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Development of Computer Program STROD for Start-up Control Rod Programming of BWR

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1. Start-up Program STROD

The objective of STROD is to determine the control rod withdrawal sequence and flow control method from the state at which the reactor power begins to increase along the 20 % pump speed line on the power-flow control map to the optimal rated state obtained by OPROD. The withdrawal sequence below the above power is assumed to have been specified elsewhere.

The constraints covered by STROD are:
(1) operating region on the power-flow control map
(2) minimum critical heat flux ratio
(3) maximum linear heat generation rate
(4) pre-conditioned interim operating management recommendation.

The start-up method under the PC-IOMR is one of the following three:
a) No loop method, b) One loop method and c) Two loop method.
These are schematically shown in Fig. 1.

We limit the power-up method to these three, and STROD consists of the three codes: STROD-R, STROD-T, STROD-S.

STROD-R searches for the control rod pattern R* along the 20 % pump speed line that maximizes the reactor power under the constraint that the linear power density at any part of the core does not ecceed 8 kw/ft.

STROD-T determines the withdrawal sequence from zero power pattern R^{o} to the rated power pattern R^{100} via intermediated power pattern R* by the linear interporation.

STROD-S simulates the power-up for one of the above three methods using the calculated sequence.

These relations are shown in Fig. 2.

2. Program STROD-R

The searching algorithm is summarized in Fig. 3:

Step 1: Keep withdrawing until further withdrawal of any rod group violates the constraint of 8 kw/ft (inner loop).

Step 2: Insert the rod group for which the violation is maximum and repeat Step 1 (outer loop).

Step 3: Repeat Step 2 until no withdrawal becomes possible.

3. Program STROD-T

The rod position of group i is determined by the linear interpolation as follows.

step	Rod position
1	R_i^o
2	$R_i^o + \frac{R_i^* - R_i^o}{S_1} * 1$
3	$R_i^o +$ " $* 2$
.	.
.	.
S_1+1	R_i^*
S_1+2	$R_i^* + \frac{R_i^{100} - R_i^*}{S_2} * 1$
S_2+3	$R_i^* +$ " $* 2$
.	.
.	.
S_1+S_2+1	R_i^{100}

R_i^o : Initial pattern where either A or B rods are all inserted.
R_i^* : Intermediate pattern (output of STROD-R)
R_i^{100} : Full power pattern (output of OPROD)
S_1 : Step number from R_i^o to R_i^*
S_2 : Step number from R_i^* to R_i^{100}

Control rod withdrawal sequence is generated from the series of these obtained rod positions.

4. Program STROD-S

The main functions (control blocks) of STROD-S are :
(1) Withdrawal of control rods along the 20 % pump speed line under the constraint of 8 kw/ft or within a pre-conditioned region.
(2) Stop of the withdrawal at the full power pattern R^{100}
(3) Power-up by flow control within the operating region subject to the PC-IOMR
(4) Stop of the flow increase at full power
(5) Flow control to maintain the power level constant
(6) Determination of power level change by the xenon transient for constant flow
(7) Power-down by flow control.

STROD-S has six calculational modules to perform the above functions:
(1) Xenon dynamics, (2) 3-D power distribution calculation, (3) Power search, Flow search, Rod search, (4) Max.rod search, (5) Saturated Xenon, and (6) Back time.

Each control block is specified by some of the following block data: block option, control time, power, flow, sequence step no., ramp rate of power up, constraints applied for the block (maximum power, maximum flow, PC-IOMR check etc.), parameters to specify which block to perform next according to the end state of the block operation.

The last data controls the start-up trajectory (ex. go back three steps and extend the xenon holdup time to 36 hrs. if the withdrawal of rod violates the PC-IOMR. etc.)

Flow chart of STROD-S is shown in Fig. 4.

5. Application of STROD to a 460 MWe BWR

Results of OPROD and STROD-R are shown in Fig. 5 and Table 1, results of STROD-T are shown in Table 2, and results of STROD-S are shown in Fig. 6.

The accuracy of STROD-S is summarized in Tables 3 and 4 in comparison with the actual operating data.

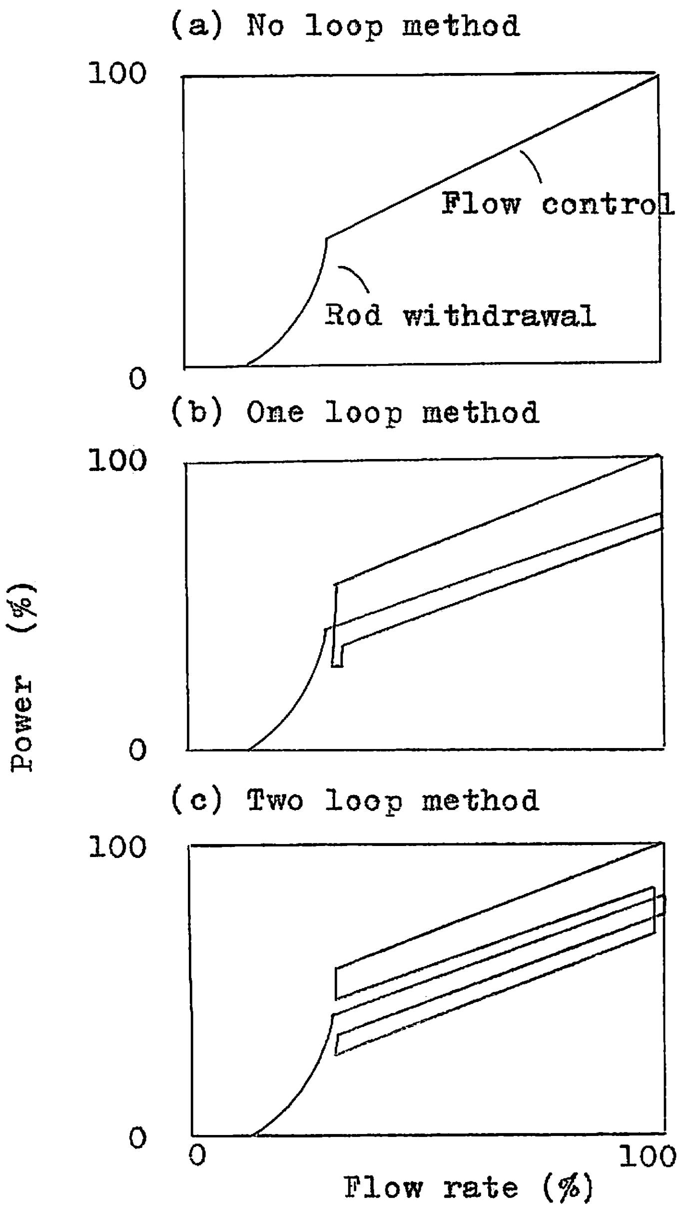
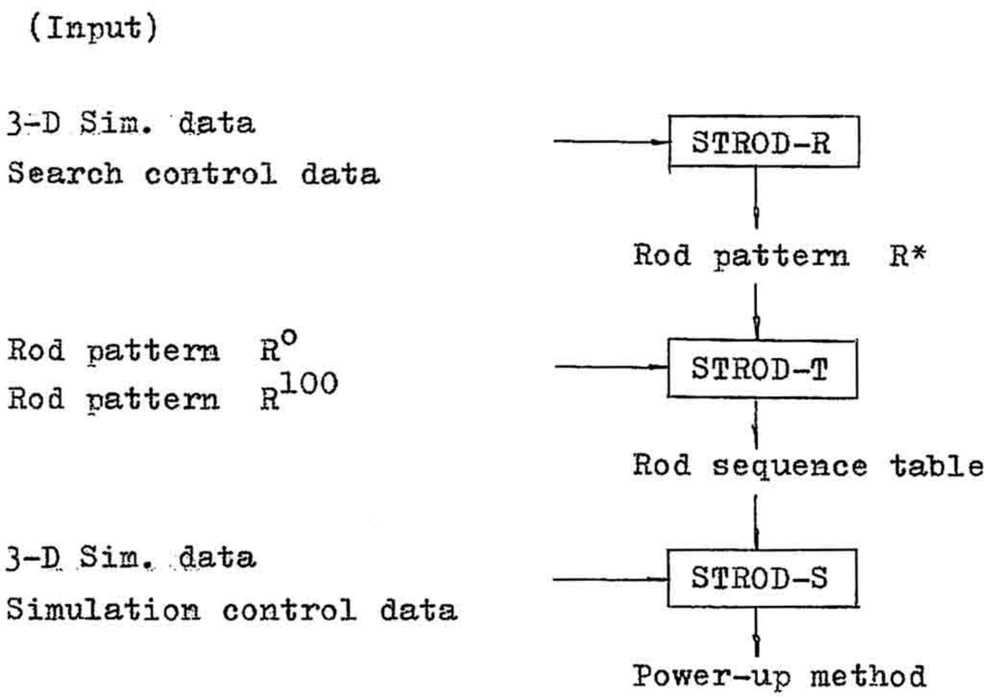


Fig. 1 Trajectories on power-flow control map at power-up operation



R^{o} : Checkerboard pattern

R^{100} : Rated power pattern (OPROD)

Fig. 2 BWR power-up programming code STROD

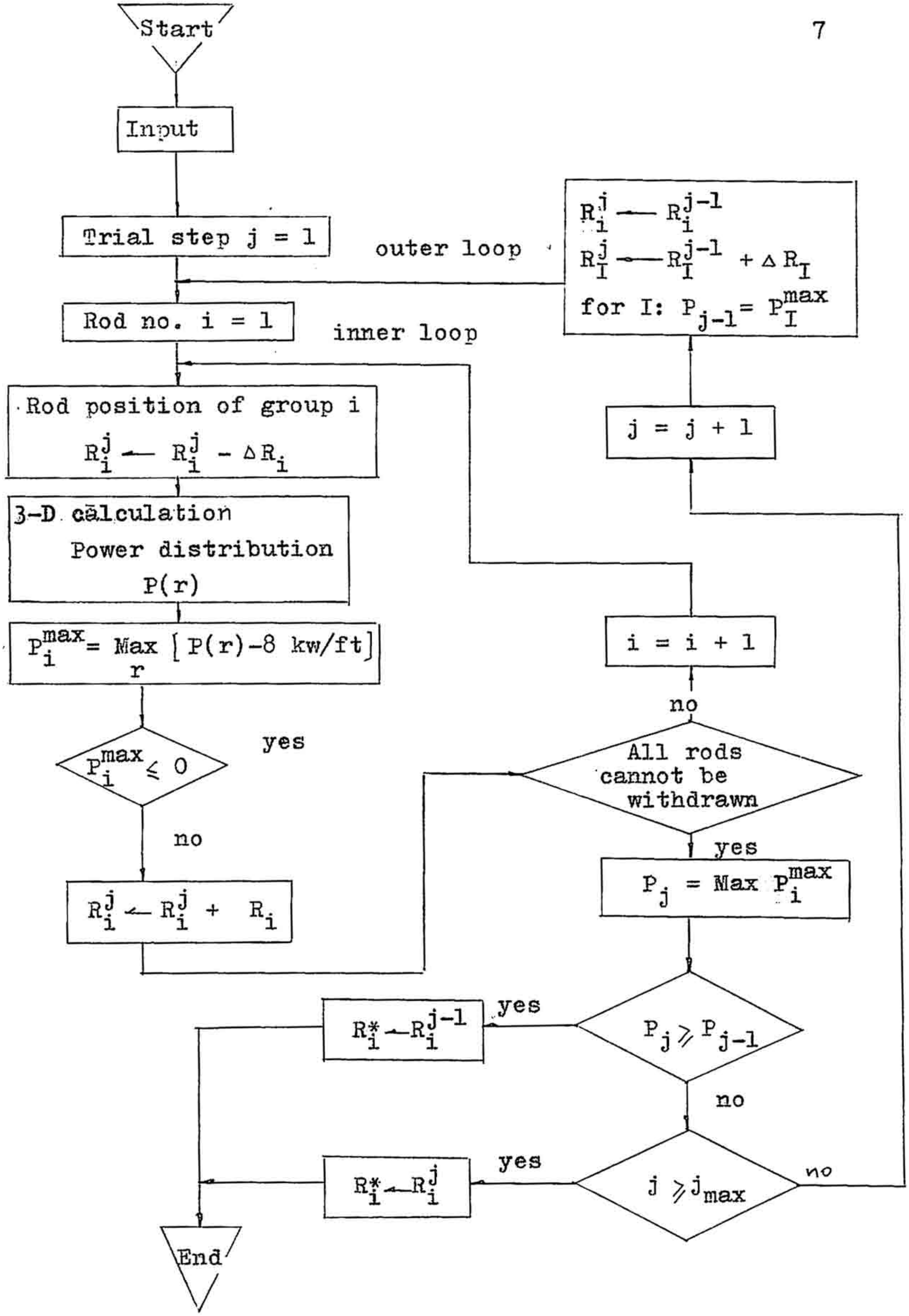


Fig. 3 Flow chart of STROD-R

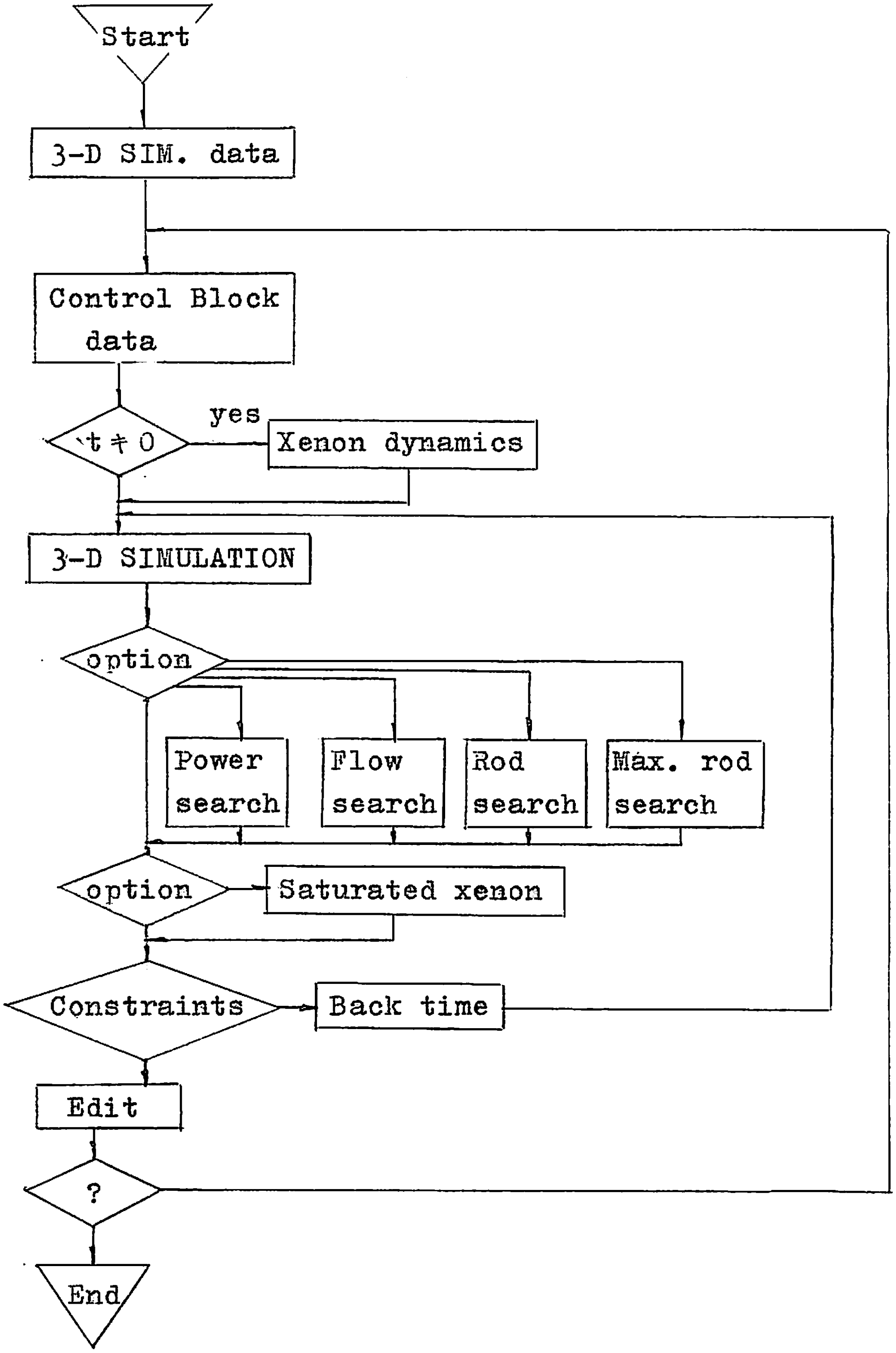


Fig. 4 Flow chart of STROD-S

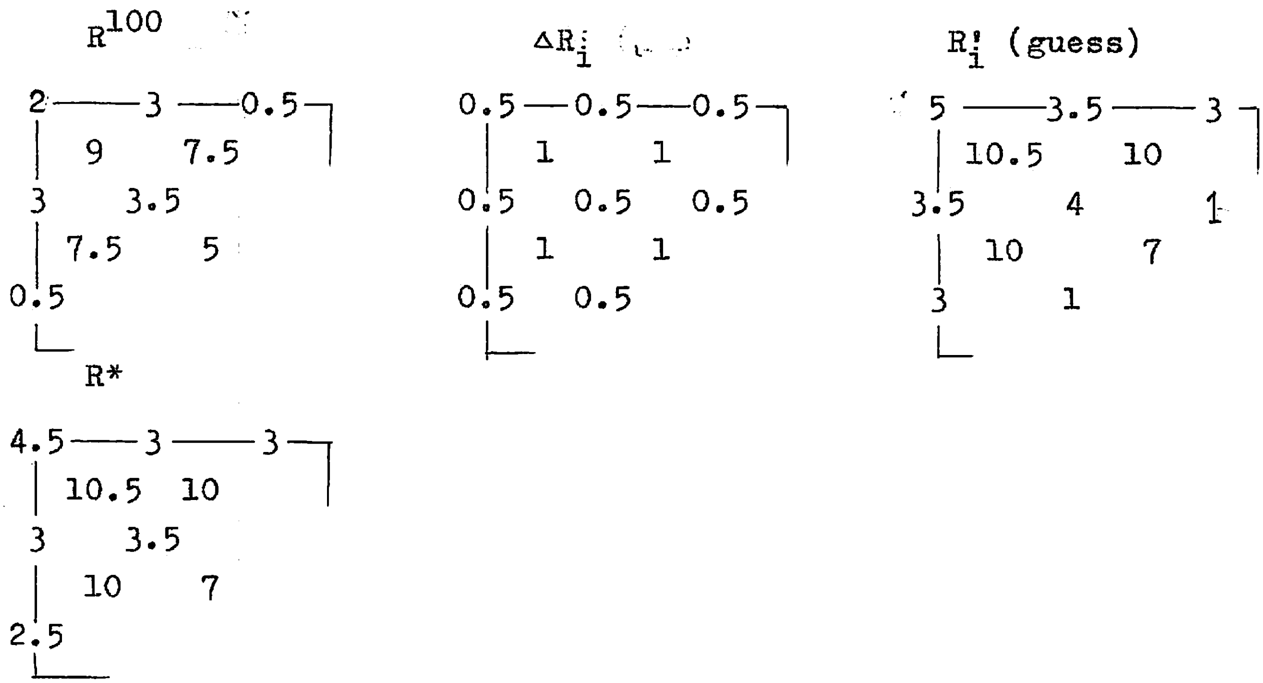


Fig. 5 Control rod pattern for rated operation R^{100} (OPROD) Allowable movement of rod per trial ΔR_i, initial guess pattern R_i' and the result of STROD-R R^*

Table 1 Results of STROD-R

Control rod pattern	Power (%)	Flow (%)	MLHGR (kw/ft)
R_i' (guess)	40.0	40.0	6.78
R* (optimal)	41.2 76.0	40.0 100.0	7.00* 11.56

* Maximum heat rate is limited to 7 kw/ft (not 8 kw/ft).

Table 2 Control rod withdrawal sequence generated by STROD-T

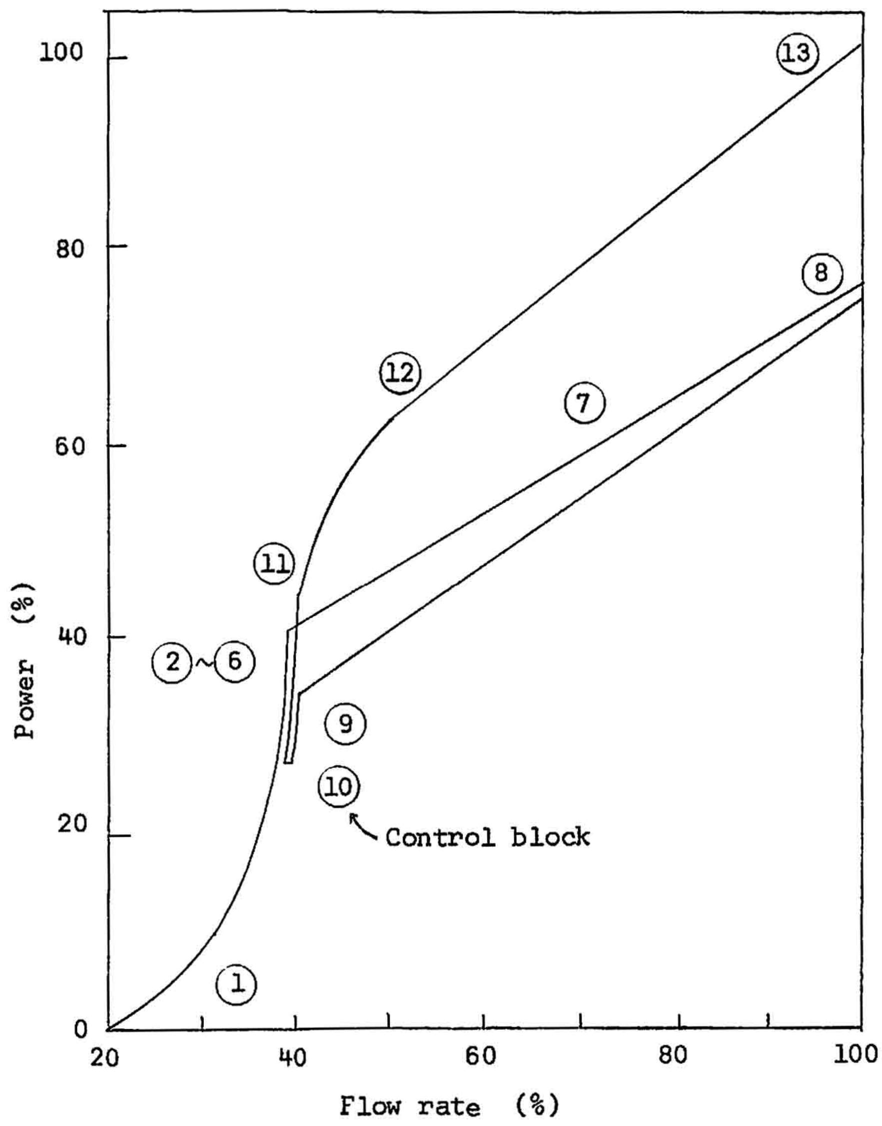
CONTROL ROD SEQUENCE

STEP	GROUP 1	2	3	4	5	6	7	8	9	10	11	12	
1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	(R^0)
2	9.5	9.5	10.0	10.0	10.5	10.5	10.0	10.0	11.0	11.5	11.5	11.5	
3	7.0	7.0	8.0	8.0	8.5	9.0	8.5	8.5	10.0	11.0	11.0	11.5	
4	5.0	5.0	6.5	6.5	7.0	7.5	6.5	6.5	9.0	11.0	11.0	11.0	
5	2.5	2.5	4.5	4.5	5.0	6.0	5.0	5.0	8.0	10.5	10.5	11.0	
6	0.0	0.0	2.5	2.5	3.5	4.5	3.0	3.0	7.0	10.0	10.0	10.5	(R^*)
7	0.0	0.0	2.0	2.0	3.5	4.0	3.0	3.0	6.5	9.5	9.5	10.0	
8	0.0	0.0	1.5	1.5	3.5	3.5	3.0	3.0	6.0	9.0	9.0	10.0	
9	0.0	0.0	1.0	1.0	3.5	2.5	3.0	3.0	5.5	8.0	8.0	9.5	
10	0.0	0.0	0.5	0.5	3.5	2.0	3.0	3.0	5.0	7.5	7.5	9.0	(R^{100})

FINE SEQUENCE

STEP	GROUP 1	2	3	4	5	6	7	8	9	10	11	12
1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
2	9.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
3	9.5	9.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
4	9.5	9.5	10.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
5	9.5	9.5	10.0	10.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
6	9.5	9.5	10.0	10.0	10.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0
7	9.5	9.5	10.0	10.0	10.5	10.5	12.0	12.0	12.0	12.0	12.0	12.0
8	9.5	9.5	10.0	10.0	10.5	10.5	10.0	12.0	12.0	12.0	12.0	12.0
9	9.5	9.5	10.0	10.0	10.5	10.5	10.0	10.0	12.0	12.0	12.0	12.0

⋮



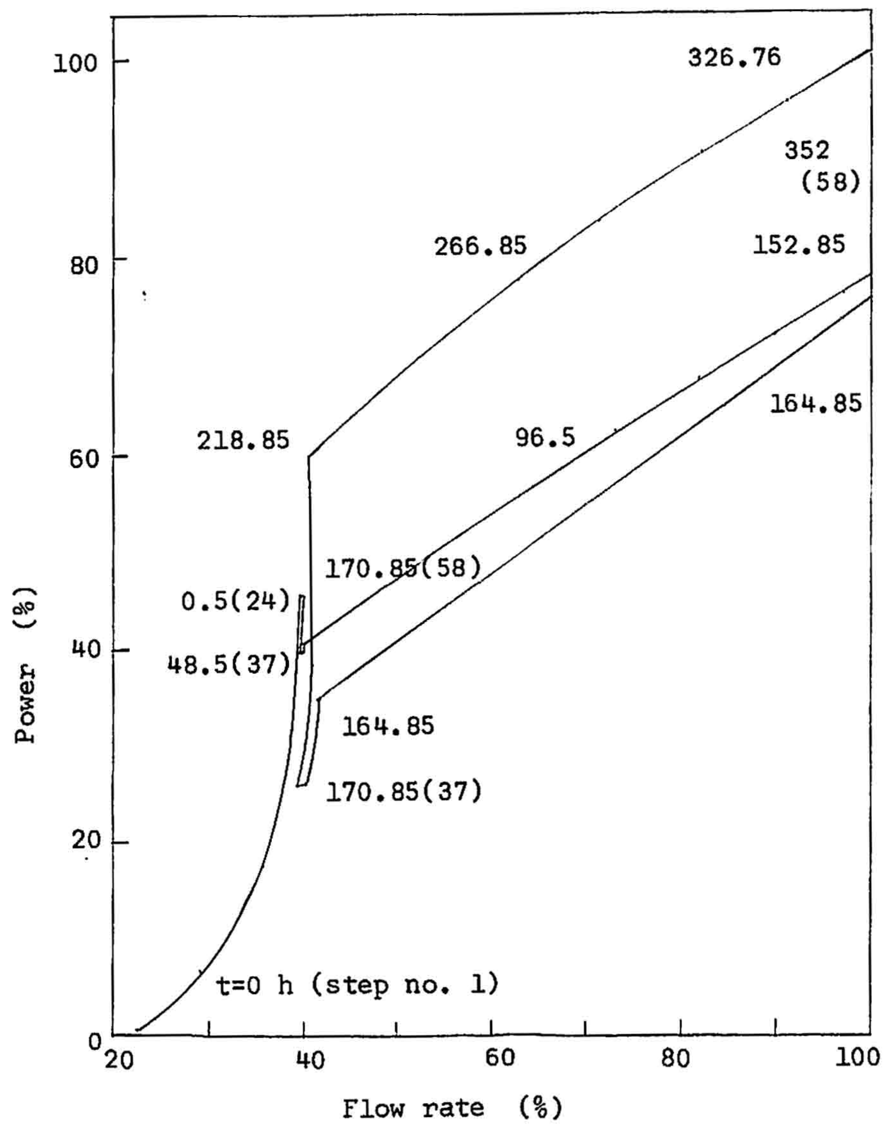


Fig. 6 Results of STROD-S (left: input, right: result)

Table 3 Neutron multiplication factor obtained by STROD-S

Rod pattern	Flow rate	Thermal power	keff
75 % pattern	40 % 100	40～45 % 73～77	1.0047 1.0001
100 % pattern	40 % 90	50～64 % 97	1.0056 1.0012

Table 4 Error in TIP readings calculated by STROD-S

	case 1	case 2
Thermal power (%)	46.7	97.3
Flow rate (%)	39.3	90.5
TIP average error σ [a]	0.059	0.069
Max. TIP reading *		
measured	1.86	1.70
STROD	1.98	1.67
STROD-measured	0.12	-0.03

a $$\sqrt{1/N \sum_{\text{All nodes}} (TIP_{measured} - TIP_{STROD})^2}$$

* TIP readings are normalized by their average.