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EXPERIENCE WITH COMPUTER BASED SYSTEMS APPLIED TO BOILING WATER REACTOR POWER PLANT

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Abstract

Experience with computer applications in a boiling water reactor (BWR) power plant to on-line anomaly detection and diagnostic system, on-line power distribution prediction system, plant monitoring system with computer based console, and core management system with computer network is briefly described. The first three are associated with process computer applications to help plant operations and the last one is related to the on-line system for core management.

1. Introduction

The applications of on-line digital computers to nuclear power plants is a natural trend to improve plant performance, including economic aspects and safety implications. On-line computers are now used as important and, in some cases, indispensable components in the control systems of most nuclear power plants.

In this paper, our experience with computer applications for BWR plants is briefly described. This review does not intend to give a survey of all aspects of computer applications to nuclear power plants in the Hitachi Ltd. It gives a review of recent developments at the Atomic Energy Research Laboratory. The first three topics are associated with process computer applications to help plant operations. The last one is related to the on-line system for core management.

2. On-line Anomaly Detection and Diagnostic System

Nuclear reactor diagnostic techniques have been developed in an effort to improve safety and availability of nuclear power plants. As for diagnostic techniques, there are two approaches ; frequency-domain and time-domain analysis of the reactor signals. We have developed[1~5] a diagnostic method based on time-domain analysis. This method has the advantage of treating transient state of the process.

The aims of the diagnosis system are :

(1) To detect anomalies of the nuclear systems at an early stage,
(2) To identify their causes or locations,
(3) To give information of corrective action as soon as possible.

The anomaly detection system for a reactor core based on the reactivity balance method had already been developed.[1] The test conducted using Japan Material Testing Reactor, proved that the reactivity balance was a feasible method to detect anomaly of the reactor core. After this success, the diagnosis system[2] has been developed to apply to a BWR in which there are many feedback loops to reactivity and there are several control systems which influence reactor core dynamics greatly, whereas there are few feedback loops in JMTR. Consequently, dynamic models including feedback loops and control systems are utilized to detect anomalies of the plant. A block monitoring index has been introduced. The change of this index corresponds to a change in characteristics of plant equipment.

Diagnostic Method

The diagnosis consists of two stages. The first one is to calculate differences between observed variables and corresponding estimated variables. The second stage is to calculate block monitoring indices and to maintain survaillance over the plant equipment using them. The conceptual diagram is shown in Fig. 1.

In Fig. 1, the differences E_i, called error signals, between the observed process parameters X_i and the corresponding parameters $\hat{X}_i$ calculated by the dynamic models, are neary equal to zero under a normal plant condition, assuming that the models are adjusted to the plant subsystems. One of the error signals, at least, is far from zero under an abnormal plant condition. If the instrumentation 2 in Fig. 1 is abnormal, the two error signals are far from zero. The performance changes of plant equipment are indicated as changes of the corresponding block monitoring indices B_j.

Diagnosis System

The system developed utilizes the linealized dynamic model including feedback loops and control systems and covers the reactor core, the main steam line and the pressure control system, the feedwater system, and the primary loop recirculation system, which are divided into twenty different equipments. Sixteen error signals are calculated by taking the differences of the measured variables and the corresponding variables estimated by the dynamic model, from which twenty block monitoring indices are generated to maintain survaillance over the major plant equipments.

Diagnosis is performed in every one second and the results are displayed on colour CRT.

In the diagnosis system two types of levels corresponding to different false alarm rates are considered. The lower level is aimed at an early anomaly detection, degree of certainty is therefore sacrificed. The higher level detects anomalous conditions of the plant equipment with higher degree of certainty. Consequently, a very low false alarm rate is desired. The levels corresponding to the two false alarm rates are called diagnostic caution and alarm levels, respectively. The diagnostic alarm or caution level and existing alarm level have distinct difference[3,5] The diagnostic levels are set for the deviation from the value estimated using the dynamic model which expresses normal conditions of the plant. The existing alarm levels are set independently to other process variables. Generally, using existing alarm levels, many alarms are excited as a consequence of one anomaly. However, using the diagnosis system, only one block monitoring index corresponding to anomalous equipment, is excited.

Part of the system has been installed to an existing commercial BWR power plant and is working well.

3. On-line Power Distribution Prediction System

It is useful for BWR operation to have an effective means of predicting the change in the power distribution in advance of a control rod motion, flow rate change, or following a change in the xenon number density. The prediction procedure consists of two parts : the first is to estimate the present Traversing In-Core Probe (TIP) readings as the initial conditions of the prediction, using Local Power Range Monitor (LPRM) readings when the measured TIP readings are not available ; the second is the predictional calculation itself.

Estimation of Present TIP Reading [6,7]

Estimation of the present TIP readings is based on a one-dimensional FLARE-type nuclear thermal hydraulic calculation combined with model adjusting method for making the calculated neutron flux consistent with the measured LPRM reading at its locations.

The basic nodal equation of FLARE is shown in Eq. (1) :

$$S_\ell(K) = \frac{k_{\infty\ell}(K)}{\lambda}\Big\{\sum_{i=1}^{4} S_i(K)W_i^H(K) + S_\ell(K-1)W_\ell^V(K-1) + S_\ell(K+1)W_\ell^V(K+1) + S_\ell(K)\,[1 - 2W_\ell^V(K) - (4-\alpha)W_\ell^H(K)]\Big\}, \quad (1)$$

where

ℓ = index of a monitored cell that consists of four fuel assemblies surrounding a TIP string

i = index of the monitored cells adjacent to ℓ

k = axial node number

$S(K)$ = axial distribution of neutron source

$k_\infty(K)$ = axial distribution of neutron multiplication factor

λ = effective neutron multiplication factor

$W^H(K)$ = axial distribution of horizontal neutron transport kernel

$W^V(K)$ = axial distribution of vertical neutron transport kernel

α = horizontal albedo (0 at inner core region)

To calculate the TIP readings of a designated monitored cell regardless of the surrounding cell conditions, the "neutron reflection rate", $\beta(K)$, defined in Eq. (2) is introduced :

$$\beta(K) \equiv \sum_{i=1}^{4} S_i(K)W_i^H(K)/[4S_\ell(K)W_\ell^H(K)] \quad (2)$$

By adjusting the value of $\beta(K)$, radial neutron diffusion can be considered in axially one-dimensional calculations, and thus, the three-dimensional basic nodal equation, Eq. (1), is reduced to the form of Eq. (3), which does not include radial interaction terms. This is the modified formulation of one-dimensional FLARE :

$$S(K) = \frac{k_\infty(K)}{\lambda}(S(K-1)W^V(K-1) + S(K+1)W^V(K+1) + S(K)\{1 - 2W^V(K) - 4W^H(K)[1 - \beta(K)]\}) \quad (3)$$

Channel power, Pch, and the neutron reflection rate, $\beta(K)$, are iteratively adjusted such that the calculated TIP readings are consistent with the measured LPRM readings at its location.

Numerical experiments show that the maximum estimation error, in comparison with an accurate solution of the three-dimensional calculation, is within ∿5%, and the computer running time (IBM 370/158) is ∿3 sec.

Prediction of TIP Readings [6,7]

The effect of a control rod withdrawal on power distribution is fairly localized, and a significant change arises only in the monitored cells (area a of string arrangement in Fig. 2) adjacent to the control rod moved. Attention to this locality of the phenomenon leads to an expectation that it may be possible to predict the change in power distribution by a local nuclear thermal hydraulic calculation performed in a fairly narrow region around the control rod. The method presented here is based on this assumption.

The first portion of the prediction is the identification of the model with the present state, intended to reduce the prediction error due to the inconsistency of the calculation model with measured TIP readings. The present TIP readings of 12 monitored cells shown in Fig. 2 are transformed to the cell average power distributions, $S_\ell(K)$, by using a predetermined relation among TIP readings, power, void, and control rod arrangement. Using the values $S_\ell(K)$ thus obtained, the three-dimensional nodal equation, Eq. (1), is solved for the present $k^0_\infty(K)$ by setting λ to unity.

The second portion is the predictional calculation. Additional reactivity is introduced by motion of a control rod, and the associated void changes are taken into account by the linearized expression[7] and Eq. (1) is solved for the four monitored cells surrounding the control rod that is moved.

The small changes in the power of the shaded channels are taken into account by Eq. (4), which is derived by linearizing Eq. (1) :

$$S_b(K) = S^0_b(K) + \frac{W^H_a(K)}{\frac{1}{K^0_{\infty b}(K)} - 1 + 2W^H_b(K)}[S_a(K) - S^0_a(K)] \tag{4}$$

where the suffix 0 represents the state before the control rod operation, and a or b refers to the geometrical arrangement of monitored cells shown in Fig. 2.

An example of numerical experiments is shown in Fig. 2. The maximum error in the prediction is $\sim$2%, and the computer running time is $\sim$2 sec.

TIP readings thus obtained are transformed into the power densities or linear heat rates and other limiting thermal quantities at the end of the predictional calculation.

A similar technique has been used in predicting the power distribution change due to flow rate change or xenon transient. Prediction error obtained is about 3%.

Redistribution of the monitored channel power to the individual assembly power uses a method similar to that used in the present periodic core performance calculation.

The accuracy has also been verified by benchmark experiment with measured data. The required core memory and computation time are adequate for on-line application. A man-machine interaction procedure has been developed using a colour CRT. The on-line application of this system is in progress.

4. Plant Monitoring System by Computer Based Console

A conventional main control console of a 460MWe-class BWR nuclear power plant usually measures about 20 meters long, and has about 270 indicators and recorders, 1,200 lamps, 600 alarm annunciators on display panels, and 600 control switches on a control desk. In order to effectively operate the plant with this conventional control console, the operator is required to perform a wide range of activities including complex plant monitoring. At present, this requirement is being met by several well-trained operators working in a well-coordinated team. But in order to improve operator-plant interface and to operate the plant by a necessary minimum number of operators, it is indispensable that the console be reduced in size and plant information be centralized.

We have designed the prototype console "COCONUT" for BWR power plants with a generating capacity in the range of 460MWe. The prototype console is made up of a supervisor's console and an operator's console with corresponds to the conventional main control console.

For the operator's console (Fig. 3) of the COCONUT[8,9] we tried to carry out rationalization to the extreme and, to make one-man control possible, reduced the size to one-tenth the conventional. The display panel consists of color CRTs, a summary status display, and alarm annunciators. The control desk consists of control switches and a data access key board for CRT display control.

Plant data necessary for plant monitoring are displayed on three color CRTs, separately for the reactor auxiliary system, the reactor system, and the turbine generator system. The functions of plant monitoring[8,9] will be described later in this paper.

The supervisor's console (Fig. 4) has been newly designed in consideration of the situation of BWR power plant operation in Japan. It consists of a CRT and a data access keyboard. The supervisor can monitor the plant status as well as the operator's console, and can block the operator's operation, if necessary.

Conversational Information Display

The usefulness of CRT displays strongly depends on how to use the pictures on the CRT to access promptly the desired plant data. So we developed a conversational information display procedure[10], whereby access to plant data can be made in conversational form while watching the CRT display and, at the same time, plant status can be monitored.

In the conversational information display procedure, the access procedure is divided into three levels in a hierarchical structure, in accordance with process system and operational mode. First, the operator requests display of the process system or operational mode related to the desired plant data. Secondly, the operator selects an item among subsystems or submodes related to the desired plant data. Thirdly, by selecting a component from among the components, all data showing the status of the component will be displayed together with their schematic diagram.

On the CRT screen, the schematic diagram is shown on the left half of the screen and analog data and reference messages are indicated on the right half. Operating status of valves, pumps, etc. in the schematic diagram is shown by different forms of component symbols. Analog data are usually represented in percentage by bar graphs, but digital values can be displayed simultaneously as necessary.

Since plant data and schematic diagram are displayed simultaneously in each step of data access, the operator can grasp instinctively the plant condition at any time.

The data access keyboard consists of access procedure control buttons, ten keys for designating the desired information, and digital display demand buttons.

Automatic Prior Information Display

In the event that plant operation is upset the operator cannot make quick response with manual access procedure, even though the procedure may be simplified. To cope with a plant upset condition, automatic selection and CRT display of relevant information would be a desirable function. But it is extremely difficult for the system designer to predetermine the information to be displayed in a plant upset condition. It is not wise to display more than necessary information for safety operation. We have developed an automatic prior information display procedure.

In the case of conventional consoles, when an alarm occurs, the operator looks at the alarm message and gets a rough idea of the source of trouble. Then, he has to select and monitor the instruments on the console to decide whether the components are capable of continuing operation or not, and takes steps for plant shutdown or power down, if necessary. Because of the uncertainty of operating information and ambiguity of operaring conditions, it has been difficult to determine definitely a source of alarms and to decide whether the components can be operated. A well-trained operator empirically selects proper information which has a minimum of uncertainties and which consequently allows definite determination from a large amount of operating information.

In the automatic prior information display procedure, a process computer is substituted for the operator's skill and intuition in the selection of information mentioned above. Here, the concept of a measure of information as defined in the information theory is introduced, and the uncertainties, with which the operator makes a decision according to operating information, is quantified.[11] This method simulates the decision process of the operator, so that the intrinsic vagueness in man's decision process and the operator's experience can be incorporated.

These functions of plant monitoring enable the operator to perform promptly and simply the monitoring of varying plant conditions. The prototype, however, is rationalized to the utmost, so that utility and redundancy have to be taken into consideration for commercial use of the COCONUT.

5. Core Management System with Computer Network

Optimization of core management is a tremendous task due to large amount of information and many inter-related problems involved. It is felt necessary to develope a system under which all the necessary information is well organized and controlled and each management tasks is well administrated.

A BWR core management system which meets these requirements has been designed for a more efficient operation of several BWR plants. Schematic diagram of the proposed system is shown in Fig. 5. The basic idea is to establish a computer network by which to realize the faster transmission and the centralized management of information. The system comprises three computers of different size and purpose : process computer(s) for monitoring at reactor site(s), a center computer for administration possibly at the head office of utility and a large scientific computer for planning and evaluation at a computer center. The process and the large computers are connected to the center computer by data transmission line.

The planning system developes short and long term operating strategy. This includes control rod programming and refueling scheduling and is often called as in-core management. The basic tools for this system have already been developed.[12~15] The monitoring system is for on-line use. This includes core performance evaluation, core performance prediction and operating sequence modification. The first one is for monitoring the core state periodically and/or on demand, and all the commercial BWR's are equipped with this monitoring function. The second one is for predicting how much the power distribution changes before the actual operation takes place for control rod withdrawal or flow rate change as mentioned before. The third one is for modifying, for example, the startup sequence if the actual reactor state is found to be different from what has been predicted by the planning system. The latter two are now under development. Operating history evaluation system analyzes the reactor operating history in detail and provides back data for the other two systems. Three dimensional nuclear thermal hydraulic codes are used to calculate gross[16,17] and local[18] power distributions of fuel assemblies.

To demonstrate the feasibility and the merits of such a system, operating history evaluation system has been chosen and materialized along the concept mentioned above. Three computers used are HIDIC-500 (process computer), HITAC-8250 (center computer) and IBM-370/158 (large computer). These three are located at different places in Hitachi Ltd.

The feasibility study is successful and the results obtained confirm the merits of such a system. These are (1) quick response by data communication for unexpected change of operation, evaluation of operating history and planning of operating strategy, (2) reduction of man-power and computing cost by minimized intervention of human labor, (3) quick understanding of core state by visual display.

Further effort is required to integrate the above somewhat separately developed systems into a toal plant management system. Optimum structure of process computer and interface with various tasks are now in study.

6. Concluding Remarks

In summary, we feel that on-line computer is a very necessary part of nuclear power plant instrumentation systems as operator-advisory aids. The improvement of total plant performance is a tremendous task due to a large amount of information involved and many associated safety and economics problems that are inter-related to each other. The on-line computer takes a very important role for helping plant operation and management.

Our development of the on-line computer applications is now focused on the computer based console. We are making an effort to integrate the functions of operator-advisory aids into the computer based console.

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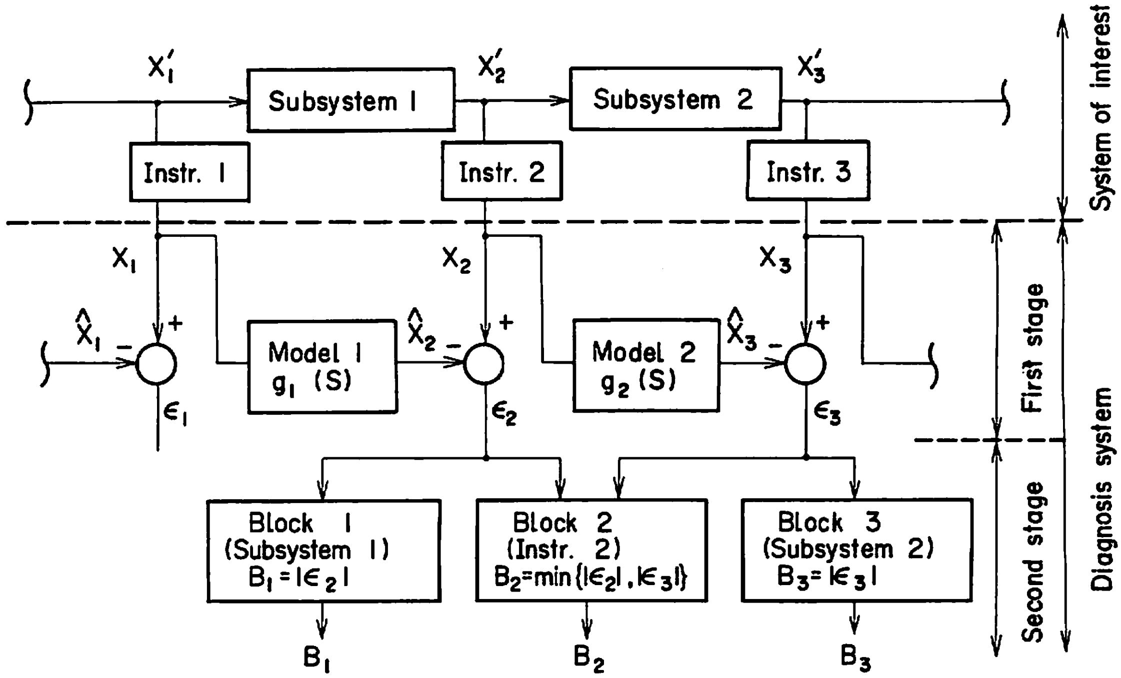

Fig. 1 Conceptual diagram of diagnosis

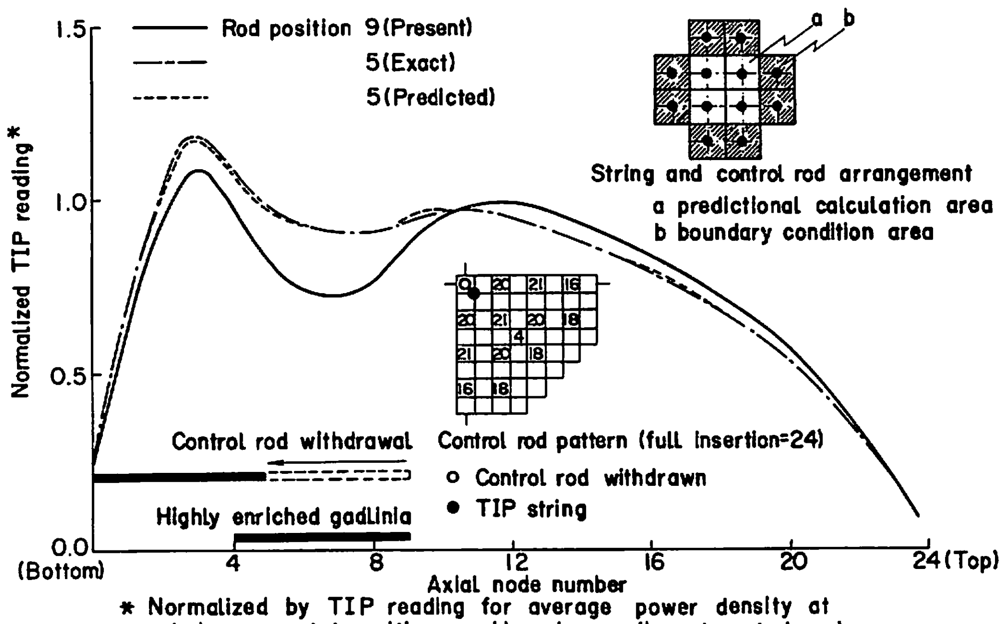

Fig. 2 An example of TIP reading prediction.

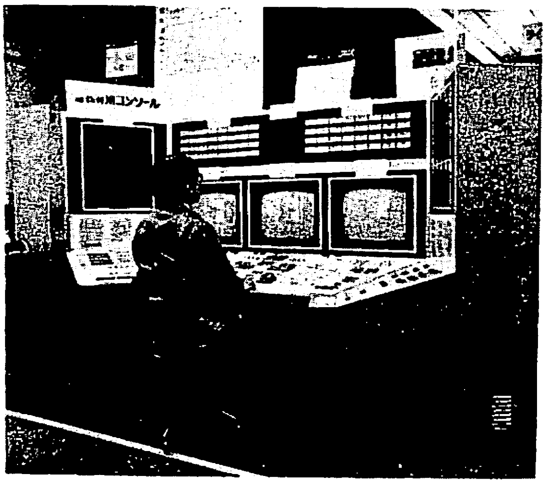

Fig. 3 Operator's Console.
The console measures 3m in width, 1.6m in height, and 0.8m in depth.

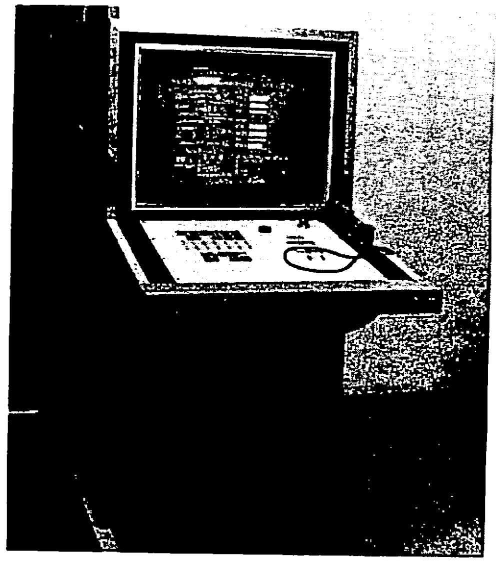

Fig. 4 Supervisor's Console
This console is 0.65m wide, 1.3m high, and 0.8m deep

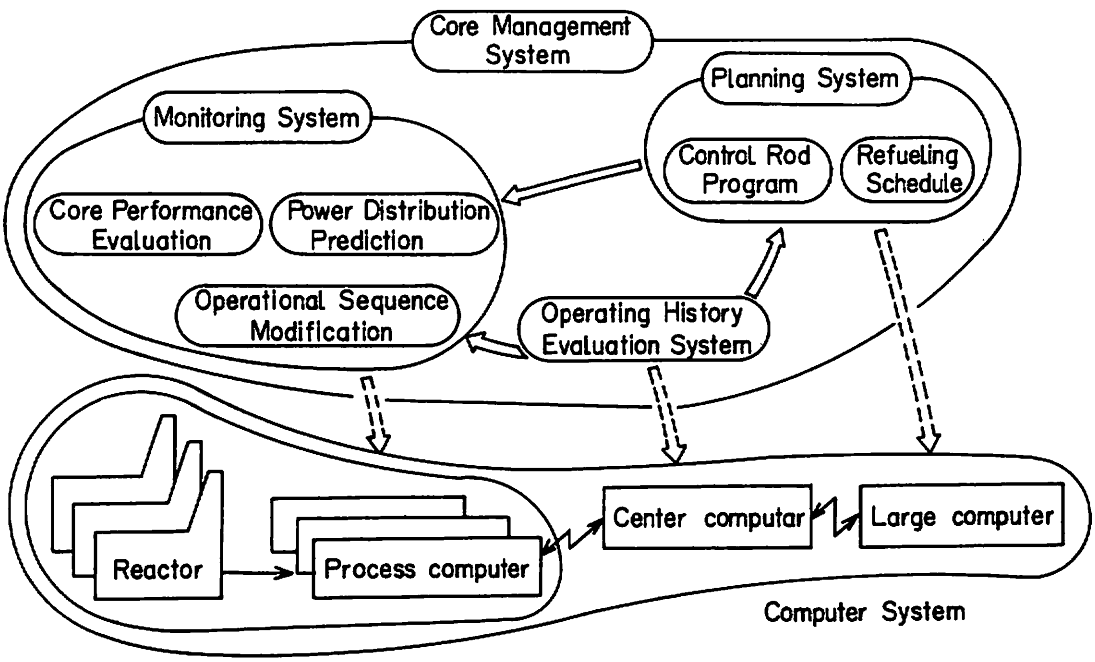

Fig. 5 Overview of Core Management System for BWR's