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CONTRIBUTION OF FUEL VIBRATIONS TO EX-CORE NEUTRON NOISE DURING THE FIRST AND SECOND FUEL CYCLES OF THE SEQUOYAH-1 PRESSURIZED WATER REACTOR

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CONTRIBUTION OF FUEL VIBRATIONS TO EX-CORE NEUTRON NOISE DURING THE FIRST AND SECOND FUEL CYCLES OF THE SEQUOYAH-1 PRESSURIZED WATER REACTOR[1]

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ABSTRACT

Noise measurements were performed during the first and second fuel cycles of the Sequoyah-1 pressurized water reactor (PWR) to observe long-term changes in the ex-core neutron signatures. Increases in the ex-core neutron noise amplitude were observed throughout the 0.1- to 50.0-Hz range. In-core noise measurements indicate that fuel assembly vibrations contribute significantly to the ex-core neutron noise at nearly all frequencies in this range, probably due to mechanical or acoustic coupling with other vibrating internal structures. Space-dependent kinetics calculations show that ex-core neutron noise induced by fixed-amplitude fuel assembly vibrations will increase over a fuel cycle because of soluble boron and fuel concentration changes associated with burnup. These reactivity effects can also lead to 180° phase shifts between cross-core detectors.

We concluded that it may be difficult to separate the changes in neutron noise due to attenuation (shielding) effects of structural vibrations from changes due to reactivity effects of fuel assembly motion on the basis of neutron noise amplitude or phase information. Amplitudes of core support barrel vibrations inferred from ex-core neutron noise measurements using calculated scale factors are likely to have a high degree of uncertainty, since these scale factors usually do not account for neutron noise generated by fuel assembly vibrations. Modifications in fuel management or design may also lead to altered neutron noise signature behavior over a fuel cycle.

KEYWORDS

Reactor noise; PWRs; mechanical vibration; noise analysis; Sequoyah-1 reactor; fuel assembly vibration; reactor kinetics; reactor internals; reactor shielding

INTRODUCTION

Theories have been extensively developed to explain the behavior of ex-core neutron noise due to core support barrel (CSB) vibrations (Bernard and colleagues, 1982; Robinson, Shahrokhi, and Kryter, 1977; Thie, 1973) and thermal shield motion (Bernard and colleagues, 1982; Schick and colleagues, 1978). "Scale factors" used to infer vibrational amplitudes of these structures from ex-core neutron noise measurements were obtained from detailed shielding calculations (Bernard and colleagues, 1982; Fujita and Ozaki, 1982; Robinson, Shahrokhi, and Kryter, 1977). These theories and calculations are based on the assumption that the core, comprised of many fuel assemblies, vibrates as a rigid (inflexible) body at CSB resonant frequencies and therefore can be modeled for shielding analysis as a fixed source of neutrons. The contribution of fuel assembly vibrations to ex-core neutron noise and their subsequent propagation through fission processes (a "reactivity" effect) therefore is not considered in these calculations. These assumptions usually are justified by the moderate changes in neutron noise observed over a fuel cycle and by the lack of dependence on soluble boron concentration in the frequency ranges associated with CSB motion.

The effects of reactivity perturbations on ex-core neutron noise are usually determined by a point kinetic model of the reactor dynamics (Meyer, 1980; Saxe, Verghese, and Ibrahim, 1980). It has been assumed (Mayo, 1977; Thompson, McCoy, and Lubin, 1979) that the presence of these reactivity perturbations which are caused by fuel motion, would lead to an "in-phase" (0° phase) component in the ex-core neutron noise and could therefore be separated from the "out of phase" (180° phase) component, which is caused by CSB or thermal shield motion. These point-kinetic models have also

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indicated that fuel assembly vibrations will lead to a linear dependence of the neutron noise on soluble boron concentration changes associated with fuel burnup (Meyer, 1980; Saxe, Verghese, and Ibrahim, 1980).

In order to investigate the effects of fuel assembly vibrations, in-core and ex-core neutron noise measurements were performed at a commercial pressurized water reactor (PWR) over the first and second fuel cycles. Space-dependent reactor kinetics calculations were also performed to interpret the changes observed in these noise signatures.

DATA ACQUISITION

Noise signals from four lower-half (1.8-m long) ex-core, power-range ionization chambers were monitored and cataloged continuously using a minicomputer-based data acquisition system (Smith, 1983) at Sequoyah-1, a Westinghouse 1150-MW(e) PWR. The locations of the four ex-core detectors are shown in Fig. 1a, and the corresponding core grid map is presented in Fig. 1b. The system performed on-line sampling and Fourier analysis of these noise signals. The power spectral densities (PSDs) were cataloged along with 16 operating parameters (reactor power, coolant temperatures, etc.) describing plant conditions. Analog FM tape recordings of noise signals were obtained each month and analyzed off-line in order to calculate cross-power spectral densities (CPSDs) that were not available in the on-line system. The automated data acquisition system continuously monitored these noise signals from January 26, 1981, to March 24, 1983, and subsequent noise measurements have been performed approximately every four months. In addition, a series of noise measurements were performed during the second fuel cycle using a movable, in-core, flux-mapping fission chamber.

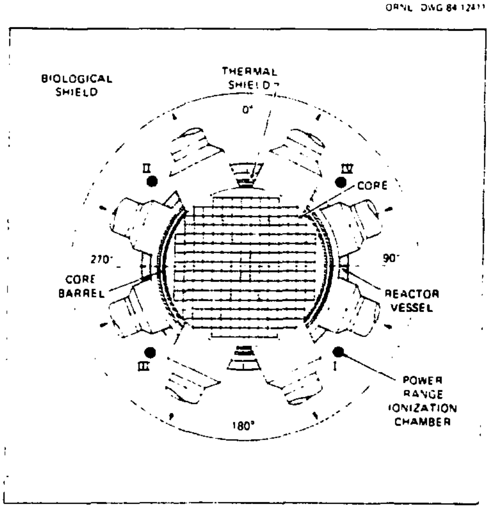

Fig. 1a. Location of ex-core detectors at Sequoyah-1 PWR.

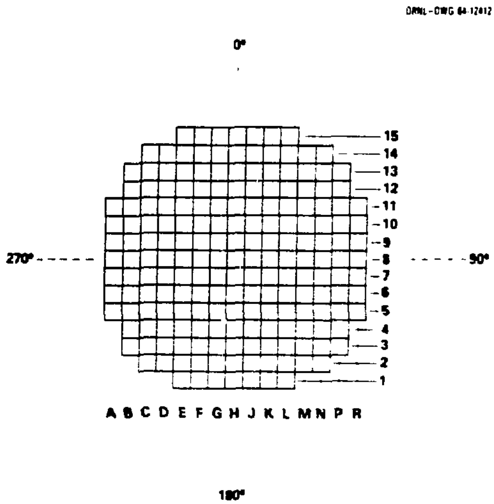

Fig. 1b. Grid map of fuel assembly locations at Sequoyah-1 PWR.

EX-CORE NEUTRON NOISE BEHAVIOR

Figure 2 shows an overlay of ex-core detector PSDs during the first cycle obtained with the automated system. Note that the greatest change in the ex-core neutron noise has occurred in the 5- to 10-Hz range.

The noise spectra were divided into ten frequency ranges that delimit significant resonances or noise sources as presented in Table 1. A list of possible noise sources in these ranges based on a comparison by Fry, March-Leuba, and Sweeney (1984) of Sequoyah-1 ex-core neutron noise with interpretations found in the open literature is included.

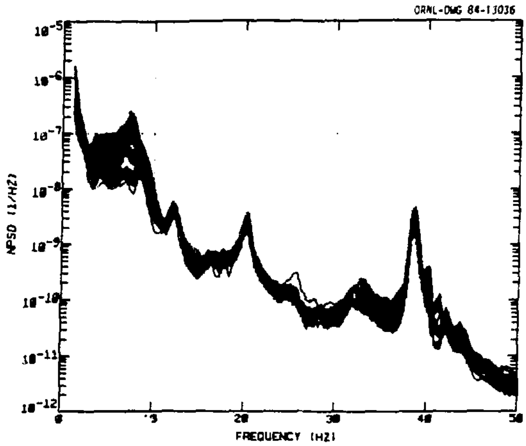

Fig. 2. Typical variation over the first fuel cycle of ex-core neutron detector power spectral densities normalized to the mean reaction rate (NPSDs) at Sequoyah-1.

TABLE 1 Frequency Ranges Studied at Sequoyah-1 and Possible Noise Sources Based on Previous Studies

Frequency range (Hz)	Possible noise sources[1]	Type of motion[2]
0.01-1	Fuel motion, temperature noise, feedback effects	Unknown
1-2	Unknown	Pendular
2-5	Fuel assembly vibration first mode	Pendular
5-10	Core support barrel motion beam mode and second mode of fuel assembly	Pendular
10-13	Thermal shield	Shell
13-18	Pressure vessel	Pendular
18-22	Pressure vessel	Shell
22-28	Unknown	In-phase
28-35	Unknown	Pendular
35-40	Core support barrel shell mode[3]	Shell

[1]As deduced from a comparison with open literature information summarized by Fry, March-Leuba, and Sweeney (1984).
[2]As deduced from ex-core detector phases.
[3]Detected with an accelerometer mounted on the bottom of the CSB of Bugey-2 but not prominent in its neutron noise.

We observed that the phase and coherence between ex-core detectors over the 1- to 50-Hz range did not change significantly over the first and second fuel cycles. We also observed that increases in the normalized root mean square (NRMS) noise occurred for all frequency ranges during the first fuel cycle and that all resonances above 10 Hz remaining at the same frequency. At the beginning of the first fuel cycle, the PSDs and CPSDs exhibited distinct resonances at 3.6, 6.7, and 8.0 Hz. The 3.6 and 8.0 Hz have been attributed by other studies (Marini and colleagues, 1982; Walton, Stokes, and Black, 1976) to be the first and second modes of fuel assembly vibration, respectively. Over the first fuel cycle, the 3.6-Hz resonance decreased to approximately 3.0 Hz with a corresponding decrease in the second mode resonant frequency. This second mode resonance merged with the 6.7-Hz resonance associated with CSB motion to form what appeared to be a single broad peak in the 5 to 7.5-Hz range as shown in Fig. 3. The resonances associated with CSB motion and second mode of the fuel assembly could be resolved as separate peaks in the spectra only at the beginning of the first fuel cycle. The NRMS at nominal full power conditions over the 0.1- to 1-Hz, 2- to 5-Hz, and 5- to 10-Hz ranges increased approximately by factors of 4, 2.5, and 4, respectively, over the first fuel cycle. The NRMS in these three frequency ranges also was found to depend linearly on soluble boron concentration changes associated with fuel burnup as shown in Figs. 4-6. The phase between cross-core detectors over the 2- to 10-Hz range was always 180° during both the first and second fuel cycles.

At the beginning of the second fuel cycle, the neutron noise amplitudes in these frequency ranges decreased to levels lower than at the end of the first cycle but higher than at the beginning of the first cycle, and resonances could be distinguished only at 3 and 7 Hz. Analog recordings of the ex-core neutron noise on August 5, 1983, and January 25, 1984, showed the NRMS in the 5- to 10-Hz range to be approximately 1.1×10^{-3} and 1.4×10^{-3} at soluble boron concentrations of 410 and 79 ppm, respectively, which are higher by a factor of 2 than first cycle values for the same boron concentrations.

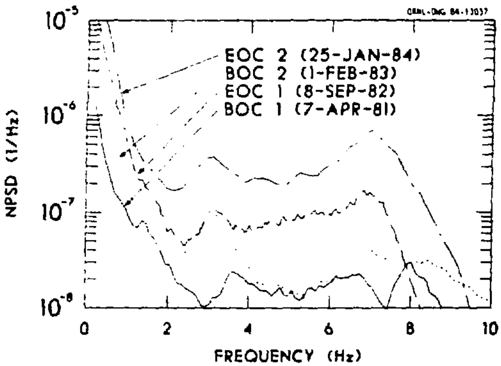

Fig. 3. Typical ex-core neutron detector NPSDs for the beginning of cycle (BOC) and end of cycle (EOC) of Fuel Cycles 1 and 2 at Sequoyah-1.

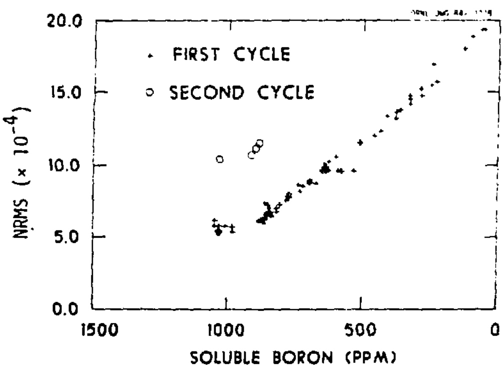

Fig. 4. Typical ex-core neutron detector root mean square noise normalized to the mean reactor rate (NRMS) over the 0.1- to 1-Hz range versus soluble boron concentration at Sequoyah-1.

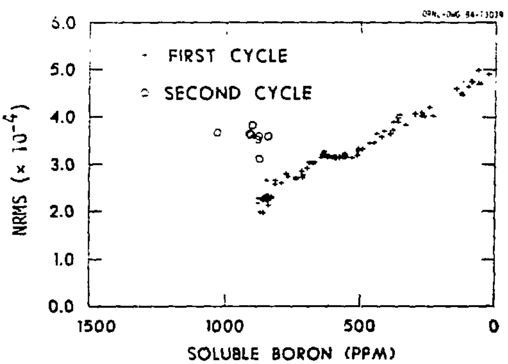

Fig. 5. Typical ex-core neutron detector noise NRMS over the 2- to 5-Hz range versus soluble boron concentration at Sequoyah-1.

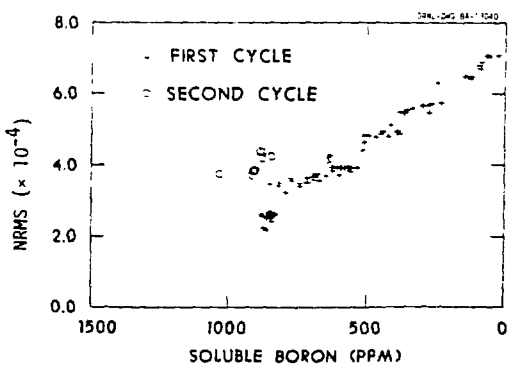

Fig. 6. Typical ex-core neutron detector noise NRMS over the 5-10-Hz range versus soluble boron concentration at Sequoyah-1.

IN-CORE NEUTRON NOISE BEHAVIOR

In-core neutron noise measurements were performed on April 28, 1983, (second fuel cycle) in Sequoyah-1 at a soluble boron concentration of 700 ppm. A 0.48-cm-diam by 5.33-cm-long flux-mapping fission chamber was located at radial grid locations P-4, D-12, and J-10 (Fig. 1b) and at various axial positions.

We observed that the in-core neutron noise PSDs exhibited resonances at 3.5 and 7 Hz that decreased in amplitude when the detector was moved from the core edge to the core center (grid locations P-4 to J-10, respectively) as shown in Fig. 7. Lower amplitude resonances were also visible in the PSDs at frequencies of 12, 16, 20, and 38 Hz when the detector was located at grid positions P-4 and D-12. The 3.5- and 7-Hz resonances always had a high coherence (>0.6) with at least one pair of ex-core cross-core (180° apart) detectors.[2] At higher frequencies, the coherence between the ex-core and in-core detectors did not depend on which ex-core detector was used; however, the coherence decreased as the in-core detector was moved from the core edge to the core center as summarized in Table 2.

SPACE-DEPENDENT REACTOR KINETICS CALCULATIONS

One- and two-dimensional, 3-neutron energy group, neutron kinetic models were developed to determine the spatial sensitivity of ex-core neutron detectors to fuel assembly vibrations (Clapp and colleagues, 1982; Sweeney and Renier, 1982). These calculations were extended to account for fuel composition and soluble boron concentration changes occurring over a fuel cycle (Sweeney and Renier, 1983; 1984). The results of these calculations indicated:

- Fuel assembly vibrations throughout the core can contribute significantly to ex-core neutron noise.
- The amount of ex-core neutron noise caused by fuel assembly vibration at a given core location increases with burnup, presence of burnable poison rods, and spatial correlation of the vibration-forcing function (common forcing functions such as CSB vibration vs multiple independent forcing functions).
- Phases of cross-core detectors are 180° for the majority of fuel assembly vibration locations. However, fuel assembly vibrations on the core periphery can cause significant deviations (as much as 90°) from this phase behavior as shown in Fig. 8.

INTERPRETATION OF RESULTS

The ex-core neutron noise increases observed in the 5- to 10-Hz range were interpreted as resulting from two primary mechanisms: excitation of the fuel assembly second mode of vibration caused by CSB motion and enhanced fuel assembly vibration-induced neutronic perturbations due to fuel burnup and soluble boron concentration changes. The neutron noise increases observed in the 5- to 10-Hz range

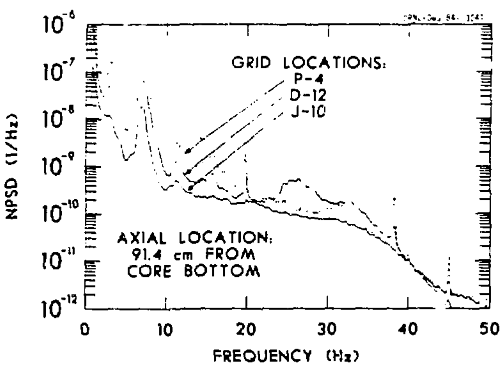

Fig. 7. In-core neutron detector NPSDs at three radial locations in Sequoyah-1.

[2]Detector D-12 exhibited high coherence in these frequency ranges at axial levels other than 91.4 cm from the core bottom.

TABLE 2 Coherence between In-Core and Ex-Core Detectors at Sequoyah-1 PWR

In-Core Location[1]	Frequency (Hz)	Coherence Ex-core detector I	II	III	IV
	3	0.9	0.8	0.1	0.2
	7	0.9	0.9	0.2	0.2
P-4	12	0.5	0.3	0.2	0.1
Core edge	16	0.7	0.6	0.5	0.5
	20	0.7	0.7	0.7	0.7
	38	0.9	0.9	0.9	0.9
	3	0.1	0.2	0	0
D-12[2]	7	0.1	0.2	0.2	0.2
Near core	12	0	0.1	0	0
edge	16	0.1	0.1	0	0
	20	0.5	0.5	0.4	0.5
	38	0.3	0.3	0.3	0.3
	3	<0.1	0	0.6	0.6
J-10	7	0.2	0.1	0.9	0.9
Near core	12	0	0	0.1	0.1
center	16	0	0	0.1	0.1
	20	<0.1	<0.1	<0.1	<0.1
	38	0	0	0	0

[1]Axial level of 91.4 *cm from the core bottom.*
[2]Detector D-12 exhibited high coherence (approximately 0.8) at 3 and 7 Hz with ex-core detectors I and II at other axial levels.

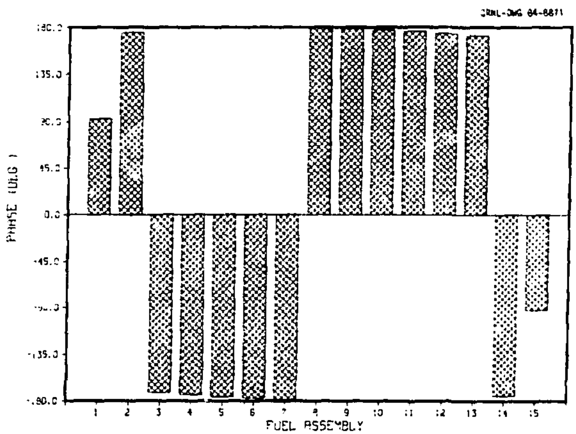

Fig. 8. Predicted CPSD phase between cross-core (180° apart) ex-core neutron detectors resulting from individual fuel assembly vibrations along the core centerline in a space-dependent reactor kinetics calculation at 3 Hz (Sweeney and Renier, 1984).

follow similar behavior observed in the 2- to 4-Hz range (dominated by the fuel assembly fundamental mode) and frequencies below 1 Hz. The in-core measurements indicate that increases in neutron noise above 10 Hz also may be the result of enhanced fuel assembly vibration-induced neutronic perturbations due to changes in fuel composition and flux gradients on the core periphery. Based on the spatial behavior of coherences between in-core and ex-core neutron detectors, these measurements show that the excitation of fuel assembly vibrations is different in the frequency ranges above and below 10 Hz: Below 10 Hz, the excitation mechanism appears to be CSB pendular vibration-induced movement of the core support plate, while above 10 Hz, the mechanism is likely to be core support structure shell-mode vibrations mechanically or acoustically (pressure waves in the coolant) transmitted to the peripheral fuel assemblies.

The high coherence below 10 Hz between an in-core detector and certain pairs of ex-core detectors is indicative of preferential directions of fuel assembly vibrations or their exciting forces. The high coherences between an in-core detector on the core periphery and all ex-core detectors also has been observed by Mayo and Currie (1977) and was attributed to shell-mode vibrations of the thermal shield and CSB.

CONCLUSIONS

The results of theoretical calculations and experimental measurements indicate that fuel assembly vibrations are significant sources of ex-core neutron noise in the 0.1- to 50-Hz range. We postulate that resonances in the ex-core neutron noise, usually associated with a particular structural vibration, are detected indirectly through coupled fuel assembly vibrations. Theoretical calculations and the experimental measurements show that separation of reactivity and attenuation effects on the basis of a 0 or 180° phase [so called in-phase/out-of-phase decomposition (Mayo, 1977)] may yield misleading results because perturbations propagating through fission processes also can yield 180° phases between cross-core detectors. Inference of preferential CSB motion directions on the basis of coherence also may yield misleading results because these coherences may be influenced heavily by preferential direction fuel or core support plate vibrations. Amplitudes of CSB vibrations inferred from ex-core neutron noise measurements using calculated scale factors are also likely to have a high degree of uncertainty because scale factors usually do not account for neutron noise generated by fuel assembly vibrations.

Also, as a result of our investigations we conclude that neutron noise measurements performed infrequently may not provide adequate surveillance of the CSB and other internal structures since it may be difficult to separate changes in the noise spectrum resulting solely from motion of these structures from changes caused by fuel motion and burnup. Noise signatures therefore should be obtained at periodic intervals during each fuel cycle. The contribution of fuel assembly vibrations to neutron noise also implies that changes in fuel loading or fuel design may lead to significant changes in the behavior of these signatures over a fuel cycle.

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