CONF

CONF-8110107--2

DE82 002737

APPLICATION OF NOISE-ANALYSIS METHODS TO MONITOR STABILITY OF BOILING WATER REACTORS[1]

B. R. Upadhyaya[2], J. March-Leuba[2], D. N. Fry[3], and M. Kitamura[4]

Prepared for the
Third Specialists' Meeting on Reactor Noise (SMORN-III)
October 26-30 1981, Tokyo, Japan

[1]Research sponsored by the Office of Nuclear Regulatory Research, U. S. Nuclear Regulatory Commission, under Interagency Agreement 40-551-75 with the U. S. Department of Energy under Contract W-7405-eng-26 with the Union Carbide Corporation.

[2]Department of Nuclear Engineering, The University of Tennessee, Knoxville, Tennessee, 37916, USA.

[3]Instrumentation and Controls Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37830, USA.

[4]Department of Nuclear Engineering, Tohoku University, Sendai, 980, Japan.

Prepared for the Specialists Meeting on Reactor Noise (SMORN-III)
October 26-30, 1981, Tokyo, Japan.

APPLICATION OF NOISE ANALYSIS METHODS TO MONITOR STABILITY OF BOILING WATER REACTORS

B. R. Upadhyaya*, J. March-Leuba*, D. N. Fry** and M. Kitamura***

*Dept. of Nuclear Engineering, The University of Tennessee, Knoxville, TN 37916, USA
**Instrumentation and Controls Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA
***Dept. of Nuclear Engineering, Tohoku University, Sendai, 980 Japan

ABSTRACT

The dynamic stability of Boiling Water Reactors (BWR's) is influenced by the reactor control system and its interaction with external load demand, channel thermal hydraulic properties, and coupled neutronic-thermal-hydraulic dynamics. The latter aspect of BWR stability which is affected by void reactivity feedback, coolant flow rate and fuel-to-coolant heat transfer characteristics is studied in this paper using the normal fluctuation data. The feasibility of overall core stability trend monitoring using neutron noise and the relationship between stability and two-phase flow velocity in a fuel channel are studied. Time series modeling of the average power range monitor (APRM) detector signal, and bivariate analysis of adjacent local power range monitor (LPRM) detector signals are used to determine the neutron impulse response, spectral characteristics and two-phase flow velocity using data from an operating BWR. The results of analysis show that the APRM noise signal can be used to monitor changes in the closed-loop output stability of BWRs (but not the absolute stability as determined by the reactivity-to-neutron power transfer function), and that a positive correlation exists between stability and two-phase flow velocity in a fuel channel. Furthermore, the temporal behavior of the neutron signal for short and long data records indicates that there is no smoothing of the spectral resonance frequency, nor subsequent distortion of the computed decay ratio when long data records were used. The primary perturbation source affecting the void reactivity is being investigated using the relationship between APRM signal and the process variables.

KEYWORDS

BWR stability monitoring; void reactivity feedback; normal fluctuation data; two-phase flow velocity; time series modeling; APRM and LPRM detector signals; temporal behavior.

INTRODUCTION

Three types of stability can be identified in Boiling Water Reactors (BWR's) (General Electric, 1977). These are: 1. Total plant stability, which is associated with reactor control systems and their interaction with external load demand. 2. Channel thermal-hydraulic stability, influenced by the momentum dynamics of two-phase flow in a heated channel. 3. Coupled neutronic-thermal-hydraulic stability influenced by the void reactivity feedback in a BWR. The latter is affected by the circulating water acting as both a coolant and a moderator. In operating BWR's the neutronic-thermal-hydraulic stability is of primary concern, because changes in the operating conditions can strongly influence the reactor stability margin. This "reactivity" stability corresponds to the reactivity to power transfer function dynamics.

Analytical studies (Otaduy-Bengoa, 1979) and small perturbation tests (Carmichael, 1978; Woffinden, 1981) showed the basic structure of this transfer function which can be represented by a pair of complex poles in the 0.3-0.7 Hz frequency range, and a zero at a lower frequency. Figure 1 is a block diagram of the dynamic processes related to power generation in a BWR core. The moderator void reactivity feedback is more dominating than the feedback due to fuel temperature coefficient of reactivity.

The feasibility of using the neutron noise signal for stability related measurements in BWR's was first suggested by Tsunoda et al. (1978). Further studies (Sides, 1979; Fukunishi, 1978) have shown that the power spectral density of the neutron noise in BWR's exhibits a noticeable resonance in the frequency range 0.3-0.7 Hz. Based on these earlier studies, the feasibility of monitoring changes in the stability using time series modeling of neutron noise was determined (Upadhyaya,1979, 1980a, 1981). Stochastic modeling, using reactor pressure noise as input and APRM signal as output, was developed (Wu, 1981) and found to give results comparable to those obtained from perturbation tests; however, during normal reactor operation the pressure noise is more of an effect than a variable causing changes in the power. Hence the reactivity cannot be assumed to be driven by the pressure fluctuations in the core. On the contrary, studies by Bergman and Gustavsson (1979) and by (March-Leuba, 1981) indicate that the total core flow rate is the primary cause of reactivity perturbation. Thus, to obtain the dynamic transfer function, it is necessary to identify the reactivity perturbation source. The neutron noise technique gives the output stability that does not require the identification of a driving function. Only in the case of a wideband driving source, both output and transfer function stability analyses coincide. For most common situations, the relative changes in the output stability are representative of relative changes in the reactor stability. Improper choice of the process variable (perturbing the reactivity) would give a wrong representation of reactor stability. The purpose of the present work is to establish the correspondence between output stability and transfer function stability.

In this work three aspects of BWR stability will be presented. These are:

1. Overall core stability monitoring using neutron noise.

2. Relationship between stability and two-phase velocity.

3. The temporal behavior of neutron noise signal.

Univariate analysis of APRM detector signal and bivariate analysis of two LPRM detector signals (located 36 inches apart at positions B and C in a vertical detector string) were performed using empirical time series models. Since the time series model is a causal representation of system dynamics, we can effectively model the system for both short-and long-term changes in performance parameters.

The problem statement and the general approach for stability analysis are presented in ANALYSIS OF BWR STABILITY. TIME SERIES MODELS AND SIGNAL FLOW CHARACTERIZATION describes the general time series models, model parameter estimation, impulse response estimation and signal flow graphs from bivariate modeling. Applications of the techniques to data from two operating BWRs are discussed in STABILITY MONITORING USING OPERATIONAL DATA. Both APRM and LPRM detector signals are analyzed to evaluate the objectives stated above. Finally, some concluding remarks and practical implications of BWR stability monitoring are given.

ANALYSIS OF BWR STABILITY

Statement of the Problem

The purpose of this study is to evaluate operational data to establish a technique to monitor the stability trends of BWRs. Specifically three aspects of BWR stability have been studied:

1. Overall core stability monitoring using neutron noise.

2. The relationship between stability and two-phase velocity in a fuel channel.

3. The variation in the stability and spectral characteristics as a function of time.

Both dynamic model analysis (Otaduy-Bengoa, 1979) and perturbation tests (Carmichael, 1978) clearly indicate the damped oscillatory nature of the reactivity-to-power closed-loop transfer function. A sustained oscillation of the neutron power could cause undesirable changes in the fuel property. When this information is needed within a short period of time, it is necessary to process short data records effectively. Our studies show that both univariate and multivariate time series models can be efficiently developed to extract this information. The general form of the model is given by the autoregressive (AR) process

$$X(k) = \sum_{i=1}^{n} A_i \; X(k-i) + V(k) \qquad (1)$$

where

$X(k) = \{x_1(k),\ldots,x_m(k)\}$ = vector of random variables at sample k.

$\{A_i\}$ = (mxm) AR coefficient matrix.

$V(k) = \{v_1(k),\ldots,v_m(k)\}$ = vector of random noise sources.

The models are used to derive both time domain and frequency domain signatures. Because of the linear nature of the AR process no nonlinear minimization methods are necessary to estimate the model parameters.

Definition of Stability Parameters

Figure 2 shows a typical impulse response of a stable damped oscillatory system. If the response is described by a second order system then the impulse response can be written as

$$x(t) = A \exp(-\sigma t)\sin(\omega_d t) \qquad (2)$$

For a general system the degree of stability is defined by the least stable characteristic root of the system response function. We will characterize the stability index in terms of the decay ratio of the neutron impulse response function. Referring to Fig. 2 the decay ratio is given by

$$DR = A_2/A_1 \qquad (3)$$

This is a function of both the attenuation factor σ, and the period T of damped oscillation. By comparing with the second order system response, we can define an equivalent damping coefficient as

$$\xi = \frac{\delta}{(4\pi^2 + \delta^2)^{1/2}} \qquad (4)$$

where $$\delta = \ln(A_1/A_2) \qquad (5)$$

For stability $0 < DR < 1$, $0 < \xi < 1$. The decay ratio is very sensitive to changes in A_1 or A_2, except when it is close to unity. The damping coefficient ξ is a more robust parameter, even though both are in the range (0,1) for stability.

TIME SERIES MODELS AND SIGNAL FLOW CHARACTERIZATION

The companion paper (Kitamura, 1982) in this proceedings describes the method of parameter estimation of autoregressive time series models and associated system descriptors. In this section we will describe the use of empirical models for stability analysis and two-phase velocity estimation.

Time Series Modeling

Let $X(t) = \{x_1(t), x_2(t), \ldots, x_m(t)\}$ be a set of jointly stationary ergodic random processes with finite variance. The dynamic relationship among a set of signals can be represented by the process (Parzen, 1961)

$$X(k) = \sum_{i=1}^{n} A_i \; X(k-i) + V(k) \qquad (6)$$

where

$X(k) = (x_1(k), x_2(k), \ldots, x_m(k))$ is the vector of signals at sample time k.

$\{A_i\}$ = (mxm) parameter matrices.

$V(k) = (v_1(k), v_2(k), \ldots, v_m(k))$ is the vector of noise sources at sample time k.

V(k) satisfies the following conditions

$$E[V(k)] = 0, \; E[V(j)V(k)^T] = Q\,\delta_{jk}. \tag{7}$$

The implication here is that the noise source is a white noise sequence, or that the constructed model satisfies this condition through a fictitous noise source. The univariate autoregressive model is given by

$$x(k) = \sum_{i=1}^{n} a_i x(k-i) + v(k) \tag{8}$$

In neutron noise analysis using Eq. (8) we will assume that the model is constructed such that the residual sequence is white. In practice, v(k) can be identified as a wideband reactivity perturbation. The set of parameter $\{A_1, A_2, \ldots, A_n\}$ are estimated using the multi-dimensional Yule-Walker equations

$$C(k)^T = \sum_{i=1}^{n} A_i C(k-i), \; k=1, 2, \ldots, n \tag{9}$$

where

$$C(k) = E[X(t)X(t-k)T] \tag{10}$$

The noise covariance matrix is determined from

$$Q = C(0) - \sum_{i=1}^{n} A_i C(i)^T \tag{11}$$

The optimal model order n is selected based on a criterion function due to Akaike (1974). Sometimes it is necessary to apply modification of this criterion (Kitamura, 1980).

Estimation of Stability Parameters

The neutron power impulse response is derived using the univariate model given by Eq. (8). The impulse response is recursively calculated using

$$x_I(k) = \sum_{i=1}^{n} a_I x_I(k-i), \; x_I(1) = 1.0$$
$$x_I(\ell) = 0 \text{ for } \ell < 0. \tag{12}$$

The decay ratio and the damping coefficients are directly calculated from the impulse response function using Eqs. (3) and (4). The power spectrum of the signal is obtained by Fourier transforming Eq. (8) to give

$$S_{xx}(f) = \frac{S_{vv}(f)}{\left| 1 - \sum_{k=1}^{n} a_k \exp(-j2\pi fk\Delta t) \right|^2}, \; |f| < \frac{1}{2\Delta t}, \tag{13}$$

where $S_{vv}(f) = \sigma^2\Delta t$. The spectral resonance frequency is obtained as the frequency at which $S_{xx}(f)$ is a maximum. This procedure is used for both APRM and LPRM detector signal analysis.

Two-Phase Flow Velocity Measurement

To determine the relationship between stability and two-phase flow velocity in a BWR, it is necessary to estimate this velocity using LPRM detector noise signals. A bivariate analysis of adjacent LPRM noise signals is performed using the AR modeling of two signals. The change in the moderator density and transit of the steam bubbles past neutron detectors, cause fluctuations in the detector response. If the bubble formation is uniform between adjacent detectors, then a transit time delay dynamics can be identified using the two detector responses. Assuming a pure delay dynamics between detectors 1 (upstream) and 2 (downstream) we can write

$$X_2(t) = C\, X_1\,(t-\tau) \quad (14)$$

where C is a constant and τ is the transit time. The phase lag between X_2 and X_1 is given by $\phi(f) = -2\pi f\tau$. Thus the phase is linearly related to the frequency.

The bivariate AR model is used to estimate the cross power spectrum between x_1 and x_2. The spectral matrix is given by

$$S_{xx}(f) = [H(f)^{-1}]\, Q\, [H(f)^{-1}]^* \quad (15)$$

where * indicates complex conjugate transpose and

$$H(f) = I - \sum_{k=1}^{n} A_k \exp(-j2\pi f k\Delta t) \quad (16)$$

$$S_{xx}(f) = \begin{bmatrix} S_{x_1x_1}(f) & S_{x_1x_2}(f) \\ S_{x_2x_1}(f) & S_{x_2x_2}(f) \end{bmatrix} \quad (17)$$

The phase relationship is then calculated from

$$\phi = \tan^{-1}\{\mathrm{Im}\, S_{x_1x_2}/\mathrm{Re}\, S_{x_1x_2}\} \quad (18)$$

The transit time is determined from the slope of the phase function $\phi(f)$.

<u>Coherence, Feedback and Spectral Decomposition for Bivariate Systems</u>

The bivariate model can be used to determine the signal flow map and the nature of feedback between detector responses. Consider the power spectral matrix assuming $Q = \mathrm{diag}\,(q_{11}, q_{22})$. The accuracy of this decomposition must be validated using the orthogonalization procedure described in (Upadhyaya, 1980b). The spectral decomposition is given by

$$S_{xx}(f) = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} q_{11} & 0 \\ 0 & q_{22} \end{bmatrix} \begin{bmatrix} h_{11}^* & h_{21}^* \\ h_{12}^* & h_{22}^* \end{bmatrix} \quad (19)$$

$\{h_{ij}\}$ are the elements of the inverse of matrix $H(f)$.

The individual spectra are given by

$$S_{11} = |h_{11}|^2 q_{11} + |h_{12}|^2 q_{22} \quad (20a)$$

$$S_{22} = |h_{21}|^2 q_{11} + |h_{22}|^2 q_{22} \quad (20b)$$

$$S_{12} = h_{11} h_{21}^* q_{11} + h_{12} h_{22}^* q_{22} \quad (20c)$$

We define the signal contribution ratios as follows:

$$(SCR)_{11} = \frac{|h_{11}|^2 q_{11}}{S_{11}}, \quad (SCR)_{12} = \frac{|h_{12}|^2 q_{22}}{S_{11}} \quad (21)$$

$$(SCR)_{21} = \frac{|h_{21}|^2 q_{11}}{S_{22}}, \quad (SCR)_{22} = \frac{|h_{22}|^2 q_{22}}{S_{22}} \quad (22)$$

Now we define a complex coherence function as

$$\frac{S_{12}}{\sqrt{S_{11} \cdot S_{22}}} = \frac{h_{11}\sqrt{q_{11}}}{\sqrt{S_{11}}} \cdot \frac{h_{21}^{*}\sqrt{q_{11}}}{\sqrt{S_{22}}} + \frac{h_{12}\sqrt{q_{22}}}{\sqrt{S_{11}}} \cdot \frac{h_{22}^{*}\sqrt{q_{22}}}{\sqrt{S_{22}}}$$

$$= R_{11} \cdot R_{21}^{*} + R_{12} \cdot R_{22}^{*} \tag{23}$$

Using Eqs. (21-23) we have the relationships

$$|R_{11}|^2 + |R_{12}|^2 = (SCR)_{11} + (SCR)_{12} = 1 \tag{24}$$

$$|R_{21}|^2 + |R_{22}|^2 = (SCR)_{21} + (SCR)_{22} = 1 \tag{25}$$

If $(SCR)_{12} = 0$, that is the noise source at detector 2 does not contribute to the response at detector 1, this implies $|R_{12}| = 0$ and $|R_{11}| = 1$. The coherence function takes the following form:

$$\gamma_{12}^2 = \frac{|S_{12}|^2}{S_{11} \cdot S_{22}} = |R_{11}|^2 |R_{21}|^2 = |R_{21}|^2. \tag{26}$$

But $|R_{21}|^2 = (SCR)_{21}$, giving the result

$$\gamma_{12}^2 = (SCR)_{21} \tag{27}$$

This result can be related to feedback between sensors.

Figure 3 shows the block diagram of the two-signal system. Writing the transformation matrix in the form

$$H(f) = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \tag{28}$$

$$H(f)^{-1} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \frac{1}{A_{11}A_{22} - A_{12}A_{21}} \begin{bmatrix} A_{22} & -A_{12} \\ -A_{21} & A_{11} \end{bmatrix} \tag{29}$$

The system equations can be written in the frequency domain as

$$X_1(f) = \frac{-A_{12}}{A_{11}} X_2(f) + \frac{1}{A_{11}} V_1(f) \tag{30}$$

$$X_2(f) = \frac{-A_{21}}{A_{22}} X_1(f) + \frac{1}{A_{22}} V_2(f) \tag{31}$$

From Fig. 3, the blocks are identified as

$$G_{21} = \frac{-A_{12}}{A_{11}}, \; G_{12} = \frac{-A_{21}}{A_{22}} \tag{32}$$

Now $(SCR)_{12} = 0 \longrightarrow h_{12} = 0 \longrightarrow A_{12} = 0.$ (33)

From Eqs. (32) and (33) it follows that

$$G_{21} = 0 \tag{34}$$

$G_{21}(f)$ is the feedback transfer function from x_2 to x_1. In actual application to detector response analysis, we can state the result as follows: If $(SCR)_{12} \approx 0$ and $\gamma_{12}^2 = (SCR)_{21}$, then it follows that the fedback from sensor 2 to sensor 1 is small. In addition, the signal contribution ratios $(SCR)_{12}$ and $(SCR)_{21}$ can be used to determine the signal flow path, such as the direction of mass flow from one point to another.

STABILITY MONITORING USING OPERATIONAL DATA

The methods discussed in the previous sections are applied to noise data from two operating BWR-4's at two different operating conditions. Both APRM and LPRM noise signals are analyzed to study the overall stability behavior and the time dependent nature of neutron noise.

Analysis of APRM Signals

APRM noise signals from two different reactors were analyzed using univariate autoregressive models. This data corresponds to two different operating conditions: The first data set (BWR1) was recorded during cycle 1 at 100 percent power (Sides, 1979). The second data set (BWR2) was acquired during cycle three at 62 percent power and 42 percent flow rate (Woffinden, 1981). From theoretical and perturbation test analysis of the second data set a decay ratio close to 0.5 is estimated for BWR2 and a decay ratio close to zero for BWR1.

Table 1 shows the decay ratios estimated from the univariate AR modeling of neutron noise. Figures 4a and 4b show the APRM power spectra and Figs. 5a and 5b show the corresponding impulse response functions. These results clearly indicate the high sensitivity of the neutron noise signature to operating conditions with different stability margins. In addition, the numerical values of the decay ratio from perturbation test and noise analysis compare well in their relative magnitude. Thus, both theoretical and experimental analysis indicate that the stability trends can be effectively monitored using univariate neutron noise analysis. This technique measures the output stability; only in the case of wideband driving noise this is equivalent to the transfer function stability. However, the trends of both stability estimates are similar and as the decay ratio tends to unity, the two estimates will coincide. In addition, the ouput stability monitoring is not influenced by the choice of an input, and hence during abnormal operating conditions its estimate is more reliable than any non-perturbing transfer function analysis.

Table 1. Data Information and Stability Parameters for the sample cases from two BWR's

	BWR1	BWR2
Data record length (sec)	600	153.6
Sampling interval (sec)	0.1	0.06
AR model order	10	10
Impulse response decay ratio (DR)	0.024	0.37
Damping coefficient (ξ)	0.51	0.16
Peak frequency of power spectrum (Hz)	0.38	0.35

Relationship Between Stability and Two-Phase Flow Velocity

A theoretical analysis of random fluctuations of BWR stability was studied by Akcasu (1961) using a second order differential equation formulation of the reactivity. He suggested that the variations in the stability margin of a BWR might occur due to random fluctuations in the steam production rate, and hence the steam velocity in a fuel channel. We present a correlation analysis of BWR stability and steam velocity using normal operation data. As discussed earlier, the two-phase velocity is estimated by analysis of the neutron noise data from two LPRM (B-C) detector signals (Upadhyaya, 1980).

Figure 6 is a BWR-4 core map showing LPRM detector string locations. LPRM's B and C at location 32-33 are used for analysis. C detector noise is used for stability analysis, and B-C detector signals are used for two-phase velocity estimation. An earlier study showed (Upadhyaya, 1981) that the stability margin calculated from detectors in the same string exhibit similar behavior. The use of B-C detector pair for two-phase flow velocity estimation is found to be a good representation of the bubble velocity in a fuel channel (Sweeney, 1980).

A typical phase plot between B-C detector responses is shown n Fig. 7. The linear nature of the phase is quite evident in the frequency range 1-9 Hz where the coherence between the two detectors is also high (see Fig. 8). The signal contribution ratios of detector B response from local noise at C ($(SCR)_{12}$), and of detector C response from local noise at B ($(SCR)_{21}$) are shown in Fig. 9. A comparison of these two can be used to determine the flow path. Ten data records, each of length T = 100 sec. are processed to estimate the stability margin and the two-phase velocity. The relationship between these two parameters can be determined by computing the correlation coefficient ρ as

$$\rho_{\xi v} = \frac{\sum_{i=1}^{N} (\xi_i - \overline{\xi})(v_i - \overline{v})}{\{[\sum_{i=1}^{N} (\xi_i - \overline{\xi})^2][\sum_{i=1}^{N} (v_i - \overline{v})^2]\}^{1/2}} \quad (35)$$

where $|\rho| < 1$. A value of $\rho_{\xi v}$ close to 1, indicates that the parameters ξ and v change in concert with each other. For the present analysis $\rho_{\xi v} = 0.77$. This shows a positive correspondence between ξ and v. Increased void passage rate has a stabiliziing effect on the core dynamic response. This analysis would provide additional understanding of the BWR noise behavior in relating low frequency phenomena (less than 1 Hz) with high frequency phenomena (greater than 1 Hz).

Temporal Variation in the Neutron Noise

It was suggested by Bergman and Gustavsson (1979) that averaging large records of data might result in the smoothing of spectral features, specifically the spectral resonance structure. Our analysis of small (100 sec) and large (1000 sec.) data records shows that both stability margin and spectral peak frequency fluctuate in a random fashion about the estimated mean value. Furthermore, our studies indicate that there is no smoothing of the spectral peaks. Thus, short data records can be used to monitor the time dependent nature of stability in a "snapshot" fashion.

Table 2 summarizes the results of this study using data from BWR1.

SUMMARY AND CONCLUSIONS

Stability monitoring in operating BWR's and related aspects of the problem are presented. Both APRM and LPRM detector noise signals have been used in our study. Estimation of neutron power impulse response function, spectral signature comparison, and two-phase flow velocity estimation were performed using univariate and bivariate time series models. The results presented will not only provide us with the basic information on stability, but additional insight into the nature of BWR noise relationship at different frequency ranges. The following are the conclusions from our analysis of BWR stability and neutron noise behavior using data from operating reactors.

1. The APRM noise signal can be used to monitor changes in the output stability of BWR's. The computation of the stability margin is not influenced by the choice of input process signals. The analysis presented in this paper will not provide us with the closed-loop stability margin of BWR's which is defined by the reactivity-to-neutron power transfer function.
2. A positive correlation (equal to 0.77 for the analyzed data) exists between damping coefficient and two-phase flow velocity in a fuel channel.
3. The temporal behavior of the neutron signal for short and long data records indicates that there is no smoothing of the spectral resonance frequency, nor any subsequent distortion of the decay ratio when long data records were used.

The methods developed provide an efficient procedure for on-line monitoring of stability changes in BWR's, and for assessing the effects of various operating conditions on power fluctuation during power generation and plant maneuvering. Studies are currently underway to improve the estimate of stability margin by identifying the primary reactivity perturbation source.

Table 2. Stability analysis using short and long data records

	10 samples, each record = 100 s.	One sample of length = 1000 s.
(LPRM-C)	Mean	
Decay ratio	0.107	0.096
Damping coefficient	0.35	0.35
Peak frequency	0.55	0.56
Transport time (s)	0.167	0.167
Two-phase flow velocity (m/s)	5.46	5.46

Correlation coefficient between damping coefficient and two-phase flow velocity = 0.77

ACKNOWLEDGMENT

The authors are indebted to P. Otaduy-Bengoa of the Instrumentation and Controls Division of Oak Ridge National Laboratory for the many discussions during the course of this research project. The last author extends his gratitude to K. Sugiyama of Tohoku University, Japan for providing this research opportunity.

This work was performed under the sponsorship of the U.S. Nuclear Regulatory Commission under contract with the Union Carbide Corporation.

REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. IEEE Tran. Aut. Cont., Vol. AC-19, pp. 716-723.

Akcasu, A. Z. (1961). Mean square instability in boiling reactors. Nucl. Sci. and Eng., Vol. 10, pp. 337-345.
Bergman, S., and I. Gustavsson (1979). Identification of global noise in a boiling water reactor by means of spectral and parametric method. J. Nucl. Sci. and Tech., Vol. 16, pp. 77-88.
Carmichael, L. A., and R. O. Niemi (1978). Transient and Stability Tests at Peach Bottom Atomic Power Station Unit 2 at End of Cycle 2. EPRI, NP-564.
Fukunishi, K. (1978). Noise source estimation of boiling water reactor power fluctuation by autoregression. Nucl. Sci. and Eng., Vol. 67, pp. 296-308.
General Electric Co. (1977). Stability and Dynamic Performance of the General Electric Boiling Water Reactor. Topical report, NEDO-21506.
Kitamura, M. and B. R. Upadhyaya (1980). An improved time series modeling approach for diagnosis and surveillance of reactors. Proc. ANS/ENS Topical Meeting on Thermal Reactor Safety, Knoxville, Vol. 1, pp. 293-300.
Kitamura, M. and B. R. Upadhyaya (1982). Cause and effect analysis of neutronic and process signals in a boiling water reactor. Proc. SMORN-III, Tokyo, Japan.
March-Leuba, J. (1981). Stability of Boiling Water Reactors. MS Thesis, University of Tennessee, Knoxville (to be published).
Otaduy-Bengoa, P. J. (1979). Modeling of the Dynamic Behavior of Large Boiling Water Reactors, Ph.D. Dissertation, University of Florida, Gainesville.
Parzen, E. (1961). An approach to time series analysis. Ann. Math. Stat., Vol. 32, pp. 951-989.
Sides, W. H. et al. (1979). Identification of neutron noise sources in a boiling water reactor. Proc. SMORN-II, Pergamon Press, New York, pp. 119-135.
Sweeney, F. J. (1980). A Theoretical Model of Boiling Water Reactor Neutron Noise. Ph.D. Dissertation, University of Tennessee, Knoxville.
Tsunoda, T. et al. (1978) NAIG annual review, Nippon Atomic Industry Group, pp. 21-24.
Upadhyaya, B. R. and M. Kitamura (1979). Monitoring BWR Stability using time series analysis of neutron noise. Tran. Am. Nucl. Soc., Vol. 33, p. 342.
Upadhyaya, B. R., M. Kitamura, and T. W. Kerlin (1980a). Multivariate signal analysis algorithms for process monitoring and parameter estimation in nuclear reactors. Annals of Nucl. Energy, Pergamon Press, Vol. 7, pp. 1-11.
Upadhyaya, B. R., M. Kitamura (1980b). Analysis of relationship between stability and flow parameters in a BWR. Tran. Am. Nucl. Soc., Vol. 35, p. 593.
Upadhyaya, B. R., and M. Kitamura (1981). Stability monitoring of boiling water reactors by time series analysis of neutron noise. Nucl. Sci. and Eng., Vol. 77, pp. 480-492.
Woffinden, F. B., and R. O. Niemi (1981). Low-Flow Stability Tests at Peach Bottom Atomic Power Station Unit 2 During Cycle 3. EPRI, NP-972.
Wu, S. M., M. S. Ouyang, and T. Ungpiyakul (1981). Stochastic Modeling of On-Line BWR Stability. EPRI, NP-1753.

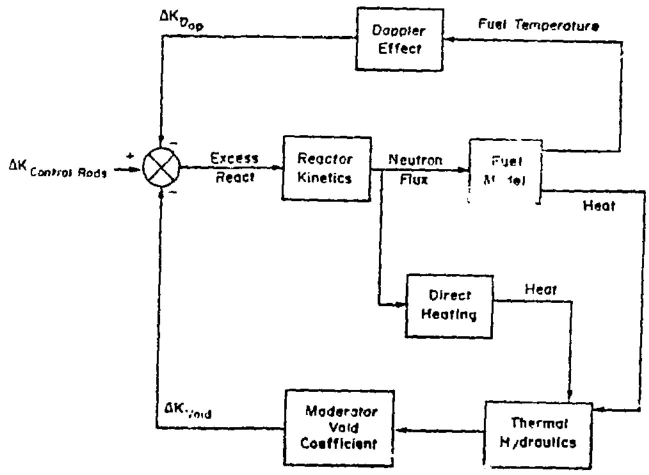

Fig. 1. Block diagram showing the dynamic processes related to power generation in a BWR core.

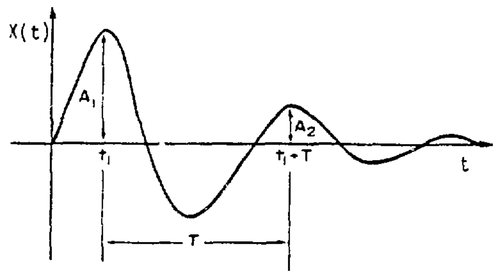

Fig. 2. Typical impulse response function of a stable damped oscillatory system.

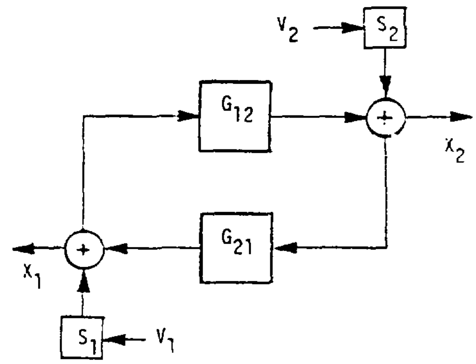

Fig. 3. Block diagram of a bivariate time series model.

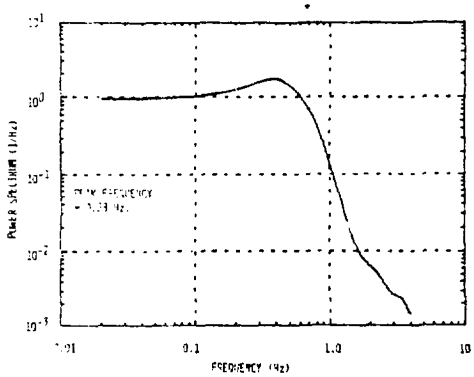

Fig. 4a. Power spectrum of BWR1 neutron noise from AR(10) model of the APRM signal.

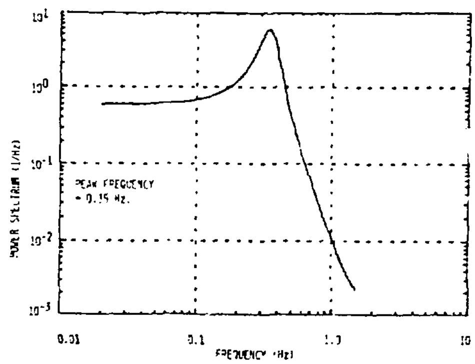

Fig. 4b. Power spectrum of BWR2 neutron noise from AR(10) model of the APRM signal.

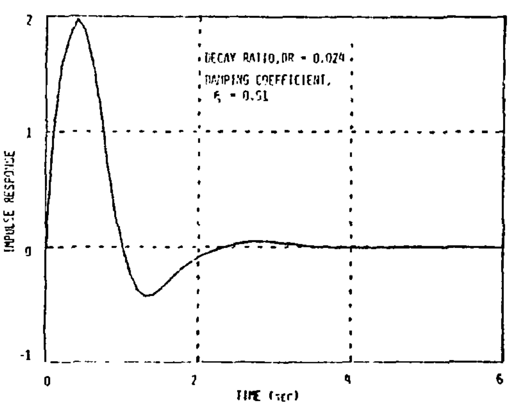

Fig. 5a. Impulse response function of BWR1 neutron noise from AR(10) model of the APRM signal.

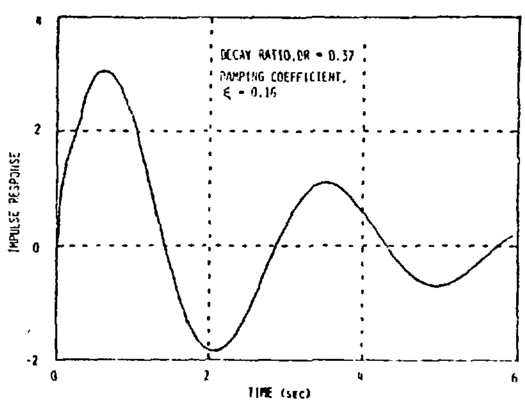

Fig. 5b. Impulse response function of BWR2 neutron noise from AR(10) model of the APRM signal.

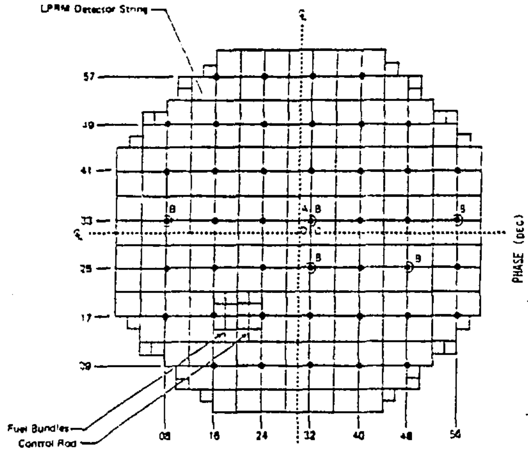

Fig. 6. BWR-4 core map showing LPRM detector string locations.

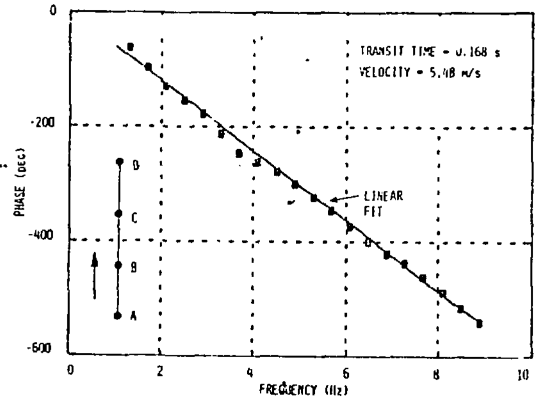

Fig. 7. Phase lag between LPRM B and C detector signals from bivariate time series model and the linear least-squares fit.

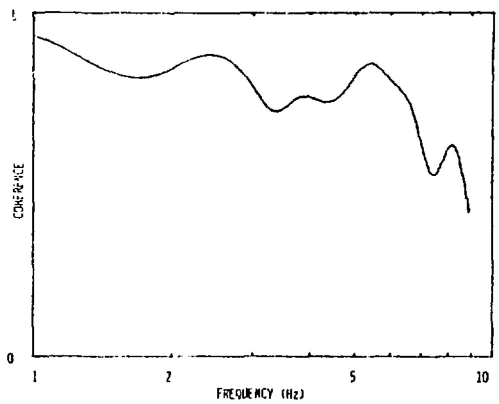

Fig. 8. Coherence function between LPRM B and C detector signals from bivariate time series model.

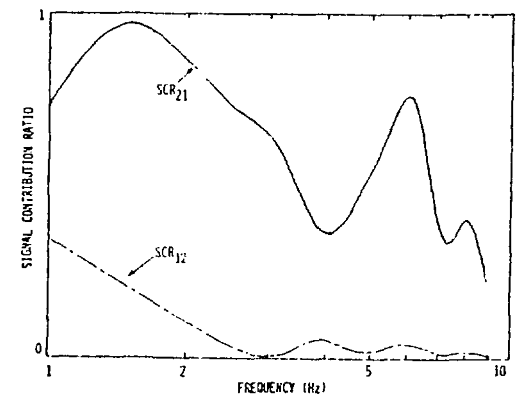

Fig. 9. Signal contribution ratio analysis: SCR_{ij} is the fractional contribution to the power spectrum of signal i from the noise source of signal j. 1 = LPRM B signal, 2 = LPRM C signal.