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Development of Computer Program INROD for Intermediate Term Control Rod Programming of BWR

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1. Control Rod Programming of BWR

Figure 1 shows the classification of BWR control rod programming. Control rods are grouped into four patterns A_1, A_2, B_1 and B_2 at the rated power condition depending on the selection of the inserted rods and the combination of the deep and the shallow rods. These patterns are exchanged at every about 500 to 1500 MWD/T to assure the local uniformity of fuel burnup.

(1) Long term program
determines the the rod positions at the beginning of each pattern during one cycle.

(2) Intermediate term program
determines the withdrawal sequence during one pattern interval to compemsate for the reactivity change by fuel burnup.

(3) Start-up program
determines the withdrawal sequence from zero power with all rod inserted to the rated power together with flow control.

(4) Pattern change program
determines the rod sequence for pattern change.

To meet the above requirement, the control rod programming system is made up of the four different codes which are shown in Fig. 2.

2. Intermediate Term Control Rod Programming Code INROD

The objective is to determine the control rod withdrawal sequence using the Long term results as the initial starting guess.

The algorithm employed is briefly described.

1) Modify the rod position by the method described in 3) if the keff of the starting point calculated by using the OPROD pattern is outside the allowable limit of keff critical.

2) Insert the rod when the reactivity increases and withdraw the rod when the reactivity decreases with fuel burnup.

3) Determine the withdrawal sequence with either of the following two methods.

(a) Determine the group and the depth of the rod that minimizes the performance index among those for which the MLHGR and MCHFR after withdrawal satisfy the constraints. Select the rod group for which the MLHGR after withdrawal is the minimum if all of the rod group violate the constraints.

(b) Determine the group and the depth of the rod according to the input specified group order. Skip the rod group if the withdrawal of this group violates the constraints. Select the rod group for which the MLHGR after withdrawal is the minimum if all of the rod group violate the constraints.

The performance index is calculated by either of the two according to the input option.

$$J = \sum_i \sum_j \sum_k (P_{ijk} - P^L_{ijk})^2/V \qquad (1)$$

$$J = \text{Max} \left| P_{ijk} - P^L_{ijk} \right| , \qquad (2)$$

where P_{ijk}: Normalized power at ijk of INROD,

$\bar{P}^L_{ijk}$: Normalized power at ijk of OPROD and

V : Core volume.

The amount of rod movement of group i, Δr_i has to be specified by input. The procedure of 3) is summarized in Fig. 3

in case of the rod withdrawal and the total procedure is summarized in Fig. 4.

3. Application of INROD to a 460 MWe BWR

The results of INROD applied to a 460 MWe BWR are briefly described.

Control rod grouping and rod operating order are shown in Fig. 5.

Figure 6 and 7 show the time variation of keff, rod density, MFLPD and MCHFR. Figure 8 shows average axial exposure distribution obtained by OPROD and INROD.

Tables 1 and 3 summarize the rod withdrawal sequence of the first cycle.

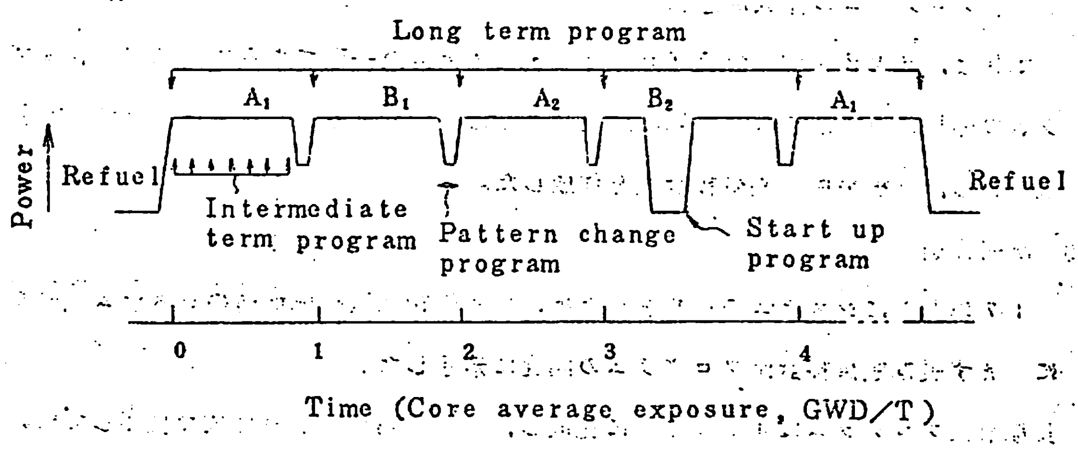

Fig. 1. Classification of BWR control rod programming

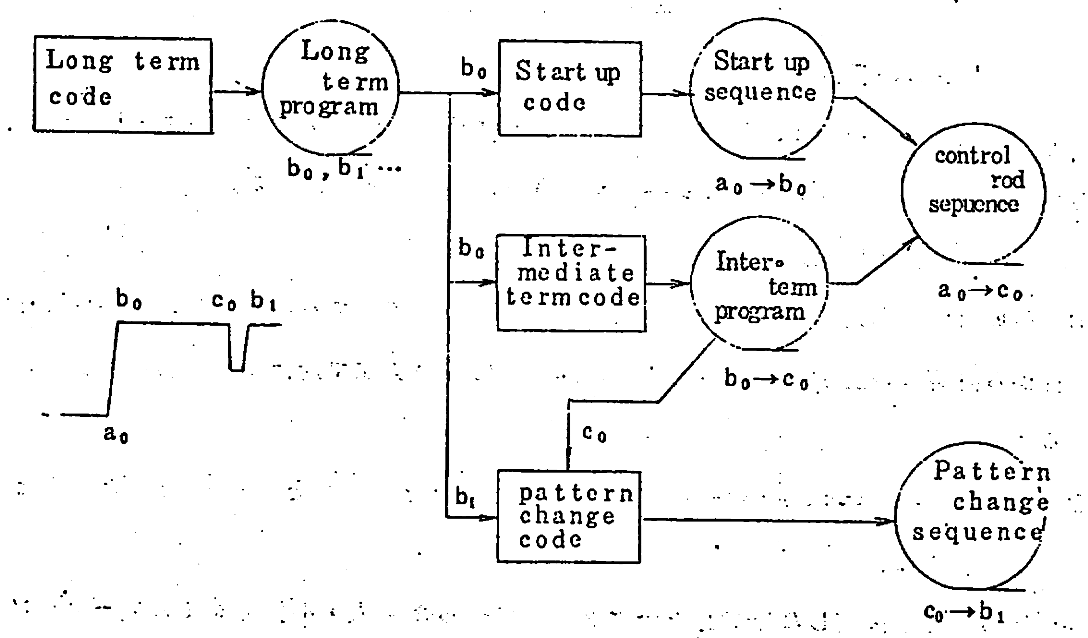

Fig. 2. BWR control rod program system

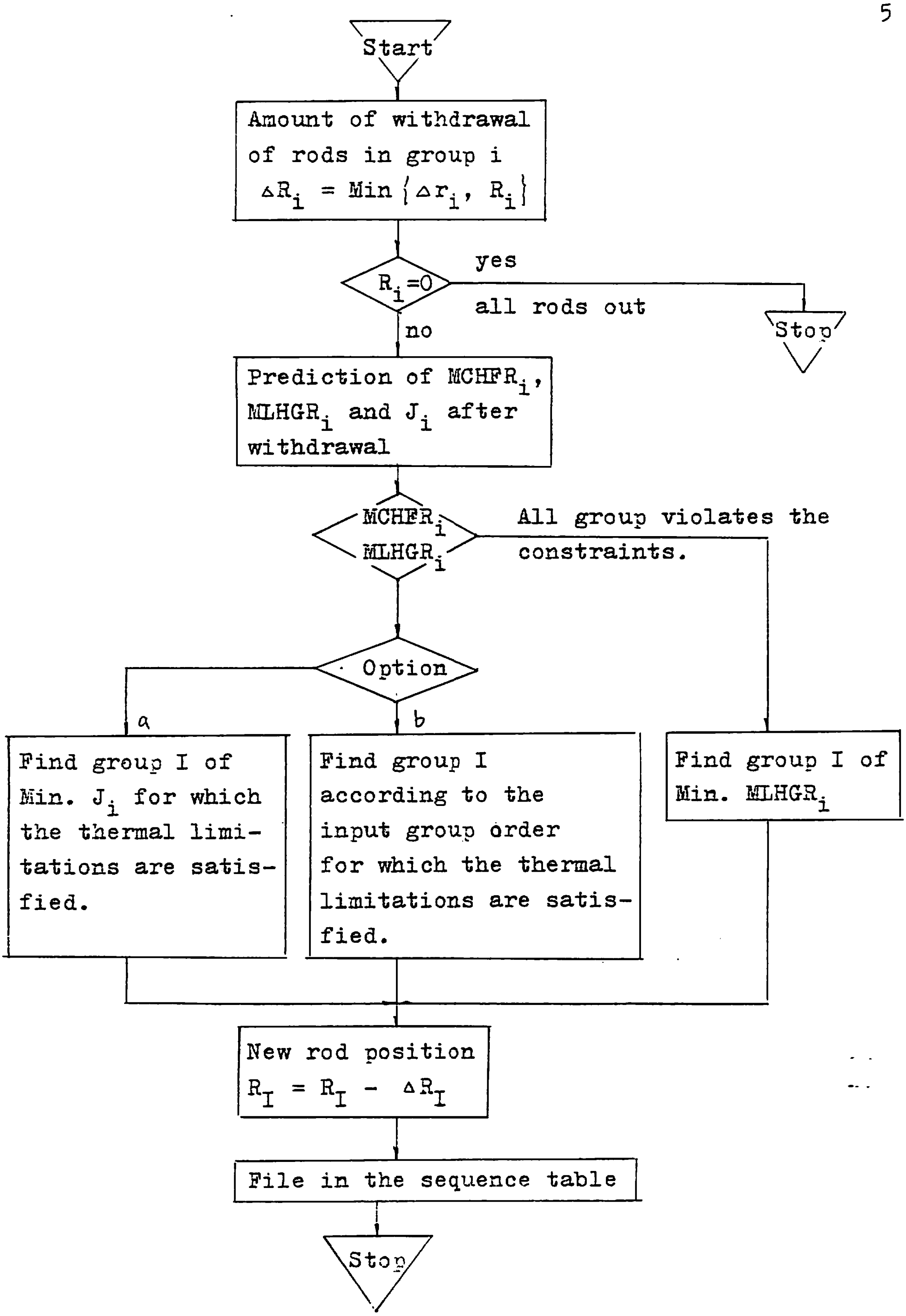

Fig. 3 Determination of rod sequence for rod withdrawal

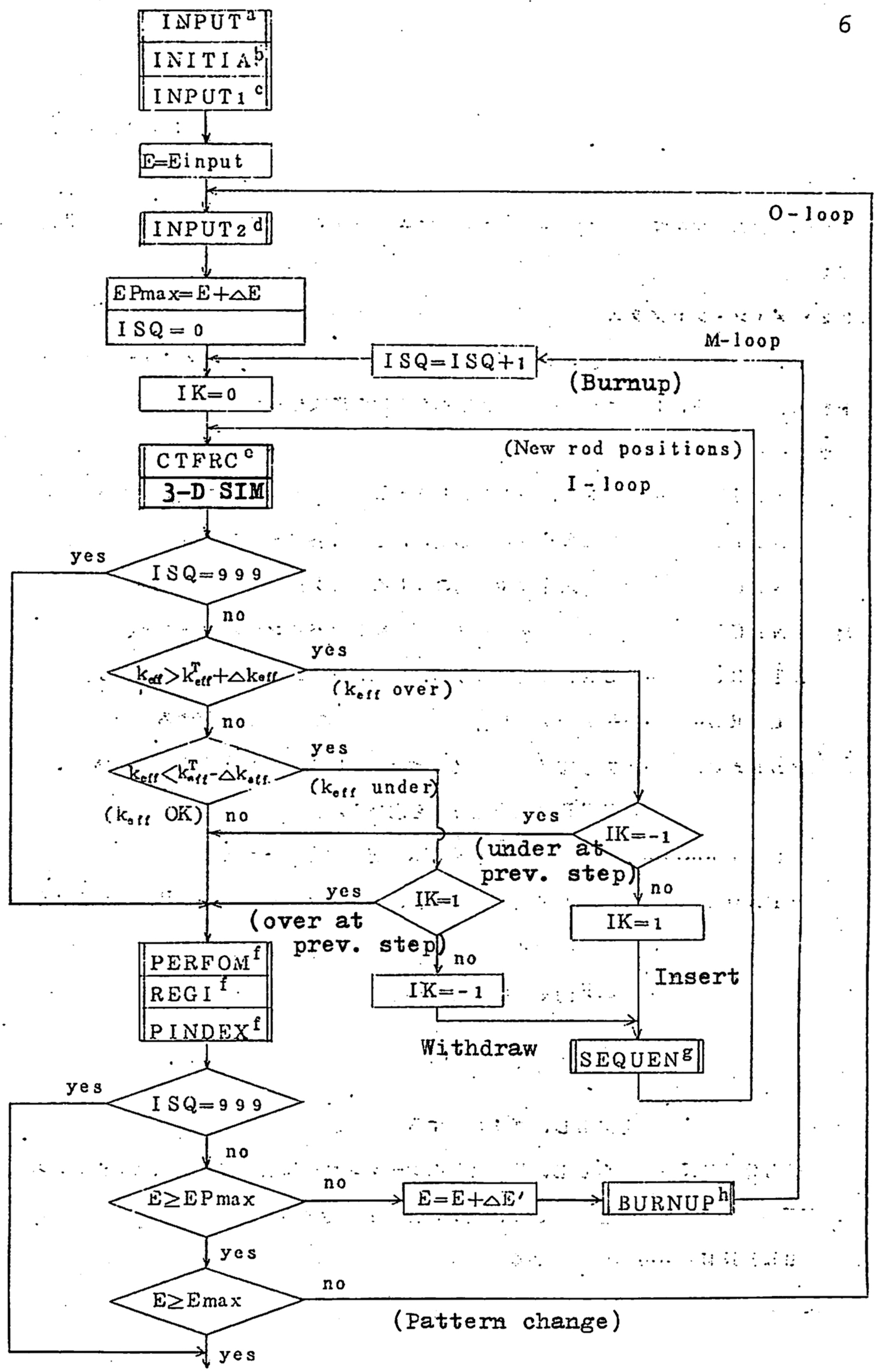

Fig. 4. Main algorithm of INROD

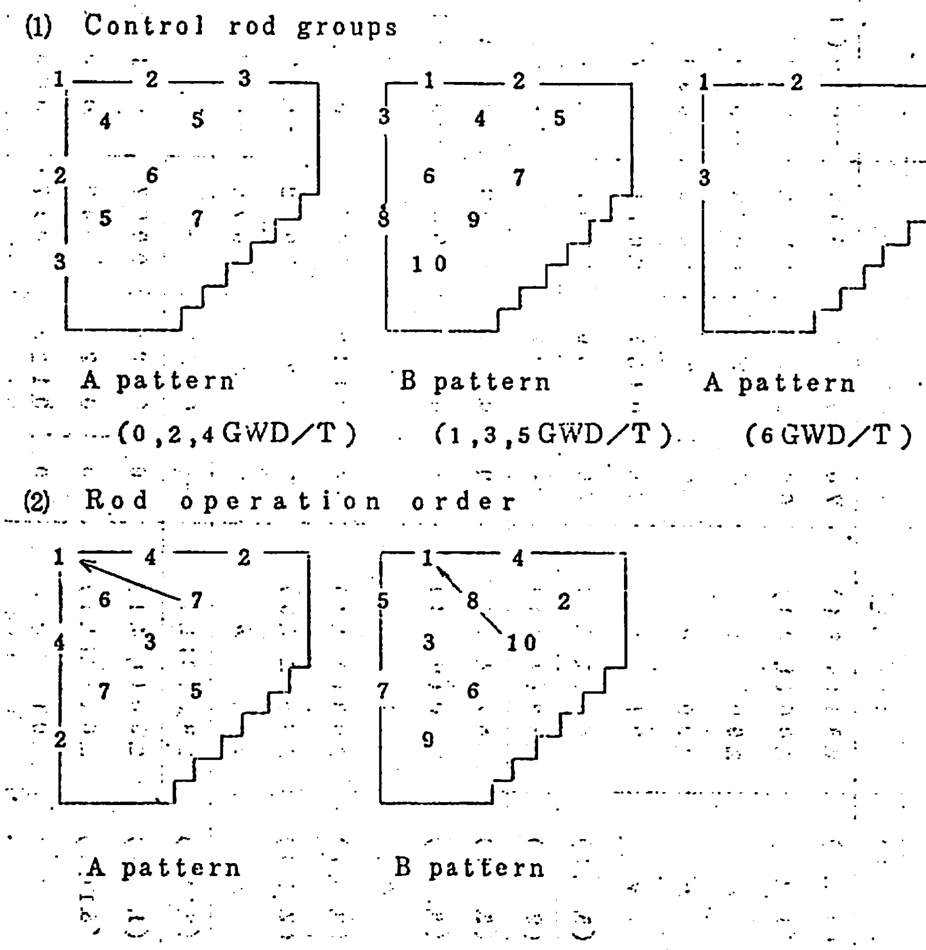

Fig. 5 Control rod groups and rod operation order

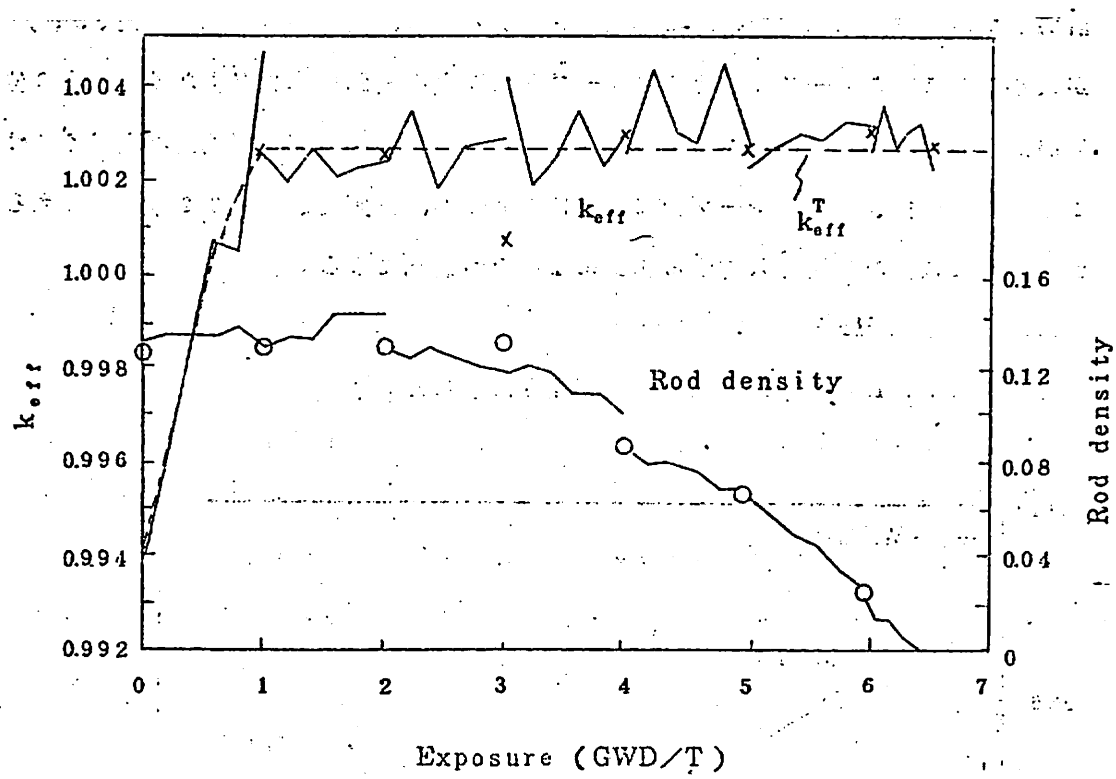

Fig. 6. Nentron multiplication factor and rod density calculated by OPROD and INROD × and ○ are results of OPROD.

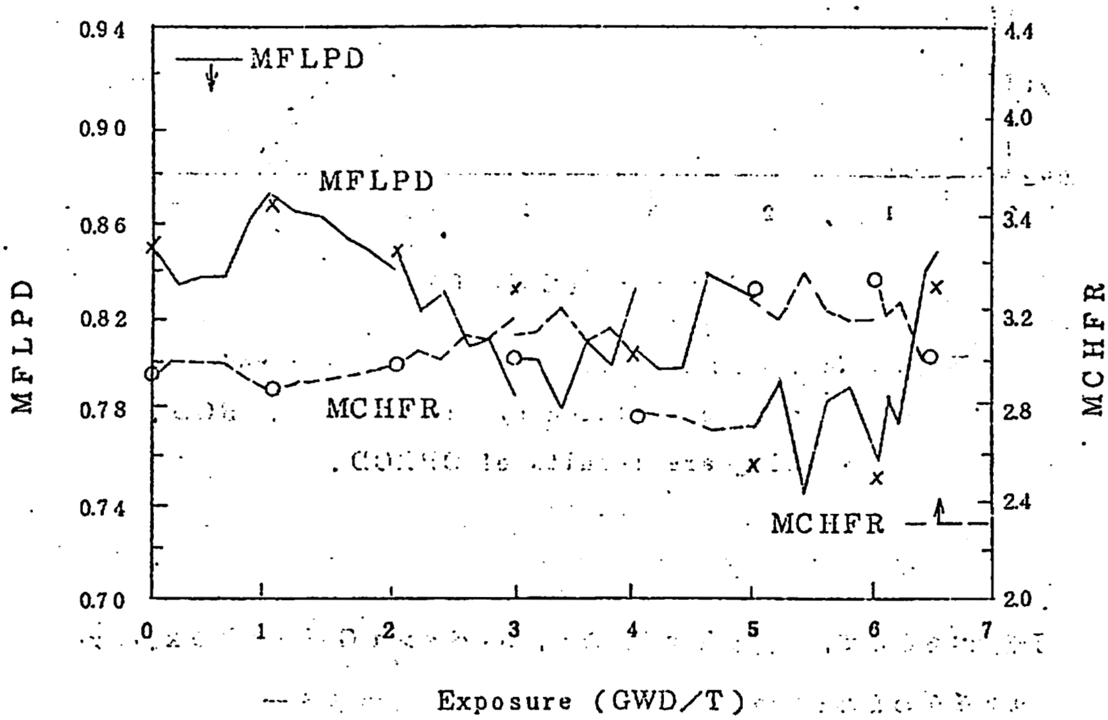

Fig. 7. Maximum fractional linear power density and minimum critical heat flux ratio obtained by OPROD and INROD × and ○ are results of OPROD. The operational constraints are 0.926 for MFLPD and 2.25 for MCHFR.

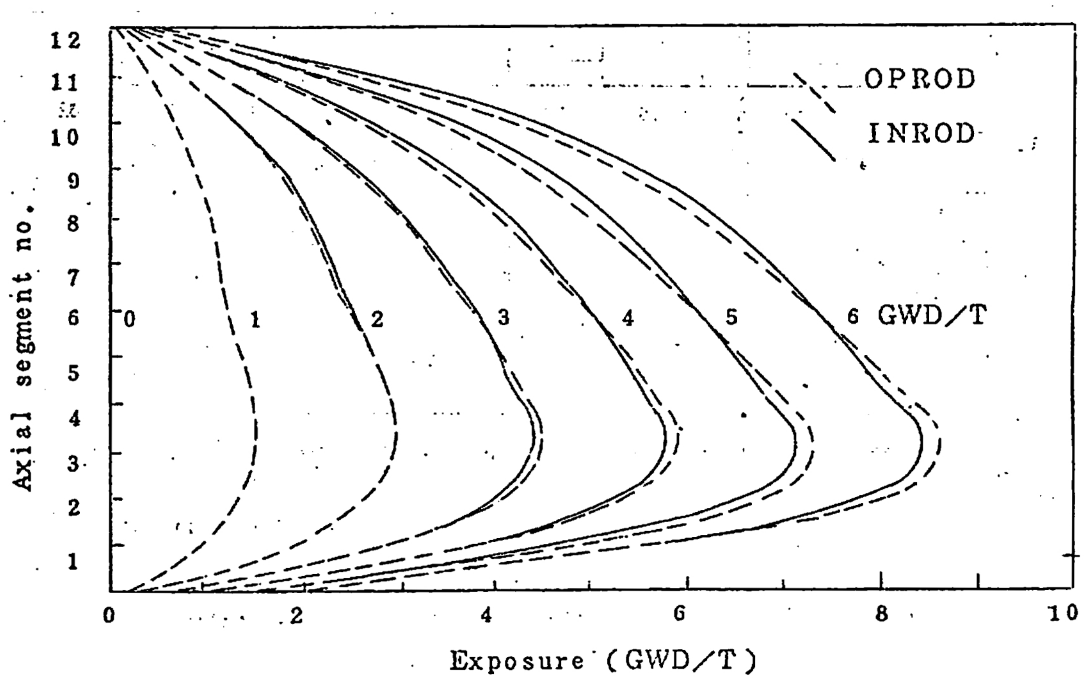

Fig. 8 Axial average exposure distributions obtained by OPROD and INROD

Table 1. Summary of the intermediate term control rod programming for 460 MWe BWR

Pat.	Exposure (GWD/T)	k_{eff}	MFLPD(i,j,k)	MCHFR(i,j,k)	RP	Rod density	$\sqrt{J}$	Δp_{max}(i,j,k
A_1	0*	0.9936	0.828(5, 7,5)	3.02(5, 7,5)	70	0.131	0.061	-0.78(5, 7,4
	0.2	0.9954	0.818(9,11,3)	3.05(9,11,3)	68	0.138	0.108	-0.84 〃
	0.4	0.9981	0.820 〃	3.05 〃	〃	〃	0.110	-0.84 〃
	0.6	1.0003	0.820 〃	3.05 〃	〃	〃	0.113	-0.84 〃
	0.8	1.0000	0.843(1, 3,3)	2.96(1, 3,3)	67	0.141	0.100	-0.82 〃
	1.0	1.0036	0.821(5, 7,5)	3.04(5, 7,5)	68	0.138	0.118	-0.84 〃
B_1	1.0	1.0027	0.865(2, 4,4)	2.89(2, 4,4)	70	0.127	0.008	-0.03(3, 8,2
	1.2	1.0022	0.859(6,11,4)	2.91(6,11,4)	68	0.132	0.036	-0.43(1, 5,6
	1.4	1.0029	0.858 〃	2.91 〃	〃	〃	0.037	-0.43(1, 6,6
	1.6	1.0024	0.847 〃	2.95 〃	65	0.141	0.084	-0.86(2, 4,4
	1.8	1.0027	0.842 〃	2.97 〃	〃	〃	0.086	-0.86 〃
	2.0	1.0027	0.836 〃	2.99 〃	〃	〃	0.090	-0.87 〃
A_2	2.0	1.0024	0.844(8,11,4)	2.96(8,11,4)	70	0.128	0.002	0.01(5, 7,4
	2.2	1.0022	0.838 〃	2.98 〃	〃	〃	0.006	-0.02(9,11,4
	2.4	1.0034	0.841(9,11,3)	2.97(9,11,3)	73	0.120	0.060	0.76(1, 3,3
	2.6	1.0028	0.831 〃	3.01 〃	〃	〃	0.063	0.73 〃
	2.8	1.0022	0.819 〃	3.05 〃	〃	〃	0.067	0.70 〃
	3.0	1.0044	0.853(7,10,5)	2.93(7,10,5)	75	0.110	0.098	0.74(2, 5,5
B_2	3.0*	1.0019	0.831(4,10,4)	3.01(4,10,4)	70	0.127	0.087	0.82(1,10,2
	3.2	1.0034	0.837(4,10,3)	2.98(4,10,3)	74	0.117	0.135	0.89(1, 6,2
	3.4	1.0024	0.825(4,10,3)	3.03(4,10,3)	74	0.117	0.132	0.87(1, 6, 2
	3.6	1.0028	0.800(2, 4,5)	3.12(2, 4,5)	75	0.113	0.136	0.79 〃
	3.8	1.0032	0.777 〃	3.22 〃	78	0.105	0.134	0.76(7,11, 8
	4.0	1.0028	0.763 〃	3.27 〃	79	0.103	0.146	0.82(7,11, 7
A_1	4.0	1.0027	0.809(1,11,9)	2.79(1,11,9)	70	0.086	0.017	0.05(6, 5, 2
	4.2	1.0030	0.795(2,10,7)	2.76 〃	71	0.083	0.049	0.34(2, 6,10
	4.4	1.0031	0.800(2,10,8)	2.74 〃	72	0.079	0.093	0.42(2, 5,10
	4.6	1.0029	0.837(2,10,6)	2.69 〃	73	0.076	0.118	0.81(2,10, 6
	4.8	1.0032	0.827(2,10,7)	2.68 〃	74	0.072	0.169	0.78 〃
	5.0	1.0030	0.829 〃	2.69 〃	75	0.069	0.201	0.80(2, 6, 9
B_1	5.0	1.0024	0.780(4, 6,4)	3.20(4, 6,4)	70	0.066	0.033	0.09(8, 9, 2
	5.2	1.0043	0.802(1, 6,4)	3.12(1, 6,4)	74	0.051	0.091	0.78(1, 6, 4
	5.4	1.0025	0.787 〃	3.17 〃	〃	〃	0.086	0.75 〃
	5.6	1.0042	0.766(1, 6,3)	3.26(1, 6,3)	78	0.035	0.141	0.77(1, 6, 3
	5.8	1.0023	0.749 〃	3.34 〃	〃	〃	0.139	0.76(4,10, 7
	6.0	1.0029	0.758(5,10,5)	3.29(5,10,5)	81	0.025	0.160	0.81(1, 6, 2
A_2	6.0	1.0027	0.753(1, 8,5)	3.32(1, 8,5)	70	0.024	0.036	0.11(8,10, 2
	6.1	1.0026	0.763(1, 7,4)	3.27(1, 7,4)	72	0.020	0.049	0.42(1, 8, 4
	6.2	1.0028	0.778(5,11,4)	3.21(5,11,4)	74	0.014	0.090	0.83(1, 8, 2
	6.3	1.0031	0.796(5,11,3)	3.14(5,11,3)	76	0.007	0.123	0.94(4,11, 2
	6.4	1.0028	0.777(4,11,3)	3.21(4,11,3)	77	0.005	0.122	0.95 〃
	6.5	1.0024	0.843(1,11,2)	2.96(1,11,2)	79	0	0.158	1.19(1,11, 2

Table 2. Control rod sequence of 460 MWe BWR

Exposure (Pattern)	Step no.	Control rod group no. 1	2	3	4	5	6	7	8	9	10	Rod density
0 ~ 1 GWD/T (A₁)	67	2	4	1	12	7.5	4	4.5				0.141
	68	2	4	1	12	7	4	4.5				0.138
	69	2	4	1	12	7	4	3.5				0.134
	70*	2	3	1	12	7	4	3.5				0.131
1 ~ 2 GWD/T (B₁)	65	4.5	3	12	10.5	5	1		5.5	8	4	0.141
	66	4.5	3	12	10.5	5	1		5.5	8	3	0.138
	67	4.5	3	12	10.5	5			5.5	8	3	0.134
	68	3.5	3	12	10.5	5			5.5	8	3	0.132
	69	3.5	3	12	9.5	5			5.5	8	3	0.129
	70	3.5	3	12	9.5	5	[ ]	[ ]	4.5	8	3	0.127
2 ~ 3 GWD/T (A₂)	70	11	11	3		5	10.5					0.128
	71	10	11	3		5	10.5					0.127
	72	10	11	2	–	5	10.5					0.124
	73	10	11	2		5	9.5					0.120
	74	10	10	2		5	9.5					0.117
	75	10	10	2		4	9.5					0.110
3 ~ 4 GWD/T (B₂)	70*	10	8		3	1	11	7	2		5	0.127
	71	10	7		3	1	11	7	2		5	0.125
	72	10	7		3	1	11	7	1		5	0.124
	73	10	7		2	1	11	7	1		5	0.120
	74	10	7		2	1	11	7	1		4	0.117
	75	10	7		2	1	11	6	1		4	0.113
	76	9	7		2	1	11	6	1		4	0.112
	77	9	7		2	1	11	6	1		4	0.108
	78	9	7		2		10	6	1		4	0.105
	79	9	6		2		10	6	1		4	0.103
4 ~ 5 GWD/T (A₁)	70				6	9.5						0.086
	71				6	9						0.083
	72				6	8.5						0.079
	73				5	8.5						0.076
	74				5	8						0.072
	75				5	7.5						0.069

Table 2. continued

		1	2	3	4	5	6	7	8	9	10	
5 ∼ 6	70			12	8				4.5	3		0.066
GWD/T	71			10.5	8				4.5	3		0.064
(B_1)	72			10.5	8				4.5	1.5		0.058
	73			10.5	8				3	1.5		0.056
	74			10.5	6.5				3	1.5		0.051
	75			9	6.5				3	1.5		0.048
	76			9	6.5				3			0.043
	77			9	6.5				1.5			0.040
	78			9	5				1.5			0.035
	79			7.5	5				1.5			0.033
	80			7.5	5							0.030
	81			7.5	3.5							0.025
6 ∼ 6.5	70	12	4.5	3.5								0.024
GWD/T	71	11	4.5	3								0.022
(A_2)	72	10	4	2.5								0.020
	73	9.5	3.5	1.5								0.017
	74	8.5	3	1								0.014
	75	7.5	2	0.5								0.011
	76	6.5	1									0.007
	77	4.5	0.5									0.005
	78	2.5	0.5									0.003
	79											0