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# A New Method of Startup Planning for Boiling Water Reactors

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Based on a heuristic approach, a practically applicable startup process for BWR's that minimizes the xenon transient effects has been derived, which answers this highly nonlinear complex multi-stage optimization problem, while satisfying the current constraints imposed for fuel integrity. The resulting PCP (Pre-Conditioning with Peripheral Rod Operation) method features an intermediate control rod pattern, with central region identical with the rated control rod pattern and with certain control rods fully inserted in the peripheral region. This method has been successfully applied to the initial startup of a commercial BWR, and the expected performance was confirmed from operating data.

***KEYWORDS: BWR type reactors, startup planning, control rods, reactor operation, flow control, heuristics, simulations, xenon dynamics, fuel integrity, preconditioning***

## I. INTRODUCTION

Considerable efforts have been directed in the field of core management to realizing an operation that is both safe and economical, through studies, among others, of power distribution control. The limits to local power density and its rate of change currently applied to insure fuel integrity provide a challenging problem to those interested in this domain. The power level and distribution in a BWR (boiling water reactor) are regulated by adjusting the control rod and/or the coolant flow rate.

The present paper discusses a new startup strategy for the BWR. The startup process constitutes a multi-stage decision making problem on a complicated system involving three-dimensional nuclear-thermal-hydraulic coupled reactor kinetics to which the associated phenomena of xenon dynamics and control operation must be taken into consideration. This intricate situation demands considerable computing time even for simulation calculations, which makes it desirable to establish some systematic approach for treating the startup problem.

The aim held in view in conducting the present study was to develop a systematic approach for deriving a practical startup procedure with a minimum number of trial and error

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steps, and to establish on the basis of this procedure a new method of startup planning[1]. The complexity of the problem necessitated resorting to a heuristic algorithm developed by observation and analysis of the phenomena that are involved.

## II. HEURISTIC ALGORITHM FOR SEMI-AUTOMATIC SEARCH

### 1. Definition of Control Problem

The objective of this work was to seek an applicable startup procedure that satisfies the constraints of practical importance in power maneuvering operations.

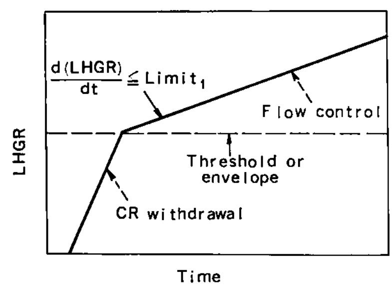
The control variables are the position of the control rods inserted into the core and the coolant flow rate, both being function of time. The system dynamics requires to be treated by three-dimensional BWR simulation with the reactivity feedback of transient xenon as well as that of thermal hydraulic coupled effects taken into account. The constraints that must be satisfied are classified into three groups[2][3]:

Group 1: Constraints on MLHGR (Maximum Linear Heat Generation Rate) and MCPR (Minimum Critical Power Ratio)——These constraints are imposed to ensure the requisite thermal margin and to promote effective fuel burnup.

Group 2: Constraints on the operating region——The operating conditions require to remain within predetermined limits specified by a minimum pump speed line, a rod block line, a maximum power line, a maximum flow line and a recirculation pump cavitation limit line.

Group 3: Constraints on local power change——The rate of change in generated power must at no point cause PCI (Pellet Clad Interaction) such as to endanger fuel integrity: Rapid local power increases by control rod withdrawal is permitted only below a certain threshold level, above which level the power can be raised only at a rate within a prescribed slope, and only by regulating the coolant flow rate. (Fig. 1)

This threshold of LHGR can, however, be adjusted to some extent by preconditioning* the fuel to higher LHGR. This concept is known as enveloping.




Control rods can be moved only in the region below the threshold level or envelope. Above this level, power must be controlled by regulating the core flow, and with the rate of power increase limited within a prescribed value.

**Fig. 1** Constraints emanating from fuel considerations

The prevalent trend is toward relaxation of the constraints of Group 3, and considerable effort is being directed today to establishing revised limits determined from analysis of ramp tests on irradiated fuel and from evaluation of operating data obtained on commercial plants.

### 2. General Approach

The search of a startup procedure is divided into two phases: Phase 1——generation of the control rod withdrawal sequence, and Phase 2——semi-automatic search of the startup

* The fuel becomes "preconditioned" when it undergoes a certain LHGR during a certain period of time. The resulting locus of the LHGR level along the axial direction of the fuel bundle is called the "preconditioned envelope".

procedure. These two phases are iterated until finally an acceptable procedure is obtained.

Three computer programs have been developed, all of which are based on 3-D coarse mesh BWR simulation. These programs have the functions shown in **Fig. 2**, where their input/output relationships are also indicated. In the flow chart, the parameters listed in the column at left are the inputs to the functions to which the arrow-marks lead, and outputs of the functions from which the arrow-marks emanate.

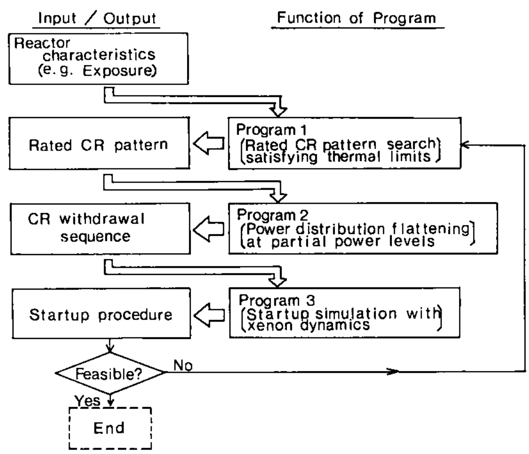



**Fig. 2** Functions and input/output relationships of three programs

(1) Phase 1: Generation of Control Rod Withdrawal Sequence

The first two functions are used to generate a standard sequence. The reactor characteristics, such as exposure distribution, are the inputs for the first program, which employs heuristic and mathematical programming methods[4]. The program optimizes the rated control rod patterns, with particular attention paid to maximizing deep rod insertion throughout the cycle to satisfy the thermal limits of Group 1. The rated control rod patterns thus obtained serve as input to the second program, which also employs a similar heuristic algorithm.

This second program seeks intermediate control rod patterns for partial loads that maximize the power level under the given constraints. Here, the principle adopted is to obtain the flattest possible power distribution at the partial loads, in order to bring the power to the rated value within a minimum period of time. The standard control rod withdrawal sequence is derived by interporation of the resulting intermediate and the previously obtained rated control rod patterns. At every power level of the sequence, each control rod must remain inserted to a depth greater than at the succeeding level. The principle used in the interpolation is to withdraw the shallower rods first, because they will generally become more difficult to withdraw later at higher power levels, on account of the bottom power peaking that would be induced by the withdrawal of these rods. The sequence thus obtained is used as a basic standard, to be later modified if necessary, possibly in off-sequence treatment.

(2) Phase 2: Heuristic Algorithm for Semi-automatic Search of Startup Procedure

The above sequence becomes the input for the third program. This simulates, with xenon dynamics considered, the startup procedure subject to the constraints of Groups 1, 2 and 3. The program uses a selected built-in algorithm (**Fig. 3**), which can also be considered heuristic.

The startup process is divided into a set of operation blocks, each of which provides a specific operation I. Let an operation I at the stage $n$ be expressed by the operation command $i_n$, then the problem is to find the best sequence of $i_n$. The end state $j_n$ of the block can be determined for the operation command $i_n$ considering the possible results $J$ of the operation I.

Functions associated with each operation block are power, flow and control rod searches, the last named with or without involvement of xenon dynamics, and time step

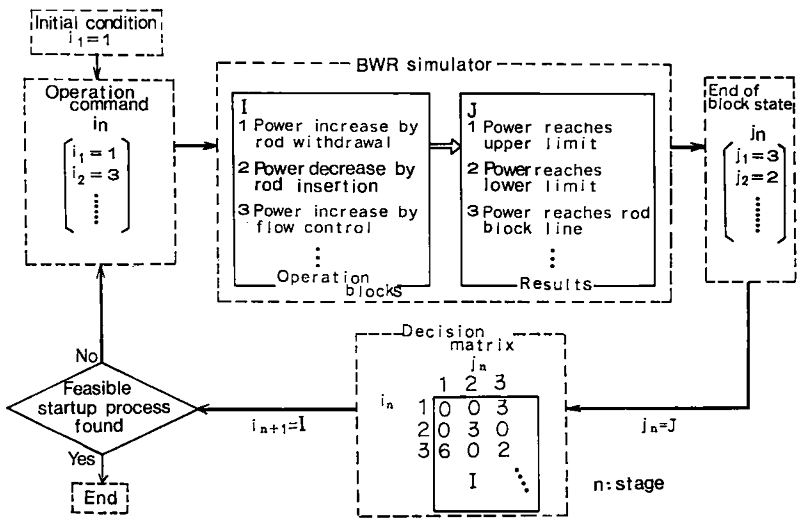


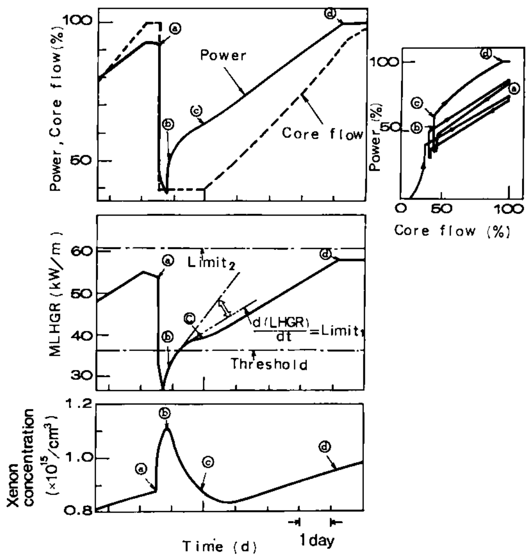

**Fig. 3** Control algorithm employed in Program 3 of Fig. 2

control. With these functions, it is possible to simulate the operations of: (a) power increase ($I=1$) or decrease ($I=2$) by control rod manipulation; (b) power increase ($I=3$) or decrease ($I=4$) by core flow regulation; and (c) maintenance of power at prescribed level by adjustment of control rod ($I=5$) or of coolant flow ($I=6$). The possible end states of each operation considered are: (1) power at its upper ($J=1$) or lower ($J=2$) limit; (2) power at rod block line ($J=3$); (3) flow at its upper ($J=4$) or lower ($J=5$) limit; (4) MCPR at its limit ($J=6$); (5) local power change constraints violated ($J=7$); (6) rod sequence at its target value ($J=8$); (7) no more residual operation time available ($J=9$); and (8) operation block ended normally (all constraints satisfied, $J=10$).

The BWR simulator performs the operation I so as to satisfy the operation command $i_n$, which is determined by the end state $j_{n-1}$ of the preceding operation block. The decision matrix provides the next operation command $i_{n+1}$ from the new end state $j_n$ reached by the simulation. For example, let the operation of the first block ($n=1$) be power increase by control rod withdrawal ($I=1$), *i.e.* by the operation command $i_1=1$. Further assume that the power level reaches the rod block line ($J=3$) as a result of this operation, *i.e.* $j_i=3$. Examination of the decision matrix indicates the operation at the next block ($n=2$) to be $I=3$. This determines the operation command at the next block as $i_2=3$, *i.e.* power increase by flow control. This procedure is repeated until a feasible startup process is found. The decision matrix is established on the basis of physical considerations in advance of the startup process evaluation for each combination of input operation and resultant output. In most of the cases encountered, the decision for the next action was clear and straightfoward. The startup procedure is obtained as the output of these reiterated simulations.

## III. Control of Xenon Dynamics and Proposal of New Startup Procedure

The startup characteristics of the currently employed loop method are studied first. **Figure** 4 shows the problem treated with this method when applied to a core of high heat generation rate in reference to the threshold level (Group 3 constraint). The three diagrams on the left-hand side indicate the progress of core characteristics accompanying the last two ramps ⓐ—ⓑ and ⓒ—ⓓ marked in the key diagram at right. The primary objective of looping is to make maximum use of reactivity change induced by the xenon transient. Following the reduction of power from ⓐ by flow control, the xenon transient is initiated: The xenon concentration begins to increase. Under the cover provided by the xenon poisoning effect, the control rods can be withdrawn directly to acquire the rated pattern, while the heat generation is below the threshold level——at ⓑ. There ensues rapid burnup of the xenon, causing a sharp recovery of power to ⓒ and, in all the cases examined, the rate of power increase was found to intersect the threshold line at a slope exceeding the limit prescribed from fuel integrity considerations. This finding would indicate the necessity of devising a procedure that would minimize the xenon transient effect, and or which would effectively raise the threshold level by stretching out the envelope.




The three diagrams at left depict the core behavior during the last loop ⓐ to ⓑ indicated in the key diagram at right. The problem here is to ease the exessively steep slope of the LHGR maintained beyond the threshold level, following xenon burnup.

**Fig. 4** Progress in time of power, core flow, MLHGR and xenon concentration accompanying ramped change of power, as determined by loop method

Physical considerations point toward three possible methods for reducing the LHGR change rate through effective utilization of the xenon transient.

(1) Reduction of the power level at the end of the power-up ramp

(2) Reduction of the xenon hold up time

(3) Use of a preconditioning control rod pattern to stretch out the envelop.

These three methods are schematized in **Fig. 5,** where in each of the three diagrams the dotted arrow indicates the manner in which the slope of LHGR is eased at its intersection with the threshold line by mitigating the xenon transient. Of the three method considered, the choice was made for a combination of Methods 2 and 3, which are compatible with each other, and whose effects are additive. Method 1 was discarded for its adverse effect on Method 3, when combined with it.

For stretching out the envelope by Method 3, it is necessary to satisfy at least the two conditions of:

(1) Every control rod withdrawn during the preconditioning steps to the depth prescribed by the rated pattern or to a shallower position, in consideration of the very small LHGR at the corner pins adjacent to the inserted control rods, the envelope established after power increase by flow control not being sufficiently high at these points to permit rod withdrawal at a lower power level.

(2) Two different control rod patterns used for establishing a good envelope throughout the core.

In addition to these conditions, careful control of power distribution is required for effectively stretching out the envelope, particulary in the lower part of the core, which is

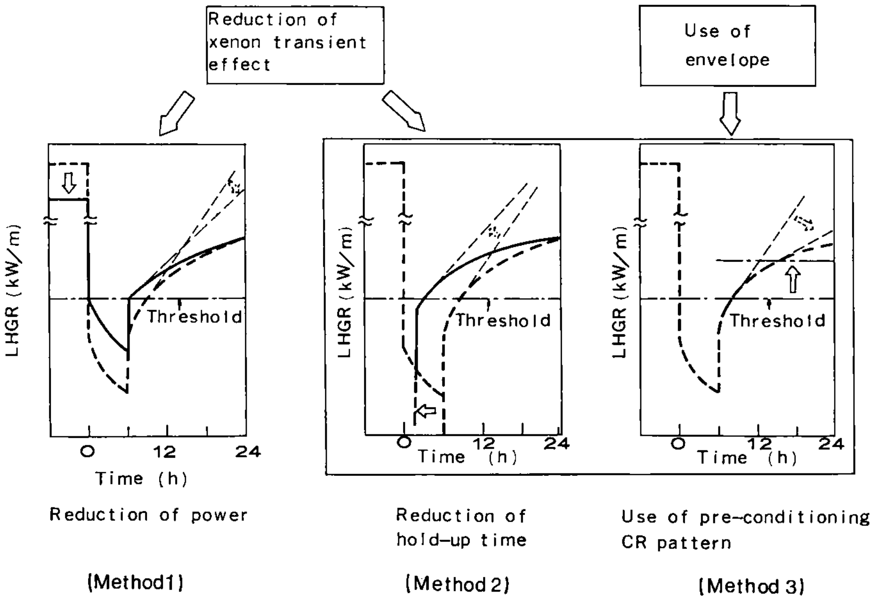



**Fig. 5** Three possible methods for eliminating maintenance beyond threshold level of exessively steep rise shown by LHGR

usually a delicate operation in BWR.

From these considerations, simple modification of the rated pattern would appear to be the most effective for stretching out the envelope, and this has led to development of the PCP (Pre-Conditioning with Peripheral Rod Operation) method. The method is described in **Fig. 6,** where it is compared with the results obtained from the conventional method for a typical 2 loop (3 ramp) procedure. The control rod pattern $CR_i$ represents the pattern used in the $i$-th ramp. The final rated pattern is obtained at the third withdrawal at ⓑ. Power and envelope distributions at the bundles marked ■ are discussed.

In the conventional method shown at left, the envelope established at the end of the second ramp with the control rod pattern $CR_2$ is given as the sum of the threshold and the power distribution (solid line) at ⓐ. The next withdrawal of the control rods to the final pattern $CR_3$ results in the power distribution indicated by the dotted line, which is inside the envelope; but the power level thereafter rises with the decline of xenon influence, until at ⓒ it aquires the distribution indicated by the chain line. It should be noted that this overshoot always results in overstepping the preconditioning envelope upon withdrawal of the control rod from 17 to 15 (marked bundles).

In the proposed method, shown at right in Fig. 6, use is made of a special control rod pattern, which is characterized by (a) a rod pattern in the central region effecting a shift directly to the rated pattern $CR_3$; (b) full insertion of certain peripheral rods to reduce the power level. The resulting power distribution at the point ⓐ in time—somewhat distorted in the radial direction—forms in the central region an envelope of such shape as to cover the power overshoot over the entire length of fuel at the time ⓒ. At the final withdrawal, only the peripheral rods are moved, leaving the central region exempt from appreciable change of power distribution at this stage, while the envelope established at the first ramp remains effective in the peripheral region. In this way, the PCP method can satisfy all constraints.

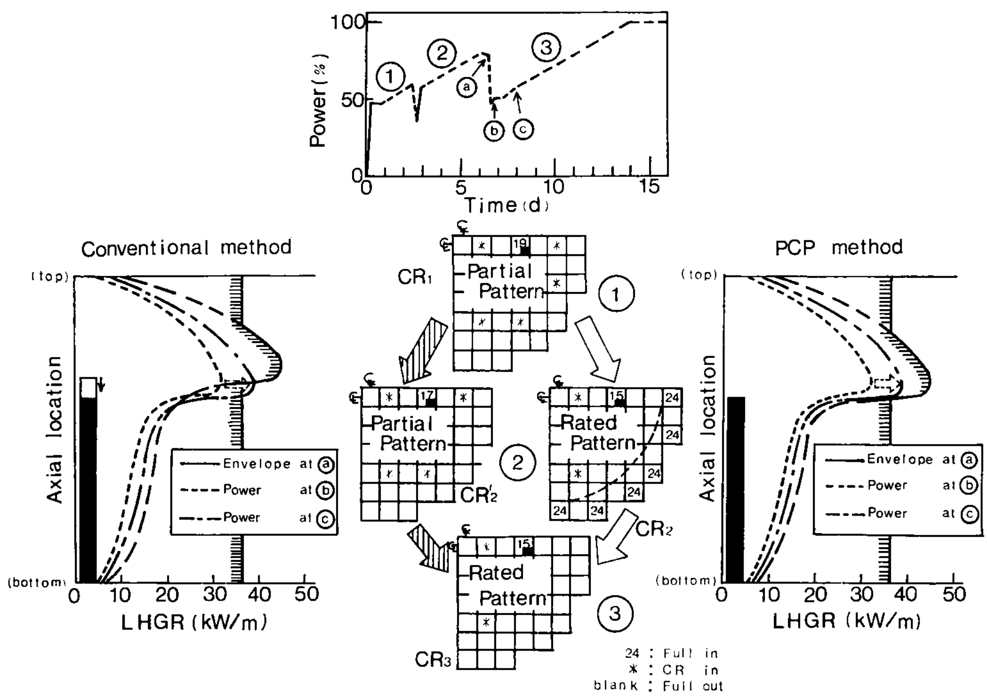



**Fig. 6** PCP method, compared with conventional procedure

The PCP method possesses the following merits:

(1) Full establishment of the preconditioned envelope throughout the core

(2) Simple application in actual practice with the PCP pattern easily determined from the rated pattern.

(3) Small number of control rods handled during startup operation.

## IV. Application to Commercial Startup Operation

The PCP method has been applied to the startup operation of a commercial BWR of high linear heat generation rate.

The PCP pattern was treated as an off-sequence pattern, by reason of the reinsertion step affecting the peripheral rods, and the normal sequence was modified accordingly. This combined sequence served as input for the third program of Fig. 2, to determine the intermediate control rod patterns for the individual ramps, as well as the progress in time of the core power and the core flow rate during startup operation. The thermal power and the MLHGR are shown in **Fig. 7** as functions of time. The trajectories predicted by

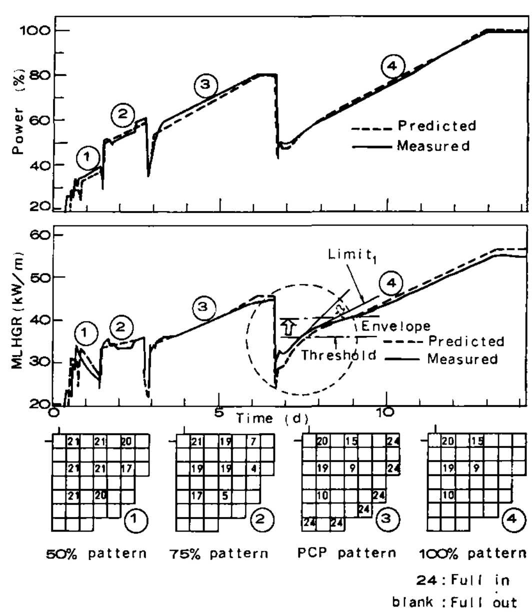



**Fig. 7** Results of PCP method applied to startup tests of reference BWR

this code system are seen to agree well with the data obtained from actual reactor operation. It was confirmed from the outputs of process computer and of the on-line core performance prediction system[5] that the LHGR change rate actually exceeded the limit at the threshold level, but that the envelope had been sufficiently stretched to cover the xenon transient as seen from the configuration of the part encircled by dotted line in Fig. 7.

## V. SUMMARY

The startup of a BWR is a typical multi-stage decision making process. The difficulties encountered in this operation stem from phenomena involving three-dimensional nuclear-thermal-hydraulic coupled reactor kinetics, some of the constraints being related to the local power level and its rate of change.

Optimization of this complex startup process had in the past appeared to be beyond the capability of present-day computers. Intuitively, however, the problem appeared to be manageable by division into two phases: (a) generation of control rod withdrawal sequence, and (b) semi-automatic search by a heuristic algorithm, this algorithm to be a stagewise optimization based on observations and careful analysis of the startup dynamics. Study of the startup characteristics indicated that the rate of LHGR change at the threshold level exceeded the prescribed limit of local power change rate in the interval following the final withdrawal of control rods for producing the rated configuration. Hence a new procedure was sought which would on one hand ease the rate of power change by minimizing the xenon transient effect, and on the other hand stretch out the envelope.

The resulting startup procedure is the PCP (Pre-Conditioning with Peripheral Rod Operation) method, which provides a straightforward answer to the two objectives cited above. This startup method is characterized by an intermediate rod pattern that has its central region identical with the rated power pattern with certain rods fully inserted in the peripheral region.

This new method was successfully applied to the initial startup operation of a commercial BWR of high linear heat generation rate. Operating data confirmed that the operational constraints were completely satisfied, thus demonstrating that a practically useful startup procedure has been derived with this systematic approach.



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