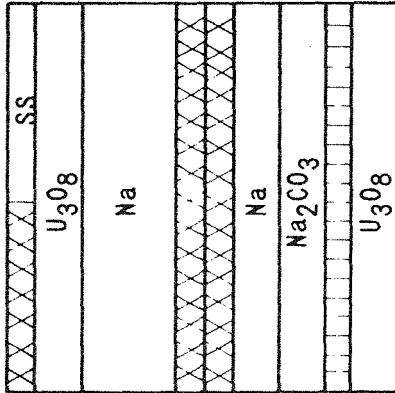
Fig. 1. Sectional Views of ZPPR Assemblies 9 and 10



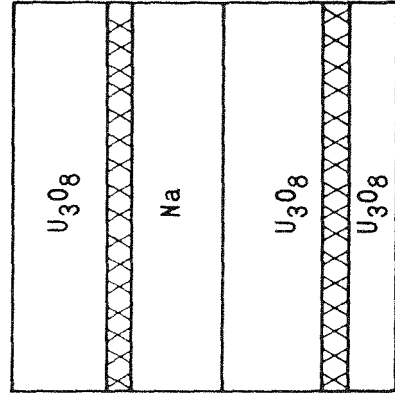
SINGLE FUEL COLUMN



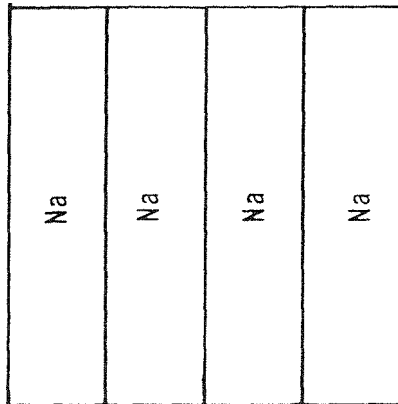
DOUBLE FUEL COLUMN



AXIAL BLANKET



RADIAL BLANKET



SODIUM CHANNEL



CONTROL ROD

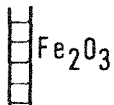


Fig. 2. Sectional Views of Major Drawer Loadings