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Technical Notes

On-Line Prediction of the Power Distribution Within Boiling Water Reactors

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ABSTRACT

A method for on-line prediction of the power distribution within boiling water reactors has been developed. The prediction procedure consists of two parts: the first is to estimate the present Traversing In-Core Probe (TIP) readings using Local Power Range Monitors (LPRM) readings, which is required to give the initial condition of the predictional calculation; the second is to predict the TIP readings after motion of a control rod. Results of numerical experiments show that the TIP readings are predicted, with reasonable accuracy, within a short computer time and a small core memory. It is felt that this method is suitable for on-line computer application.

I. INTRODUCTION

It is useful for boiling water reactor (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.

This Note presents a method to predict the Traversing In-Core Probe (TIP) readings after a control rod motion and to estimate the present TIP readings using the Local Power Range Monitor (LPRM) readings alone. The latter gives the initial condition of the predictional calculation when the measured TIP readings are not available. The results of numerical experiments show that the proposed method gives the TIP readings or its change with reasonable accuracy within a short computing time and a small computer memory, and that it seems to be suitable for on-line use.

II. METHOD AND RESULTS

II.A. Estimation of Present TIP Readings

Estimation of the present TIP readings is based on a one-dimensional FLARE-type nuclear thermal hydraulic calculation[1] combined with model adjusting method for making the calculated neutron flux consistent with the measured LPRM readings at its locations.

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

$$S_l(\kappa) = \frac{k_{\infty l}(\kappa)}{\lambda}\left\{\sum_{i=1}^{4} S_i(\kappa)W_i^H(\kappa) + S_l(\kappa-1)W_l^V(\kappa-1) + S_l(\kappa+1)W_l^V(\kappa+1) + S_l(\kappa)\left[1 - 2W_l^V(\kappa) - (4-\alpha)W_l^H(\kappa)\right]\right\} , \quad (1)$$

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

κ = axial node number

$S(\kappa)$ = axial distribution of neutron source

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

λ = effective neutron multiplication factor

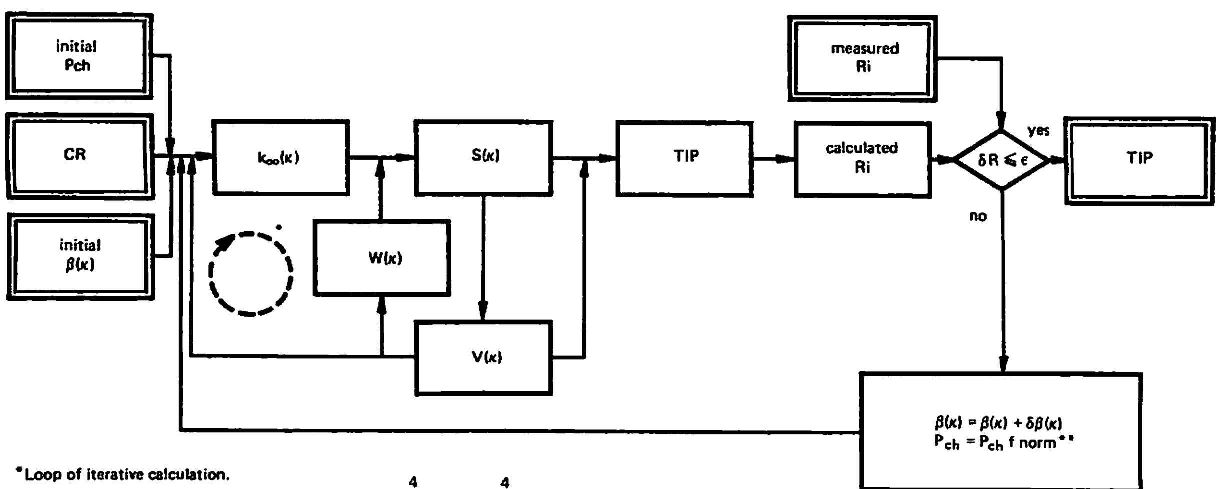
$W^H(\kappa)$ = axial distribution of horizontal neutron transport kernel

$W^V(\kappa)$ = 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

[1] D. L. DELP et al., "FLARE, A Three Dimensional Boiling Water Reactor Simulator," GEAP-4598, General Electric Company (1964).



*Loop of iterative calculation.

**Normalization factor f norm is defined by: $f\ norm = \sum_{i=1}^{4} R_i^{meas} / \sum_{j=1}^{4} R_i^{cal}$

Fig. 1. Flow diagram of present TIP reading estimation.

"neutron reflection rate," $\beta(\kappa)$, defined in Eq. (2) is introduced:

$$\beta(\kappa) \equiv \sum_{i=1}^{4} S_i(\kappa)W_i^H(\kappa)/[4S_i(\kappa)W_i^H(\kappa)] \quad . \qquad (2)$$

By adjusting the value of $\beta(\kappa)$, 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:

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

Channel power, Pch, and the neutron reflection rate, $\beta(\kappa)$, are iteratively adjusted such that the calculated TIP readings are consistent with the measured LPRM readings at its location. Adjustment of $\beta(\kappa)$ is performed by reference to the LPRM readings using Eq. (4), which is obtained on the analogy of the linearized relation between $\delta\beta$ and δS:

$$\left.\begin{aligned} &\delta\beta_i \propto \delta R_i/R_i^c \\ &\delta\beta_i \leq (\delta\beta_i/\max|\delta\beta_i|)\Delta\beta_{\lim} \\ &\Delta\beta_{\lim} = \Gamma\,\Delta\beta_{\lim}^0 \quad (\Gamma = 0.5 \text{ or } 2.0) \end{aligned}\right\} \quad , \qquad (4)$$

where

$\delta\beta_i$ = correction of neutron reflection rate at LPRM position i

δR_i = difference between calculated and measured LPRM readings

R_i^c = calculated LPRM readings

$\Delta\beta_{\lim}$ = correction limit of neutron reflection rate

$\Delta\beta_{\lim}^0$ = correction limit of neutron reflection rate at the preceding correction step

Γ = acceleration factor.

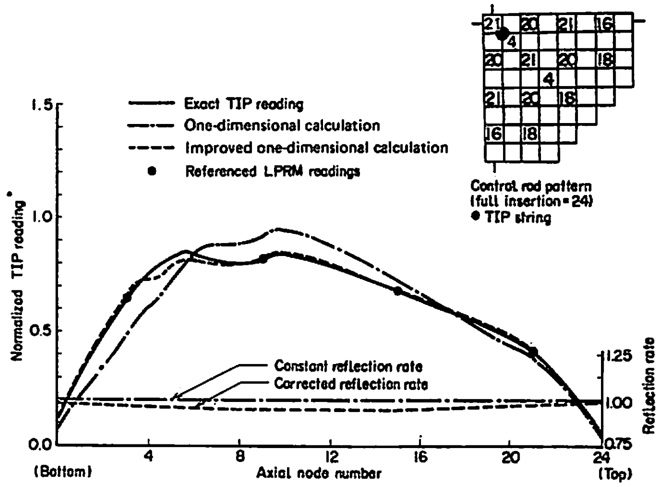
Equation (4) states that the components of the correction vector $\delta\beta_i$ are distributed in proportion to $\delta R/R^c$, with its maximum value being limited to $\Delta\beta_{\lim}$. The value of the acceleration factor Γ is determined by its sensitivity to the calculated LPRM readings. Nodewise $\beta(\kappa)$ is obtained by the linear interpolation or extrapolation of $\delta\beta_i$ at LPRM positions thus determined. The channel power is reestimated by normalizing the summation of the four calculated LPRM readings to that of the measured values at each iteration.

The estimation procedure of present TIP readings is summarized in Fig. 1.

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. Figures 2 and 3 show two examples of estimated TIP readings, together with the solutions of both accurate three-dimensional calculation and ordinary one-dimensional calculation, assuming a flat boundary condition which corresponds to $\beta(\kappa) = 1.0$.

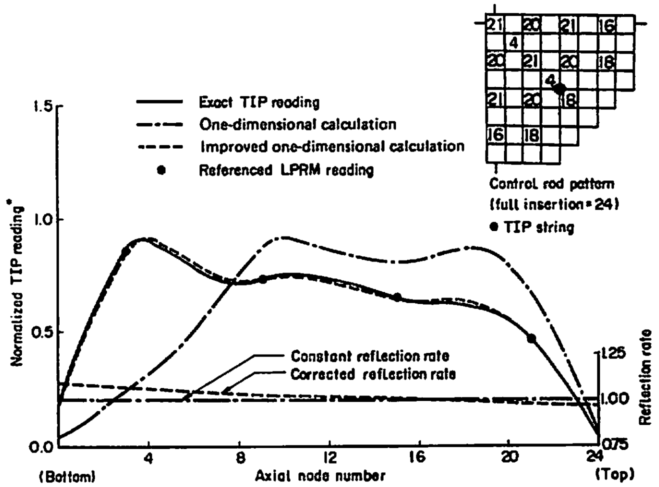
II.B. Prediction of TIP Readings After a Control Rod Withdrawal

The effect of a control rod withdrawal on power distribution is fairly localized, and a significant change arises only in the monitored cells adjacent to the control rod



*Normalized by TIP reading for average power density at rated power state with no void and no adjacent control rods.

Fig. 2. An example of present TIP reading estimation (case 1).



*Normalized by TIP reading for average power density at rated power state with no void and no adjacent control rods

Fig. 3. An example of present TIP reading estimation (case 2).

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.

Figure 4 shows the monitored strings whose TIP readings are to be predicted. Initial conditions are the present TIP readings measured or their corresponding values estimated by the method described in Sec. II.A.

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. 4 are transformed to the cell average power distributions, $S_l(\kappa)$, by

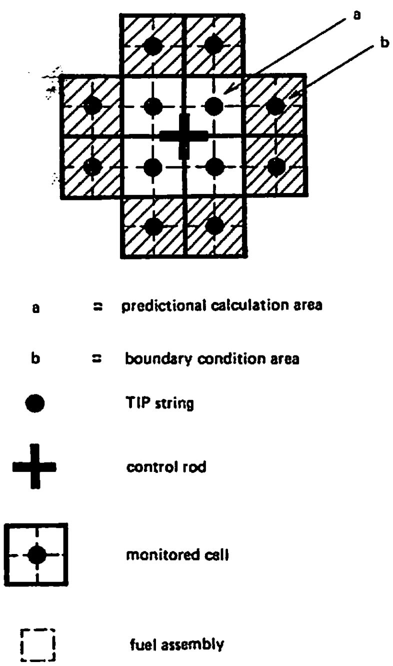


Fig. 4. String and control rod arrangement.

using a predetermined relation among TIP readings, power, void, and control rod arrangement. Using the values $S_l(\kappa)$ thus obtained, the three-dimensional nodal equation, Eq. (1), is solved for the present $k^0_\infty(\kappa)$ 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 for $k_{\infty l}(\kappa)$ in Eq. (5), and Eq. (1) is solved for the four monitored cells surrounding the control rod that is moved,

$$k_{\infty l}(\kappa) = k^0_{\infty l}(\kappa) + \Delta k_\infty\, [CR(\kappa), V(\kappa)] \quad , \tag{5}$$

where

$k^0_{\infty l}(\kappa)$ = infinite multiplication factor before control rod motion

$V(\kappa)$ = void fraction

$\Delta k_{\infty l}(\kappa)$ = change in infinite multiplication factor introduced by the control rod moved.

The small changes in the power of the shaded channels are taken into account by Eq. (6), which is derived by linearizing Eq. (1):

$$S_b(\kappa) = S^0_b(\kappa) + \frac{W^H_a(\kappa)}{\frac{1}{k^0_{\infty b}(\kappa)} - 1 + 2W^H_b(\kappa)}\,[S_a(\kappa) - S^0_a(\kappa)] \quad , \tag{6}$$

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. 4. Equations (1) and (6) form an inhomogeneous source problem.

The whole TIP-reading prediction process stated in this section is summarized in Fig. 5.

Results of numerical experiments are shown in Figs. 6 and 7. They show the predicted TIP readings after the control rod withdrawals of one and four notches, respectively. Each of them is shown together with the accurate calculations of the power density both before and after the control rod motion. The maximum error in the prediction is ~2%, and the computer running time is ~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.

III. CONCLUSION

The method presented here evaluates the power distribution, or a change in the distribution, with satisfactory accuracy within a short computation time, and requires

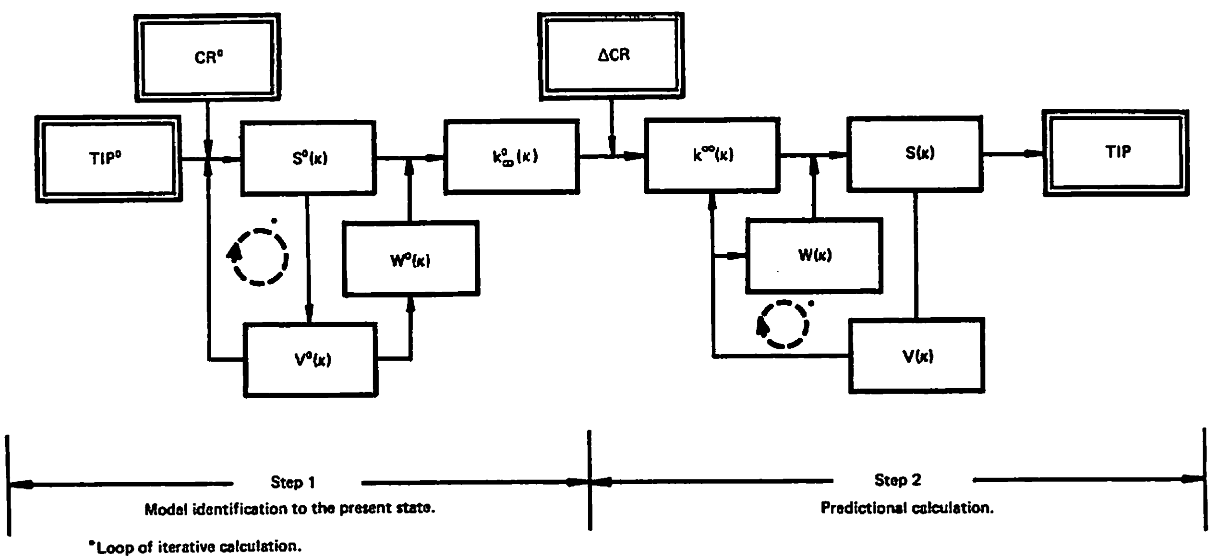
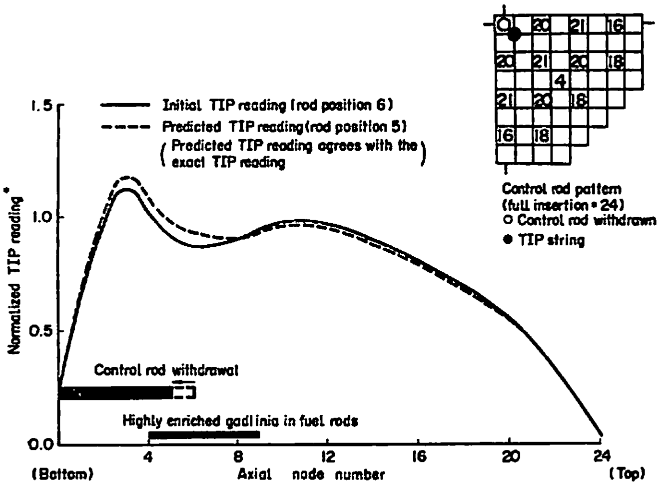
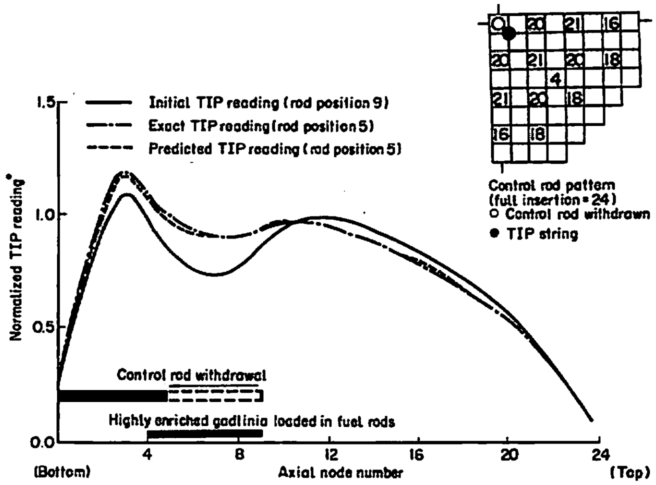


Fig. 5. Flow diagram of TIP reading prediction.



*Normalized by TIP reading for average power density at rated power state with no void and no adjacent control rods.

Fig. 6. An example of TIP reading prediction (case 1).



*Normalized by TIP reading for average power density at rated power state with no void and no adjacent control rods.

Fig. 7. An example of TIP reading prediction (case 2).

only a small core memory. It is felt that this method is suitable for on-line use, and can be expected to be an additional effective function supplementary to the current core performance evaluation programs. The method presented here will be a useful means for confirming safe operation, particularly at the startup or restartup of BWRs.

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