Journal of NUCLEAR SCIENCE and TECHNOLOGY, 19[7], pp. 513~520 (July 1982). 

# Simple Method to Predict Power Level and Core Flow Rate of Boiling Water Reactors by Using One-Point Core Model

Kikuo UMEGAKI, Takashi KIGUCHI and Hiroshi MOTODA

*Energy Research Laboratory, Hitachi, Ltd.**

*Received May 27, 1981*
*Revised November 16, 1981*

A simple one-point core model has been developed to predict startup and load following features of boiling water reactors (BWRs). The variables used in this model are core thermal power, core flow rate, xenon concentration and control rod pattern, where the last variable is expressed in terms of the corresponding thermal power at the rated core flow. The number of parameters to be identified is only three, and they are determined by flow control line, xenon reactivity coefficient and power reactivity coefficient. These parameters can be adjusted by using the actual operating data of BWR plants.

The accuracy of the one-point core model was evaluated in some typical startup operations of a reference 800 MWe class BWR. The prediction errors of the model were within 2% of relative power in comparison with results of a three-dimensional BWR core simulator and within 3% in comparison with the operating data. Use of this one-point core model, with xenon-iodine maps, should successfully predict reactor conditions, even when employing only simple hand-calculations.

***KEYWORDS:*** ***one-point core model, startup planning, load following, control rod pattern, flow control, xenon, simulation, BWR type reactors, flow rates, thermal power, accuracy, errors, reactor simulators***

## I. INTRODUCTION

Core management is one area of common interest to both utilities and vendors. Considerable effort is being expended to realize qualified operation from the viewpoints of both safety and economy. And within the area, planning for startup and for control rod pattern exchange are among the most important tasks for boiling water reactor (BWR) plants. In these operations, power level is controlled by means of core recirculation flow and control rods.

A startup control rod programming code system(1) has already been developed for an off-site computing system to find a good, feasible startup procedure. An on-line core performance evaluation and prediction system(2) has also been developed to monitor the power distribution at the reactor site by an on-line process computer. Appropriate operation has been realized by using these program systems which analyze the power distribution through multi-dimensional models. However, as the computing time required for the analysis is not negligible, it is desirable to develop a much more simplified core model that can be alternatively used at the reactor site.

Consequently, a simple one-point core model was developed to shorten the calculation time and to predict core state very rapidly in the case of an unscheduled power change

* *Moriyama-cho, Hitachi-shi 316.*

at the reactor site. This model, coupled with xenon dynamics, was put into a simple core simulator which has three prediction functions of power level, core flow rate and control rod pattern.

The purpose of this paper is to introduce the simple one-point core model and to demonstrate its usefulness by some examples.

## II. ONE-POINT BWR CORE MODEL

In one-point approximation, thermal power is represented by control rod density, core flow rate and xenon concentration. The functional relationships of these variables are approximated by the following equations.

### 1. Flow Control Line

To describe the relation between core thermal power and core flow rate, the flow control line is first approximated by

$$P=P_s+(aP_s+b)(F-1.0)\,, \tag{1}$$

where $P$: Core thermal power (normalized by rated value)
$F$: Core flow rate (normalized by rated value)
$P_s$: Core thermal power at rated core flow (normalized by rated value)
$a, b$: Parameters.

### 2. Core Thermal Power at Rated Core Flow

Core thermal power at the rated core flow is expressed by control rod pattern and xenon concentration as in Eq. (2)

$$P_s=CR+cCR(Xe_{sat}-Xe)\,, \tag{2}$$

where $CR$: Control rod pattern (represented by power level)
$Xe_{sat}$: Equilibrium xenon concentration at $P=CR$
$c$: Parameter $((\Delta P/P)/\Delta Xe)$.

In this equation, the variable $CR$ represents the core thermal power that corresponds to the control rod pattern in question at the rated core flow assuming an equilibrium xenon concentration. In startup operations of a BWR, a control rod pattern is often designated as the $x$% pattern, where $x$% is a relative thermal power that corresponds to the control rod pattern at the rated core flow. The variable $CR$ is equivalent to the $x$ value and usually calculated by a three-dimensional core simulator. The parameter $c$ is the ratio of relative power change to xenon concentration change.

One of the characteristics of this model is that control rods are treated in terms of power level for the corresponding control rod pattern. This is different from the usual method in which they are treated in terms of reactivity[3].

### 3. Xenon-iodine Dynamics

Core average xenon concentration is determined by the following equations:

$$\frac{dI(t)}{dt}=\gamma_I\Sigma_f\phi(t)-\lambda_I I(t)\,, \tag{3}$$

$$\frac{dXe(t)}{dt}=\lambda_I I(t)+\gamma_{Xe}\Sigma_f\phi(t)-\lambda_{Xe}Xe(t)-\sigma_{Xe}Xe(t)\phi(t)\,, \tag{4}$$

where $Xe(t), I(t)$: Xenon and iodine concentrations

$\gamma_{Xe}, \gamma_I$: Fission yields of xenon and iodine

$\lambda_{Xe}, \lambda_I$: Decay constants of xenon and iodine

$\Sigma_f$: Macroscopic fission cross section

$\sigma_{Xe}$: Microscopic absorption cross section of xenon

$\phi(t)$: Core average thermal neutron flux.

(It is assumed that thermal neutron flux is proportional to thermal power.)

### 4. Prediction Functions

The three prediction functions of power level, core flow rate and control rod pattern represented by $CR$ can be added to the one-point core model, with or without xenon dynamics. If two of the above three variables were given, the remaining variable could be estimated by using Eqs. (1) and (2). Therefore, startup, load following or other power maneuvering procedures can be predicted by trial and error method using these prediction functions.

## III. PARAMETER IDENTIFICATION

The number of parameters to be adjusted in the one-point core model is only three ($a$, $b$ and $c$). They are determined by flow control line, xenon reactivity coefficient and power reactivity coefficient. The parameters are first identified for a reference BWR of 800 MWe class using a FLARE[(4)]-type three-dimensional core simulator.

### 1. Flow Control Line Fitting

The flow control line is a locus of core thermal power that corresponds to core flow rate change, assuming an equilibrium xenon concentration at the rated core flow. **Figure 1** shows the flow control lines for different control rod patterns. The circled points which indicate the results from the three-dimensional simulator, can be approximately connected by straight lines. The parameters $a$ and $b$ in Eq. (1) are determined using the least squares method. Relative power $P$ can be fitted within $\pm 1\%$ error.

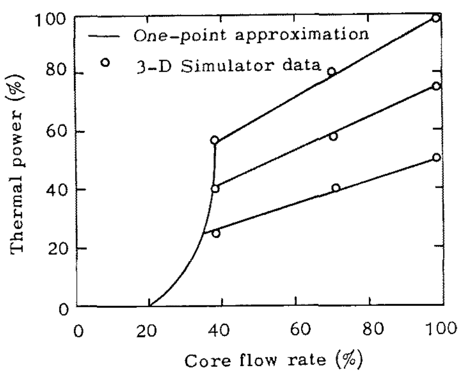



**Fig. 1** Flow control lines for different control rod patterns

### 2. Xenon Reactivity Coefficient

A linear relation between core average xenon concentration and its reactivity is assumed in the one-point model. It can be expressed by

$$\Delta k / \Delta Xe = \text{constant}. \qquad (5)$$

Actually, the xenon reactivity coefficient depends on a three-dimensional spatial distribution of xenon concentration in the reactor core, and it takes a slightly different value under each control rod pattern. **Figure**

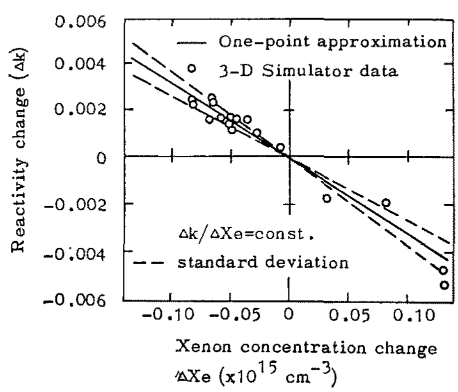



**Fig. 2** Xenon reactivity coefficients

2 shows results from the three-dimensional core simulator and the one-point approximation. The standard deviation is about 15% under the various control rod patterns.

### 3. Power Reactivity Coefficient

The power reactivity coefficients estimated under various core thermal power levels are shown in **Fig. 3**. A functional relationship can be assumed between relative power and power reactivity coefficient. The empirical equation can be expressed by

$$\Delta k/(\Delta P/P)=\text{constant}. \qquad (6)$$

The standard deviation is about 12% in the range of 30∼100% power. The parameter $c$ in Eq. (2) can be calculated by the xenon reactivity coefficient in Eq. (5) and the power reactivity coefficient in Eq. (6).

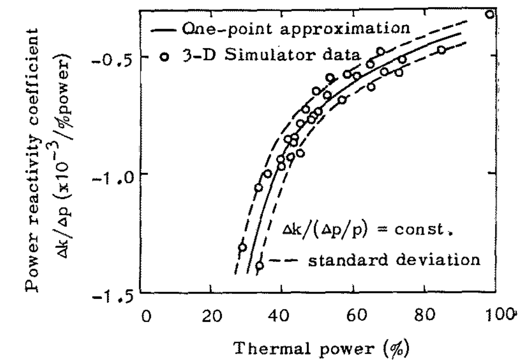



**Fig. 3** Power reactivity coefficients estimated for various power levels

It is clear from Eqs. (1) and (2) that power level is basically calculated by the control rod pattern $CR$ which is expressed in terms of thermal power and flow rate using the flow control line approximation. The effect of xenon concentration change is converted to the power change from $CR$ in Eq. (2) at the rated core flow. The second term of Eq. (2) is, in general, within 10% of the first term throughout the startup or control rod pattern exchange operation. Therefore, the calculation error in thermal power caused by the ambiguity of parameter $c$ is expected to be smaller than 2%.

## IV. Accuracy Evaluation

A simple core simulator which has three prediction functions of core thermal power, core flow rate and control rod pattern represented by $CR$, with or without xenon dynamics, was developed using the one-point approximation model. A typical startup operation was simulated to evaluate the model accuracy.

**Figure 4** shows an example of a one-loop startup operation procedure on a power-flow map calculated by a three-dimensional BWR core simulator. Three kinds of power maneuvering operation are shown in the figure. Operation ① is a power increase by control rod withdrawal, ② is a power increase by flow control, and ③ is a power reduction by flow control. The objective of the looping is to withdraw control rods below the threshold power level by using the xenon transient.

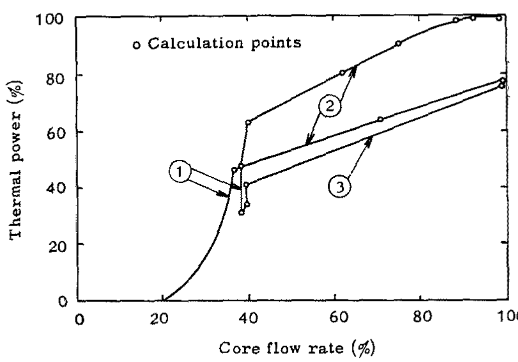



**Fig. 4** Calculation points used to evaluate accuracy of one-point core model in one-loop startup operation

The relative thermal power and core average xenon concentration are compared between the one-point and the three-dimensional core simulator through the one-loop startup operation in **Fig. 5**. The variable $CR$ in the one-point model is given by the results with the three-dimensional core simulator. The difference of power is within ±2% throughout the startup operation and it is not necessary to change the values of the parameters *a*, *b* and *c* even if the control rod pattern is changed.

It was confirmed that the one-point model can be used for rapid prediction of core state. It was also noted that this model was simple enough to be implemented on a programmable pocket calculator.

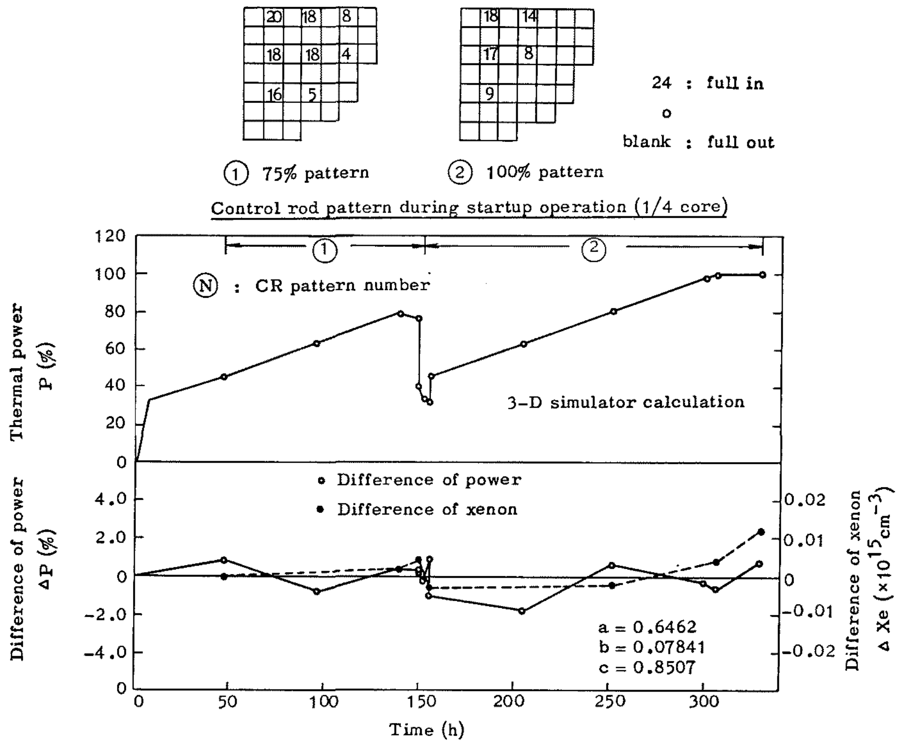


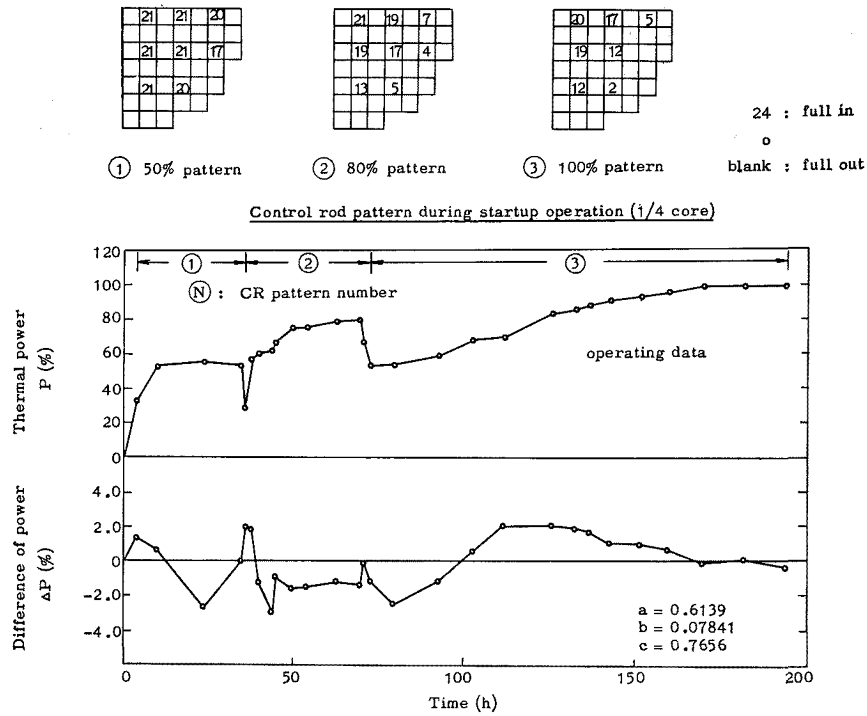

**Fig. 5** Accuracy evaluation of one-point core model by three-dimensional core simulator

## V. Parameter Adjustment by Operating Data

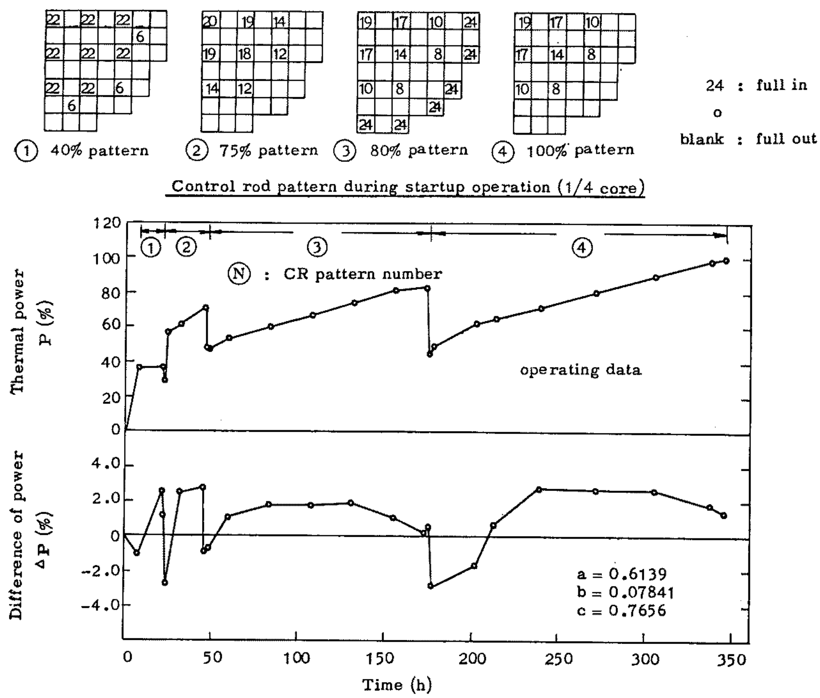
For the purpose of practical application at the reactor site, the parameters *a*, *b* and *c* can be adjusted by actual operating data. Usually, the parameters are periodically identified by a three-dimensional core simulator for each operating cycle. Then, they are adjusted to minimize the difference in power or flow between the one-point model and the operating data over the first power maneuvering operation in the cycle.

In this study, the parameters were adjusted for the first cycle of the reference 800 MWe class BWR. Then, the accuracy of the one-point model was evaluated in some startup operations of the first cycle. The variable *CR* was estimated by the three-dimensional core simulator for the one-point approximation. **Figure 6** (a) and (b) show examples of the accuracy evaluation of the one-point core model. The same parameters were used in the one-point calculation of each startup operation. The maximum power difference was kept within ±3%, even if the control rod pattern was changed.

In order to improve the accuracy of the one-point model, it would be better to update the parameters when they are applied to new reload cycles in which fresh fuel bundles are loaded. However, the same parameters can be used in the same operating cycle.




(a) Two-loop startup operation

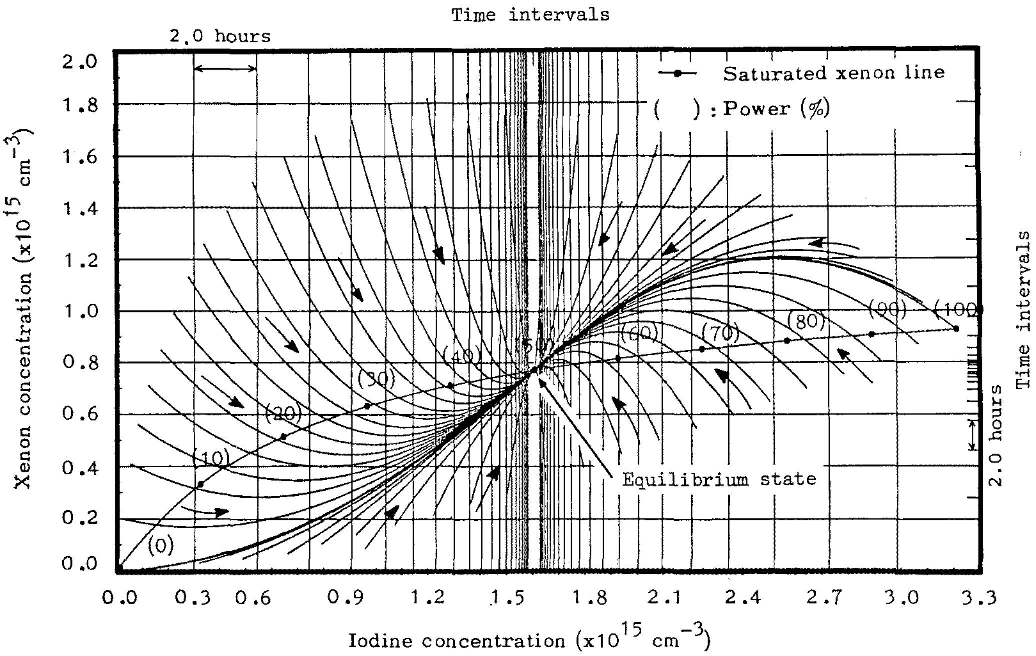



(b) Three-loop startup operation

**Fig. 6**(a),(b) Example of accuracy evaluation of one-point core model by actual operating data

## VI. Simple Prediction Method Using Xenon-iodine Maps

A simple core state prediction method using the one-point core model and xenon-iodine maps was developed to deal with unscheduled power change at the reactor site. **Figure 7** plots an example of core average xenon and iodine concentration loci that correspond to step changes of thermal power to the 50% rated level. It is obvious from Eq. (3) that the change rate of iodine concentration $(dI(t)/dt)$ depends on the iodine concentration itself under the constant power level, and thus, a time axis can be added to the $X$-axis. Assuming an equilibrium iodine concentration, a supplemental time axis can be added to the $Y$-axis in the same way.



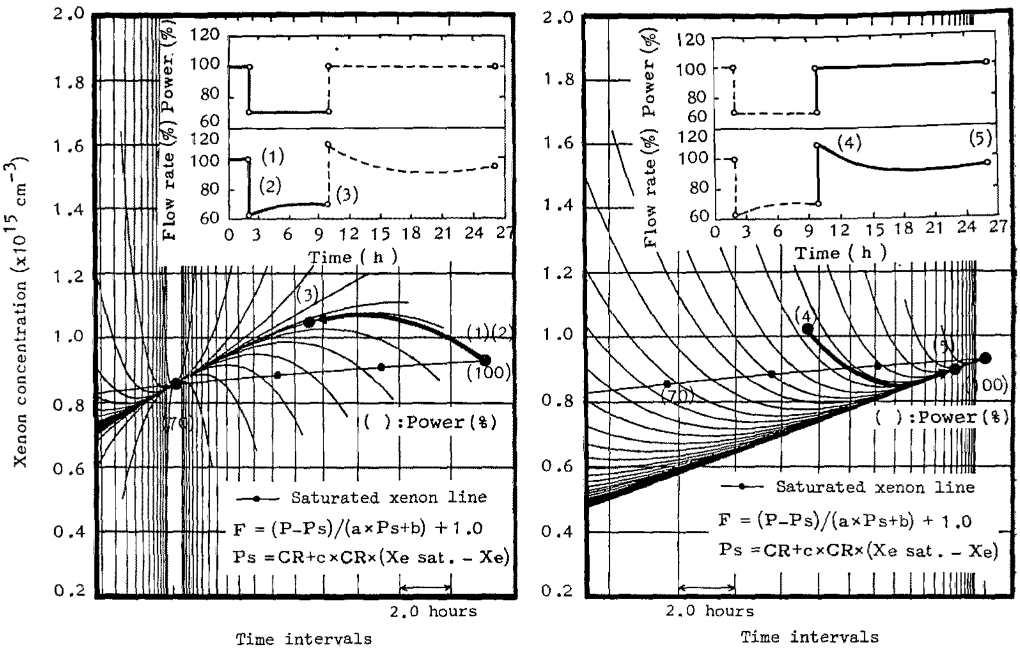

Time axes are added to $X$ and $Y$ axes according to iodine and xenon concentration changes.
**Fig. 7** Xenon-iodine map of step power change to 50% rated value

Thermal power or core flow rate can be approximately predicted by considering the xenon dynamics on these maps. For instance, load following operation (100-70-100% power) is shown in **Figs.** 8(a) and (b). At first, the core thermal power is decreased to 70% from the rated value. The core flow rate to keep the power constant for 8 h is calculated by using xenon-iodine maps and the one-point core model. Next, the core flow rate to recover and keep the thermal power at its rated value is calculated in the same way.

This method is simple enough to be done even by hand-calculations.

## VII. Conclusions

A simple one-point core model which has four variables and three parameters was developed to predict core state rapidly. One of the characteristics of this model is that control rods are treated in terms of power level for the corresponding control rod pattern. This is different from the current method in which they are treated in terms of reactivity.




(a) Flow rate predication for low power operation

(b) Flow rate predication for high power operation

**Fig.** 8(a),(b) Examples of flow rate prediction in load following operation

The two main advantages of the new model are easy adjustment of the parameters, and simple handling of the control rod effect. The model parameters are determined by flow control line, xenon reactivity coefficient and power reactivity coefficient. They can be adjusted by actual operating data.

The prediction errors of this model in terms of relative power is within $\pm 2\%$ compared with the three-dimensional simulator, and within $\pm 3\%$ compared with actual operating data.

A simple core state prediction method was also developed using the one-point core model and xenon-iodine maps. Example predictions of core flow rate for a load following operation were given using this method.

This one-point core model is simple enough to be implemented on a programmable pocket calculator or by hand-calculations.


## ACKNOWLEDGMENT

The authors would like express their thanks to Drs. K. Taniguchi, S. Yamada and S. Kobayashi of Energy Research Laboratory, Hitachi Ltd. and Dr. H. Hiranuma and Mr. I. Yokomi of Hitachi Works, Hitachi Ltd., for their support and useful discussions.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