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IN-CORE COOLANT FLOW MONITORING OF PRESSURIZED WATER REACTORS USING TEMPERATURE AND NEUTRON NOISE[1]

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ABSTRACT

Noise measurements were performed at the Loss-of-Fluid-Test (LOFT) and Sequoyah-1 pressurized water reactors (PWRs) in order to investigate the possibility of inferring in-core coolant velocities from cross-power spectral density (CPSD) phases of core-exit thermocouple and in-core neutron detector signals. These noise measurements were used to investigate the effects of inlet coolant temperature, core flow, reactor power, and random heat transfer fluctuations on the noise-inferred coolant velocities. The effect on the inferred velocities of varying in-core neutron detector and core-exit thermocouple locations was also investigated. Theoretical models of temperature noise were developed, and the results were used to interpret the experimental measurements.

Results of these studies indicate that the neutron detector/thermocouple phase is useful for monitoring core flow in PWRs. Our results show that the interpretation of the phase between these signals depends on the source of temperature noise, the response times and locations of the sensors, and the neutron dynamics of the reactor. At Sequoyah-1 we found that the in-core neutron detector/core-exit thermocouple phase can be used to infer in-core coolant velocities, provided that the measurements are corrected for the thermocouple response time.

KEYWORDS

Reactor noise; PWRs; noise analysis; Sequoyah-1 reactor; temperature noise; neutron noise; coolant velocity; flow measurements.

MASTER

INTRODUCTION

Previous experimental noise measurements (Sweeney and Upadhyaya, 1982, 1983) in pressurized water reactors (PWRs) have indicated that the linear phase versus frequency behavior of the cross-power spectral density (CPSD) phase between a neutron detector and core-exit thermocouple might be utilized to infer in-core coolant velocities. Pór (1981) and Katona and colleagues (1982), however, observed that coolant velocities inferred from the CPSD phase between neutron detectors and a core-exit thermocouple at the Borssele reactor [a 470 MW(e) KWU PWR] were approximately 50% lower than design values.

To investigate the feasibility of using in-core neutron detector and core-exit thermocouple noise signals to monitor in-core coolant flow, experimental measurements were performed at the Loss-of-Fluid-Test (LOFT) reactor [a highly instrumented 55 MW(th) scale model of a PWR] and the Sequoyah-1 PWR [a Westinghouse 1100 MW(e) reactor]. Theoretical models of temperature and neutron noise were also developed to interpret the experimental results.

IN-CORE COOLANT VELOCITY MEASUREMENTS

LOFT Measurements

In-Core, Cobalt-60 self-powered neutron detector (SPND) and 0.16-cm diam K-type, core-exit thermocouple noise signals at the LOFT reactor were cross correlated. The neutron detectors were located at axial levels of 28, 68, 112, and 155 cm above the core bottom and core-exit thermocouples at 2.5, 33, and 124 cm above the top of the core (the LOFT core is 168 cm high). We observed that the

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maximum coherence was approximately 0.4 and the CPSD phase was linear over the 0.1 to 2-Hz frequency range for the thermocouple located at 2.5 cm and all neutron detector locations. The coherence and slope of the CPSD phase versus frequency were independent of the axial or radial location of the neutron detectors. A measurement using an in-core flow venturi yielded a coolant velocity of 3.8 m/s for 100% of design coolant flow rate. Using this value and the time delay of 0.25 s inferred from the slope of the neutron detector/thermocouple CPSD phase, an "equivalent transport distance" of 94.3 cm between the sensors was obtained. When the coolant flow was reduced to 65%, the coolant velocity inferred from the CPSD phase (Fig. 1) and the equivalent transport distance of 94.3 cm was 2.7 m/s, which agreed well with the 2.6 m/s value obtained with the flow venturi. This result indicates that even if the neutron noise generated by coolant temperature perturbations is space independent (point kinetic behavior), it may be possible to infer coolant velocities and to monitor core flow using neutron noise/core-exit thermocouple noise signals.

A neutron detector located 66 cm from the core bottom was cross correlated with thermocouples located at 2.5, 33, and 124 cm above the core at 100% flow. We observed that as the thermocouple distance from the top of the core increased, the coherence decreased (Fig. 2) and the slope of the phase versus frequency line (Fig. 3) increased (indicating increasing time delay between the two signals). The inferred coolant velocities were 3.8, 2.5, and 1.9 m/s, respectively, for thermocouples located 2.5, 33, and 124 cm above the core. The assumed transport distance for these inferred velocities was the previously mentioned 94.3-cm equivalent transport distance added to the distance of the thermocouple above the core top. These results indicate that, as expected, thermocouples located far from the top of the core are unlikely to yield good estimates of the coolant velocity inside the core. It is likely that the 50-cm distance between the top of the core and the core-exit thermocouple at the Borssele reactor is the cause of the discrepancy observed by Katona and colleagues (1982) between inferred and expected in-core coolant velocities.

Sequoyah-1 Measurements

Noise measurements were performed at Sequoyah-1 utilizing a movable in-core, flux-mapping fission chamber and a 0.32-cm diam, K-type, core-exit thermocouple located approximately 10 cm from the top of the core. The neutron detector was positioned radially near the core center and at various axial positions.

It was observed that the CPSD phases between the two signals were nearly linear over the 0.1 to 1.5-Hz range, and the slopes of the phase versus frequency plots decreased as the neutron detector was moved from near the bottom of the core (measurement 1) to near the top of the core (measurement 6) as shown in Fig. 4. Coolant velocities were inferred from these slopes using the actual

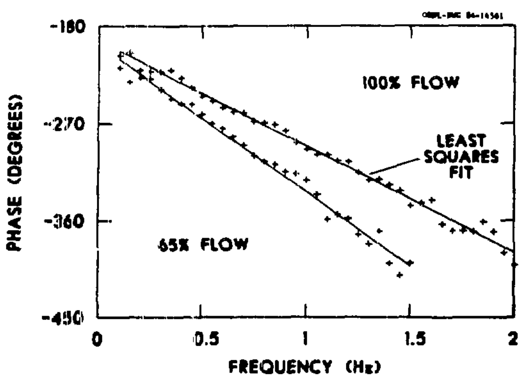

Fig. 1. CPSD phase between an in-core neutron detector and a core exit thermocouple 2.5 cm above the core for 65 and 100% flow at LOFT.

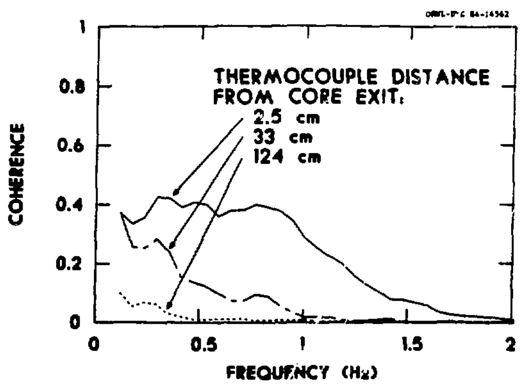

Fig. 2. CPSD coherences between an in-core neutron detector at 66 cm from the core bottom and core-exit thermocouples located at 2.5, 33, and 124 cm above the top of the LOFT core.

distance separating the detectors, and the results are summarized in Table 1. The discrepancies between the noise-inferred and expected (4.82 m/s indicated in the Sequoyah-1 Final Safety Analysis Report) coolant velocities increased as the distance between the sensors decreased. It was postulated that this trend is a consequence of the increasing contribution of the thermocouple time response to the total time delay (coolant transport time + thermocouple response) between signals as the detectors are moved closer together.

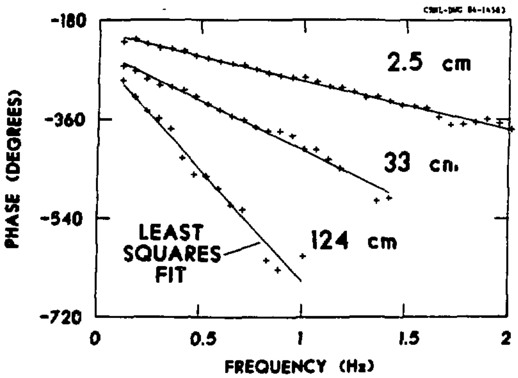

Fig. 3. CPSD phases between an in-core neutron detector at 66 cm from the core bottom and core-exit thermocouples located at 2.5, 33, and 124 cm above the top of the LOFT core.

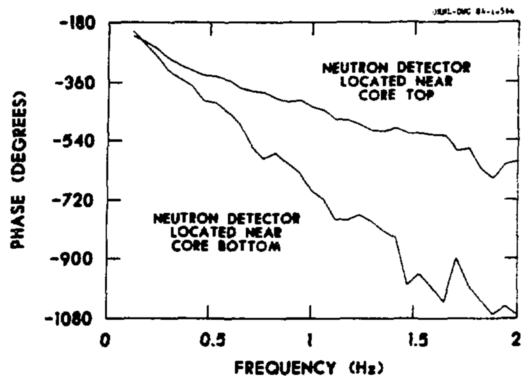

Fig. 4. CPSD phases between a movable in-core neutron detector at near the core bottom (measurement 1) and core top (measurement 6) in the Sequoyah-1 reactor.

TABLE 1 Coolant Flow Velocities Inferred from In-core Neutron/Core-exit Temperature Noise CPSD Phase with No Correction for Thermocouple Response Time at Sequoyah-1 PWR

Measurement	Distance between neutron detector and thermocouple (cm)	Maximum coherence*	Inferred coolant velocity (m/s)†
1	403.6	0.11	3.1
2	317.7	0.35	2.9
3	287.3	0.40	3.1
4	135.1	0.43	1.9
5	102.1	0.45	1.6
6	63.5	0.50	1.1

*Frequency range 0.1 to 1.5 Hz.
†For comparison, the Sequoyah-1 Final Safety Analysis Report lists the design average coolant velocity as 4.82 m/s.

It was also observed that the maximum coherence over the 0.1 to 1.5-Hz range increased from less than 0.1 when the neutron detector was near the core bottom to more than 0.4 when the detector was near the top of the core as shown in Table 1. These results suggest that the sources of temperature noise at Sequoyah-1 are spatially distributed and statistically uncorrelated (i.e., spatially independent) and therefore are probably the result of turbulence or random heat transfer processes rather than perturbations in the core-inlet temperature or flow. The observed spatial dependence of the neutron detector/thermocouple phase and coherence shows that neutronically, Sequoyah-1 does not respond as a "point reactor" to coolant temperature fluctuations above 0.1 Hz.

Previous studies by Sweeney and Upadhyaya (1982, 1983) have shown that the relatively long thermocouple response time (estimated to be 0.7 to 1.0 s) at Sequoyah-1 compared to the coolant transport time adversely affects coolant velocities inferred from ex-core neutron/thermocouple noise measurements.

To remove the effect of the thermocouple time response from the in-core measurements at Sequoyah-1, it was assumed that the in-core neutron detector spatial sensitivity was small in the axial direction. The neutron detector/thermocouple CPSD can then be described by (Sweeney and Upadhyaya, 1983, 1984)

$$CPSD(\omega) = |\delta S(\omega)|^2 \, |G(\omega)| \, e^{j[\theta(\omega)-\omega\tau]} \, , \qquad (1)$$

where $|\delta S(\omega)|^2$ is the temperature noise power spectral density (PSD), $|G(\omega)|$ is the coolant temperature-to-thermocouple output transfer function magnitude, $\theta(\omega)$ is the transfer function phase (due to its response time characteristics), and τ is the true coolant transport time between the neutron detector and thermocouple locations. By dividing two CPSDs (subscript 1 and 2) obtained with the same core-exit thermocouple/in-core neutron detector pair but with the neutron detector located at different axial positions for each measurement, the thermocouple phase is removed and the resulting phase behavior is due solely to the coolant transport time between the neutron detector locations:

$$\frac{CPSD_1(\omega)}{CPSD_2(\omega)} = \frac{|\delta S_1(\omega)|^2}{|\delta S_2(\omega)|^2} \, e^{-j\omega(\tau_1 - \tau_2)} \, , \qquad (2)$$

where $\tau_1 - \tau_2$ is the net coolant transport time between neutron detector locations 1 and 2.

A typical pair of combined (ratioed) measurements yield a linear phase versus frequency plot as shown in Fig. 5 with an intercept near 0°. The results of applying this correction are summarized in Table 2. In general, best agreement between the expected and noise-inferred coolant velocities is obtained when the neutron detector locations are separated by at least 90 cm. It was also found that small errors in transit time resolution (as a result of relatively slow sampling rates) or low signal coherence can lead to large errors in the inferred velocities when the detectors are closely spaced.

The above results indicate that by virtue of the space-dependent nature of temperature noise sources and its associated neutron noise, it may be possible both to monitor for and locate localized in-core flow blockages in a large commercial PWR.

CORE-EXIT TEMPERATURE NOISE ROOT MEAN SQUARE (RMS) VERSUS CORE ΔT

Tsunoda (1976) observed in an out-of-core test loop that the RMS temperature noise of a fuel assembly exit thermocouple increased linearly with increasing ΔT across the assembly under normal conditions. When localized blockages or power skews were introduced, the RMS noise deviated from the original behavior. To investigate the possibility of monitoring core-exit temperature noise alone for indications of localized coolant flow abnormalities, the RMS of core-exit temperature noise was measured over the 0.1 to 1-Hz range at LOFT and Sequoyah-1 at various power levels thereby measuring various temperatures (core ΔT). We observed that the RMS temperature noise varies linearly with core ΔT and as the core ΔT approaches 0°C, the temperature noise also approaches 0°C RMS for both LOFT and Sequoyah-1 as shown in Fig. 6. We concluded from these results that core-exit temperature noise may be useful in detecting localized power skews, flow blockages, or hot spots.

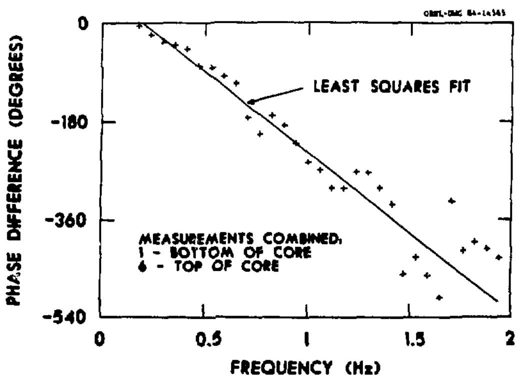

Fig. 5. CPSD phase difference between two sets of neutron detector/thermocouple measurements (measurements 1 and 6) at Sequoyah-1, which removes the effects of the thermocouple response time.

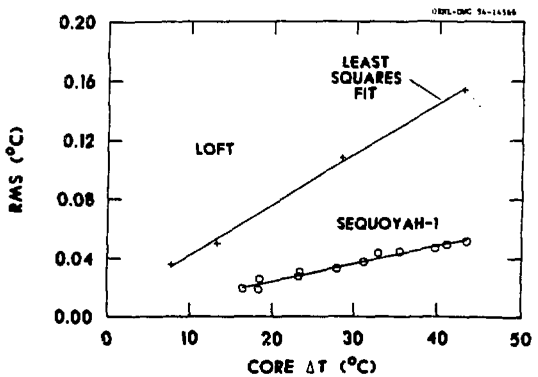

Fig. 6. Core-exit thermocouple root mean square (RMS) noise versus core temperature rise (ΔT) at LOFT and Sequoyah-1.

TABLE 2 Inferred Coolant Flow Velocities Corrected for Thermocouple Response Time at Sequoyah-1 PWR

Measurements combined	Distance between neutron detector locations (cm)	Inferred coolant velocity (m/s)
1,3	116.3	4.8
1,6	340.1	4.5
2,6	254.2	3.9
3,5	185.2	4.3
3,6	223.8	4.4
4,6	71.6	4.6

THEORETICAL MODELS OF TEMPERATURE AND NEUTRON NOISE

The work of Katona and colleagues (1981) indicated that the CPSD phase between a neutron detecter and core-exit thermocouple depended on the source of the coolant temperature fluctuations. They concluded that only core-inlet coolant temperature fluctuations can lead to time delays that are directly related to the coolant transport time between the two sensors. We therefore developed nodal and distributed parameter models to interpret experimental observations.

Nodal Models

Single and multi-node models of thermal-hydraulics and heat transfer processes were developed to investigate the contribution of reactor power, coolant flow, and core-inlet temperature fluctuations to core-exit temperature noise (Sweeney and Upadhyaya, 1983; Upadhyaya and Sweeney, 1983). The results of these models indicate that core flow perturbations produce a core-exit temperature dependence on core ΔT of the form

$$\delta T_i = \frac{\delta \dot{m}}{\bar{\dot{m}}} \Delta T_i \qquad (3)$$

where

δT_i = temperature fluctuations at the outlet of the ith node

$\delta \dot{m}$ = coolant flow rate (velocity) fluctuations

$\bar{\dot{m}}$ = mean coolant flow rate

ΔT_i = coolant temperature rise between the outlet of the ith node

A similar relationship is obtained for random heat transfer processes, which would lead to the previously mentioned linear dependence of core-exit temperature noise on core ΔT at LOFT and Sequoyah-1. These results also indicated that the core-exit temperature noise would not be a linear function of core ΔT nor pass through 0°C RMS at 0°C core ΔT if core-inlet temperature fluctuations were significant.

These results were confirmed by noise measurements at LOFT in which the coherence of a core-inlet thermocouple was found to be low (<0.1) with both a core-exit thermocouple and a neutron detector, and a linear phase versus frequency behavior was not observed. Coherence of a core pressure drop (core ΔP) sensor with both the neutron detector and core-exit thermocouple was >0.4 over the 0.1 to 1-Hz range at LOFT. The contribution of flow-rate fluctuations to neutron noise was also observed by Cannon and Clemmo (1980). We concluded from these results that core flow fluctuations rather than core-inlet temperature fluctuations are the dominant temperature noise source at LOFT.

Distributed Parameter Model

A distributed parameter dynamic model of fuel heat conduction, heat transfer, and coolant transport was developed that included direct neutronic heating of the coolant (Shieh and Upadhyaya, 1984).

Coolant temperature fluctuations were assumed to arise from the fluctuations of four sources: heat generation (power), flow rate (velocity), coolant inlet temperature, and random heat transfer (turbulence).

LOFT results. The distributed parameter model was applied to the LOFT reactor by assuming coolant- and fuel-temperature reactivity feedback and a point kinetic model of the reactor dynamics. A summary of the results follows.

- The neutron detector/core-exit thermocouple phase is linear, with frequency for each of the perturbation sources.
- The frequency range over which a linear phase versus frequency is obtained is bounded by feedback effects which are important below 0.1 Hz, and a sink (minimum) or resonance at frequencies above 2 Hz that is dependent upon the perturbation source and the coolant transport time through the core (similar to the results of Mogilner, 1971).
- Because of the time required for fuel to coolant heat transfer (up to several seconds), heat source fluctuations are important only below 0.1 Hz, and the resulting neutron/thermocouple phase does not approach 180° at low frequencies. Random heat transfer sources yield very low (approximately 0) coherence between the detectors because of the spatial averaging effect of the point kinetics assumption. The predicted slope of the neutron detector/thermocouple phase is 79.5°/Hz for coolant velocity perturbations, which agrees well with the 89.3°/Hz obtained from experimental measurements.

On the basis of predicted and experimental evidence it was concluded that coolant velocity (flow) fluctuations are the dominant source of coolant temperature noise in the 0.1 to 2-Hz range at LOFT.

Sequoyah-1 results. Because of the similarities in the behavior of the RMS temperature noise versus core ΔT at LOFT and Sequoyah-1, it was postulated that coolant velocity fluctuations were also the dominant source of core-exit temperature noise at Sequoyah-1. The distributed parameter model was applied to the Sequoyah-1 reactor, and a highly localized (space-dependent) neutron detector sensitivity to coolant temperature fluctuations was assumed. In contrast to the LOFT results, coolant flow fluctuations lead to predicted velocities that are approximately twice the coolant flow velocity observed at Sequoyah-1. The previously mentioned increasing coherence with decreasing separation distance between the neutron detector and thermocouple observed at Sequoyah-1 would also require an axially-increasing, nonpropagating contamination of the neutron detector signal for any assumed noise source other than random heat transfer. Based on these results, we concluded that the most likely source of core-exit temperature noise at Sequoyah-1 is a random heat transfer process such as turbulence.

SUMMARY AND CONCLUSIONS

Experimental and theoretical results from LOFT and Sequoyah indicate that neutron detector/thermocouple phase is useful for monitoring core flow in PWRs. Our results show that the interpretation of the coolant velocities inferred from these signals depends on the source of temperature noise, the response times and locations of the sensors, and the neutron dynamics of the reactor. At Sequoyah-1 we found that the neutron detector/core-exit thermocouple phase can be used to infer in-core coolant velocities provided that the measurements are corrected for the thermocouple response time. We also observed at LOFT that in-core coolant velocities can be inferred and core flow can be monitored with these signals even in a reactor with point kinetic neutron dynamics. These results combined with the observed RMS temperature noise behavior and the out-of-pile test results of Tsunoda (1976) show that temperature noise can provide useful diagnostic information in PWRs.

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