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ZPPR STUDIES OF CONTROL ROD INTERACTIONS IN HETEROGENEOUS CORES*

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Introduction

Control rod interactions in several heterogeneous configurations have been measured and compared with calculations in recent ZPPR programs. In some cases these interactions are factors of 2-3 higher than comparable rod interactions in equivalent homogeneous cores. Variations in rod interactions have been observed in heterogeneous cores with different degrees of coupling between the core rings.

The significance of rod interactions to designers is primarily in establishing rod bank worths and in possible licensing implications. In the heterogeneous cores studied at ZPPR, the worth of the bank of outer ring control rods is considerably enhanced by a strong positive interaction among the rods. The licensing question has to do with removing a rod from that bank, as in the case of a rod run-out, stuck rod, or loading error. Removal of a single rod from a group of six rods results in a very large apparent worth for the single rod removed.

Configurations

The configurations (designated ZPPR-7B, 7C, 7G, and 8F) in which the rod interactions were measured, as well as others in the ZPPR-7 & 8 series, were built in support of the heterogeneous core design for the CRBR project[1]. Sectional views of the configurations are shown in Figs. 1-3. ZPPR-7B & 7C were early designs which differed because plutonium build-up was simulated in the internal blankets of 7C. The 7G configuration had six additional rod positions in the outer ring and three fewer in the inner ring, as well as a slightly modified internal blanket ring. In ZPPR-8F the last internal blanket ring was substantially modified to enhance the worth of the rods on the flats of the hexagon.

A consistent rod numbering scheme has been used to describe the experiments, although the number and distribution of rods differed among the four configurations. This numbering scheme is based on that for the 19 rods in the homogeneous CRBR design. Among the several CRBR designs, allowable rod positions (CRPs) remained inviolate, although the number of rods varied from 12-19. The six inner ring positions (2,3,...7) are referred to as the row-4 (R4) rods, while the 12 outer ring positions (8,9,...19) are the row-7 (R7) rods. Rods on the flats of the hexagon are designated by an F, while those on the corners are designated by C. Hence, the six outer ring corner rods (8,10,12,14,16,18) are known as 6R7C.

Experimental Technique

The modified source multiplication technique, calibrated by inverse kinetics analysis of a rod drop, was used for all measurements. The basic method was described in detail by Carpenter[2] in a paper at the NEACRP specialists meeting in 1976. Improvements in precision since that time have allowed rod interactions to be measured with confidence.

Uncertainties in rod worth measurements for this series are in the range of 0.5 - 2.0% for statistics. For symmetric patterns, uncertainties in the source correction add another 0.1 - 0.3%. For very asymmetric configurations that are far subcritical, the latter uncertainty can be as much as 2 - 3%. The calibration error is about 0.8% and the change in β_{eff} is less than 0.7% for all configurations. Overall uncertainties for rod interactions are typically 2 - 4%.

Calculational Method

Calculations were made by a method commonly used for control rod analysis at ZPPR and elsewhere[3]. After processing the ENDF/B-IV data with the MC^2-II and SDX codes to treat ZPPR cell heterogeneity, a 28-group library was obtained containing cross sections appropriate to each reactor region. The following method was then used for the "reference" calculations:

- xy diffusion theory
- 9 energy groups
- 4 mesh points per ZPPR matrix position, equivalent to 16 mesh points per CRP (or subassembly-sized region)
- zone and group-dependent pseudo-absorption cross sections derived to match the axial leakage at the core/axial blanket interface
- rod worth defined as $-\Delta k/(k_1 k_2 \beta)$.

Control Rod Interactions in ZPPR-7B and 7C

The ZPPR-7B and 7C configurations, contained six row-4 and six row-7 control rod positions. The rod measurements and calculations are described in detail in Ref. 1 and only a selection of the results are included here. Assembly 7C was identical to 7B in the zone layout but a part of the fuel was moved from fuel regions into the internal blankets to simulate conditions later in the burnup cycle. The reference configurations for both assemblies contained only CRPs. For simplicity in the subsequent analysis, there was no simulation of partly inserted control rods. The change from 7B to 7C produced very large differences in power distributions, control rod worths and other physics parameters.

Control rod interactions in 7B and 7C are shown in Table I. (Interactions are defined as the percentage difference between the worth of a group of rods and the sum of the individual worths.) The largest interaction is 55% for the

6R7C rods which is reduced to 30% in 7C and may be compared with a value of about 20% for a similar rod group in a homogeneous core. Table I also shows the differences in rod worths between 7B and 7C. The row-4 rod worths are 40 to 60% higher in 7C while the row-7 rod worths are 20% lower in some cases. These changes were well predicted by calculation.

Control Rod Interactions in ZPPR-7G

The ZPPR-7G loading with fifteen control rod positions is shown in Fig. 2. The change from 7B to 7G also involved the addition of blanket subassemblies in row 6. The reference 7G core was made critical by the addition of fuel drawers at the outer edge rather than by a change in fuel enrichment. This, plus the addition of blanket assemblies, results in rod worths and interactions being significantly different from those in 7B, but the absolute changes were regarded as less important than the ability to check the C/E biases with a uniform fuel drawer loading.

The interaction effects for rods in the outer ring and for rods in the inner ring are given in Tables II and III. For the outer ring, the interactions range from -20% for two adjacent rods to +65% for the bank of six corner rods. This latter interaction is higher than for the same case in ZPPR-7B, (+55%), because of the changes in core configuration. For the inner ring rods, the interactions are only a few percent. All these interaction effects are well predicted by calculation, reflecting the consistency between C/Es for the basic measurements.

An alternative way of treating interaction effects is to derive the apparent worth of inserting a rod (or rod group) when other rods are already inserted in the core. This is necessary when considering rod run-out or stuck-rod reactivity effects. Table IV shows the variation in the apparent worth of inserting one row-7 corner rod in several different cases. The case of most interest is that with 5R7C rods inserted. This case shows that a rod "run-out" from the bank of six primary rods, in the fully inserted condition, results in a reactivity increase of 7.4$. This compares with the single rod worth of 2.1$ or the mean worth of 2.8$ for each rod in the bank. The calculations slightly overpredict these interactions in each case.

Interactions between the row-4 and row-7 rods are shown in Table V. The worths of the inner ring rods, both singly and in groups, are compared with no outer ring rods, with 6R7C rods, and with 5R7C rods. With the six outer ring rods inserted, the inner ring worths are increased by between 9 and 18%. With one missing rod in the outer ring, the inner ring rod worths are strongly perturbed: Rod 6, nearest the missing row-7 rod position, is increased in worth by 100%, while rod 4, the most separated from the missing position, is decreased in worth by almost 50%. However, the total worth of the bank of 3 inner ring rods is not significantly changed.

Some other rod interaction results are given in Table VII. The first case, showing the change in worth of rods 16 and 17 -- two adjacent outer ring rods -- is important for defining control requirements. This case simulates a "stuck" secondary rod adjacent to a primary rod which has "run-out". The apparent worth of the pair of rods is increased from 2.8$ for the pair alone to 12.6$ in the group.

Worths of Control Rods and Simulated Loading Errors in ZPPR-8F

In ZPPR-8F the effect of rearrangement of the Row-8 internal blanket region of the CRBR heterogeneous design was studied. A primary motivation for this reshuffling of core and blanket assemblies was to increase the worths of the control rods in the row-7 flats. A second series of measurements studied the mitigating effects of dummy assemblies on postulated reloading errors. Because of strong flux perturbations, the worth of removing a single rod from a row-7 corner position is very large for the heterogeneous CRBR designs. In the postulated reloading error, a row-7 corner rod is replaced with a fuel assembly, resulting in the maximum positive worth for a single reloading step. By replacing the fuel assemblies adjacent to the control rods with dummy assemblies, the worth of the fuel/control interchange is reduced.

To measure the effect of dummy assemblies on the worth of the postulated loading errors, one, three, or all six of the dummy assemblies shown in Fig. 3 replaced fuel assemblies (simulated by four ZPPR fuel drawers per half). In this case, the dummy assemblies had exactly the same composition as the CRPs. The results of the measurements are given in Table VII.

The effect of the dummy assemblies on the worth of a simulated loading error is shown in Table VIII. The impact of the dummy assemblies is substantial, with a reduction of almost 4$ in exchange worth for one dummy assembly immediately adjacent to the loading error (position 16). On the other hand, the worth of a reloading error on the opposite side of the core (position 10) is increased by about 0.5$ with the dummy assembly adjacent to position 16. With six dummy assemblies present the exchange worth is reduced by only 1.2$ and with the three dummy assemblies the exchange worth in position 10 is increased by a little over 1$. These effects can be qualitatively explained by the large flux redistributions in the heterogeneous core, as shown by the control rod experiments in ZPPR-7G.

Summary

Control rod interaction effects were studied in several phases of the ZPPR heterogeneous core programs. Very strong interactions were found for the outer ring rod bank in the most decoupled system.The rod worth interactions decreased with depletion of fuel in the core zones and plutonium build-up in the blankets ($7B \rightarrow 7C$). Because of the strong interactions, the hypothetical rod run-out and stuck-rod situations impose stringent requirements on the safety shutdown system. These reactivity changes were studied in assembly 7G. Postulated reloading errors, in the worst case of replacing one row-7 corner rod by a fuel subassembly, were studied in ZPPR-8F and data were obtained on the mitigating effect of dummy assemblies during reloading.

The routine diffusion calculations gave good predictions of all the rod interactions giving vital confirmation of the design-level methods for operational and safety analysis of the power reactor.

References

1. L.G. LeSage et al., "Physics Studies of a Heterogeneous LMFBR Core in ZPPR," 1977 NEACRP meeting.
2. S.G. Carpenter, "Measurement of Control Rod Worths Using ZPPR," Specialists Meeting on Control Rod Measurement Techniques, Cadarache, April 1976.
3. A.M. Broomfield et al., "The MOZART Control Rod Experiments and Their Interpretation," Proc. Symp. on Physics of Fast Reactors, Tokyo, 1973.

TABLE I. Control Rod Interactions in ZPPR-7B and 7C

		ZPPR-7B	ZPPR-7C
(1) Inner Ring (R4)			
Measured singly:	2 x CR-3	5.14	7.10
	4 x CR-5	9.24	13.64
	Sum	14.38	20.74
Measured as a group:	6R4	14.01	22.12
Interaction		- 2.6 %	+ 6.2 %
Calculated interaction		- 2.8 %	+ 4.4 %
(2) Outer Ring (R7C)			
Measured singly:	2 x CR-10	4.90	4.08
	4 x CR-14	6.66	6.88
	Sum	11.56	10.96
Measured as a group:	6R7C	17.86	14.35
Interaction		+54.5 %	+30.9 %
Calculated interaction		+58.3 %	+30.4 %

TABLE II. ZPPR-7G Control Rod Interactions in the Outer Ring (Row 7)

Rod Group	Sum of single rod worths, $	Worth of rods measured together, $	Measured Interaction %	Calculated Interaction, %
2 adjacent rods CR (15,16)	3.558	2.858	-19.7	-21.7
2 adjacent corner rods CR (8,10)	3.553	3.221	- 9.3	-10.7
2 opposite corner rods CR (10,16)	3.985	5.392	+35.3	+35.7
3 adjacent corner rods CR (8,10,12)	5.182	4.708	- 9.1	-10.1
3 corner rods CR (10,12,16)	5.614	7.261	+29.3	+30.5
4 adjacent corner rods CR (8,10,12,14)	6.770	6.927	+ 2.3	+ 2.5
5 corner rods CR (8,10,12,14,18) (5R7C)	8.358	10.436	+24.9	+25.4
6 corner rods CR (8,10, 12,14,16,18) (6R7C)	10.383	17.084	+64.5	+68.6
6 rods on flats CR (9,11,13,15,17,19) (6R7F)	8.812	11.567	+31.3	+31.4
10 rods: two adjacent CR (16,17) missing from row 7	16.040	16.220	+ 1.1	+ 3.0
10 rods: two opposite CR (9,16) missing from row 7	15.644	20.219	+29.2	+27.8
12 row 7 rods	19.195	28.826	+50.2	+50.6

TABLE III. Control Rod Interactions in the Inner Ring of ZPPR-7G

Rod Group	Sum of single rod worths, $	Worth of rods measured together, $	Measured Interaction, %	Calculated Interaction, %
CR (4,6)	3.192	3.262	+2.2	+1.8
CR (2,4,6)	4.713	4.957	+5.2	+5.2
CR (4,6) with 6R7C	3.637	3.645	+0.2	+0.6
CR (2,4,6) with 6R7C	5.305	5.422	+2.2	+2.3
CR (4,6) with 5R7C	4.143	4.234	+2.2	+0.1
CR (2,4,6) with 5R7C	4.940	5.047	+2.2	-2.0

TABLE IV. Variation In Worth of CR 16 With Different Insertion Patterns in ZPPR-7G

Other Rods inserted	Apparent Worth of Inserting rod 16 Measured	Calculated	Change in worth of CR 16
None	2.025	2.130	--
CR 17	1.325	1.326	- 35%
CR 10	3.396	3.639	+ 68%
CR (10,12)	4.040	4.327	+100%
5R7C	6.648	7.369	+228%
5R7C + CR 6	5.271	5.719	+160%
5R7C + CR 4	7.519	8.282	+271%
5R7C + CR (4,6)	6.059	6.650	+199%
5R7C + CR (2,4,6)	7.043	7.763	+248%

TABLE V. Variation in the Inner Ring Rod Worths in ZPPR-7G

Inner ring rods	No outer ring rods inserted	6R7C Inserted		5R7C Inserted	
	Worth, $	Worth, $	Change, %	Worth, $	Change, %
CR 6	1.671	1.969	+18	3.346	+100
CR 4	1.521	1.668	+10	0.797	− 48
CR (4,6)	3.262	3.645	+12	4.234	+ 29
CR (2,4,6)	4.957	5.422	+ 9	5.047	+ 2

TABLE VI. Variations in Rod Group Worths in ZPPR-7G

Rod Group	Other Rods Inserted	Group Worth, $	Change in Worth, %
CR (16,17)	none	2.858	--
	10 outer ring	12.606	+341
CR (2,4,6)	none	4.957	--
	12 outer ring	4.250	- 14
6R7F	none	11.567	--
	6R7C	11.742	+ 2
CR 14	none	1.588	--
	CR (8,10,12)	2.219	+ 40
CR (8,10,12)	none	4.708	--
	CR (14)	5.339	+ 13
CR 12	none	1.593	--
	CR (10,16)	1.869	+ 17
CR 12	none	1.593	--
	CR (8,10)	1.487	- 7
12R7	none	28.826	--
	CR (2,4,6)	28.119	- 2

TABLE VII. Results of Control Rod and Simulated Loading Error Measurements in ZPPR-8F

Configuration[a]						
CRs	FA[b]	DAs[c]	Worth,$	Statistical Uncertainty,%	Uncertainty Due to Source Correction[d],%	C/E
8,10,12,14,18	--	--	10.73	0.75	1.2	1.040
8,10,12,14,16,18	--	--	17.68	0.82	0.1	1.061
9,11,13,17,19	--	--	11.20	1.01	0.5	1.018
9,11,13,15,17,19	--	--	15.19	0.67	0.1	1.033
8,9,10,11,12,13, 14,17,18,19	--	--	18.45	1.03	2.1	1.013
8,9,10,11,12,13, 14,15,16,17,18,19	--	--	33.40	1.33	0.1	1.044
8,10,12,14,18	16	--	6.25	1.80	2.6	0.981
8,10,12,14,16,18	--	16	18.46	0.47	0.1	1.073
8,10,12,14,18	16	16	10.93	0.91	1.1	1.038
8,12,14,16,18	10	16	6.51	1.37	2.8	0.979
8,10,12,14,16,18	--	8,12,16	19.72	0.69	0.2	1.073
8,10,12,14,18	16	8,12,16	11.22	0.71	1.5	1.044
8,12,14,16,18	10	8,12,16	7.15	1.35	2.9	0.994
8,10,12,14,18	16	8,10,12,14,16,18	12.72	0.87	1.7	1.015
8,10,12,14,16,18	--	8,10,12,14,16,18	22.96	1.03	0.1	1.041

[a]See Fig. 3 for definition of these configurations.

[b]FA: Fuel assembly inserted in control rod position, CRP number indicated in column.

[c]DA: Dummy assembly inserted in place of fuel assembly adjacent to the CRP noted in the column. See Fig. 3 for these positions.

[d]Uncertainty due to source worth correction to measurement. Assumed to be 10% of the difference between the source worth ratio and 1.0, but never less than 0.1%. Not included is uncertainty in the reference reactivity (∿0.8%) and the uncertainty due to changes in β_{eff} (<0.7% for all cases).

TABLE VIII. Worth of Replacing One Control Rod in the Outer Ring Corners with a Fuel Assembly

Fuel/Rod Exchange Position[a]	Positions[a] of Dummy Assemblies	Worth[b] of Exchange, $	C/E
16	--	11.43 ± 0.35	1.105
16	16	7.53 ± 0.16	1.124
10	16	11.95 ± 0.35	1.125
16	8,12,16	8.50 ± 0.19	1.111
10	8,12,16	12.57 ± 0.39	1.118
16	8,10,12 14,16,18	10.24 ± 0.31	1.074

[a]See Fig. 3 for these positions.

[b]Uncertainties due to statistics and source worth correction.

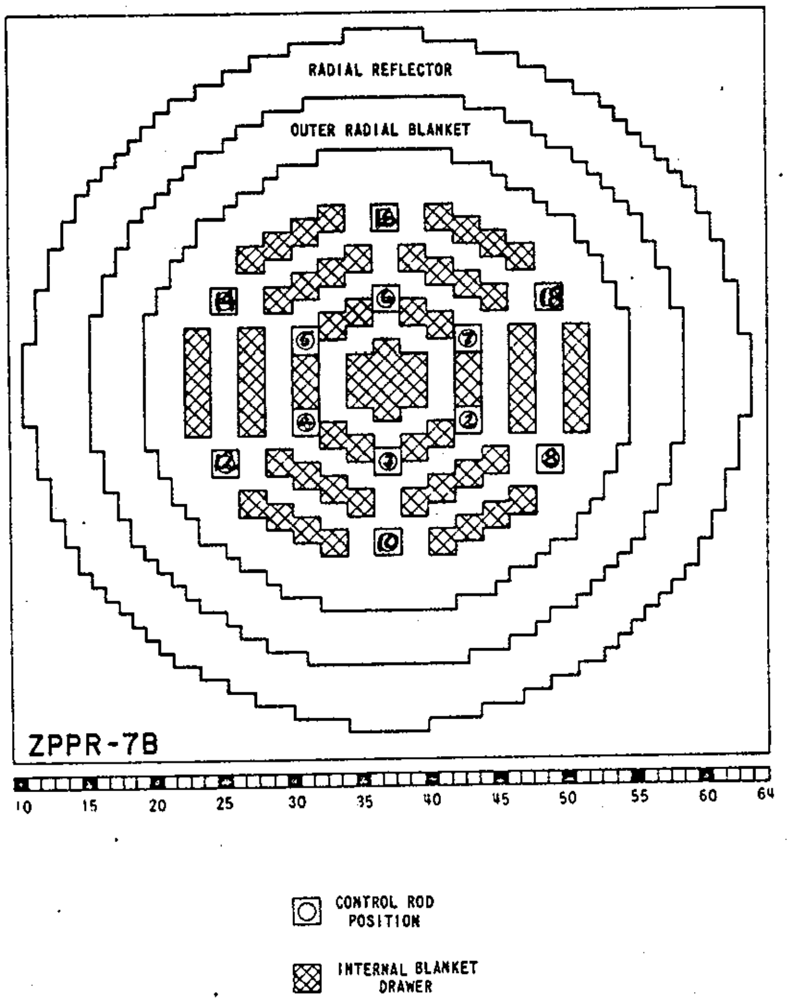


Fig. 1: ZPPR-7B and 7C

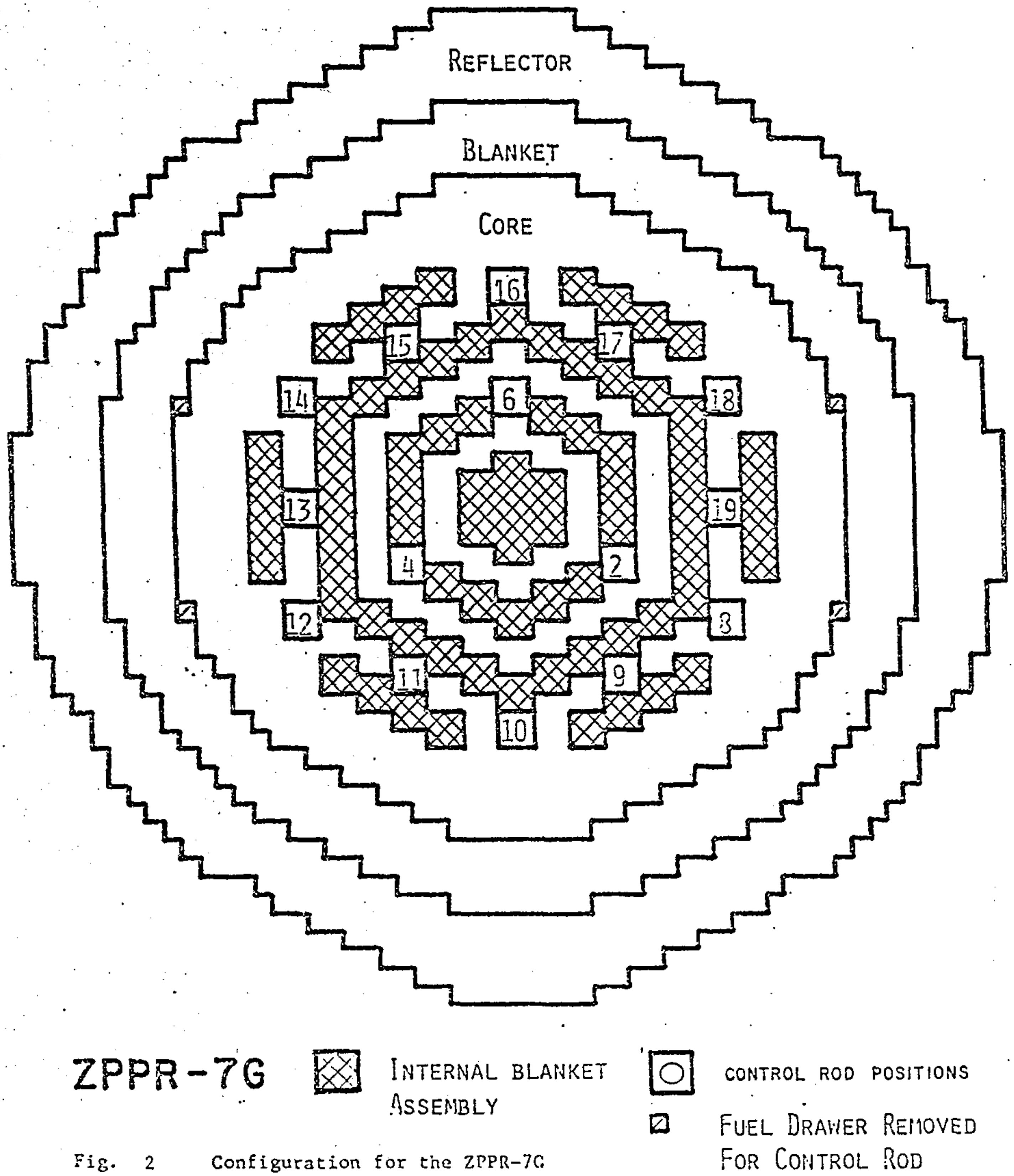
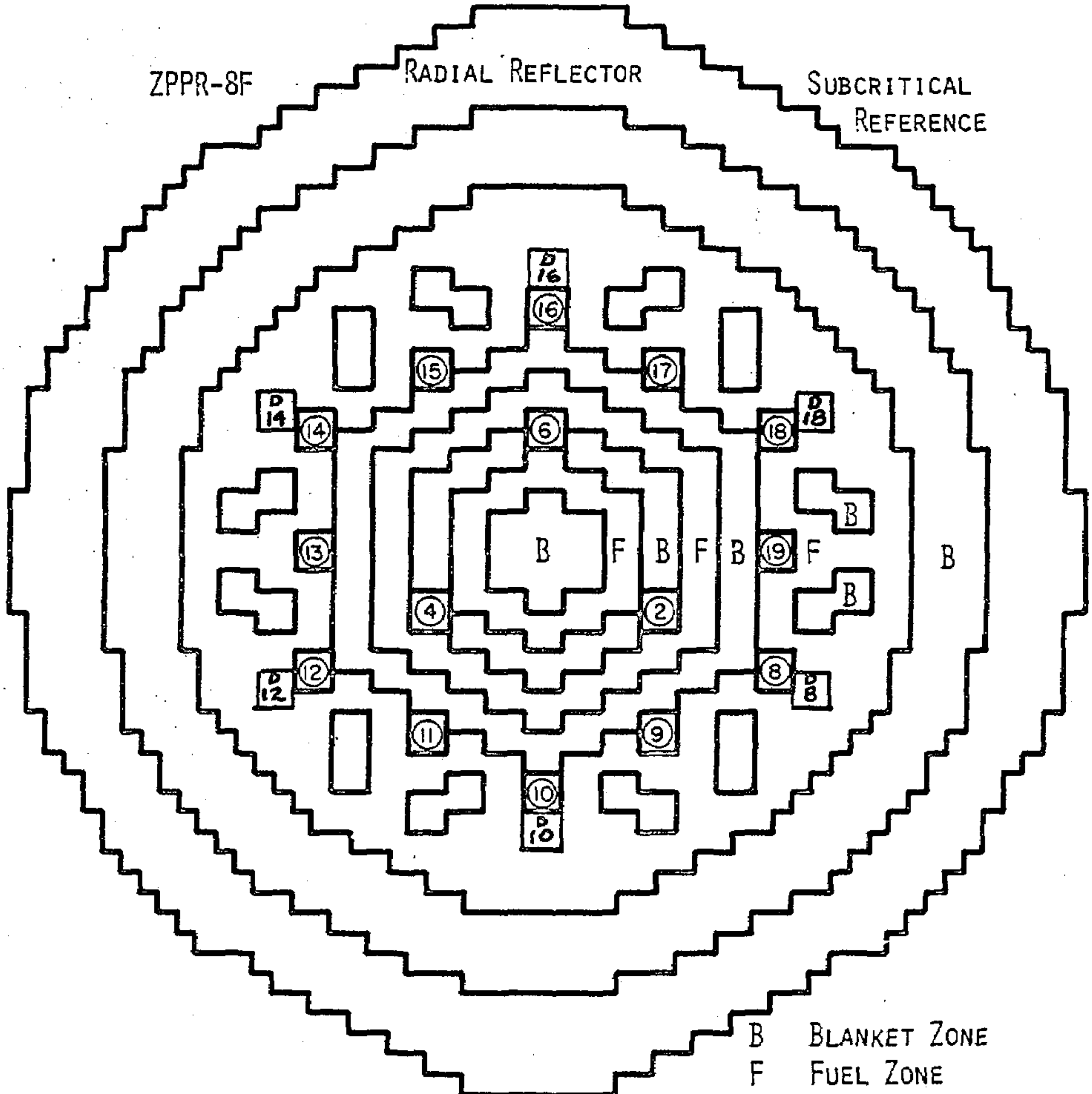


Fig. 2 Configuration for the ZPPR-7G Control Rod Measurements



2, 4, 6, 8-19 Control Rod Positions
D-8, D-10, ... D-18 Dummy Assembly Positions

Fig. 3: ZPPR-8F