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B. R. Upadhyaya
F. J. Sweeney
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37831

D. J. Shieh
Institute of Nuclear Energy Research, Taiwan

O. Glockler
The University of Tennessee
Knoxville, Tennessee 37996-2300

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D. J. Shieh
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Department of Nuclear Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2300, USA

ABSTRACT - The behavior of the phase relationship between neutron flux and core-exit temperature fluctuations in a pressurized water reactor (PWR) is studied as a function of the moderator temperature coefficient of reactivity (α_c). PWR operational data indicates that the neutron noise and core-exit temperature noise cross power spectrum phase is linear in a certain frequency range, and approaches -180 deg at low frequencies. Extensive modeling studies applied to the LOFT reactor shows that this low frequency phase behavior changes when α_c is positive, approaching zero deg at low frequencies. The analysis further showed that in the LOFT reactor, coolant flow rate fluctuation is the primary driving source causing neutron noise and core-exit temperature fluctuations. This conclusion was also confirmed by independent studies. The neutron noise-coolant temperature phase behavior may be used as a single method of monitoring the moderator temperature coefficient of reactivity during different stages of a PWR fuel cycle.

1. INTRODUCTION

In-core dynamics of fluctuations in process variables in pressurized water reactors (PWRs) was studied in the past by several investigators (Katona et al., 1982; Sweeney et al., 1985; Glöckler et al., 1986), with primary applications to flow monitoring, and detecting the effects of reactivity changes on neutron noise spectrum. Recent research in this area (Shieh, 1985, Shieh et al, 1987) revealed the connection between neutron noise and core-exit coolant temperature noise cross power spectral density (CPSD) phase behavior as a function of the moderator temperature coefficient of reactivity (α_c) in a PWR. Some vendors require that α_c be non-positive for nominal power operation (1973, 1974, 1975). The direct method of α_c measurement requires corrections (to remove fuel temperature feedback effect) based on experimental and theoretical calculations. The complexity of establishing the value of this parameter motivated us to develop a simple but effective method of monitoring the sign of α_c using PWR operational data.

The paper presents a systematic modeling of in-core noise signal dynamics in a PWR with point reactor kinetics behavior, such as in the Loss-of-Fluid Test (LOFT) reactor. The multinodal model analysis showed (Shieh, 1985) that the feasibility of using the noise signals to monitor α_c depends on the perturbation source. The results of modeling analysis of the LOFT reactor showed that (a) there is a range of frequencies in which the phase between the in-core neutron detector noise and core-exit temperature noise is linear, (b) the frequency range of the linear phase behavior is limited by the primary sink frequency of the corresponding transfer function, (c) for the case when α_c is negative, the phase angle at low frequencies approaches -180 deg, (d) the phase angle approaches zero-degree when α_c is positive, and (e) the results from the model study and from PWR operational data, it can be concluded that in the LOFT reactor the primary perturbation source is the core coolant flow rate fluctuation. This last conclusion was recently established by a multivariate autoregressive analysis of pump Δp, core Δp, in-core neutron detector and core-exit thermocouple signal analysis (Glöckler and Upadhyaya, 1987), and by experimental measurements at LOFT and commercial PWRs (Sweeney et al., 1985).

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ABSTRACT - The behavior of the phase relationship between neutron flux and core-exit temperature fluctuations in a pressurized water reactor (PWR) is studied as a function of the moderator temperature coefficient of reactivity (α_c). PWR operational data indicates that the neutron noise and core-exit temperature noise cross power spectrum phase is linear in a certain frequency range, and approaches -180 deg at low frequencies. Extensive modeling studies applied to the LOFT reactor shows that this low frequency phase behavior changes when α_c is positive, approaching zero deg at low frequencies. The analysis further showed that in the LOFT reactor, coolant flow rate fluctuation is the primary driving source causing neutron noise and core-exit temperature fluctuations. This conclusion was also confirmed by independent studies. The neutron noise-coolant temperature phase behavior may be used as a single method of monitoring the moderator temperature coefficient of reactivity during different stages of a PWR fuel cycle.

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The paper presents a systematic modeling of in-core noise signal dynamics in a PWR with point reactor kinetics behavior, such as in the Loss-of-Fluid Test (LOFT) reactor. The multinodal model analysis showed (Shieh, 1985) that the feasibility of using the noise signals to monitor α_c depends on the perturbation source. The results of modeling analysis of the LOFT reactor showed that (a) there is a range of frequencies in which the phase between the in-core neutron detector noise and core-exit temperature noise is linear, (b) the frequency range of the linear phase behavior is limited by the primary sink frequency of the corresponding transfer function, (c) for the case when α_c is negative, the phase angle at low frequencies approaches -180 deg, (d) the phase angle approaches zero-degree when α_c is positive, and (e) the results from the model study and from PWR operational data, it can be concluded that in the LOFT reactor the primary perturbation source is the core coolant flow rate fluctuation. This last conclusion was recently established by a multivariate autoregressive analysis of pump Δp, core Δp, in-core neutron detector and core-exit thermocouple signal analysis (Glöckler and Upadhyaya, 1987), and by experimental measurements at LOFT and commercial PWRs (Sweeney et al., 1985).

[1] Institute of Nuclear Energy Research, Taiwan.
[2] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.
[3] Visiting research associate from the Central Research Institute for Physics, Budapest, Hungary.

In Sect. 2 the results of in-core data analysis from four different PWRs are summarized. A detailed nodal model of PWR neutronic-thermal hydraulic dynamics and the computation of various frequency domain signatures from the model are described in Sect. 3. The results of model simulation and comparison with experimental data analysis results are discussed in Sect. 4. Summary and concluding remarks are given in Sect. 5.

2. RESULTS OF PWR IN-CORE SIGNAL ANALYSIS

In order to establish the phase behavior between the neutron noise signal and the core-exit thermocouple signal at low frequencies we will present results of data analysis from different PWRs. We want to emphasize that the higher frequency behavior of calculated phase will be affected by the location of the detectors (in-core, ex-core neutron detectors and the location of thermocouples from the core-exit). Noise data from four different PWRs were analyzed. These plants are

(1) 55 MW (thermal) LOFT pressurized water reactor.
(2) 1140 MW (electric) commercial PWR (USA).
(3) 477 MW (electric) Borssele PWR (Netherlands).
(4) 440 MW (electric) Paks PWR Unit II (Hungary).

Figure 1 shows the CPSD phase relationship between core-exit thermocouple and in-core neutron detector signals in the LOFT reactor at 100% power and 100% coolant flow. The LOFT reactor contains cobalt self-powered neutron detectors (ND) at four different axial positions, 27.9, 68.6, 111.8 and 154.9 cm above the bottom of the core. The core-exit coolant temperature was measured by K-type thermocouples (TC) located at fuel bundle upper grid. The extrapolated linear phase approaches -180 deg at low frequencies. We want to consider the frequency range (above 0.1 Hz) where the flow propagation effect is dominating the phase. Similar behavior was observed at power levels 25%, 50% and 75%, and at different flow rates. As the flow rate decreases, the phase slope increases, indicating larger transit time (Sweeney et al, 1985).

Figure 2 shows the neutron-temperature CPSD phase relationship in a 1140 MW (electric) commercial PWR at 100% power. The phase has a linear behavior in the frequency range 0.1-1.5 Hz, with the low frequency extrapolation approaching -180 deg. Figure 3a shows the phase between in-core ND and core-exit TC in the Borssele PWR (477 MWe) at full power and flow condition. The corresponding CPSD is shown in Fig. 3b which shows a significant sink frequency at about 2.35 Hz (Upadhyaya and Turkcan, 1984). Sink frequencies are characteristics of systems with flow and heat transfer (Kosaly and Mesko, 1972). The sink frequency is a function of the flow rate and the axial flux shape (Shieh, 1985). Finally, the phase between in-core ND and core-exit TC signals for the Paks Unit II PWR is shown in Fig. 4 (the phase is linear in the frequency range 0.1-0.8 Hz). Once again the out of phase behavior at low frequencies is evident.

In all the above cases the moderator temperature coefficient of reactivity was known to be negative. The extrapolated phase angle approaches -180 deg in all the cases. These are strong evidences for us to postulate that when α_c is positive the extrapolated phase angle at zero frequency would approach the zero-deg phase. This method is shown to be "not sensitive to changes in the Doppler coefficient and provides a nonambiguous technique for monitoring the sign of α_c."

3. DYNAMIC MODELING OF PROCESS FLUCTUATIONS IN A PWR CORE

3.1. Purpose of Modeling

The primary goal of modeling discussed in this section is to study the dynamics between neutron power and coolant temperature, and the effects of varying α_c. The dynamic behavior depends on the perturbation source, and it is necessary to establish this cause for a given PWR. The fuel temperature and the moderator temperature affect the neutron power in different frequency ranges. Because of large fuel to coolant heat transfer time constant, the higher frereactor contains cobalt self-powered neutron detectors (ND) at four different axial positions, 27.9, 68.6, 111.8 and 154.9 cm above the bottom of the core. The core-exit coolant temperature was measured by K-type thermocouples (TC) located at fuel bundle upper grid. The extrapolated linear phase approaches -180 deg at low frequencies. We want to consider the frequency range (above 0.1 Hz) where the flow propagation effect is dominating the phase. Similar behavior was observed at power levels 25%, 50% and 75%, and at different flow rates. As the flow rate decreases, the phase slope increases, indicating larger transit time (Sweeney et al, 1985).

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A multinodal model of the LOFT reactor was developed to study neutronics-thermal hydraulics dynamics. This consists of point reactor kinetics with two delayed-neutron groups, 10 fuel nodes, 10 cladding nodes, and 20 coolant nodes. The perturbation sources considered are: core inlet temperature disturbance, core coolant velocity disturbance, random heat transfer disturbance, and heat source perturbation. For the coolant velocity disturbance we consider simulataneous changes in the velocity along the channel, and possibly caused by fluctuations in pump Δp. The random heat transfer disturbance is assumed to be caused by turbulent flow, causing random changes in the local heat transfer coefficient.

3.2. The Nodal Model Development

The multinodal model of the LOFT reactor as described by Shieh et al (1985) is given below. A single channel geometry with a cylindrical fuel region is considered with n fuel nodes, n cladding nodes, and 2n coolant nodes. (See Table 1 for Nomenclature).

Neutronic equations:

$$\frac{d}{dt}\left(\frac{\delta N}{No}\right) = -\frac{\beta}{\Lambda}\frac{\delta N}{N_o} + \frac{\alpha_f}{\Lambda}\frac{1}{\sum W_{fi}}\sum_{i=1}^{n} T_{fi}W_{fi}$$

$$+ \frac{\alpha_c}{\Lambda}\frac{1}{\sum W_{ci}}\sum_{i=1}^{2n} T_{ci}W_{ci} + \sum_{i=1} \lambda_i \frac{\delta C_i}{N_o} + \frac{S(t)}{\Lambda} \quad . \tag{1}$$

$$\frac{d}{dt}\left(\frac{\delta C_i}{N_o}\right) = \frac{\beta_i}{\Lambda}\frac{\delta N}{N_o} - \frac{\lambda_i \delta C_i}{N_o} , \quad i=1,2 \tag{2}$$

Fuel temperature, node i=1,2,..., n:

$$\frac{d}{dt}\delta T_{fi} = \left(\frac{\delta N}{N_o}\right) N_o F_{fi}\frac{1}{m_{fi}C_{pfi}} - \frac{h_{fcli}A_{fcli}}{m_{cli}C_{pcli}}(\delta T_{fi} - \delta T_{cli}) \quad . \tag{3}$$

Cladding temperature, node i=1,2,...n:

$$\frac{d}{dt}\delta T_{cli} = \frac{h_{fcli}A_{fcli}}{m_{cli}C_{pcli}}(\delta T_{fi} - \delta T_{cli}) - \frac{h_{clci}A_{clci}}{m_{cli}C_{pcli}}(\delta T_{cli} - \delta T_{c(2i-1)}) \quad . \tag{4}$$

Coolant node 1:

$$\frac{d}{dt}\delta T_{c1} = \left(\frac{\delta N}{N_o}\right) N_o F_{c1}\frac{1}{m_{c1}C_{pc1}} + \frac{h_{clc1}A_{clc1}}{m_{c1}C_{pc1}}(\delta T_{cl1} - \delta T_{c1})$$

$$+ \frac{\dot{m}}{m_{c1}}(T_{in} - T_{c1}) \tag{5}$$

Coolant nodes i=2,4,..., 2n:

$$\frac{d}{dt}\delta T_{ci} = \left(\frac{\delta N}{N_o}\right) N_o F_{ci}\frac{1}{m_{ci}C_{pci}} + \frac{h_{clc(i/2)}A_{clc(i/2)}}{2m_{ci}C_{pci}}(\delta T_{cl(i/2)} - \delta T_{c(i-1)})$$

$$+ \frac{\dot{m}}{m_{ci}}(\delta T_{c(i-1)} - \delta T_{ci}) \quad . \tag{6}$$

$$\frac{d}{dt}\left(\frac{\delta C_i}{N_o}\right) = \frac{\beta_i}{\Lambda}\frac{\delta N}{N_o} - \frac{\lambda_i \delta C_i}{N_o}\ , \quad i=1,2 \tag{2}$$

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Coolant nodes i=3, 5, ..., 2n-1:

$$\frac{d}{dt}\delta T_{ci} = \left(\frac{\delta N}{N_o}\right) N_o F_{ci}\frac{1}{m_{ci}C_{pci}} + \frac{h_{clc(i+1)/2}A_{clc(i+1)/2}}{2m_{ci}C_{pci}}\left(\delta T_{cl(i+1)/2} - \delta T_{ci}\right) + \frac{\dot{m}}{m_{ci}}\left(\delta T_{c(i-1)} - \delta T_{ci}\right) \tag{7}$$

Thermocouple output:

$$\frac{d}{dt}\,\delta T_m = \frac{\delta T_{c,2n}}{\tau} - \frac{\delta T_m}{\tau} \tag{8}$$

If the coolant flow rate changes, the heat transfer coefficient will also change. Modeling this by the Dittus-Boelter equation (Re>2000) for the Nusselt number (El-Wakil, 1978)

$$N_u = \frac{hD}{k} = 0.023(\mathrm{Re})^{0.8}\,(\mathrm{Pr})^{0.4} \tag{9}$$

$$\text{Reynolds number, } \mathrm{Re} = \frac{Dv\rho}{\nu} \tag{10}$$

and Prandtl number, $\mathrm{Pr} = \frac{c\nu}{k}$ (11)

where D = equivalent diameter of coolant channel, f = coolant density, ν = viscosity, h = heat transfer coefficient, c = specific heat capacity of coolant, k = coolant thermal conductivity. Using Eq. (9), the fluctuations in h and v are related by

$$\frac{\delta h}{h} = 0.8\,\frac{\delta v}{v} \tag{12}$$

The cladding/coolant interaction is then given by

$$\delta h_{clci} = 0.8\, h_{clci}\,\frac{\delta \dot{m}}{\dot{m}} \tag{13}$$

The fluctuations in the coolant mass flow rate is factored into Eqs. (4)-(7). (See Shieh et al, 1985.) The weighting of the i-th node fuel temperature on the reactivity, W_{fi}, and the weighting of the i-th node coolant temperature on the reactivity, W_{ci}, are proportional to the square of the fraction of the power deposited in the i-th node, namely, F_{fi} and F_{ci}.

The above set of equations describe a linear dynamics

$$\dot{\underline{X}}(t) = A\underline{X}(t) + B\underline{U}(t) \tag{14}$$

where $\underline{X}$ = vector of state variables, $\underline{U}$ = input vector, A = system matrix, and B = input matrix.

3.3. Calculations in the Frequency Domain

Equation (14) is transformed to the frequency domain and is solved for the Fourier transform of $\underline{X}(t)$,

$$\underline{X}(\omega) = (j\omega I - A)^{-1}\, B\underline{U}(\omega) \tag{15}$$

where $j = \sqrt{-1}$, I = identity matrix, ω = frequency. The transfer function between the state variable x_i and the input variable u_k is given by the matrix element $[(j\omega I-A)^{-1}B]_{ik}$. The where D = equivalent diameter of coolant channel, f = coolant density, ν = viscosity, h = heat transfer coefficient, c = specific heat capacity of coolant, k = coolant thermal conductivity. Using Eq. (9), the fluctuations in h and v are related by

$$\frac{\delta h}{h} \approx 0.8 \frac{\delta v}{v} \qquad (12)$$

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$$G_{ij}(\omega) = \frac{[(j\omega I-A)^{-1}B]_{ik}}{[(j\omega I-A)^{-1}B]_{jk}} \qquad (16)$$

Thus from the matrix $[(j\omega I-A)^{-1}B]$ we can obtain transfer function between state variables (say δT_{out} and δN) for any specified input (such as coolant velocity perturbation and inlet coolant temperature perturbation).

4. APPLICATION TO THE LOFT REACTOR

4.1. Frequency Domain Results

We calculated phase and transfer function between core-exit coolant temperature and neutron power fluctuations for the inputs stated above. LOFT reactor design parameters (Reeder, 1978) were used to complete the model description. The phase relationship is linear in a certain frequency range and its slope is inversely proportional to the coolant velocity. The maximum linear phase frequency is limited by the primary sink frequency, which in turn depends on the coolant velocity and the axial flux shape. The sink frequency is a frequency at which the net fluctuation in a given signal goes to zero (Kosaly and Mesko, 1972; Kosaly et al., 1982). For the LOFT reactor, under normal conditions the linear phase frequency range is about 0.1–2 Hz (see Fig. 5) and the sink frequency is about 2.2 Hz (see Fig. 6). In Fig. 6, the transfer function gain, with inlet temperature fluctuation as the perturbation source has a peak instead of a sink effect. The primary sink frequency can be generally expressed as (Shieh, 1985)

$$f_s = c\,\frac{v}{L} \tag{17}$$

where v = coolant velocity (m/s), L = active core length (m), c = constant in the range, $1<c<2$.

A very important observation from these results is that the extrapolated phase approaches −180 deg. at low frequencies. The nominal value of α_c is −0.0767\$/C. When α_c is positive (≈0.0036/C), the low frequency phase behavior changes, with the extrapolated phase approaching zero-deg at low frequencies (see Fig. 7). The analysis clearly shows that the extrapolated neutron – core-exit temperature phase at low frequencies (−180 deg for negative α_c, zero-deg for positive α_c) depends on the sign of the moderator temperature coefficient of reactivity. We do not attempt to explain the phase behavior below about 0.1 Hz because of the combination of various effects in the 0–0.1 Hz frequency region. The results also show that if the heat source perturbation (which affects reactor power first and through heat transfer affects the coolant temperature) is the dominanat source, the low frequency phase behavior is not affected by the sign of α_c. The extrapolated phase will not approach −180 deg. at low frequencies.

4.2. Perturbation Source in the LOFT Reactor Core

Our analysis also indicated that the dominant perturbation source giving rise to neutron and core-exit temperature fluctuations is the core coolant flow rate fluctuations. The following evidence is presented to prove this fact related to the LOFT reactor.

1. Very high coherence (≈0.9) was observed by Canon and Clemo (1980) between neutron noise and coolant flow noise as measured by a venturimeter.
2. The above observation excludes the random heat transfer as the dominant disturbance.
3. Direct reactivity induced perturbations are excluded because of the entirely different nature of the phase behavior (Shieh et al., 1987).
4. The low coherence between inlet coolant temperature (T_{in}) and core-exit temperature, and T_{in} and neutron noise, excludes the possibility that inlet coolant temperature is the perturbation source (Upadhyaya, 1982).
5. Independent multivariate signal analysis of the LOFT core subsystem (Glockler and Upadhyaya, 1987) showed very clearly that the core coolant flow fluctuation as represented by the primary pump Δp was the driving noise in this system.
6. The model studies also indicate (Shieh, 1985) that if the random heat transfer is the dominating source, then the coherence between core-exit TC and in-core ND must be small. On the contrary this value is about 0.6 in the LOFT reactor.

7. As discussed in Sect. 4.1, the comparison of the model analysis result and the experi-

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7. As discussed in Sect. 4.1, the comparison of the model analysis result and the experimental result excludes the heat source perturbation as the dominant source in the LOFT reactor.

5. SUMMARY AND CONCLUDING REMARKS

We presented a detailed theoretical analysis of the in-core dynamics and perturbation sources affecting neutron and core-exit temperature noise relationship. Even though this analysis was developed for a point reactor kinetics system, the experimental results from PWRs of different sizes indicates that the moderator temperature coefficient of reactivity influences the behavior of CPSD phase between neutron noise and core-exit temperature noise. The following results highlight the modeling analysis of the LOFT reactor in-core dynamics.

1. There is a range of frequencies in which the in-core ND noise and core-exit TC signals is linear and that the slope is inversely proportional to the coolant flow rate.

2. The extent of the linear phase behavior is limited by the primary sink frequency of the core-exit coolant temperature and neutron flux transfer functions, and by feedback effects at low frequencies (below 0.1 Hz).
3. For the case when α_c is negative, the extrapolated phase angle at low frequencies approaches -180 deg for all disturbance sources except for the direct reactivity perturbations.
4. The above phase angle approaches zero-deg when α_c is positive.
5. The results of the model study and PWR operational data indicate, that in the LOFT reactor, the primary disturbance source causing core-exit coolant temperature and neutron power fluctuation is the core coolant flow rate fluctuation.

This approach for monitoring the reactivity parameter has the following features: (1) The implementation of the method will not interfere with normal plant operation. (2) α_c can be monitored at all operating conditions above 25% full power (this is the range of data available to us). (3) It is easy to track the parameter by plant personnel because of the easy distinction between the phase angles -180 deg (for negative α_c) and zero-deg (for positive α_c). This monitoring scheme is not sensitive to the actual magnitude of α_c or the value of Doppler coefficient, and is "robust with respect to measurement uncertainties."

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Table 1. Nomenclature (Shieh, et al, 1987)

δN	= variation of the neutron power
N_o	= initial neutron power
F_{fi}	= fraction of power deposited in the i'th fuel node
W_{fi}	= reactivity weighting for the i'th node fuel temperature
$S(t)$	= reactivity disturbance
m_{fi}	= i'th node fuel mass
C_{pfi}	= i'th node fuel specific heat capacity
T_{fi}	= i'th node fuel temperature
h_{fcli}	= i'th node fuel to cladding heat transfer coefficient
A_{fcli}	= i'th node fuel to cladding heat transfer area
m_{cli}	= i'th node cladding mass
C_{pcli}	= i'th node cladding specific heat capacity
h_{clci}	= i'th node cladding to coolant heat transfer coefficient
A_{clci}	= i'th node cladding to coolant heat transfer area
T_{ci}	= i'th node coolant temperature
m_{ci}	= i'th node coolant mass
C_{pci}	= i'th node coolant specific heat capacity
W_{ci}	= reactivity weighting for the i'th node coolant temperature
$\dot{m}$	= core coolant mass flow rate
T_m	= measurement of core-exit coolant temperature
τ	= temperature sensor time constant

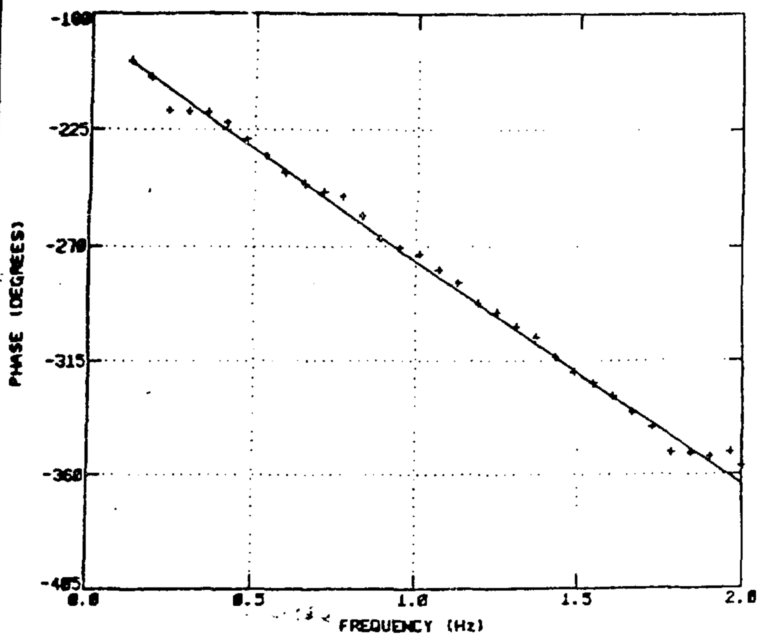


Fig. 1. Cross power spectral density phase relationship between in-core neutron detector and core-exit thermocouple noise signals in the LOFT reactor at 100% power and flow condition.

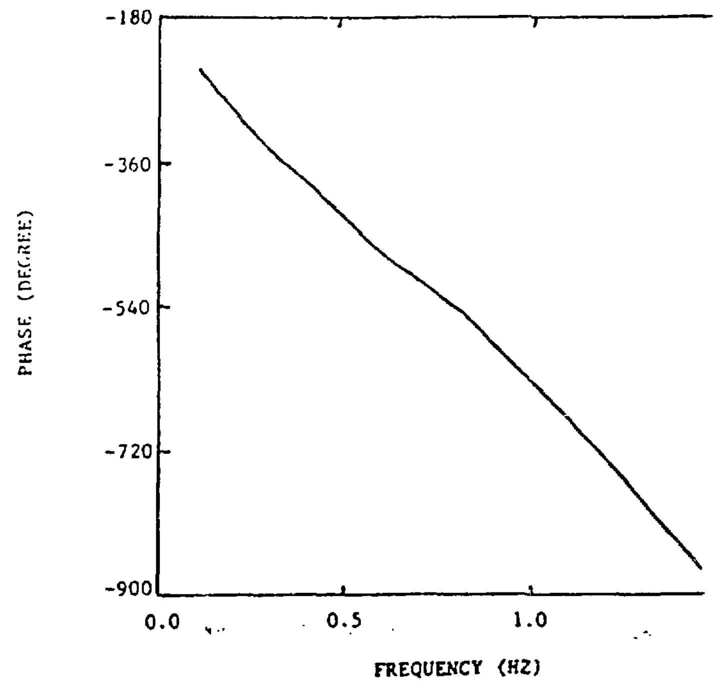


Fig. 2. CPSD phase relationship between ex-vessel neutron detector and core-exit thermoocuple noise signals in a 1140 MW(electr commercial PWR.

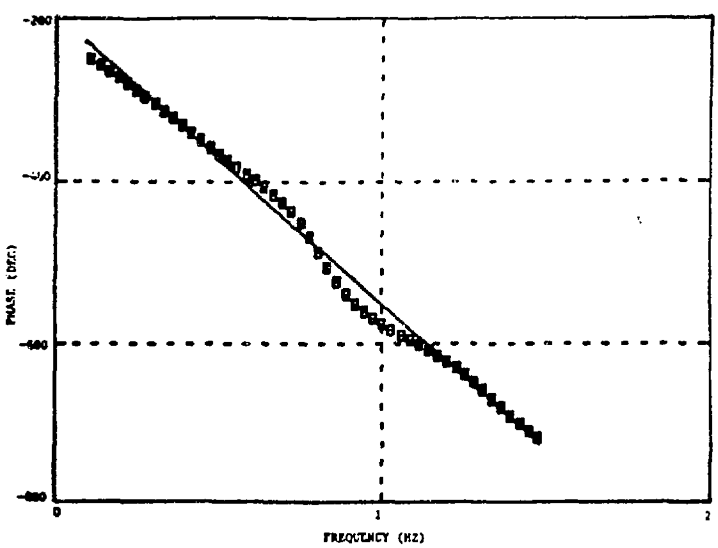


Fig. 3a. Phase relationship between in-core neutron detector and core-exit thermocouple signals in the Borssele PWR at full power and flow condition.

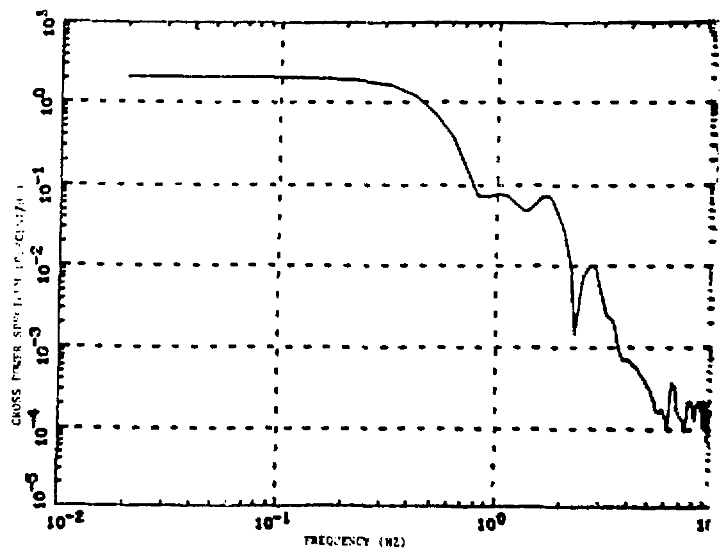


Fig. 3b. Cross power spectrum between the sign used in Fig. 3a (Borssele PWR), showing a sink frequency at about 2.35 Hz.

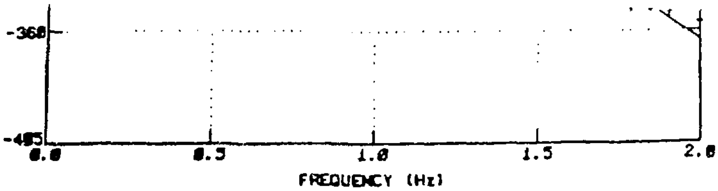


Fig. 1. Cross power spectral density phase relationship between in-core neutron detector and core-exit thermocouple noise signals in the LOFT reactor at 100% power and flow condition.

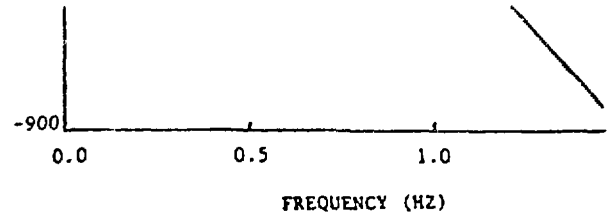


Fig. 2. CPSD phase relationship between ex-vessel neutron detector and core-exit thermoocuple noise signals in a 1140 MW(electr commercial PWR.

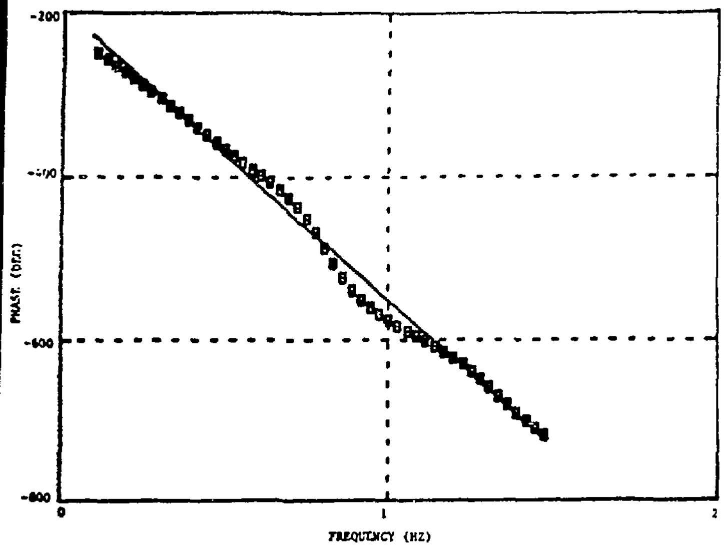
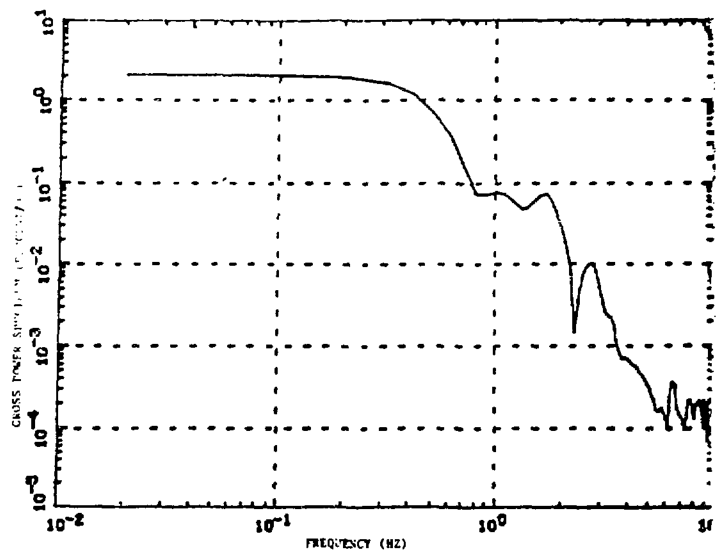


Fig. 3a. Phase relationship between in-core neutron detector and core-exit thermocouple signals in the Borssele PWR at full power and flow condition.



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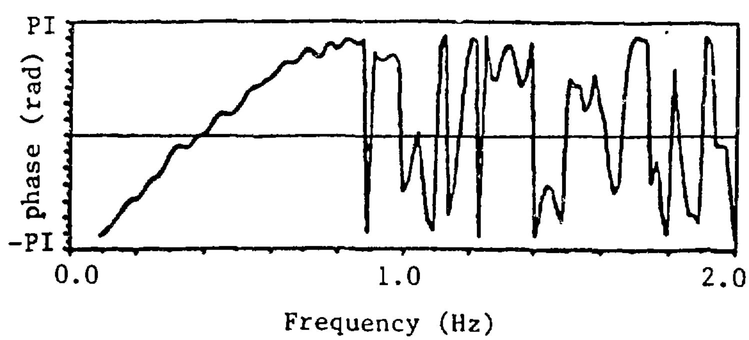


Fig. 4. CPSD Phase relationship between in-core neutron detector and core-exit thermocouple noise signals in the Paks PWR Unit 2.

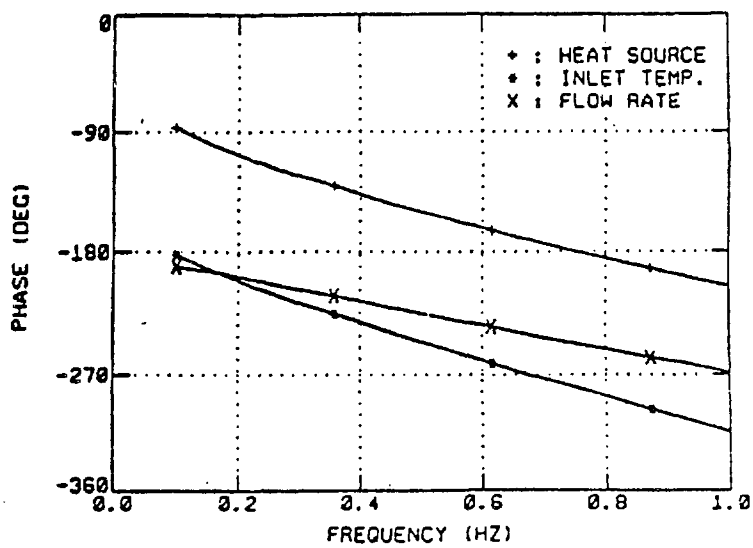


Fig. 5. The transfer function phase relationship between neutron noise and core-exit temperature noise in the LOFT reactor for various perturbation sources (theoretical model).

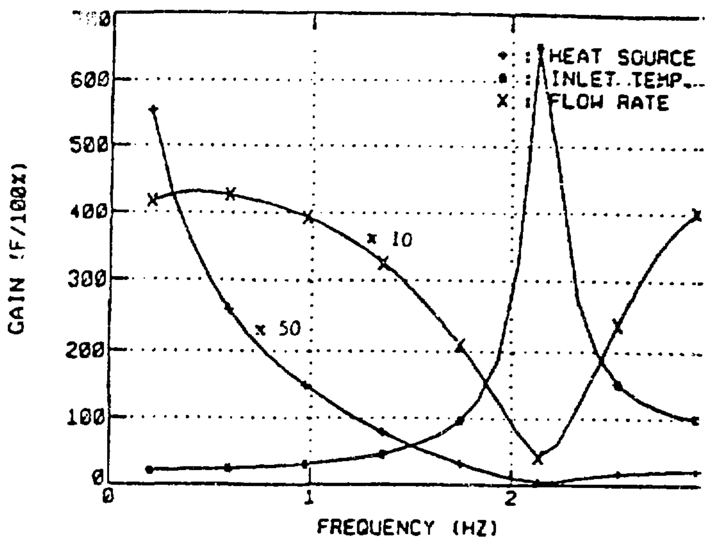
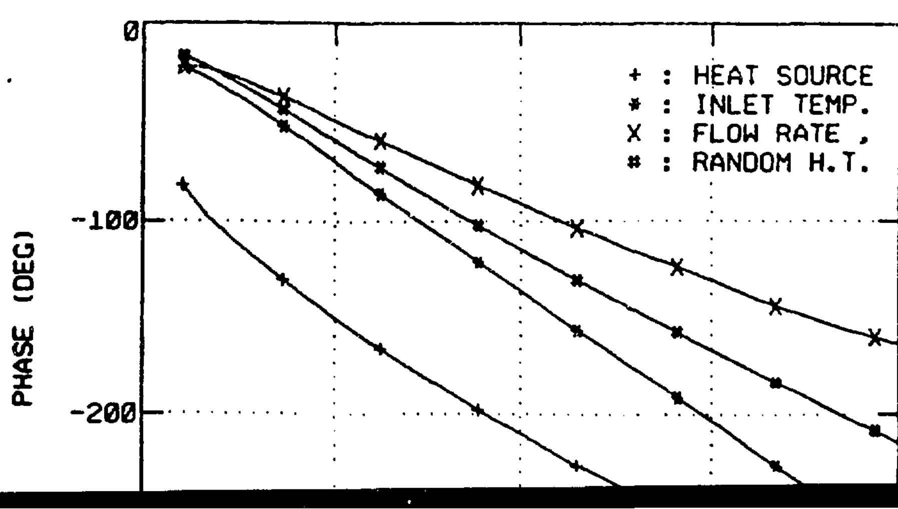
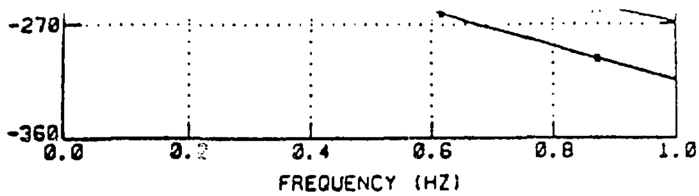


Fig. 6. The transfer function gain between neutron noise and core-exit temperature noise in the LOFT reactor for various perturbation sources (theoretical model).





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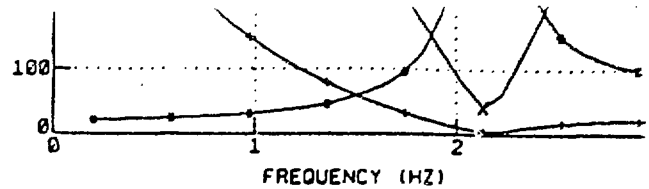

Fig. 6. The transfer function gain between neutron noise and core-exit temperature noise in the LOFT reactor for various perturbation sources (theoretical model).

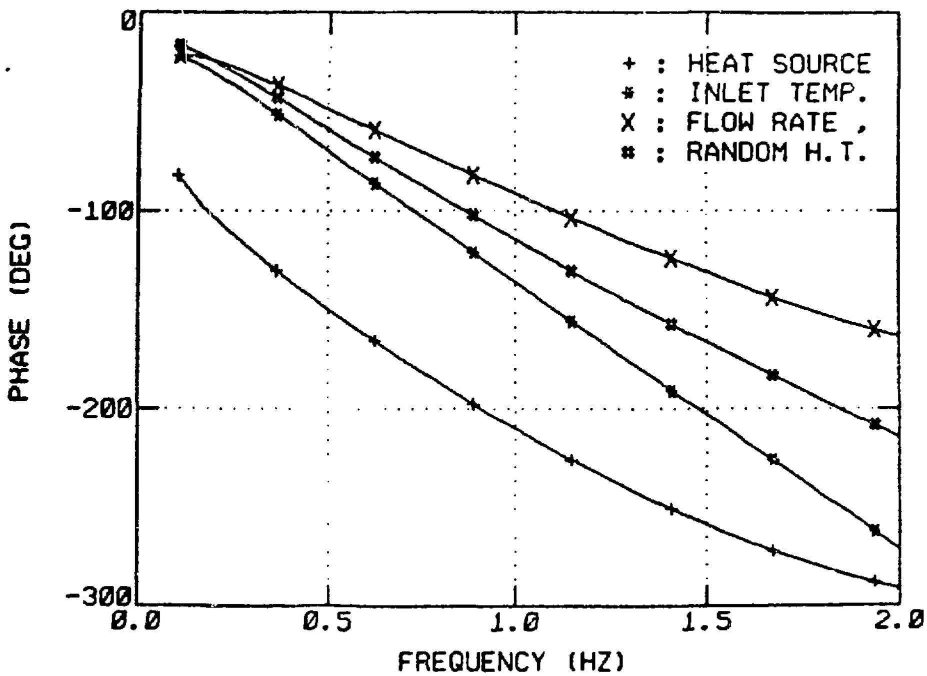

Fig. 7. The transfer function phase behavior between neutron noise and core-exit temperature noise in the LOFT reactor for various perturbation sources (theoretical model), for the case with positive moderator temperature coefficient of reactivity.