On-line Core Performance Evaluation and Operating Guidance System for BWR

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ABSTRACT

Core Performance Monitoring System has been developed for on-line core performance evaluation and operating guidance of BWR's. This system consists of three subsystems: On-line Core Performance Evaluation, On-line Power Distribution Prediction, and Operational Sequence Modification.

The On-line Core Performance Evaluation System provides the operators with the information on core performance, such as power distribution. A new method is proposed for estimating three-dimensional power distribution from in-core detector readings. In this method, three-dimensional power distribution is calculated by a kind of synthesis core simulator, which consists of horizontal two-dimensional part and three-dimensional local core part. The detector readings are used as the internal boundary condition. The introduction of synthesis technique makes the computing time short enough for on-line use.

The task of On-line Power Distribution Prediction System is to predict the change of power distribution in advance of control rod withdrawal, core flow rate change and xenon transient initiation. The change of power distribution after a control rod motion is limited to the fairly small region around the moved rod, and it is possible to predict the change by solving the three-dimensional equation in sixteen fuel bundles surrounding the control rod. The change due to flow rate change and xenon transient is also predicted by a similar way. The on-line test of this system is in progress.

The Operational Sequence Modification System is used to modify, by a heuristic algorithm, the operational sequence that has been planned in ad-

vance by the off-line calculation, if the actual core state is found to be different from the off-line calculation.

I. INTRODUCTION

On-line core performance evaluation and operating guidance are earnestly desired for safer and more efficient operation of BWR's. The system, named Core Performance Monitoring System, developed here consists of (1) Core Performance Evaluation, (2) Power Distribution Prediction and (3) Operational Sequence Modification. This system, as shown in Fig. 1, composes Computer Based Monitoring System together with Plant Operation Monitoring System, which is implemented to a computer based operators' console for the centralization of plant information on normal and abnormal operation [1], [2]. At the same time it is as well one of the three subsystems of BWR Core Management System [3], the other two of which are Planning [4], [5] and Operating History Evaluation [6]. These two functions are performed by a large computer because of the large amount of computation involved. The large computer and the process computers at reactor sites are connected by data transmission lines [3].

The On-line Core Performance Evaluation System provides the operators and plant engineers with the information on core performance, such as power distribution, and maximum linear heat generation rate. The task of On-line Power Distribution Prediction System is to predict the change of power distribution in advance of control rod withdrawal, flow rate change, and xenon transient initiation [7]. The Operational Sequence Modification System is used to modify, for example, the reactor start-up sequence prepared in advance by the Planning System, if the actual core state is found to be different from what has been predicted by the Planning System. The computer memory size and computing time required for these systems must be adequate for on-line use.

These three systems, which compose Core Performance Monitoring System, are described in this paper with emphasis on the first system.

II. ON-LINE CORE PERFORMANCE EVALUATION SYSTEM

The main function of this system is to estimate three-dimensional power distribution from in-core detector readings.

In the conventional method, fitting constants are prepared in advance of on-line use, which are used to estimate three-dimensional power distribution from the in-core neutron detector readings. From the viewpoint of memory size and computing time, the fitting method is superior to the core simulator method to be proposed. However, the relation between the detector readings and power distribution is a function of fuel type, control rod pattern, exposure distribution, etc., and it is a tremendous task to prepare the fitting constants for each core. Another problem is its poor accuracy at partial power state and asymmetric control rod pattern operation. In the proposed method, the three-dimensional power distribution is calculated by a kind of synthesis core simulator, which consists of horizontal two-dimensional part and three-dimensional local core part.

II.1 METHOD

The reactor core is divided into a number of cells, each of which consists of four fuel bundles as shown in Fig. 2. About one-fourth of the cells have monitor strings at the center, each of which has four LPRM's (Local Power Range Monitors) equally spaced along the active fuel length of the bundles. These cells are defined as "real-monitored cells," and the rest which does not have monitor strings are defined as "pseudo-monitored cells" in this paper.

In the present method, the calculation of power distribution is based on a FLARE type nodal coupling model [8]. The nodal coupling method is one of the most practical techniques because of its short computing time and small memory requirement, and fairly good agreement is obtained in comparison with the operational data or the results of detailed design calculations, when parameters included in the model, such as mixing kernels, are optimally adjusted [6].

Figure 3 shows the procedure for estimating three-dimensional power distribution from LPRM readings.

(1) A Scheme for Calculating The Power Distribution in A Real-monitored Cell

The basic equation of the nodal coupling model for real-monitored cell is

$$S_i(k) = \frac{k_{\infty i}(k)}{\lambda} \Big[W_i^V(k+1) S_i(k+1) + W_i^V(k-1) S_i(k-1) + \sum_{j \neq i}^{2} W_j^H(k) S_j(k) + \{1 - 2W_i^V(k) - (4 - \alpha_i(k)) W_i^H(k)\} S_i(k) \Big] \tag{1}$$

where	i	index of a fuel bundle in a real-monitored cell
	j	index of a fuel bundle adjacent to i in a real-monitored cell
	k	axial node number
	$S_i(k)$	neutron source
	$k_{\infty i}(k)$	infinite neutron multiplication factor
		eigenvalue
	$W_i^V(k)$	vertical neutron transport kernel
	$W_i^H(k)$	horizontal neutron transport kernel
	$\alpha_i(k)$	horizontal albedo (2.0 for flat boundary condition).

The neutron source Si(k) can be obtained from Eq.(1), if the albedo $\alpha_i(k)$ is known. In this method, the initial quess of albedo $\alpha_i(k)$ is calculated by a simple two-dimensional model to be described in the next section, and $\alpha_i(k)$ is iteratively corrected such that the calculated LPRM readings are consistent with the measured readings. The method of albedo adjustment is that at each iteration step the albedo is revised by

$$\alpha_i(k_n) \longleftarrow \{1+\varepsilon\,\delta(k_n)\}\,\alpha_i(k_n)\ , \quad n=1,\cdots,4 \tag{2}$$

where $\delta(k_n)$ is the correction factor at an axial node k_n, at which the n-th LPRM is located, and ε is the over-estimate relaxation factor (~0.2). The factor $\delta(k_n)$ is calculated by

$$\delta(k_n) = \frac{\Phi_m(k_n) - \Phi_c(k_n)}{0.25\,\Phi_m(k_n)} \tag{3}$$

where $\Phi_m(k_n)$ and $\Phi_c(k_n)$ are the measured and calculated LPRM readings, respectively. The correction factors at the other axial nodes, where LPRM's are not located, are determined by linear interpolation or extrapolation of $\delta(k_n)$ with some correction made at control rod tips. The correction of $\alpha_i(k_n)$ is repeated until the differences between the calculated and measured LPRM readings become small enough.

The use of the local core model has the following advantages:

- the convergence speed of the local core model is more rapid than that in the whole-core model, especially for large size core,
- the measured detector readings can be used for acceleration of convergence, and
- the uncertainty in the calculation model can be reduced by parameter (i.e. albedo) adjustment such that the differences between the calculated and measured LPRM readings are minimized.

(2) Estimation of the Horizontal Albedo

The horizontal albedo $\alpha_i(k)$ for a fuel bundle i in a cell is defined by

$$\alpha_i(k) = \frac{\sum_{l=1}^{2} W_l^H(k) S_l(k)}{W_i^H(k) S_i(k)} \tag{4}$$

where the summation is over the two adjacent fuel bundles outside the cell. To calculate $\alpha_i(k)$ by Eq.(4), it is only necessary to know the relative magnitudes of $Si(k)$ of neighboring fuel bundles, and not necessary to have the accurate whole core $Si(k)$ distribution. Therefore, the two-dimensional FLARE-type calculation, in which the effect of axial neutron leakage is neglected, is employed to get the horizontal source distribution for calculation of $\alpha_i(k)$.

(3) Estimation of the Pseudo-LPRM Readings in Pseudo-monitored Cells

The horizontal neutron source distribution in pseudo-monitored cells at an axial LPRM height is estimated by a two-dimensional equation (5), in which the neutron source of real-monitored cells is used as the fixed source:

$$S_i^{(n)}(k_n) = \frac{k_{\infty i}(k_n)}{\lambda} \Big[\sum_{j \neq i} W_j^H(k_n) S_j^{(n)}(k_n) + \sum_{j \neq i} W_j^H(k_n) S_j^{(m)}(k_n) + \{1 - 4W_i^H(k_n) - (2 - \beta_i(k_n)) W_i^V(k_n)\} S_i^{(n)}(k_n) \Big] \tag{5}$$

where $\beta_i(k_n)$ is vertical albedo, and the suffix (m) indicates the real-monitored cells and (n) the pseudo-monitored cells. The neutron source $S_j^{(m)}(k_n)$ are given by a series of local core calculations described in the previous section (1).

The virtical albedo, defined in Eq.(6), is necessary to get the solution of Eq.(5).

$$\beta_i(k_n) = \frac{W_i^V(k_n+1) S_i^{(n)}(k_n+1) + W_i^V(k_n-1) S_i^{(n)}(k_n-1)}{W_i^V(k_n) S_i^{(n)}(k_n)} \tag{6}$$

Since a control rod is inserted at the corner of one real-monitored cell and three pseudo-monitored cells, the axial distribution in a fuel bundle of a pseudo-monitored cell is considered to be similar to that in the nearest fuel bundle of the real-monitored cell. Therefore, the vertical albedo, $\beta_i(k_n)$, of a pseudo-monitored cell can be approximated by Eq.(6), where $S_i^{(m)}$, of the real-monitored cell, nearest to the bundle i, is substituted for $S_i^{(n)}$.

The neutron source distribution in real-monitored cells used as the fixed source in Eq.(5) is consistent with the measured LPRM readings, and the LPRM readings obtained from $S_i^{(n)}$ in Eq.(5) can be expected to be good estimates of the pseudo-LPRM readings as well as the horizontal albedo calculated from $S_i^{(n)}$ using Eq.(4).

The power distribution in pseudo-monitored cells can be estimated, using the pseudo-LPRM readings, by the same scheme as in case of real-monitored cells.

II.2 TEST CALCULATION

Test calculation was performed using a quarter core model of a BWR shown in Fig. 2. A total of four-hundred fuel bundles are loaded, in the full core, and its rated thermal output and core flow rate are 1380 MW and 48.0×10^6 lb/h, respectively. There are eight real-monitored cells in the quarter core, and each monitor string has four LPRM's at equally spaced axial locations.

The accuracy of the present method was evaluated by comparison with a reference solution of the three-dimensional whole core FLARE equations.

Figure 4 shows the pseudo-LPRM readings at four axial elevations, estimated by the present method. The discrepancy between the estimated and the reference LPRM readings is less than 5%, and RMS (root-mean-square) error is 1.7%.

The axial power distribution at the central cell is shown in Fig. 5. The maximum error in the estimated power distribution, P_4 , is 3.7% right above the tip of control rod. RMS error in the estimated nodal power distribution for the whole core is 3.3%.

The computing time for the present test calculation is summalized in Table I. The computing time per one monitored cell is about 1 sec by IBM370/158, and the required memory size is small enough for on-line use.

The proposed method does not require off-line preparation of the fitting constants to convert the detector readings to three-dimensional power distribution. High accuracy is expected at various operating conditions, because the calculation of power distribution is based on the physical model, i.e. FLARE-type model, and the model contains parameters, such as boundary condition, which can be adjusted by using the measured LPRM readings. The synthesis technique, combining local three-dimensional calculations and whole core two-dimensional calculations, makes the memory size and computing time small enough for on-line use.

III. ON-LINE POWER DISTRIBUTION PREDICTION SYSTEM

This system predicts the change of power distribution in advance of control rod withdrawal, core flow rate change, and xenon transient initiation, and the predicted results are displayed on the colour CRT of the Core Performance Monitoring Console. A basic idea of power distribution prediction is proposed in our previous paper [7]. The on-line test of this system is in progress at a commertial BWR site.

The configuration of the on-line power distribution prediction program system is shown in Fig. 6. The prediction procedure consists of two steps: the first to estimate the present TIP (Traversing In-core Probe) readings as the initial conditions of the prediction, using the LPRM readings, when the measured TIP readings are not available; the second is the predictional calculation itself, which contains the power-flow trajectory prediction and the power distribution prediction.

The present TIP readings are estimated from LPRM readings by solving one-dimensional FLARE-type nuclear thermal-hydraulic equation (7) for a monitored cell, which consists of four fuel bundles surrounding a detector string, the definition being the same as in Chapter II. The cell power Si(k) (not the bundles power) and the horizontal boundary condition (albedo) are adjusted iteratively so that the calculated TIP reading hits the LPRM readings at their locations. The iteration scheme of albedo adjustment is also the same as the method explained by Eqs.(2) and (3) in the previous chapter.

$$\begin{aligned} S_i(k) = \frac{k_{\infty i}(k)}{\lambda} \Big[& W_i^V(k-1) S_i(k-1) + W_i^V(k+1) S_i(k+1) \\ & + \{1 - 2W_i^V(k) - (4-\alpha_i(k)) W_i^H(k)\} S_i(k) \Big] \end{aligned} \tag{7}$$

The change in power distribution after a control rod motion is localized and is limited to the fairly small region around the moved rod. Therefore, it is possible to predict the change by solving the three-dimensional equation (8) in four monitored cells adjacent to the control rod to be moved.

$$\begin{aligned} S_i(k) = \frac{k_{\infty i}(k)}{\lambda} \Big[& W_i^V(k-1) S_i(k-1) + W_i^V(k+1) S_i(k+1) \\ & + \sum_{j \neq i}^{4} W_j^H(k) S_j(k) + \{1 - 2W_i^V(k) - 4W_i^H(k)\} S_i(k) \Big] \end{aligned} \tag{8}$$

The first part of the prediction is the model identification (k_∞ identification), to reduce the prediction error induced by the modeling error in the FLARE equations. Equation (8) is solved for $k_{\infty i}(k)$, by using the present TIP readings prepared as the initial condition in the first step.

The second part is the prediction calculation. Equation (8) is solved in the four monitored cells. The infinite multiplication factor $k_{\infty i}(k)$, used in this calculation, is given by

$$k_{\infty i}(k) = k^{0}_{\infty i}(k) + \Delta k_\infty(\Delta \mathrm{CR}, \Delta \mathrm{Void}) \qquad (9)$$

where $k^{0}_{\infty i}(k)$ is the identified multiplication factor in the first part, and the change of k_∞ due to control rod movement and the associated void change are linearized. The power change in the cells outside these four cells is approximated by a linearized equation of Eq.(8) that is valid for small change of power distribution.

A similar technique is used to predict the power distribution change due to flow rate change and xenon transient.

The method of estimating the individual bundle power is similar to the method for on-line core performance evaluation explained in Chapter II.

The power-flow trajectory is predicted by criticality search with a whole core axially one-dimensional FLARE model, the critical eigenvalue of which is adjusted from the actual operating history by adaptive learning algorithm.

The accuracy of the predicted results has been evaluated by using the data of operating BWR's, and is found to be good enough for the purpose of operating guidance. The RMS errors are 3% for the present TIP reading estimation, 7% for the power distribution prediction and 3% for the thermal power level prediction. The required computer memory and computing time are adequate for on-line use as well as in Chapter II. A man-machine interaction procedure has been developed using a colour CRT. The on-line test of this system is in progress.

IV. OPERATIONAL SEQUENCE MODIFICATION SYSTEM

This system is used to modify the operational sequence that has been prepared in advance by the Planning System, if the actual core condition is found to be different from the plan. The basic idea is to modify the operational sequence by using a simple core simulator, and to verify the results by the Power Distribution Prediction System.

The core simulator is an axially one-dimensional core model, and the parameters contained in the model are adjusted adaptively by operating data.

The operational sequence, i.e. control plan of core flow rate and control rod density, is modifyed by a heuristic algorithm using the adaptive core simulator, and the results is confirmed by the Power Distribution Prediction System from the viewpoint of three-dimensional power distribution.

V. CONCLUSION

Three systems, which compose Core Performance Monitoring System for BWR's, have been proposed. Various techniques, such as power distribution synthesis, local core calculation, model adjustment, etc., have been introduced to make the computing time and the required computer memory size small enough for on-line use, and to assure the calculated results accurate enough for the operators' appropriate judgements.

In Fig. 7, the Core Performance Monitoring Console for on-line test of Power Distribution Prediction System is shown. The console is equipped with a colour CRT for information selection, and a keyboard and a core map display for function selection and input data setting. The on-line test of Power Distribution Prediction System is in progress, using this console and a process computer HIDIC-80, to demonstrate the usefulness of this system for safer and more efficient operation of BWR's. The test of the other two systems is also now being planned.

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TABLE I Computing time of power distribution estimation for the test calculation

Calculation step	Dimension of FLARE calculation	Number of FLARE calculations	Computing time (IBM 370/158)
Estimation of horizontal albedo	2–dimension 12 x 12	4	8 sec
Calculation of power distribution in real–monitored cells	3–dimension 2 x 2 x 24	8	7
Estimation of pseudo–LPRM readings and albedo	2–dimension 12 x 12	4	4
Calculation of power distribution in pseudo–monitored cells	3–dimension 2 x 2 x 24	22	16
Total	——	——	35 sec

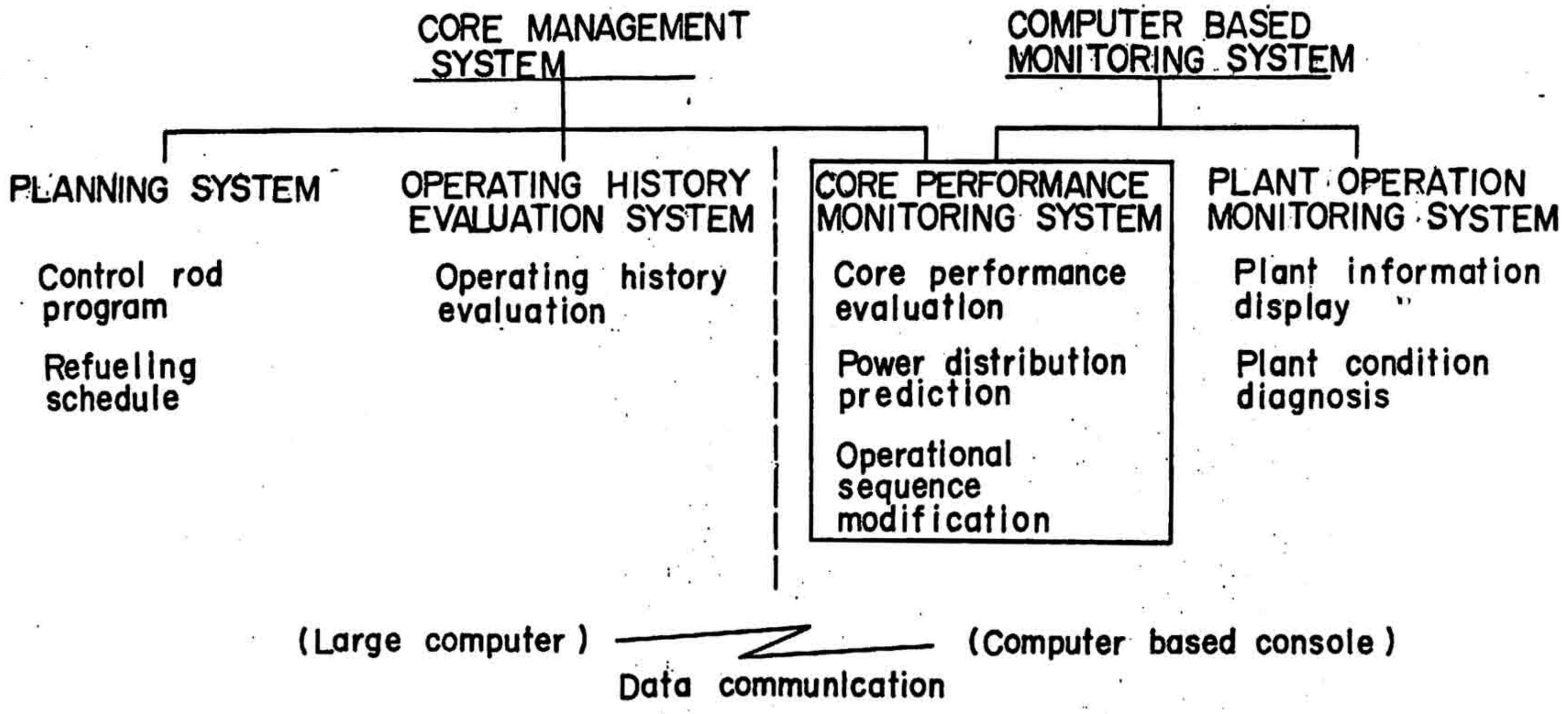

Fig. I Overview of core management and computer based monitoring systems for boiling water reactors

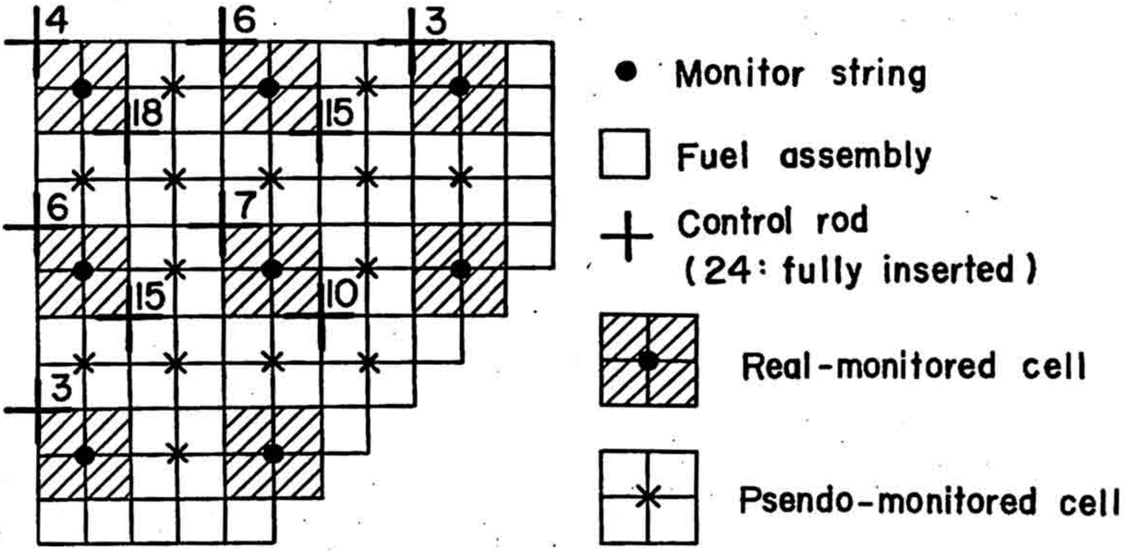

Fig.2 Real- and pseudo-monitored cells and an example of control rod pattern

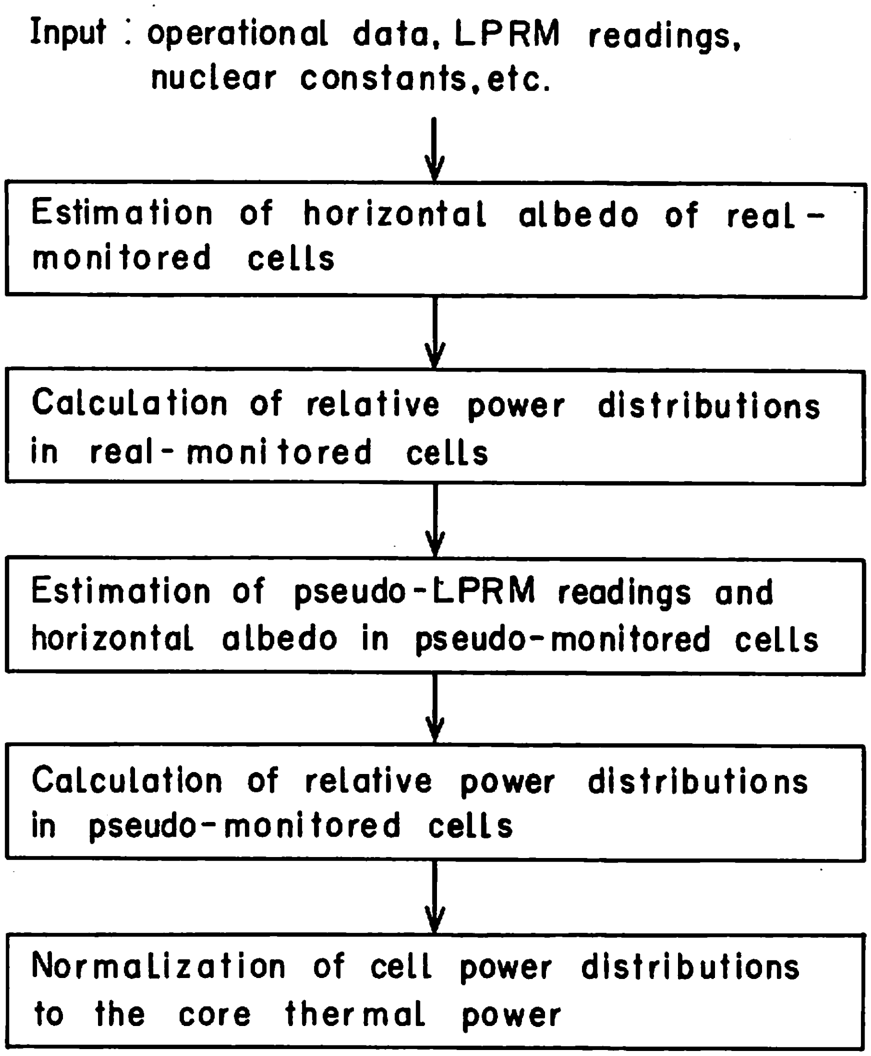

Fig. 3 Procedure for estimating three-dimensional power distribution from LPRM readings

	25.2 0.6		36.3 -0.3	
25.5 0.9	25.6 0.6	28.2 -0.4	42.7 -0.8	52.4 0.4
	28.8 0.1		39.9 -0.4	
36.7 -0.5	43.4 -0.3	40.1 -0.3	31.0 -1.4	
	52.9 0.5			

Axial position – A (lowest)

	61.5 -2.0		57.3 -0.1	
61.4 -2.1	60.4 -2.9	60.4 -1.0	55.8 1.1	53.9 -0.3
	60.3 -1.0		49.8 -0.9	
57.2 0.0	55.7 1.0	49.7 -1.0	33.5 -1.2	
	53.6 -0.6			

Axial position – B

	50.3 0.3		46.7 -0.1	
50.2 0.2	51.3 -0.1	52.4 -0.3	46.3 -0.2	39.0 -1.0
	52.0 -0.7		49.2 -1.3	
46.2 -0.6	45.7 -0.9	48.8 -1.7	35.7	
	38.5 -1.5			

Axial position – C

	46.4 -0.3		36.5 0.0	
46.2 -0.5	44.9 -0.6	41.5 0.1	35.0 0.5	23.8 0.0
	41.1 -0.3		29.6 0.1	
36.2 -0.3	34.5 0.0	29.4 -0.1	20.6 -0.1	
	23.6 -0.2			

Axial position – D (highest)

XX.X	Estimated LPRM reading
X.X	difference from exact reading

Fig. 4 Estimated LPRM readings in pseudo-monitored cells and difference from those obtained by three-dimensional whole core calculation

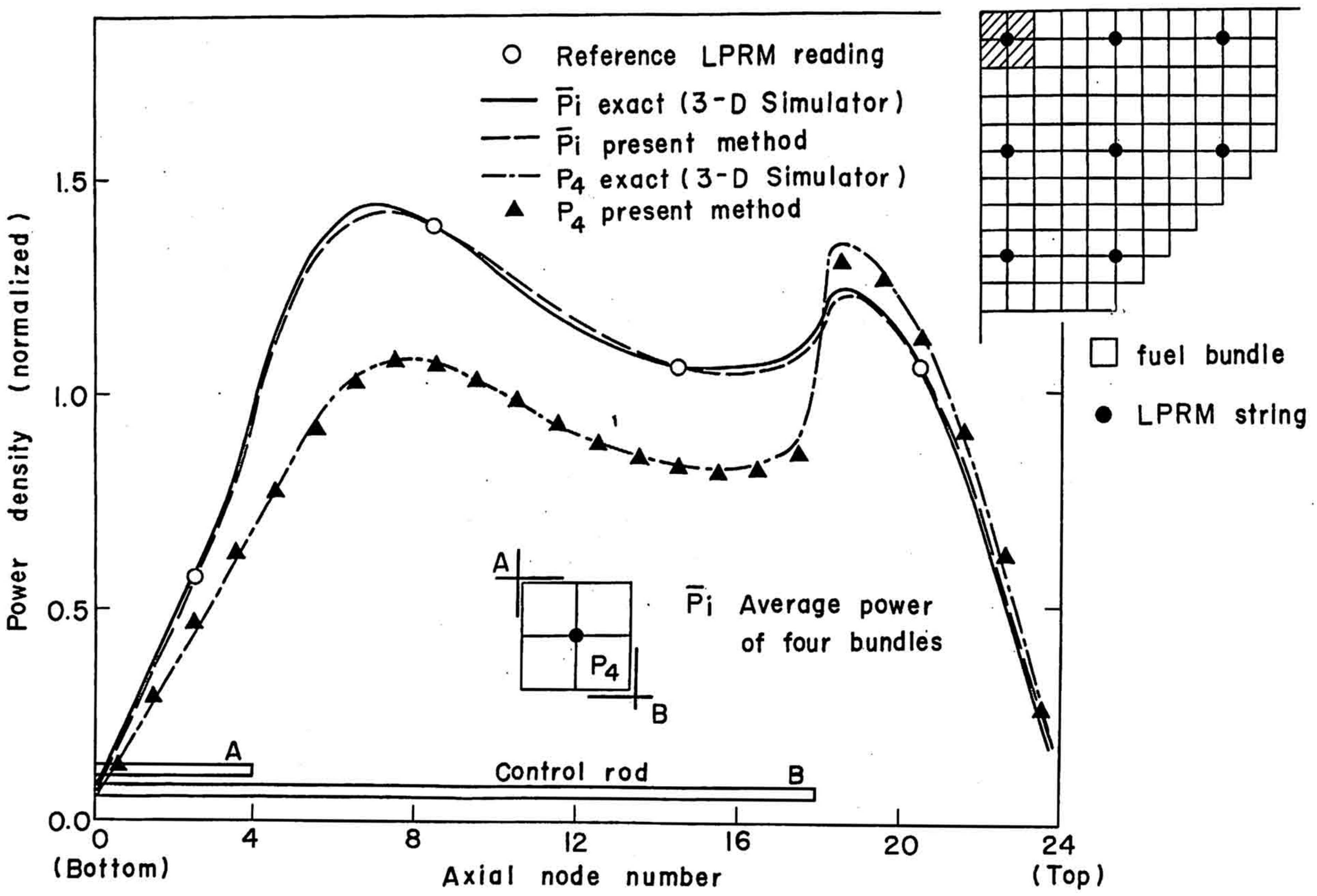

Fig.5 Power distribution estimated from LPRM readings

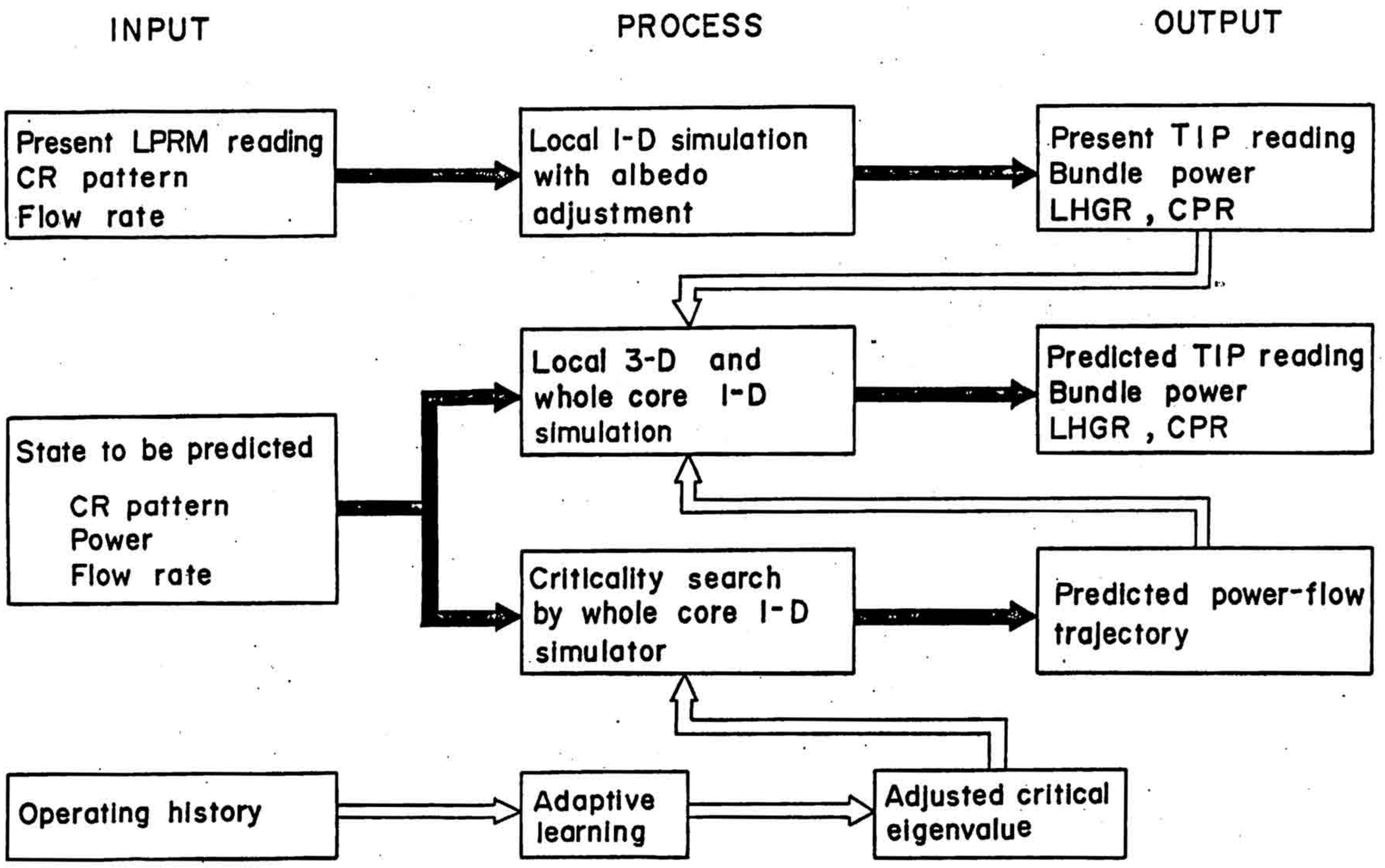

Fig.6 Configuration of power distribution prediction program system

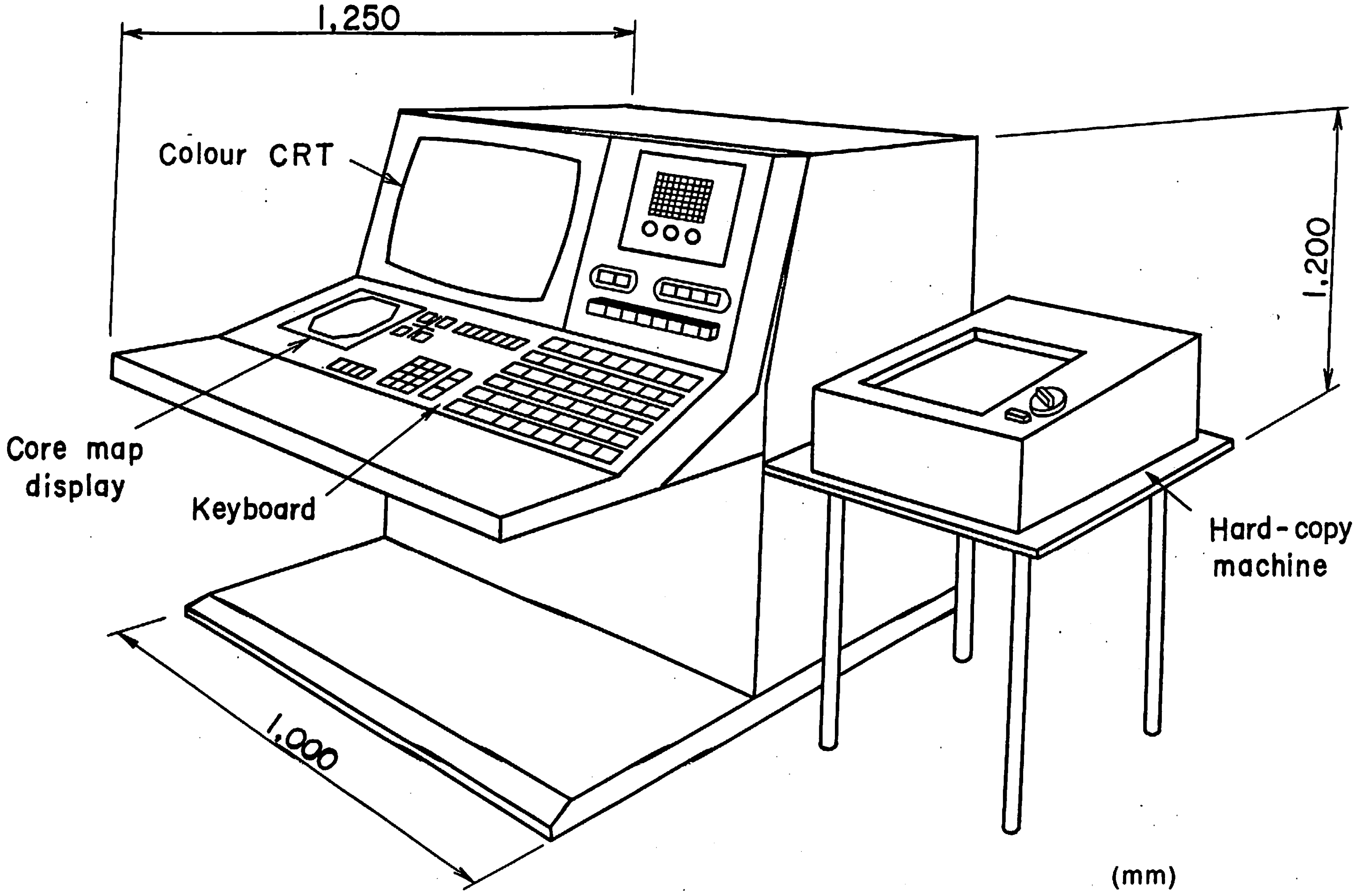

Fig.7 View of Core Performance Monitoring Console