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ZPPR ASSEMBLY 3 CONTROL ROD WORTH MEASUREMENTS

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The primary goal of the ZPPR Assembly 3 program was to measure individual and multiple control rod (CR) worths. These data were required to resolve design issues, dependent upon the effects of B_4C CR's, for a plutonium-fueled fast reactor core of the size currently considered for the LMFBR Demonstration plant. Assembly 3 was a two-zoned, 2400-liter core system. Its configuration was similar to Assembly 2 except for the nineteen simulated CR's or sodium-steel filled control rod positions (CRP's). Three burnup stages, denoted as phases and shown in Fig. 1, were studied--Beginning-of-cycle (Phase 3), Middle-of-cycle (Phase 2), and End-of-cycle (Phase 1B). Reactor parameters, in addition to CR worths, were characterized as a function of the inserted CR pattern and fuel enrichment. Plutonium fuel enrichment was varied, to obtain criticality for each phase, by uniformly replacing 1/4-in. columns of U_3O_8 with 7/8-in. Fe_2O_3 and 1/8-in. plutonium-aluminum alloy plates. These Pu-Al plates, called spikes, were nominally distributed throughout the inner- and outer-core columns in the ratio of 2 to 3; which was similar to the fissile ratio of the two zones. Inner- and outer-core volumes were held invariant.

Control rods were simulated in four drawer unit cells containing natural B_4C, steel, and sodium. For all the fully-inserted cases, discussed below, the CR's were located in the 36-in. high core. The remainder of the channel and the control rod positions (CRP's) were filled with steel-clad sodium canisters.

The worths of single and multiple CR's were all measured with the reactor subcritical relative to the reference phase CR pattern and spiking distribution. The subcritical measurement techniques selected depended upon the degree of subcriticality. For single CR's, rod drop, source jerk, polarity coherence, and subcritical multiplication were normally used. Techniques suitable for the multiple CR's were polarity coherence and subcritical multipliation. Subcritical multiplication data were obtained with counters located both interior and exterior to the reactor. Consistent agreement was obtained for all measurement techniques for the single CR's. Phase to phase multiple CR worth comparisons, discussed below, were normally based upon the subcritical multiplication technique results derived from a fission counter located at the core center. This latter choice was dictated by the applicability over the wide range of subcriticality encountered, and the ability to correct for detector efficiency changes as determined by xy diffusion theory calculations.

A set of single and multiple CR worth results, based on four CR designs, is listed in Table I. Each of these four basic CR designs was selected to achieve a worth per CR of nominally 2.10 dollars at their respective radial locations. Design A CR (for CRP-1) contained 4.58 kg of B_4C, design H (for CRP's 2-7, inner ring of rods) contained 5.62 kg, design J (for odd-numbered outer ring of rods) contained 8.60 kg, and design I (even numbered outer ring of rods) contained 13.16 kg. Front drawer views of designs H, I, and J are shown in Fig. 2.

The numbers in Table I under the Control Rod Grouping heading correspond to the positions of fully-inserted CR's. The CR numbering convention is shown in Fig. 1.

Corrections were applied for ^{241}Pu decay and for minor differences in temperature and ZPPR half closure. From these data, it was possible to determine the total CR worth available in the assembly, the CR shutdown worth for each phase, and intercompare single and multiple CR worths whose insertion patterns were common to the various phases.

Data in Table I can also be used to estimate the effect of burnup on control worth. Selecting, for instance, the Phase 3 CR insertion pattern as a basis, the relative worth of the other multiple CR insertion patterns can be computed (see Table II). The resulting worths exhibit very little variation as a function of burnup, e.g., for fully inserted CR's 2-19 the relative CR worth is -21.38 ± 0.33, -20.03 ± 0.22, and -21.04 ± 0.15 dollars for Phases 1B, 2, and 3 respectively. It should be noted that a separate experiment showed that the presence of Pu-Al spikes near CR's had a measureable effect on the worth of the individual CR's. The small variation of worth as a function of burnup is probably associated more with the local fuel density than with the overall fuel density.

Assembly 3, Phase 1B data confirmed that for a uniform fuel enrichment distribution, the worth of various CR patterns depend upon the distribution of the CR's (see Table III). Starting from a configuration where all CR's were initially withdrawn, the summation of the worths of single CR's was greater than the measured group worth when groups of CR's were adjacent and less than the group worth when the CR's were nonadjacent. For example, the individual worths of CR's 2, 8, and 9 in Phase 1B were -2.03 ± 0.01, -1.93 ± 0.01, and -1.93 ± 0.01 dollars respectively. Adjacent group rod worths were -3.69 ± 0.02 for CR's 8 and 9, and -4.94 ± 0.02 for CR's 2, 8, and 9. Resulting worth ratios relative to the summation of individual rod worths were 0.93, 0.91, 0.88, and 0.84. For the non-adjacent type CR groupings, the worth ratios were 1.07 for CR's 2 and 5, 1.08 for CR's 8 and 14, and 1.06 for CR's 2, 4, and 6.

Additional rod interaction effects were measured relative to the worth of a type A CR in CRP-1 (see Table IV). Central worth changes exceeding ±20% occurred as the surrounding CR patterns were varied in a symmetrical fashion. The asymmetric CR pattern study showed that combined effect of rod interactions and flux tilting could cause a 50% change in the worth of a type I rod in position 8 (see Table V).

Single and multiple rod worths measured in the normal and sodium voided Phase 3 cores are given in Table VI. The worth ratios (voided/reference) for single CR's in their normal positions were 0.88 for a 4.58 kg type A CR in position 1, an average of 0.91 for a single 5.62 kg type H CR in positions 5 and 7, and an average of 0.96 for single 8.60 kg type J CR's in positions 9, 11, and 15. Since the CR patterns were identical in the voided and normal cores, these ratios reflect the worth change due to sodium voiding and are independent of the interaction effects between CR's. The boron density effect was evident at the core center. Central worth ratios, as the B_4C mass increased, were 0.88 (4.58 kg), 0.91 (5.62 kg), and 0.98 (13.16 kg). Spatial variation was difficult to evaluate because of this B_4C mass effect. However, some spatial variation was evident in the multiple CR data. When three type H CR's were added to the inner ring, the worth ratio was 0.87. Conversely, when three type H CR's were removed from the inner ring and six type J CR's were added to the outer ring, the worth ratio was 1.02. Measurement of the boron reactivity traverse using a small boron sample likewise showed that the boron worth was reduced considerably in the inner CR ring, but changed only slightly in the outer CR ring.

TABLE I. Summary of Comparative Control Rod Worths Measured in ZPPR Assembly 3, Phases 1B, 2, and 3

No. of Rods	Control Rod Grouping	Control Rod Worth[a], $ Relative to the Phase Reference		
		Phase 1B	Phase 2	Phase 3
1	Type A in CRP-1	-2.13 ± 0.02	-1.94 ± 0.03	-2.19 ± 0.03
1	Type I in CRP-1	- -	-3.64 ± 0.03	-4.04 ± 0.06
1	Type H in CRP-1	- -	-2.16 ± 0.05	-2.41 ± 0.03
1	Type I in CRP-8	-1.96 ± 0.01	-1.87 ± 0.03	- -
1	Type H in 2(5)[b]	-2.03 ± 0.01	-1.75 ± 0.03	-1.89 ± 0.03
1	Type J in 11(17)	-2.15 ± 0.03	-2.08 ± 0.04	-2.06 ± 0.03
1	Type I in 10(16)	-2.12 ± 0.02	-2.21 ± 0.04	- -
6	2,4,6,10,14,18 (Phase 2)	-14.01 ± 0.07	0.00	- -
6	8,10,12,14,16,18	-14.88 ± 0.08	-0.70 ± 0.01	- -
9	2-7,10,14,18	-20.53 ± 0.14	-5.76 ± 0.04	- -
9	2,4,6,8,10,12,14, 16,18 (Phase 3)	-22.20 ± 0.14	-7.40 ± 0.05	0.00
12	8 - 19	-27.47 ± 0.17	-13.01 ± 0.09	-5.89 ± 0.02
12	2-8,10,12,14,16, 18	-29.28 ± 0.21	-13.88 ± 0.10	-6.54 ± 0.04
12	2,4,6,9,10,11,13, 14,15,17,18,19	-28.33 ± 0.20	-13.03 ± 0.09	-6.11 ± 0.04
18	2-19	-43.58 ± 0.30	-27.43 ± 0.22	-21.04 ± 0.15

[a]Single rod worths are averages of all measurement techniques used. Multiple rod worths are based on the subcritical multiplication values measured with a fission counter at the core center.

[b]Values in parentheses represent symmetrical positions.

TABLE II. Variation of Rod Worth with "Burnup" in ZPPR Assembly 3

No. of Rods	Control Rod Grouping	Control Rod Worth[a] ($) Relative to the Phase Reference		
		Phase 1B	Phase 2	Phase 3
1	Type A in CRP-1	2.13 ± 0.02	1.94 ± 0.03	2.19 ± 0.03
1	Type I in CRP-1	- -	3.64 ± 0.03	4.04 ± 0.06
1	Type H in CRP-1	- -	2.16 ± 0.05	2.14 ± 0.03
1	Type I in CRP-8	1.96 ± 0.01	1.87 ± 0.03	- -
1	Type H in 2(5)[a]	2.03 ± 0.01	1.75 ± 0.03	1.89 ± 0.03
1	Type J in 11(17)	2.15 ± 0.03	2.08 ± 0.04	2.06 ± 0.03
1	Type I in 10(16)	2.12 ± 0.02	2.21 ± 0.04	- -
6	2,4,6,10,14,18 (Phase 2)	+8.19 ± 0.16	+7.40 ± 0.05	- -
6	8,10,12,14,16,18	+7.32 ± 0.16	+6.70 ± 0.05	- -
9	2-7,10,14,18	+1.69 ± 0.20	+1.64 ± 0.06	- -
9	2,4,6,8,10,14,16 18 (Phase 3)	0.00	0.00	0.00
12	8 - 19	-5.27 ± 0.22	-5.61 ± 0.10	-5.89 ± 0.04
12	2-8,10,12,14,16 18	-7.08 ± 0.25	-6.48 ± 0.11	-6.54 ± 0.04
12	2,4,6,9,10,11,13, 14,15,17,18,19	-6.13 ± 0.24	-5.63 ± 0.11	-6.11 ± 0.04
18	2 - 19	-21.38 ± 0.33	-20.03 ± 0.22	-21.04 ± 0.15

[a]Single rod worths are averages of all measurement techniques used. Multiple rod worths are based on the subcritical multiplication values measured with a fission counter at the core center. Relative to the Phase 3 insertion pattern worth.

[b]Values in parentheses represent symmetrical positions.

TABLE III. Control Rod Worth Variations as a Function of the Insertion Pattern from Data Measured in ZPPR Assembly 3, Phase 1B.

No. of Rods	Control Rod Grouping	Control Rod Worth[a] ($)		Measured / Σ individuals
		Measured	Σ of individuals	
1	Type H in CRP-2	-2.03 ± 0.01	-2.03	1.00
1	Type J in CRP-9	-1.93 ± 0.01	-1.93	1.00
1	Type I in CRP-8	-1.93 ± 0.01	-1.93	1.00
		Adjacent Control Rods		
2	2 and 9	-3.69 ± 0.02	-3.96	0.93
2	2 and 8	-3.62 ± 0.02	-3.96	0.91
2	8 and 9	-3.41 ± 0.02	-3.86	0.883
3	2, 8, and 9	-4.94 ± 0.02	-5.89	0.839
		Non-adjacent Control Rods		
2	2 and 5	-4.34 ± 0.02	-4.06	1.07
2	8 and 14	-4.16 ± 0.02	-3.86	1.08
3	2, 4, and 6	-6.44 ± 0.04	-6.09	1.06

[a]Measured using the subcritical multiplication technique with a fission counter at the core center.

TABLE IV. Changes in the Worth of CR-1 for Various Symmetrical Rod Insertion Patterns in ZPPR Assembly 3

Assembly Phase	Group No.	Control Rod Grouping Plus CR-1	Worth of CR-1, $	Worth Relative to Group No. 1
1B	1	None	-2.13 ± 0.02	1.00
2	2	2,3,4,5,6 and 7	-1.53 ± 0.02	0.72
2	3	8,10,12,14 16 and 18	-2.54 ± 0.06	1.19
3	4	2,4,6,8,10 12,14,16 and 18	-2.19 ± 0.03	1.03

TABLE V. Changes in the Worth of CR-8 for Various Asymmetric Rod Patterns

Assembly Phase	Group No.	Control Rod Grouping Plus CR-8	Worth of CR-8, $	Worth Relative to Group No. 1
1B	1	None	-1.96 ± 0.01	1.00
1B	2	2	-1.65 ± 0.02	0.84
1B	3	9	-1.58 ± 0.02	0.81
1B	4	2 and 9	-1.30 ± 0.02	0.66
1B	5	14	-2.35 ± 0.02	1.20
3	6	1,2,4,6,10, 12,14,16 and 18	-3.07 ± 0.04	1.57

TABLE VI. Control Rod Worths Measured in ZPPR Assembly 3, Phase 3 in the Normal and Sodium Voided Cores

No. of Rods	Control Rod Grouping	Control Rod Worth, $		Ratio Voided/Normal	Comments
		Sodium In	Sodium Voided		
	Single Rods[b]				
1	Type A in CRP-1	-2.205 ± 0.016	-1.949 ± 0.022	0.884	Central CRP
1	Type I in CRP-1	-3.935 ± 0.061	-3.848 ± 0.063	0.978	Central CRP
1	Type H in CRP-1	-2.426 ± 0.020	-2.216 ± 0.025	0.913	Central CRP
1	Type H in CRP-5	-1.912 ± 0.028	-1.767 ± 0.020	0.924	Inner ring
1	Type H in CRP-7	-2.126 ± 0.016	-1.916 ± 0.021	0.901	Inner ring
1	Type J in CRP-9	-1.848 ± 0.013	-1.794 ± 0.018	0.971	Outer ring
1	Type J in CRP-11	-2.109 ± 0.016	-1.963 ± 0.021	0.931	Outer ring
1	Type J in CRP-15	-1.741 ± 0.013	-1.708 ± 0.018	0.981	Outer ring
	Multiple Rods[c]				
12	2-8,10,12,14,16, 18	-6.54 ± 0.03	-5.71 ± 0.08	0.873	3 inner ring CRs inserted (3,5 and 7)
12	2,4,6,9,10,11,13, 14,15,17,18,19	-6.11 ± 0.02	-5.18 ± 0.07	0.848	3 additional rods; 3 outer ring out (8, 12 and 16) and 6 outer ring in (9,11,13,15,17 and 19)
12	8-19	-5.89 ± 0.02	-5.98 ± 0.08	1.015	3 additional rods; 3 inner ring out (2,4 and 6) and 6 outer ring in (9,11,13,15,17 and 19)
18	2-19	-21.04 ± 0.07	-18.55 ± 0.26	0.882	9 additional rods; 3 inner ring in (3,5 and 7) and 6 outer ring in (9,11,13,15,17 and 19)

[a] Phase 3 reference rod pattern: 2,4,6,8,10,12,14,16,18.

[b] Measured using the source jerk technique.

[c] Measured using subcritical multiplication technique with fission counter at the core center

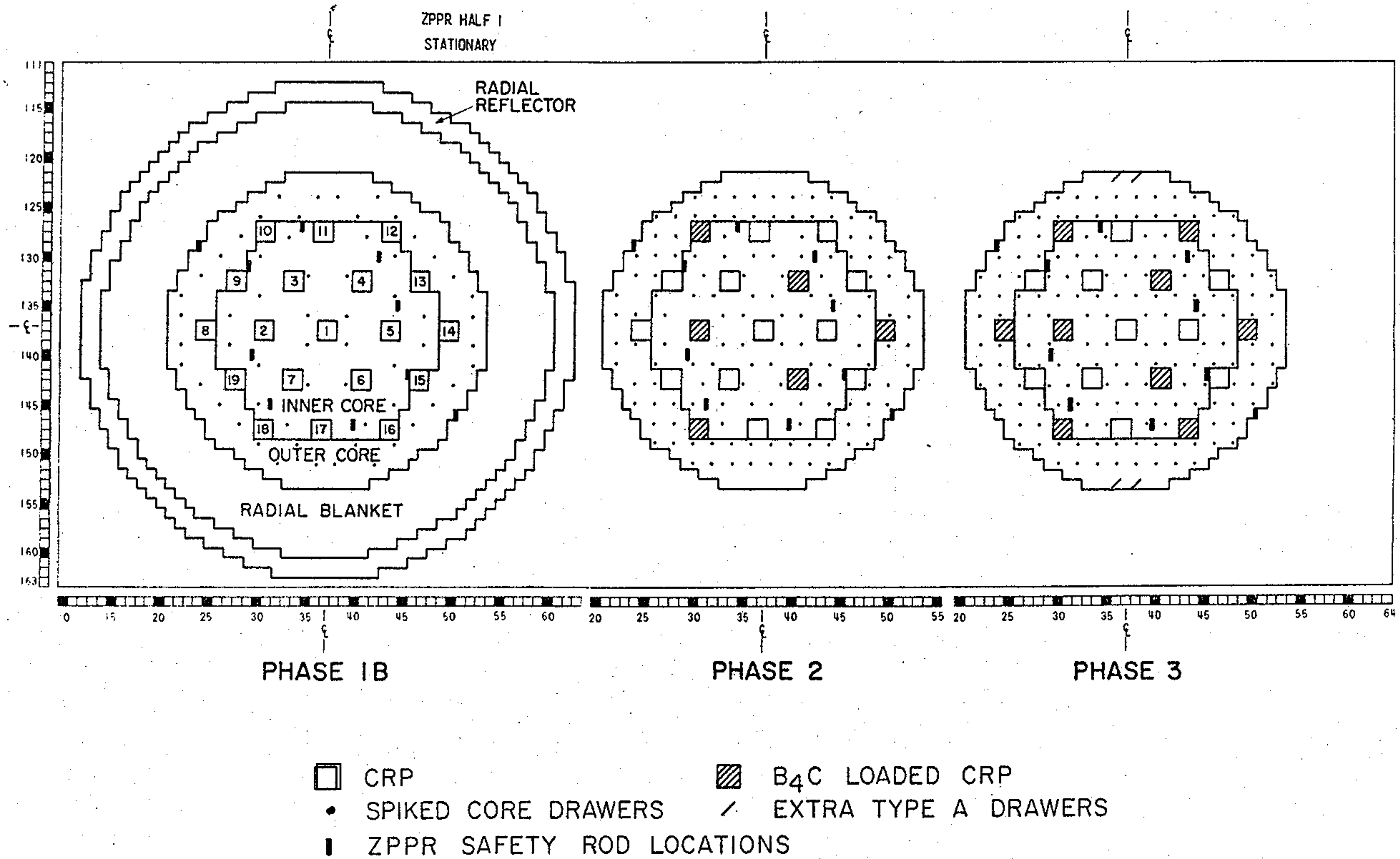

Fig. 1 Reference Configurations for Three Phases of ZPPR Assembly 3

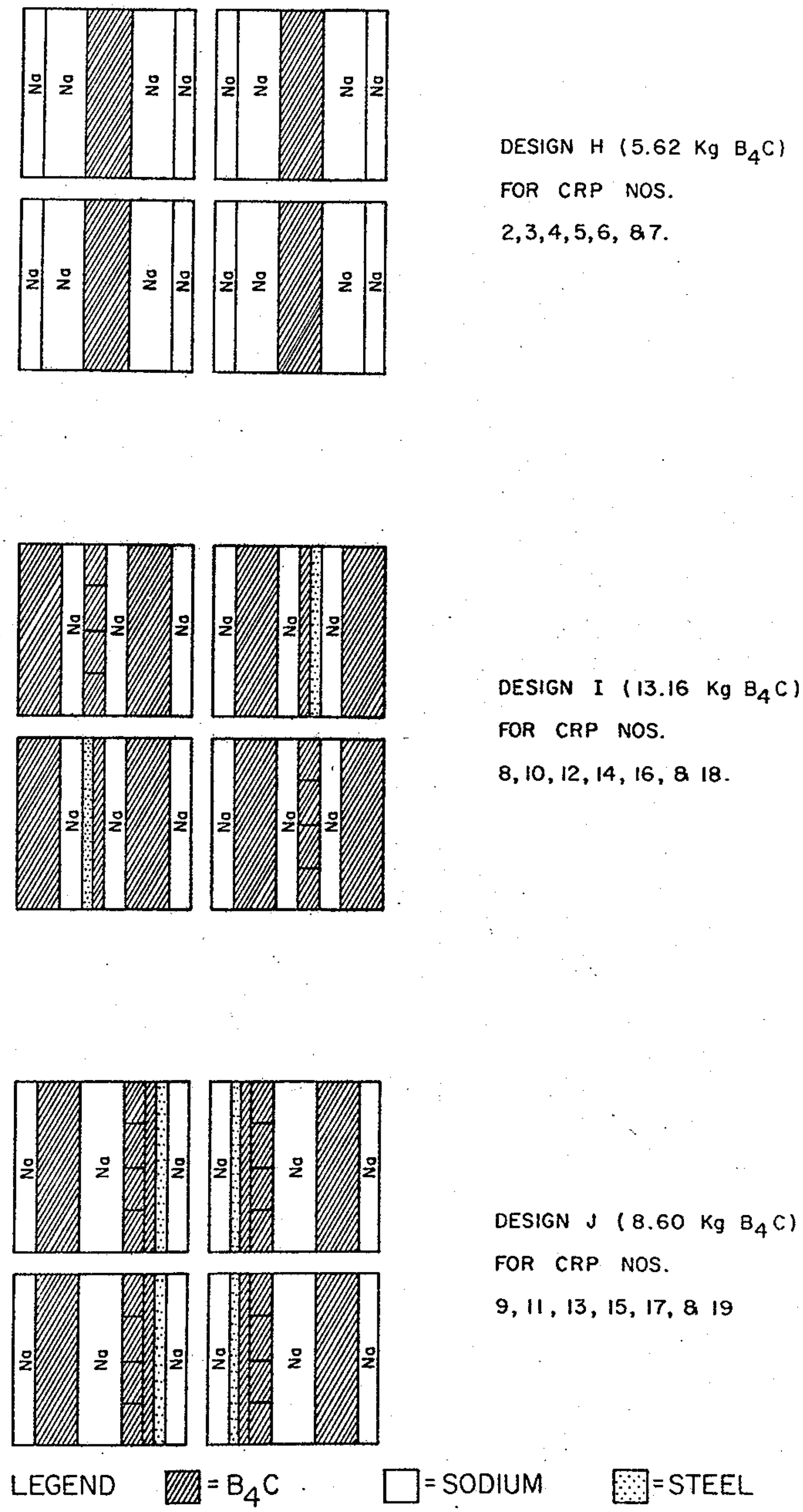

Fig. 2 Front Views of Mockup B_4C Control Rods used in ZPPR Assembly 3