FISSION REACTORS

TECHNICAL NOTE

PRINCIPLES FOR CONTROL ROD WITHDRAWAL STRATEGY DURING THE STARTUP OF BOILING WATER REACTORS

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Control rod withdrawal strategy during boiling water reactor startup is explored and verified by examples simulated with a three-dimensional nuclear-thermal-hydraulic coupled computer code with xenon dynamics included.

The study leads to the following two general principles.

1. Use of the shallow control rods should be minimized in the intermediate pattern insofar as the power peak near the bottom is within the limits for the xenon transient control.

2. Every control rod should be withdrawn at least once to the same depth or to more than that of the rated pattern, and use of two different control rod patterns is necessary for the effective stretching out of the preconditioned envelope.

INTRODUCTION

Current operational constraints on the local power density and its rate of change to insure fuel integrity are some of the concerns in writing startup procedures for boiling water reactors (BWRs). The loss-of-capacity factor associated with operation under these constraints needs to be minimized. Efforts are therefore being made to devise a procedure for an effective startup method[1] in current BWRs or to establish a new BWR core design with improved performance characteristics aimed at achieving power maneuvering flexibility.[2-4]

There are two types of constraints that must be satisfied—macroscopic and microscopic. Macroscopic constraint is on the operating region. Microscopic constraints must be satisfied for each fuel pin (Fig. 1).[a] The first (① and ②) are to secure fuel integrity by mitigating the pellet clad interaction duty of the fuel.[5,6] Rapid local power increase is prohibited above the threshold level of power or the preconditioned envelope,[b] and control rod withdrawal is permitted only below this level. The other two (③ and ④) are to secure a thermal margin, and these are the constraints on maximum linear heat generation rate (MLHGR) and minimum critical power ratio (MCPR).

A control rod programming code system has been

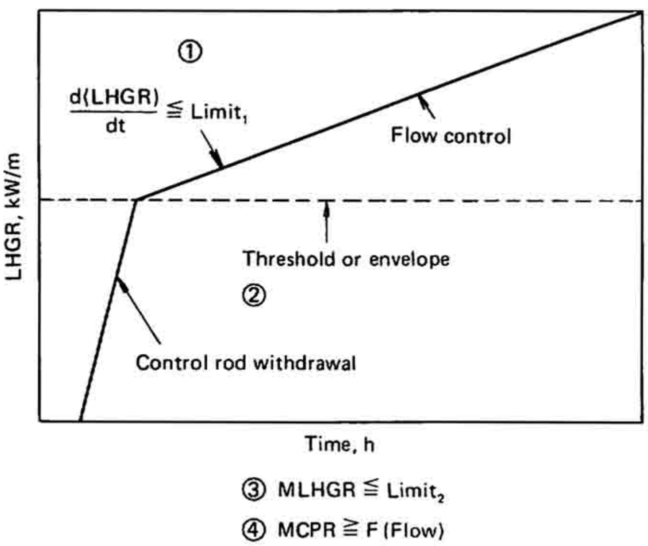

Fig. 1. Operational constraints for BWR microscopic.

[a]These microscopic constraints require monitoring of the local power density and its rate of change, which in turn requires analysis of the three-dimensional power distribution with xenon dynamics included.

[b]Fuel is said to have been preconditioned when it has experienced a certain linear heat generation rate (LHGR) for a certain period of time. The trajectory of this experienced LHGR level along the axial direction of the fuel pin is called the "preconditioned envelope."

developed to semi-automate the planning of startup programming using the heuristic algorithm.[1,7] Analyses indicated the necessity to devise a procedure to minimize xenon transient effects and to stretch out the envelope. This led to a new startup procedure, preconditioning with peripheral rods operation (PCP) method. The PCP method is characterized by an intermediate control rod pattern that is identical with the rated control rod pattern in the central region, but with some of the peripheral control rods fully inserted. This method was successfully applied to the initial startup of a commercial BWR. A modification of this technique was developed by Folk et al.[8] and applied to increase capacity factor during coastdown operation of a BWR.

The degree of difficulty of withdrawing the control rods depends in general on the rated control rod pattern and the corresponding power distribution. The purposes of this paper are to extract general principles for control rod withdrawal in view of the xenon transient control and preconditioned envelope stretch out, to review the PCP pattern from these principles, and to introduce some other applications.

CONTROL METHOD DURING STARTUP

Method of Xenon Transient Control

Power distribution during the startup process strongly depends on the control rod withdrawal sequence and the

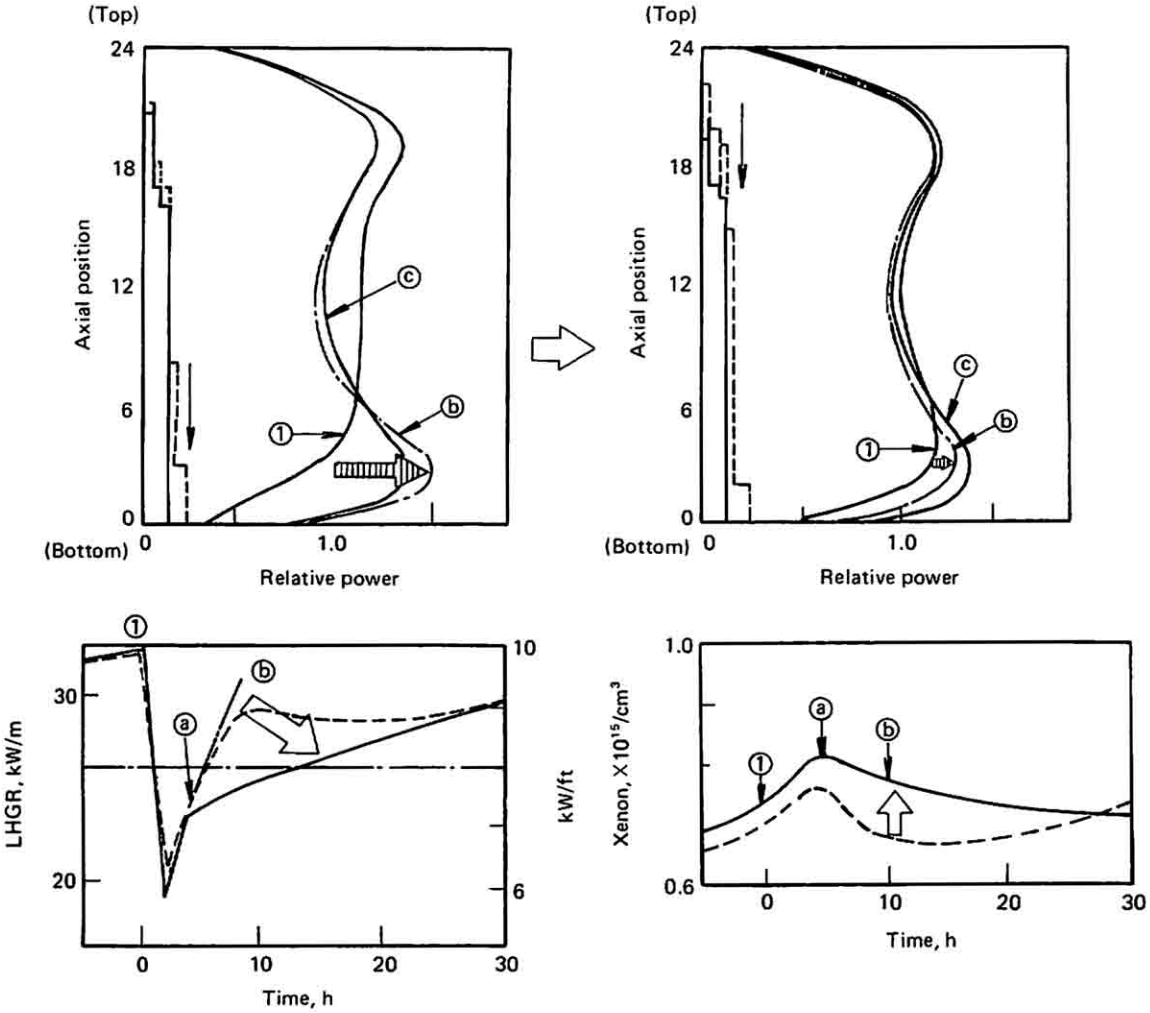

Fig. 2. Problems and principle of xenon transient control:

① end of ramp

ⓐ end of control rod withdrawal (the rated control rod pattern formed)

ⓑ middle of transient

ⓒ, xenon equilibrium

⇨ improvement.

induced xenon transient effects. The axial power distribution in a BWR tends to be skewed toward the lower part of the core due to the existence of axial void distribution. The easiest way to reduce this power peak near the bottom is to use shallow rods. (Here, "shallow" denotes a depth less than half of the core height.)

The disadvantage with regard to usage of the shallow rods arises after their withdrawal in the loop startup method.[c] It is particularly pronounced in the last loop, in which the reactivity suppression due to the xenon buildup following the reduction of power by core flow control is utilized to withdraw the control rods to form the rated pattern. This situation is depicted in Fig. 2. If the power distribution is flattened too much by use of the shallow rods (the power distribution ① of the upper left), withdrawal of these shallow rods causes a power overshoot ➪ in the lower part of core (the power distribution ⓑ of the upper left), i.e., the power distribution in the middle of the transient ⓑ becomes larger in the lower part of the core than that of the equilibrium xenon ⓒ. The change rate of linear heat generation rate (LHGR) at the threshold level exceeds the allowable limit (lower left; dotted curve). This is because of the succeeding undershoot of the xenon concentration (lower right; dotted curve).

A method to resolve this difficulty is to use an intermediate control rod pattern, which limits use of the shallow rods insofar as the power peak in the lower part of the core satisfies the constraints (the power distribution ① of the upper right). Withdrawal to the rated pattern does not cause the power overshoot in the lower part of the core, i.e., the power distribution during the transient ⓑ asymptotically approaches that of the equilibrium xenon ⓒ if the flow is kept constant, and the change rate of LHGR becomes smaller (lower left; solid curve). This is because of a disappearance in the undershoot of xenon concentration (lower right; solid curve).

The above phenomena are physically explained by the trajectory in the xenon-iodine map of Fig. 3 for the lower part of the core. The cause of the undershoot of xenon concentration after the withdrawal of the control rods is an insufficient accumulation of the iodine nuclide. It is difficult to avert this undershoot (at ⓑ of two dotted curves) by controlling the withdrawal timing (at ⓐ of two dotted curves).

The proposed method provides sufficient iodine in the lower part of the core such that the net balance of xenon determined by the rate of production due to the decay of iodine and by the rate of loss due to neutron absorption will never cause an undershoot during the transient after the control rod withdrawal, as is shown by the solid curve.

Method of Preconditioned Envelope Stretch Out

There is still another problem of violating the microscopic constraints even after having controlled the anticipated xenon transient. This occurs in the case of a BWR having a large LHGR. Figure 4 shows xenon transient

[c]This is a method now considered standard for BWR startup operation. The name comes from the shape of the trajectory on the power-flow map. It draws one or two loops on this map (two or three ramps on the power-time map) before it finally reaches the rated state.

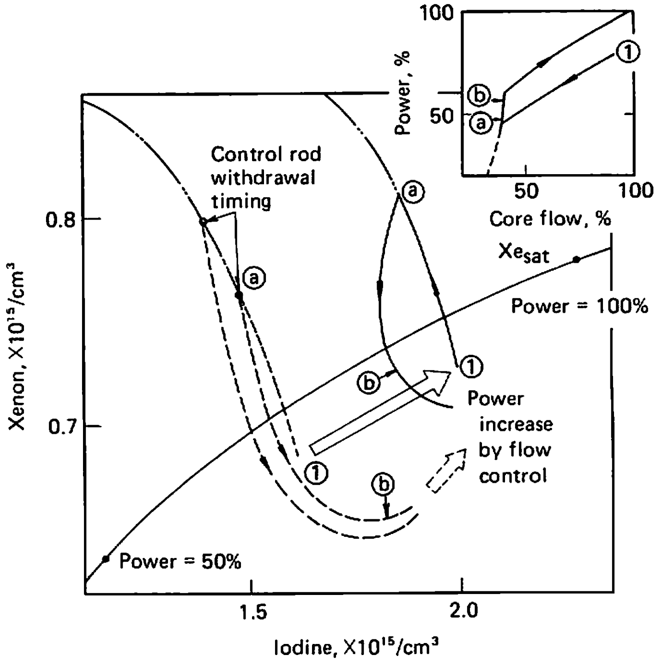

Fig. 3. Xenon-iodine map to explain method of xenon transient control:

① end of ramp

ⓐ end of control rod withdrawal (the rated control rod pattern formed)

ⓑ middle of transient

➪ improvement.

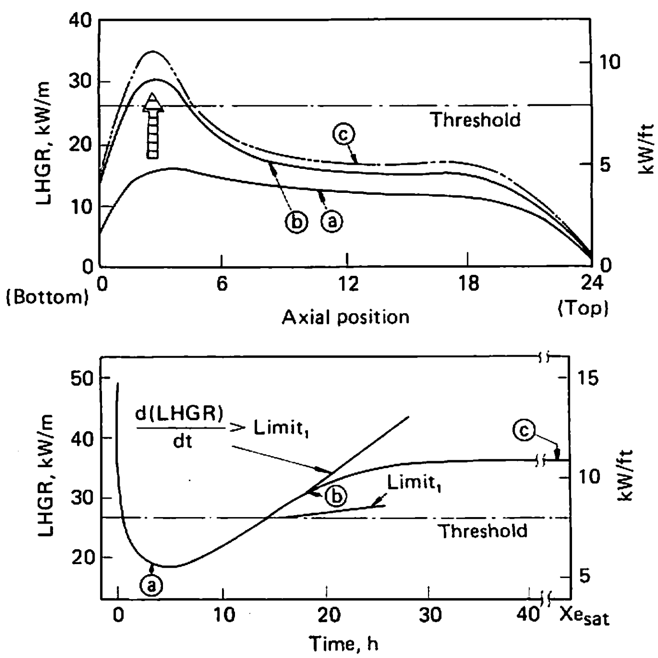

Fig. 4. Evaluation of xenon transient effects for a BWR with a large LHGR.

effects. It is evident that the overshoot of LHGR has disappeared by the method just described. However, the rate of change at the threshold is still large and exceeds its limit.

The sole way to solve this difficulty is to effectively raise the threshold level by stretching out the preconditioned envelope. Careful observations of the phenomena and accumulated experience have led to the following two principles on the preconditioning process.

1. Every control rod should be withdrawn at least once to the same depth or to more than that of the rated pattern.

2. Two control rod patterns of different configurations should be used.

The total inserted notches of an intermediate control rod pattern are larger than that of the rated pattern, and withdrawal from the preconditioned pattern to the rated pattern must satisfy the constraints. Figure 5 explains the phenomena encountered with this withdrawal and the basic principles mentioned above, assuming a location where the control rod is completely withdrawn at the rated pattern. The LHGR at the corner pin adjacent to the inserted control rod is very small (lower left). Therefore, it is hardly possible to stretch out the envelope there, and the withdrawal of this control rod presents the problem (upper left). However, if this location has been preconditioned in advance with a different rod pattern, which has no control rod inserted at this location but has other rods somewhere else, the preconditioned envelope is large enough to cover the power distribution changes by the withdrawal (lower and upper right).

APPLICATION OF THE PRINCIPLES

The PCP method previously proposed[1,7] is shown to be one of the applications that satisfies these principles. The

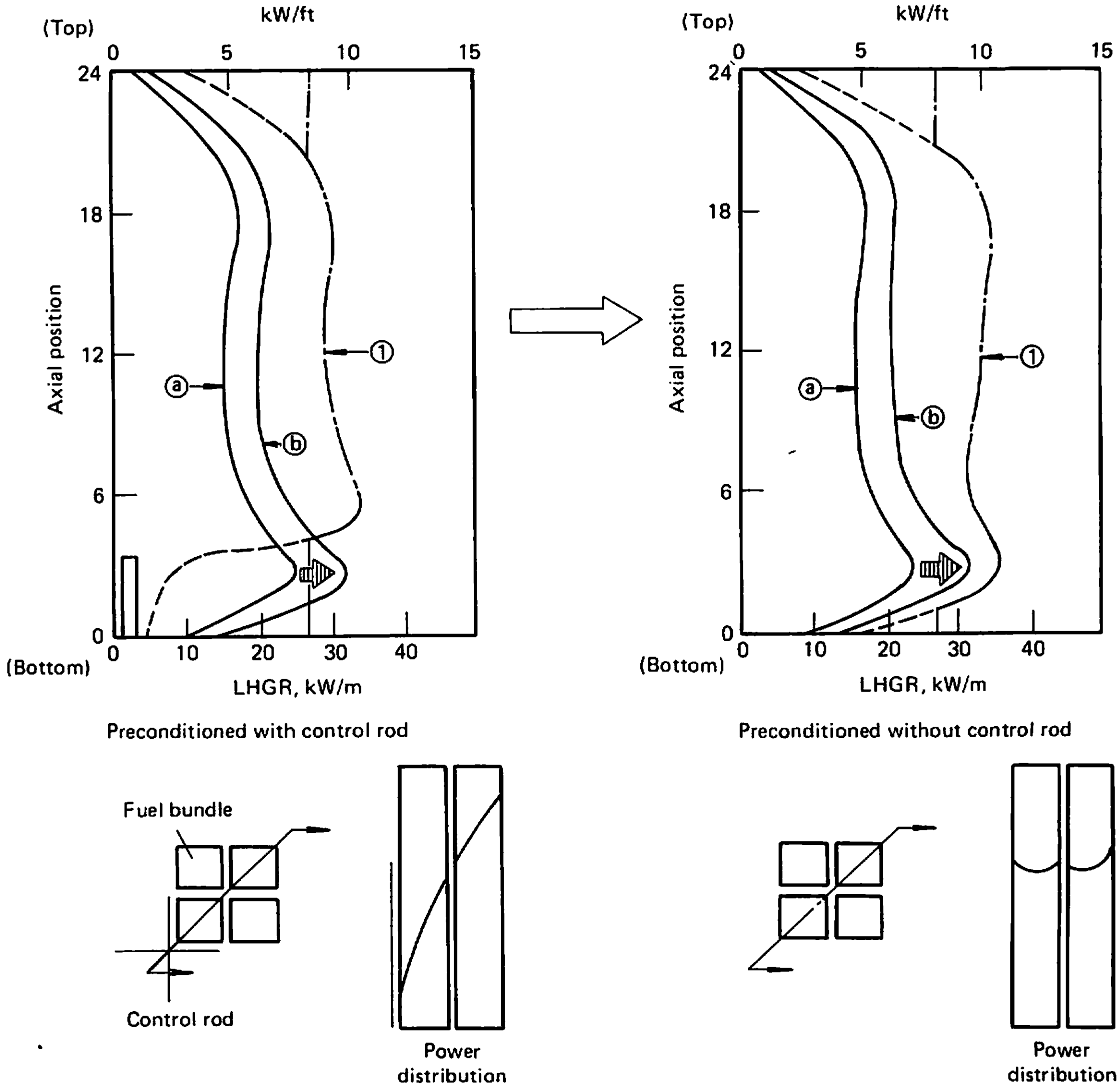

Fig. 5. Problems and basic principles of a preconditioned envelope stretch out.

envelope in the core peripheral region is stretched out by the first pattern, and that in the central region by the PCP pattern. Withdrawal of the peripheral rods does not cause a large perturbation in the central region.

In the following, two other applications that are based on these principles are given for illustration. The rated control rod patterns in these examples are composed of deep rods alone, which are arranged in circular rings. This pattern, called an R-Θ pattern, has more degrees-of-freedom for power distribution control than that of a checkerboard pattern.[4]

Figure 6 is an example applied to a BWR with a small LHGR. This is a case where only xenon transient control is required. Pattern ① is chosen to make the power density large in the lower part of core under the MLHGR limit. The resultant LHGR change rate is kept under the limit and all other constraints are also satisfied. Pattern ①′ is an alternative pattern that makes the power distribution flatter by use of more shallow control rods. However, this pattern gives too large an LGHR change rate.

Figure 7 is an example applied to a BWR with a large LHGR. This is a case where both xenon transient control and preconditioned envelope stretch out are required. The xenon transient can be controlled by pattern ②, composed of deep rods only. The envelope can be stretched out by both patterns ① and ②.

Two bundles Ⓐ and Ⓑ are chosen to illustrate the envelope stretching out. Bundle Ⓐ is controlled in pattern ② and no envelope stretch out is expected by this pattern. But it is uncontrolled in pattern ① where the control rod

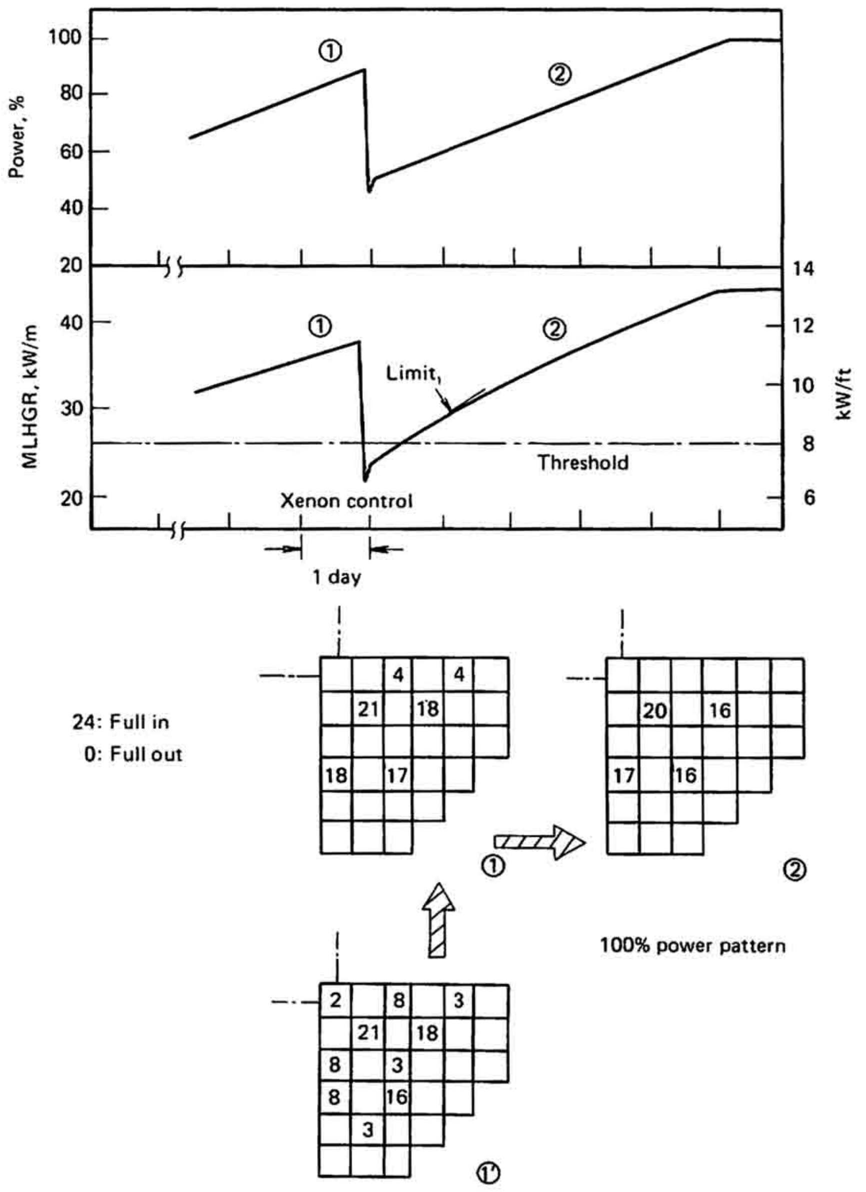

Fig. 6. Application to a BWR with a small LHGR; a case where only xenon transient control is required.

adjacent to it is completely pulled out, the same as in pattern ③. Thus the envelope stretched out by pattern ① can be utilized for withdrawal of the rod from 16 to 0 (upper left). On the other hand, bundle Ⓑ is controlled in pattern ① but uncontrolled in pattern ②. Thus, the envelope can be stretched out by pattern ② and it can be utilized at the last withdrawal to the rated pattern (upper right). Note that the control rods withdrawn this time are all apart from bundle Ⓑ. The power distribution changes in both bundles are inside the envelopes and all the constraints can be satisfied.

CONCLUSION

General principles for a startup control rod withdrawal strategy for BWRs were found through careful analysis by a three-dimensional BWR simulator.

1. Xenon transient control

   a. To limit use of the shallow control rods in the intermediate pattern, insofar as the power peak in the lower part of the core satisfies the operational constraints, thereby making the concentration of iodine large enough not to cause an undershoot

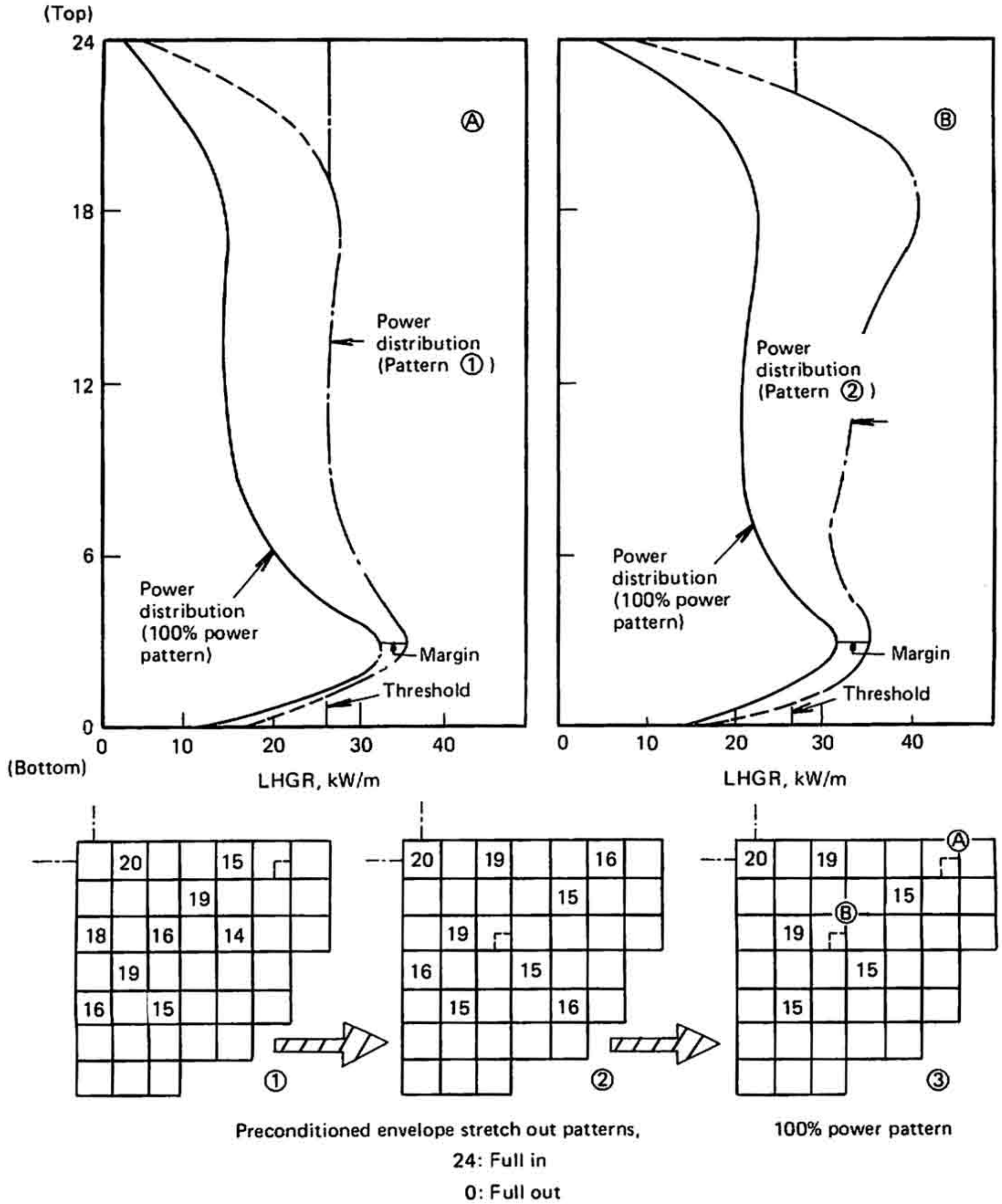

Fig. 7. Application to a BWR with a large LHGR; a case where both xenon transient control and preconditioned envelope stretch out are required.

of xenon in the lower part of the core during the transient after control rod withdrawal.

2. Preconditioned envelope stretch out

   a. To withdraw every control rod at least once to the same depth or to more than that of the rated pattern.

   b. To use two control rod patterns of different configurations. Use of a preconditioned envelope is required only when the constraints are still violated with the controlled xenon transient.

The previously proposed PCP method falls under these principles. Two other applications of these principles were given and verified by detailed simulation. These examples have demonstrated that the principles give satisfactory guidelines to generate startup control rod programming of BWRs under the current operational constraints.

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