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3. Development of Startup Control Rod Programming Code System for BWRs,

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Strong constraints are currently imposed on local power density and its rate of change for BWRs to secure fuel integrity. This makes it difficult to make planning of startup control rod programming with ample margin, particularly for BWRs of high power density.

A startup control rod programming code system has been developed to semiautomate the planning of startup programming. This system comprises three computer programs, HIROD, STROD-R, and STROD-S. each of which is based on nuclear thermal-hydraulic coupled 3-D BWR simulator with different searching algorithms. HIROD[1] employs heuristic and mathematical programming algorithms to optimize the rated control rod patterns for whole cycle with emphasis placed on deep rod search. STROD-R also employs heuristic algorithm to find rod patterns for partial load that maximize the power level under the constraints. From these patterns, rod withdrawal sequence is determined by preferentially withdrawing shallow rods first. STROD-S searches for the startup process under the operational constraints using this rod withdrawal sequence.

The algorithm used in STROD-S is shown in Fig. 1. Startup process is divided into a set of basic operation block $i = 1, 2, \ldots$ The problem is to find the best time sequence of these blocks. An index $j = 1, 2, \ldots$ is defined for each of the possible end states of each operation block and a decision matrix that correlates j to i of the next operation is used to determine the operation sequence. For example, if the power level reached the rod block line ($j_1 = 3$) as a result of control rod withdrawal ($i_1 = 1$), the next operation is to increase power level by core flow control ($i_2 = 3$).

Functions associated with each operation block are: normal eigenvalue calculation, power search, flow search, and rod search with or without xenon dynamics included. With these functions, it is possible to simulate the following operations: power hold, back time, power increase or decrease by flow control, power increase or decrease by rod operation. The possible end states of each operation considered are: operation block ended normally (constraints were all satisfied), power reached its upper or lower limit, flow reached its upper or lower limit, MCPR reached its limit, MCHFR reached its limit, PC-IOMR constraints were violated, rod sequence reached its target value, power reached rod block line, and no residual operation time was available.

The above code system has been applied to find a feasible startup control rod programming for a 784-MW(e) BWR of 51 kW/litre, loaded with three different enriched fuel assemblies, two of which contain axially distributed gadolinia pins. The survey study indicated that change rate of local power density due to xenon transient is large enough to exceed its limit, and it was necessary to devise a procedure to minimize the xenon transient effect. One of the methods is to increase the threshold power level above which withdrawal of control rods is prohibited by making the maximum use of a preconditioning envelope. For this purpose, special control rod pattern (PCP pattern: Pre-Conditioning with Periphery rods) is introduced. Figure 2 shows an example of the power-up trajectory using the PCP pattern in the second ramp. Characteristic of the PCP pattern is that the rod pattern in the central region is identical with the rated pattern and some of the periphery rods are completely inserted to reduce the power level. Because of this somewhat radially distorted power distribution, envelope in the central region established at Ⓑ is large enough to cover the xenon transient effect at the next rod withdrawal from PCP to the rated pattern (② to ③). The envelope established at the first ramp Ⓐ is effective for the peripheral region. It is confirmed that the operational constraints are completely satisfied with this method, and this PCP method has actually been applied during the startup test of the BWR mentioned above.

1. T. HAYASE and H. MOTODA, *Trans. Am. Nucl. Soc.*, 27, 727 (1977).

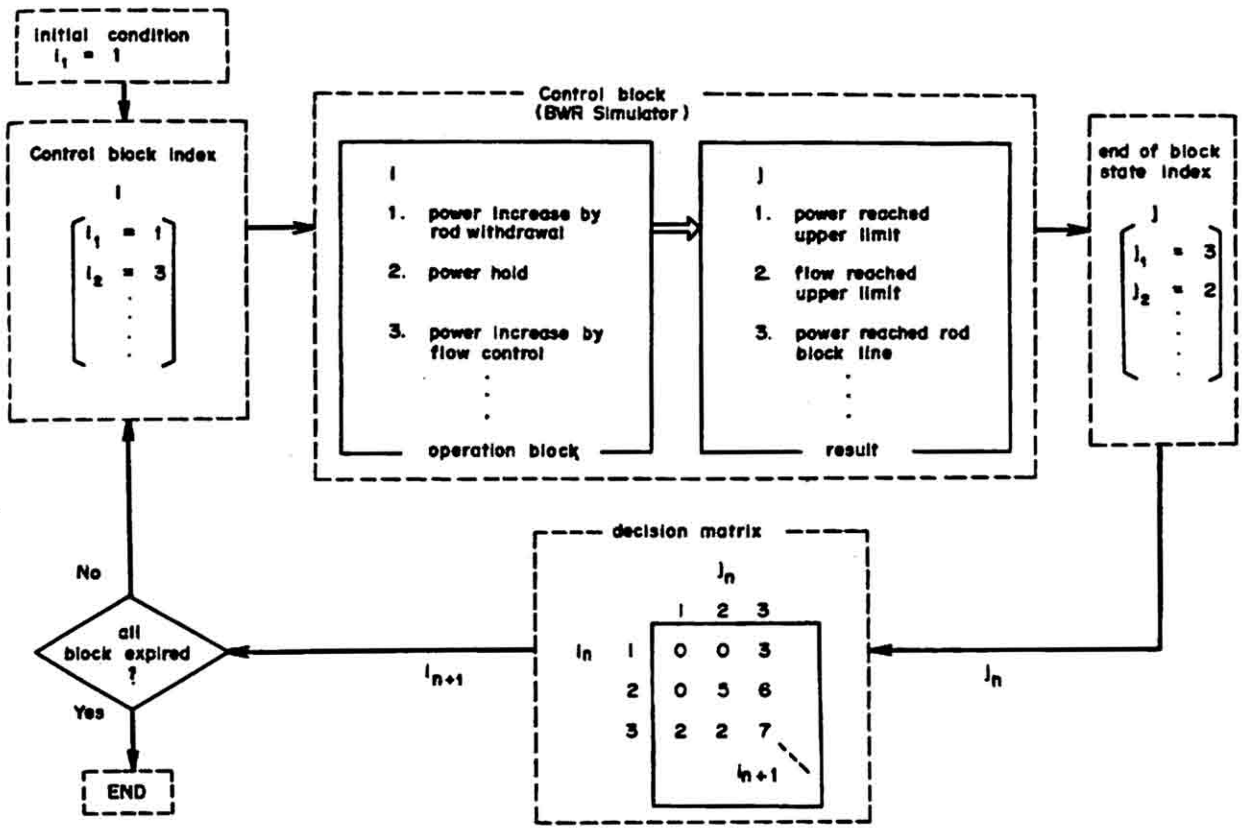

Fig. 1. Algorithm used in STROD-S.

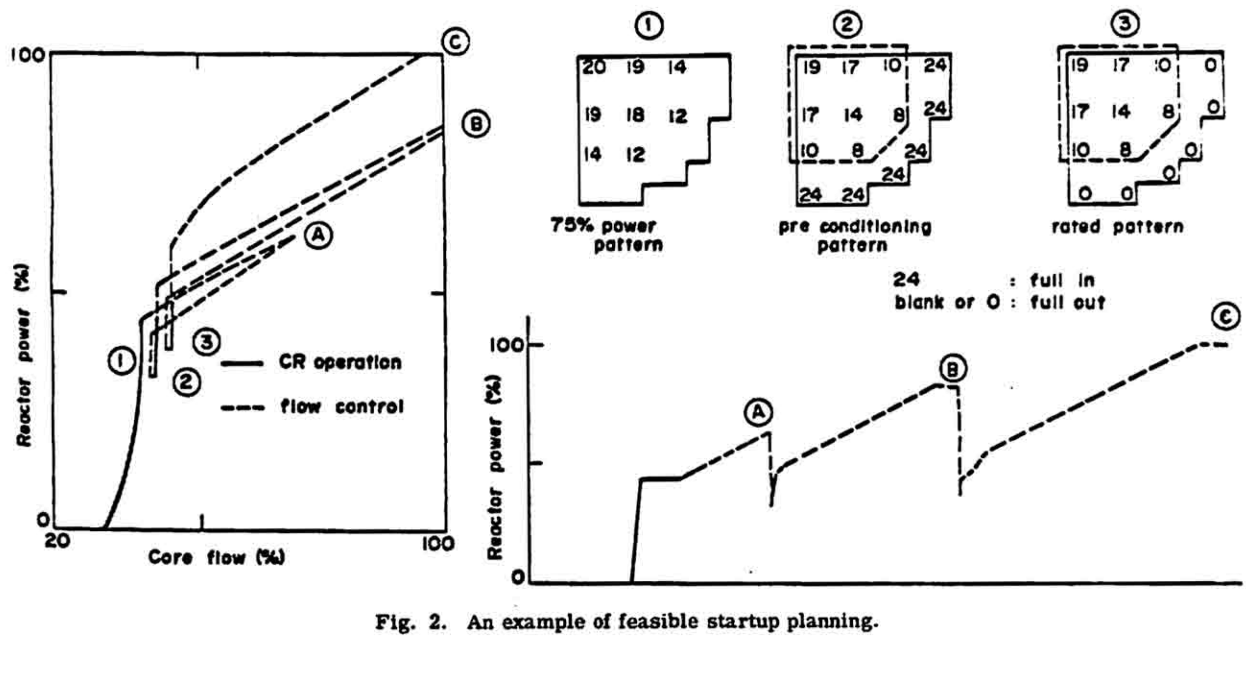

Fig. 2. An example of feasible startup planning.