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ANALYSIS OF NEUTRON-DENSITY OSCILLATIONS RESULTING FROM CORE BARREL MOTION IN THE PALISADES NUCLEAR POWER PLANT

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INSTRUMENTATION AND CONTROLS DIVISION

ANALYSIS OF NEUTRON-DENSITY OSCILLATIONS RESULTING FROM CORE BARREL MOTION IN THE PALISADES NUCLEAR POWER PLANT

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May 1974

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ABSTRACT

Neutron noise signatures were obtained on August 3, 1973, that were due to abnormal movement of the core barrel at the Palisades Nuclear Plant. Frequency spectra, rms noise, and amplitude probability density were recorded as sensed by ex-core and in-core neutron detectors. These signatures will serve as reference data for future studies of core-barrel motion at the Palisades plant. Also, the results are presented in units that should make them useful for noise diagnosis in other pressurized water reactors.

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1. INTRODUCTION

At the request of the Core Performance Branch of the Office of the Director of Regulation, U.S. Atomic Energy Commission, the authors investigated unusual neutronic noise at the Palisades Nuclear Plant in late July 1973. Previously the plant operator, Consumers Power Company (CPCO), had noted abnormal flux oscillations on the output from ex-core detectors in the plant.

CPCO and the plant designer, Combustion Engineering (CE), investigated these oscillations with noise analysis techniques and concluded that the oscillations resulted from flow-induced motion of the core barrel, which hangs from a seat machined into the reactor vessel wall. The authors spent 4 days at Palisades performing on-site noise analysis of plant signals such as in-core and ex-core neutron flux, temperature, and vibrations (sensed by ex-vessel accelerometers) with the aid of a computer-based noise analyzer. These measurements further substantiated a previous conclusion by CPCO and CE that the abnormal ex-core detector flux oscillations were attributable to changes in neutron leakage to these detectors caused by a rocking motion of the core barrel inside the pressure vessel. The results of on-site investigations are contained in a trip report[1] and a conference paper[2] and therefore will not be discussed here.

Following the on-site measurements, an analog magnetic-tape recording of plant neutron detector signals on August 3, 1973, was obtained from Combustion Engineering* so that an in-depth study of the flux oscillations could be conducted at ORNL. Shortly after this tape had been recorded, the Palisades plant was shut down because of leaks from the steam generator. While the plant was being repaired, the AEC requested that the vessel internals be visually inspected to confirm the conclusion that the core-barrel had rocked during operation. The inspection showed that a 0.25-in. thickness of metal had worn from the mating surfaces of the core support barrel flange and pressure vessel and that all fasteners holding the expansion-compensating ring in position were broken.[3]

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*The authors acknowledge the contribution by J. T. Thompson of Combustion Engineering Corporation who supplied the analog-tape-recorded plant signals for this study.

We will not attempt to discuss the details of damage or the mechanisms that resulted in the failures (see ref. 3 for details of the failure); our objective in this report is to document the noise signatures (and the method used to obtain them) associated with such anomalous mechanical conditions within the vessel, as obtained from the CE tape recording. These signatures can be compared with signatures obtained when the plant resumes operation to determine to what degree the core barrel rocking is eliminated by the corrective mechanical modifications made by CPCO and CE during the shutdown period. Also the results are in units that should make them useful for noise diagnois in other pressurized water reactors.

2. NEUTRON NOISE SIGNAL RECORDING

Signals from twelve neutron detectors were recorded by CE on August 3, 1973, using the instrumentation shown in Fig. 1.

The dc component of the signals was biased out, and the fluctuating portion was amplified (by a factor of 1 to 10 for ex-core and a factor of 500 for in-core detectors) and recorded on magnetic tape using FM electronics with a bandpass of 0 to 312 Hz. Approximately 30 min of data was recorded from each of various combinations of seven detectors. The amplifier gain and dc level of each signal were noted so that the results could be expressed in absolute units.

The approximate locations of the detectors are shown in Fig. 2 (the angular orientations of the detectors are correct in the figure, but the indicated distances between detectors are not to scale).

3. SIGNAL ANALYSIS

The recorded signals were played back and analyzed at ORNL to obtain noise amplitude distribution, root-mean-square amplitudes, power spectra, and cross-power spectra. The instrument was a fast Fourier transform time series analyzer by Hewlett-Packard, model 5451A.

All results were normalized to absolute units as described in the following sections.

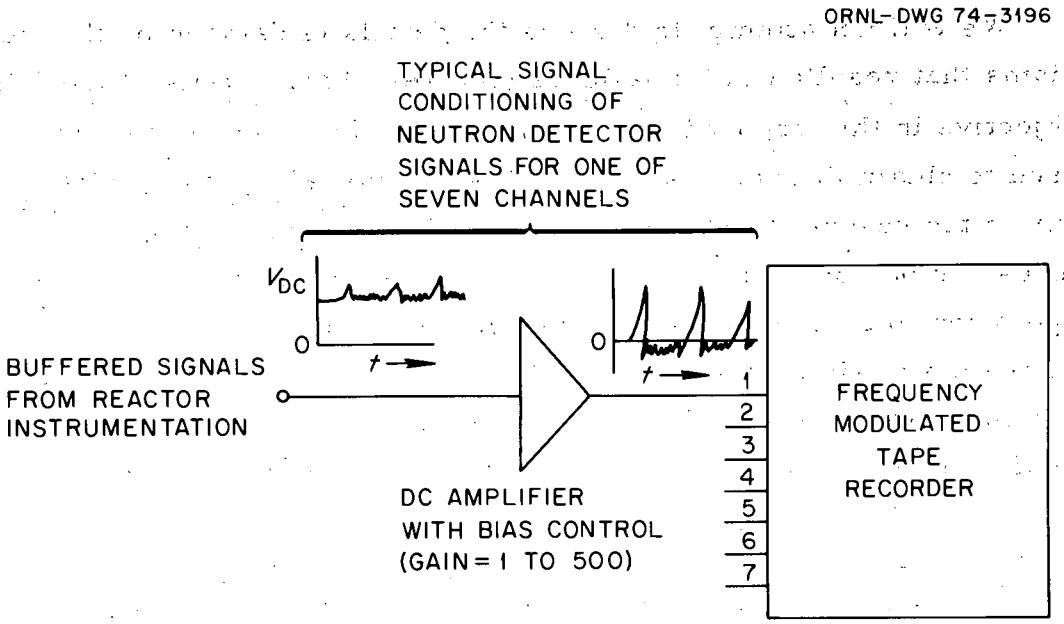

Fig. 1. Instruments for recording noise signals.

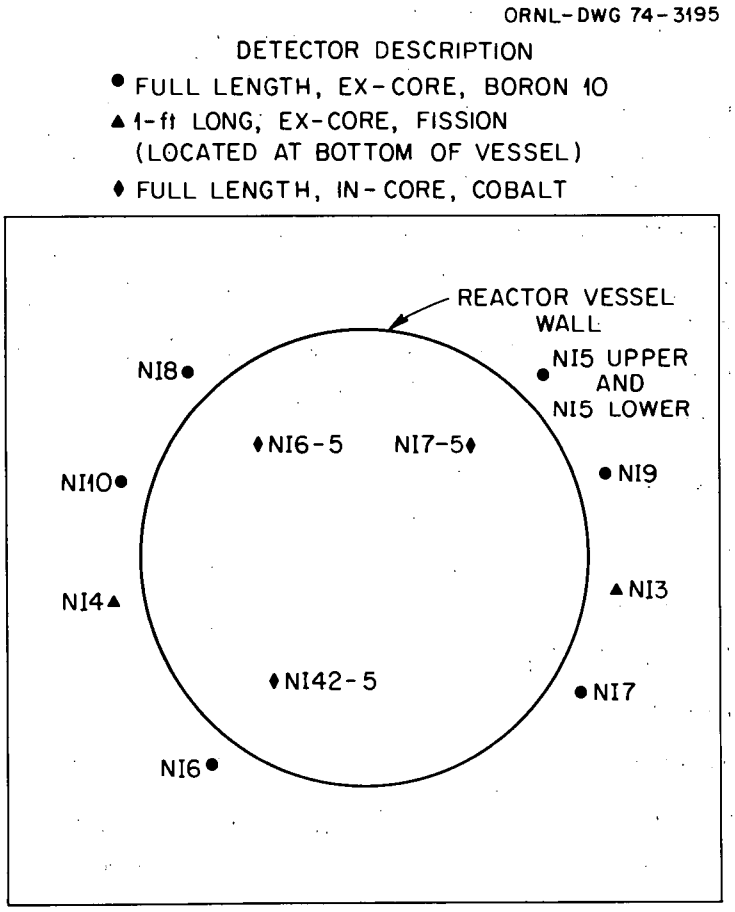

Fig. 2. Locations of neutron detectors.

3.1 Power Spectra

The power-spectral density (PSD) was computed for each detector over a frequency range from 0.04 to 10 Hz with a resolution bandwidth of 0.02 Hz. Approximately 30 min of signal was analyzed, yielding an estimated relative statistical uncertainty[4] of each PSD estimate of ±17%:

$$\epsilon = \frac{\sigma_{PSD}}{PSD_T} = \left(B_e\ T\right)^{-1/2} = \left(0.02 \times 1800\right)^{-1/2} \simeq 0.17 . \tag{1}$$

In Eq. (1) B_e is the resolution bandwidth (Hz), T is the total measurement time (sec), σ_{PSD} is the standard deviation of the PSD estimate, and PSD_T is the true PSD that would be obtained from an infinite record.

The spectra were normalized to absolute units by dividing the raw PSD's by the square of the steady-state component of the detector signal V_{DC}. Thus the spectral density units are Hz^{-1}, and such variables as detection efficiency, detector sensitivity, and preamplifier gain are accounted for properly (ref. 5 contains a development of this normalization procedure).

Spectra from different detectors and even different reactors can thus be compared on the same absolute scale. The magnitude of the cross-power spectral density (CPSD) was normalized by dividing $CPSD_{AB}$ by the product of the two steady-state signals V_{DC}^A and V_{DC}^B.

3.2 Coherence and Phase Between Signals

Another variable of interest in noise analysis is coherence, which is a measure of the commonality of two signals (A and B), i.e., the closeness of their relationship in a cause-and-effect sense. It is computed as

$$COH \equiv \gamma^2(f) = \frac{\left|CPSD_{AB}(f)\right|^2}{\left[PSD_A(f)\right]\left[PSD_B(f)\right]} . \tag{2}$$

Under this definition, two perfectly correlated signals have a coherence value of 1, and two completely unrelated noise signals have a coherence value of 0.

If two signals have a relatively high coherence, say >0.5, it is meaningful to speak of a phase relationship between them. This phase is computed as

$$\theta(f) = \tan^{-1}\left[\frac{\mathrm{ImCPSD}_{AB}(f)}{\mathrm{ReCPSD}_{AB}(f)}\right] , \tag{3}$$

where $\mathrm{ImCPSD}_{AB}(f)$ and $\mathrm{ReCPSD}_{AB}(f)$ are the imaginary and real parts of the cross-power spectral density, respectively.

3.3 Root-Mean-Square Noise

The magnitude of noise superimposed on a more or less steady-state signal can be expressed as a single number by calculating the root-mean-square (rms) noise for the bandwidth desired. If the power spectrum has already been computed, the rms value in absolute units is most easily obtained by integrating the power spectrum (in absolute units) between the desired frequency limits, f_1 and f_2, i.e.,

$$\%\ \mathrm{rms}\ (f_2 - f_1) = \left[\int_{f_1}^{f_2} \mathrm{PSD}(f)df\right]^{1/2} \times 100 . \tag{4}$$

The resulting quantity is the rms noise, expressed as a percentage of the steady-state signal level V_{DC}. The estimated relative statistical uncertainty of the rms noise is computed from

$$\epsilon = 2\left[(BT)^{1/2}\right] , \tag{5}$$

where $B = f_2 - f_1$ and T is the measurement time.

3.4 Amplitude Probability Density

Amplitude probability density (APD) and its integral (IAPS), sometimes called "cumulative probability distribution function,"[6] were calculated for each detector. Detector signals were band limited before the APD was calculated, because the APD is frequency dependent and we desired to calculate the APD for approximately the same frequency range as used for rms. Therefore, APD's for the range from 0.025 to 5 Hz were computed using a total signal time of 27 min for each of the 12 detectors. To maintain consistency with the other quantities computed (rms, PSD, CPSD), the APD was normalized to the steady-state signal level. Therefore, the APD was plotted as probability density (units of $\%^{-1}$) vs amplitude in percentage of steady-state signal level V_{DC}.

4. RESULTS

The following sections discuss the type of information that can be derived from signatures obtained from each form of analysis; the Appendix contains a documentation of the frequency spectra obtained from the nine detectors whose frequency spectra are not included in the body of this report.

4.1 Direct Noise Signal Observation

The simplest form of noise analysis is direct observation of the time behavior of a noise signal. Owing to the random nature of the signal, it is difficult to quantify signal properties solely on the basis of time history, but such observation can provide a valuable qualitative image of the signal's major characteristics. For example, observation of a signal from a typical ex-core detector (Fig. 3) shows that (1) there are large-amplitude, low-frequency spikes superimposed on the signal, (2) these spikes are consistently in one direction, and (3) they occur randomly at an average rate of approximately one every 5 sec. Although these are subjective observations, they are a good basis for understanding the results of the more detailed quantitative analyses that follow.

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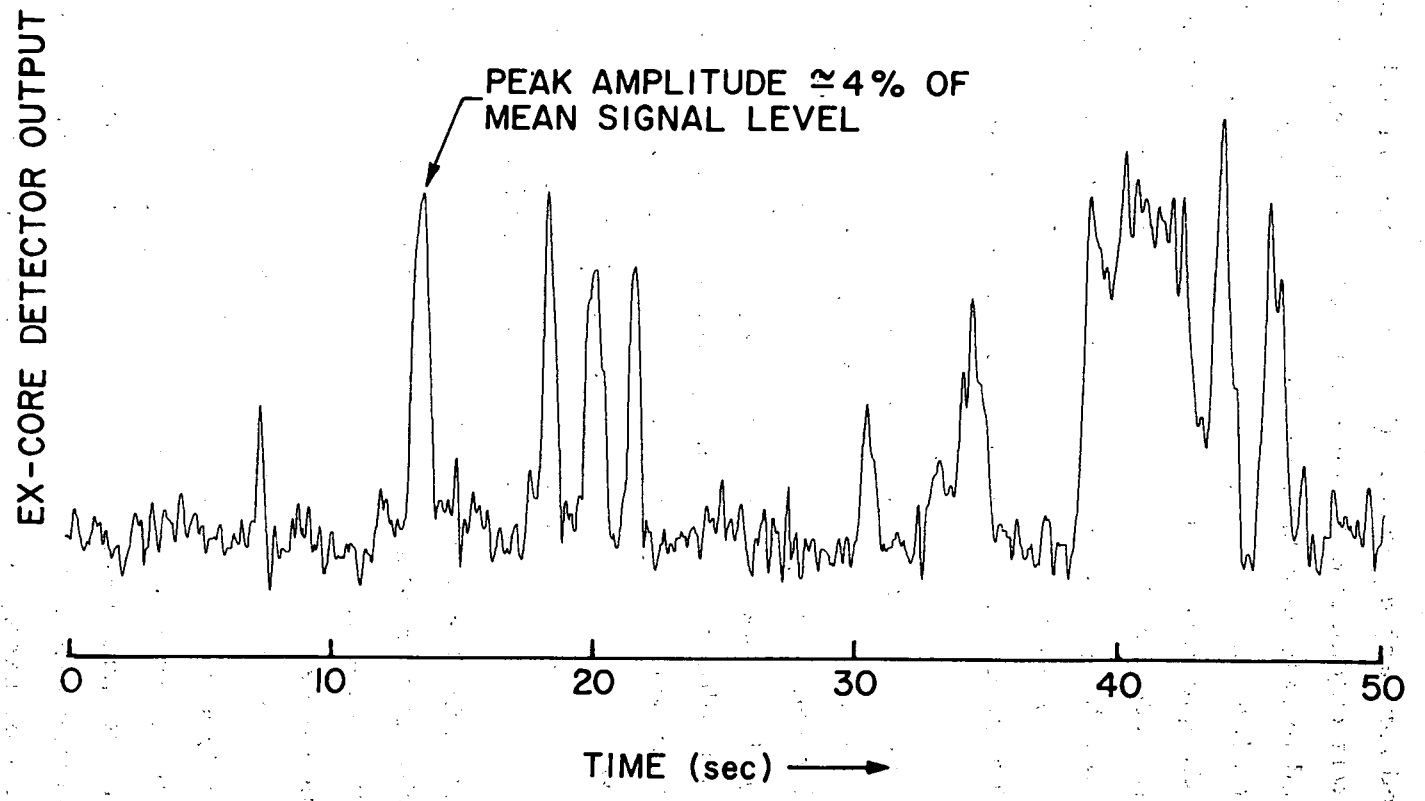

Fig. 3. Typical ex-core detector signal. Most of the steady-state signal is biased out so the noise detail can be illustrated.

4.2 Power Spectral Density

The power spectrum of an ex-core, full-length detector (NI6) is shown in Fig. 4.* The power in the signal is seen to increase sharply at low frequencies, and there is a definite inflection (the suggestion of a short plateau) between 1.0 and 2.0 Hz (note that the statistical uncertainty is only ±5% at 1.8 Hz due to averaging 11 adjacent PSD estimates before plotting). The spectrum of ex-core detector NI4 (Fig. 5), a 1-ft detector at the bottom of the vessel, has a higher amplitude than NI6 between 0.04 and 1.0 Hz. This resulted from core barrel rocking, with its pivot point at the top, thus allowing maximum movement at the bottom.

Figure 6 shows the spectrum of in-core detector NI42-5. The amplitude of noise below ~2.0 Hz is much lower than that sensed by the ex-core detectors; therefore, this shows that the core fission rate (power production) did not fluctuate in this frequency range nearly so much as would be inferred from the ex-core detectors. The spectral peak at about 2.0 Hz is more prominent than in the ex-core noise spectrum (see also Fig. 7). The source of this noise is not known, but its presence in both in- and ex-core spectra suggests that it may be a true reactor power fluctuation rather than a variation in neutron leakage.

The spectra of the other ex-core and in-core detector signals recorded by CE (6. Appendix) were similar to those already illustrated, except for slight variations in amplitude. The differences in overall noise amplitude as a function of detector location will be discussed further in the following section.

4.3 Noise Amplitude

The percentage of rms noise relative to the mean detector output level V_{DC} was computed for each of the 12 detector signals recorded by CE for frequency ranges from 0.03 to 5 Hz and 4 to 8 Hz using Eq. (4). (See Table 1.) Although these two frequency ranges were chosen somewhat arbitrarily, we believed that the lower range would be more sensitive

*The indicated statistical uncertainty in Figs. 4–7, 9, and the Appendix figures is calculated using Eq. (1).

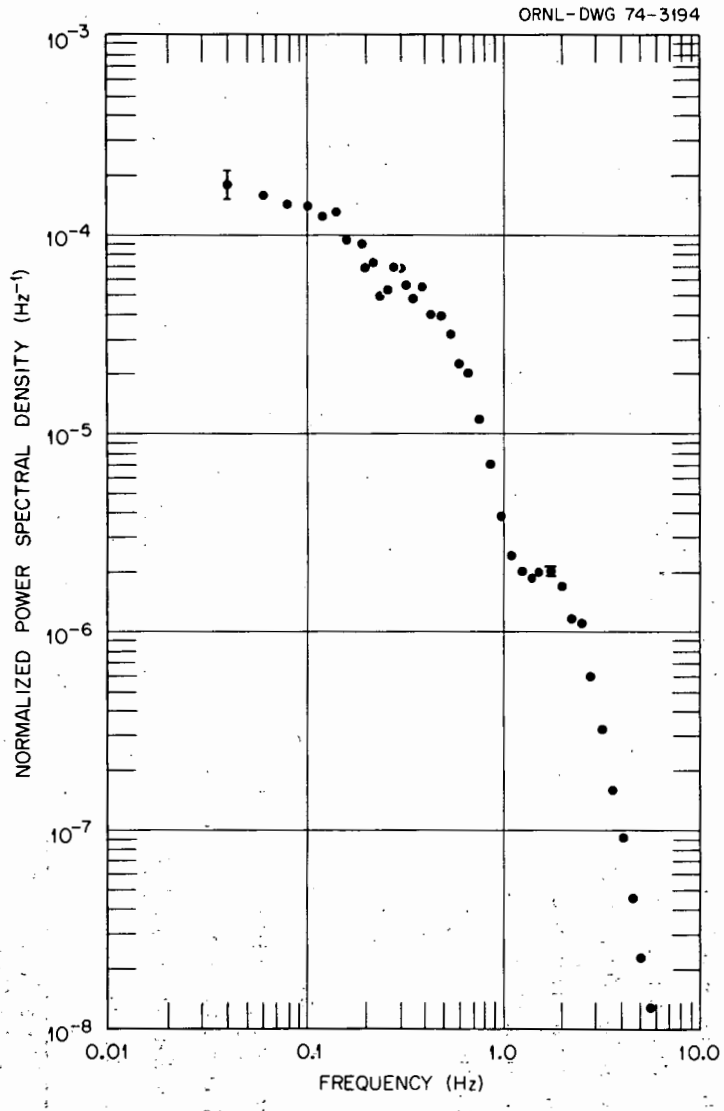

Fig. 4. Power spectrum of ex-core detector NI6.

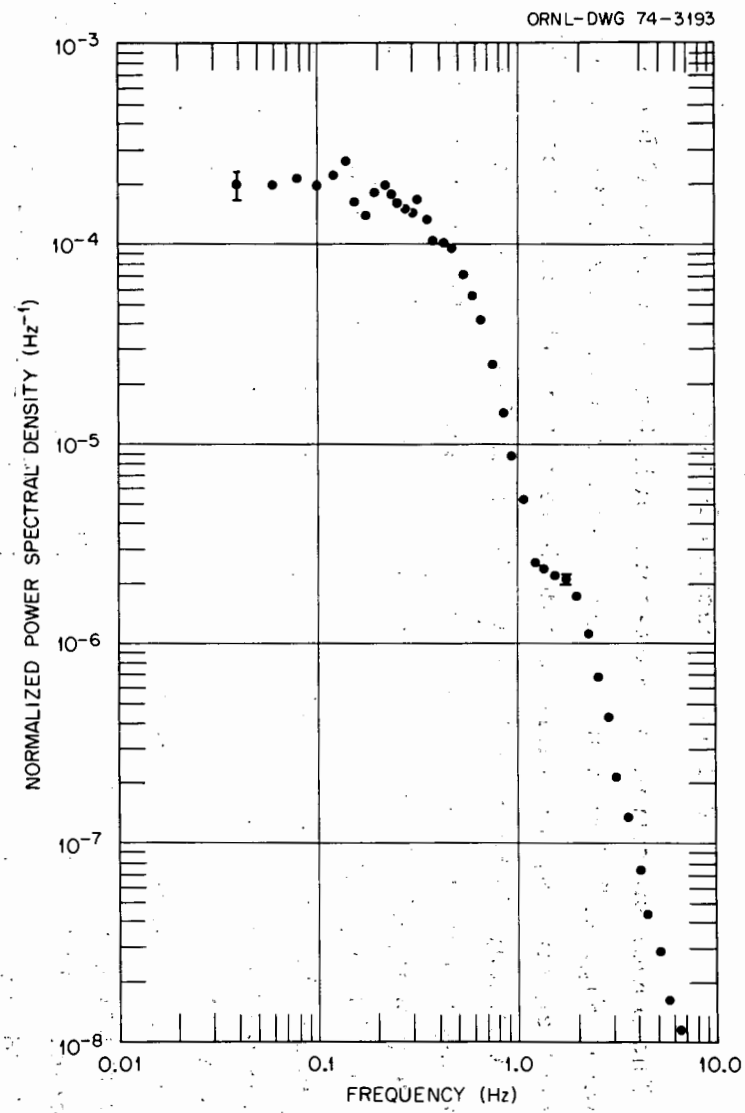

Fig. 5. Power spectrum of ex-core detector NI4.

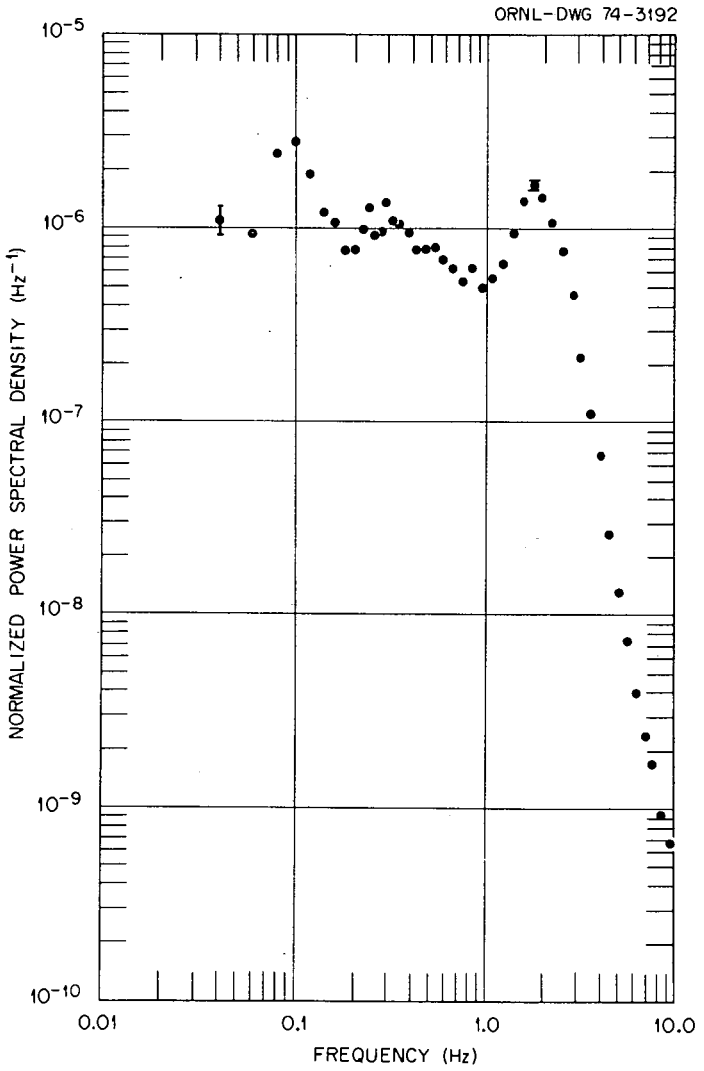

Fig. 6. Power spectrum of in-core detector NI42-5.

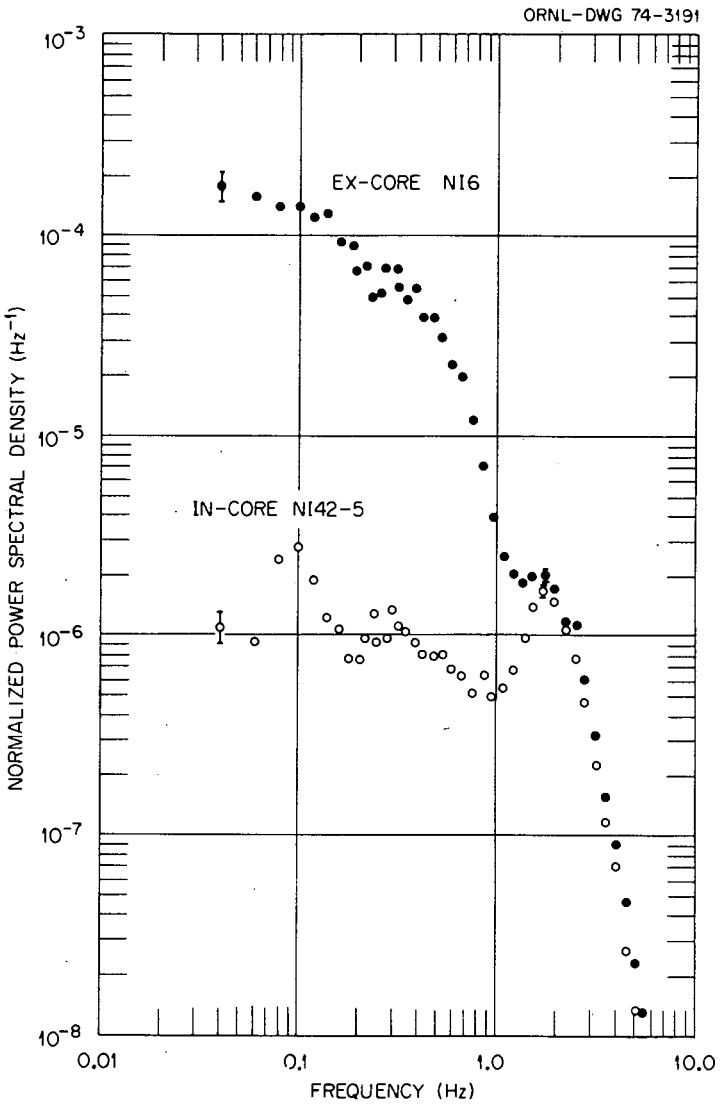

Fig. 7. Comparison of ex-core and in-core power spectra.

to the core-barrel rocking motion. PWR noise in the 4- to 8-Hz range has been determined by others to be related to core vibration.[7]

Using Eq. (5) we computed the statistical uncertainty of the results in Table 1 to be (conservatively) ±0.01% rms/mean.

Table 1. rms noise relative to mean detector output level

Detector	rms Mean (%)[a]	
	(0.03–5 Hz)	(4–8 Hz)
	A. Ex-core Detectors	
NI3	0.98	0.028
NI4	0.96	0.030
NI5 Upper	0.80	0.030
NI5 Lower	0.80	0.030
NI6	0.69	0.029
NI7	0.57	0.031
NI8	0.70	0.032
NI9	0.96	0.026
NI10	0.94	0.030
	B. In-core Detectors	
NI6-5	0.17	0.016
NI7-5	0.18	0.018
NI42-5	0.17	0.023

[a]These results are based on a 30-min data record which yields an estimated uncertainty of ±0.01% rms/mean.

Several observations can be made from these results:

1. The in-core rms noise is approximately four times less than ex-core rms noise in the 0.03- to 5-Hz range (this is equivalent to a factor of 16 in PSD as indicated by Fig. 7.)
2. The ex-core detector noise between 4 and 8 Hz is ~25 times less than it is from 0.03 to 5 Hz, which would seem to indicate that core vibration is not a significant cause of the noise.
3. Some ex-core detectors have considerably higher noise level in the 0.03- to 5-Hz range than others, which indicates that the neutron

leakage variation caused by barrel rocking is reator at some ex-core locations (a preferred direction of motion).

This latter observation is illustrated better by Fig. 8, which is a plot of 0.03- to 5-Hz noise vs the circumferential location of the detectors. These data support the supposition of a preferred direction of barrel motion, but one cannot be certain because detectors NI3, 4, 9, and 10 are not located in concrete wells as are NI5, 6, 7, and 8. A study of the effect of the concrete wells on neutron leakage vs barrel motion is beyond the scope of this investigation, but it is clear that this effect should be understood before any attempt is made to calculate the magnitude of barrel motion from the magnitude of the noise.

4.4 CPSD Analysis

Figure 9 shows a CPSD analysis of two ex-core detectors, NI6 vs NI5 lower (taken as the reference). These detector signals show high coherence over the frequency range from 0.04 to 1.0 Hz, but are opposite in phase ($\theta = -180°$). We believe the cause of this to be rocking of the barrel back and forth between the detector locations (the angular displacement between NI6 and NI5 is $-172°$, Fig. 2).

Table 2 summarizes the results obtained from CPSD analyses of the ex-core detectors, using NI5 lower as the reference detector in each case. In general, signals from detectors on the same side of the vessel as NI5 lower show small phase shifts relative to this reference, but detectors with a large angular displacement (opposite side of vessel) show phase shifts close to $-180°$. In all cases, the coherence over the frequency range from 0.04 to 1 Hz was high, indicating that all ex-core detectors are driven by a common noise source.

Earlier results from on-site analysis (ref. 2) showed that the coherence between ex-core and in-core detectors is low for frequencies below 1.0 Hz, but relatively high in the frequency range from 2 to 4 Hz. The noise in this latter frequency range is much less significant than the low-frequency noise caused by barrel rocking (Fig. 7).

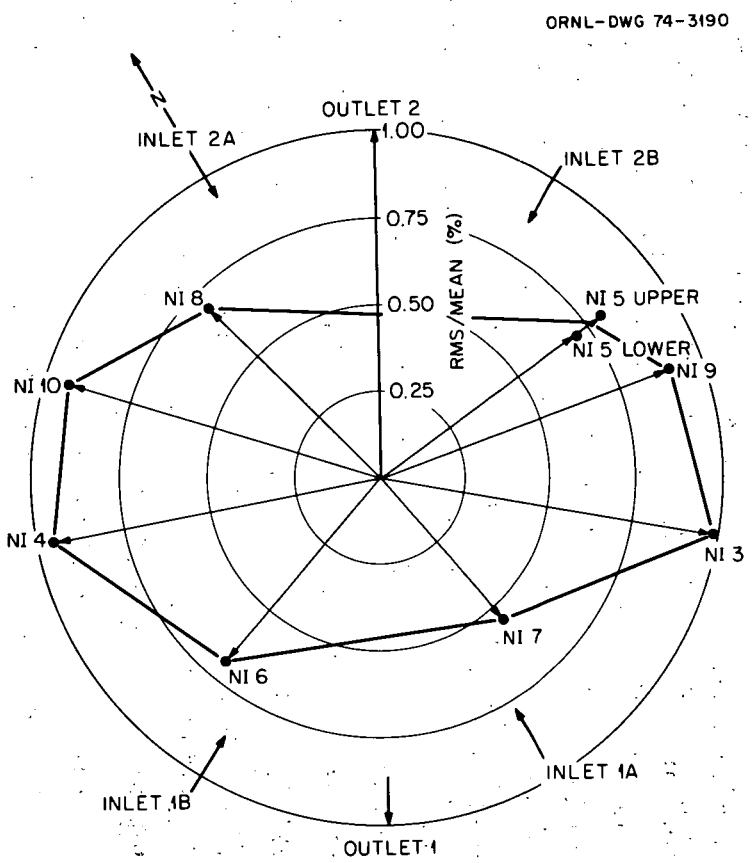

Fig. 8. Ex-core rms noise vs detector location (0.03–5 Hz).

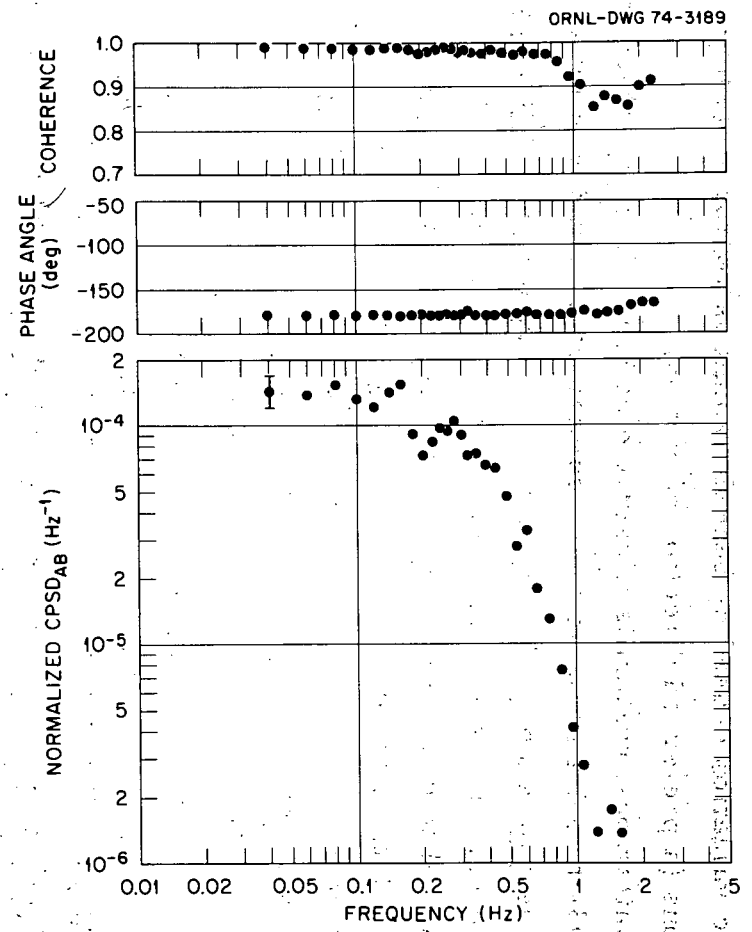

Fig. 9. CPSD analysis of NI6 vs reference detector NI5 lower.

Table 2. Results of cross spectrum analysis[a] of ex-core detectors using NI5 lower as reference detector

Detector B	$CPSD_{AB}$ $x10^4$	Phase(θ) (°)	Coherence	Angular circumferential displacement from NI5 lower (°)
NI5 Upper	1.99	−0.1	0.998	0
NI9	2.57	0.3	0.997	−26
NI3	1.88	1.5	0.985	−53
NI7	1.37	0.7	0.939	−77
NI6	1.45	−180.	0.985	−172
NI4	1.17	−180.	0.977	+145
NI10	1.77	−179.	0.969	+118
NI8	1.74	−178.	0.946	+89

[a]Analysis performed with center frequency of 0.04 Hz, resolution bandwidth of 0.02 Hz, and data record of 30 min.

4.5 Amplitude Probability Density

When signals containing spikes such as those in Fig. 3 are analyzed, the amplitude distribution of noise may provide an insight that cannot be obtained from spectral analysis. However, when computing the APD, one must consider that any filtering (both low- and high-pass) of the signal before it is processed can change the shape of the APD. Therefore, to maintain consistency, the signals were band limited to a range from 0.025 to 5.0 Hz (nearly the same as used for rms values of Table 1) before the APD was computed. Figure 10 shows a typical analysis of a detector signal (NI5 lower). Two observations can be made from this analysis:

1. The APD is not symmetric with respect to its mean value; i.e., there are larger positive (as high as 3.4% of the mean signal level) than negative (2.2%) amplitude deviations in the signal. This information implies that there is a preferred direction of motion toward NI5, with a net difference of +1.2%.
2. For 80% of the time the signal amplitude is in a range from −0.9 to +0.8% of the mean (this is the part of the APD between 10 and 90% on the IAPD, which we consider statistically reliable).

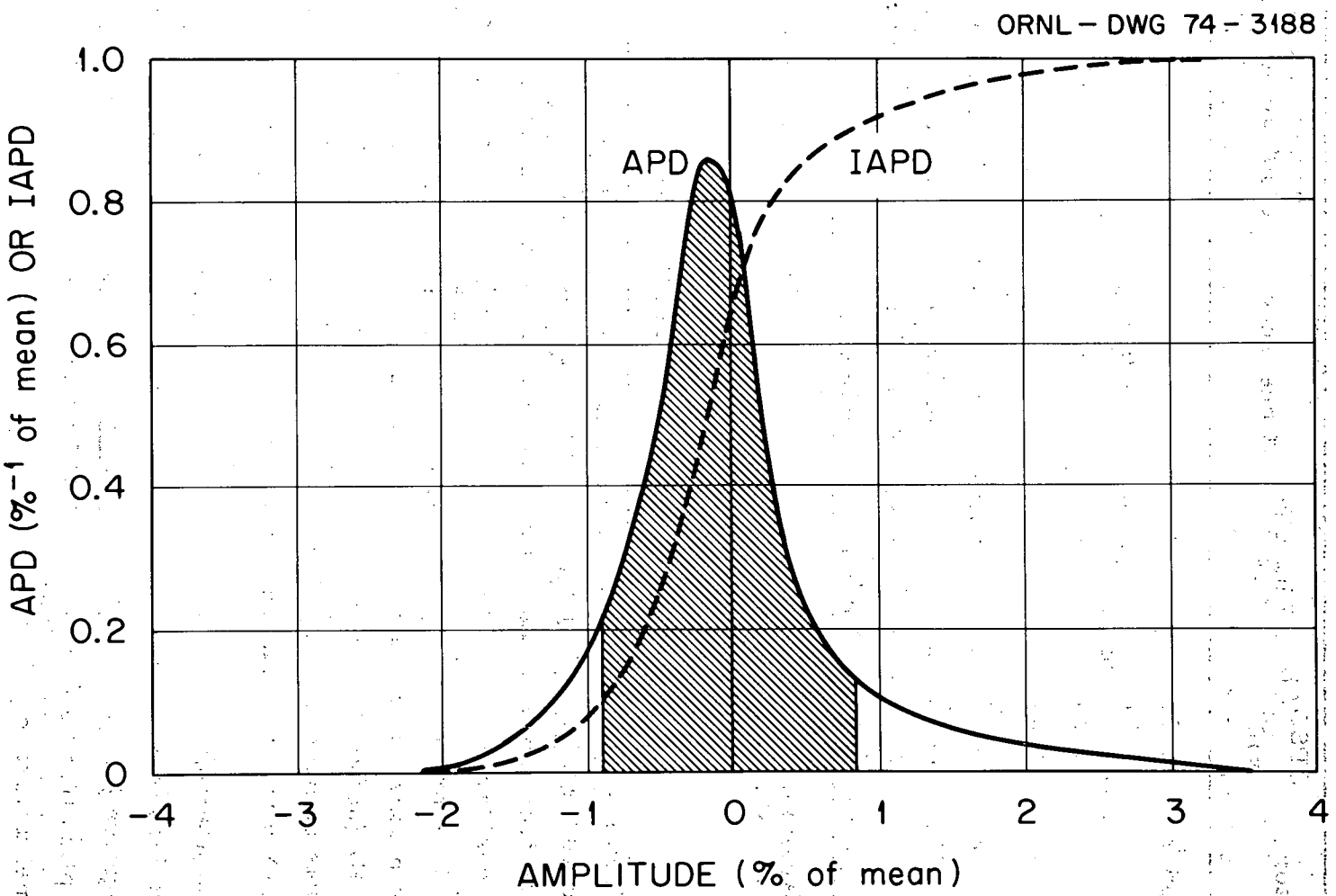

Fig. 10. Amplitude distribution analysis of NI5 lower signal for frequency range from 0.025 to 5 Hz.

Item 1, preceding, supports an assumption that the barrel is shoved toward detector NI5 by the hydraulic forces in the downcomer region between the vessel wall and barrel. The 80% probability, peak-to-peak oscillations were normalized by dividing by the rms noise for the same bandwidth which is given in Table 1. For example, using detector NI5 lower one gets

$$(80\% \text{ peak-to-peak})/\text{rms} = (0.91 + 0.82)/0.80 \simeq 2.2 . \qquad (5)$$

This ratio is comparable to a value of ~2.6 for a Gaussian noise distribution. The values of peak-to-peak amplitude/rms listed in Table 3 show that this quantity is not a sensitive indicator of barrel motion. The range of the quantity for the 12 detectors is only 2.1 to 2.8.

Table 3. Summary of APD analysis based on 30 min data record

Detector	Negative[a] amplitude (% of mean)	Positive[a] amplitude (% of mean)	Peak-to-peak[b] amplitude ÷ rms	Maximum negative amplitude (% of mean)	Maximum positive amplitude (% of mean)	Preferred direction of motion (% of mean)
NI5 Lower	−0.91	+0.82	2.2	−2.2	+3.4	+1.2
NI5 Upper	−0.92	+0.74	2.1	−2.8	+3.9	+1.1
NI9	−1.3	+1.1	2.5	−3.3	+4.4	+1.1
NI3	−1.2	+1.2	2.4	−3.5	+5.8	+2.3
NI7	−0.57	+0.61	2.1	−1.6	+2.4	+0.8
NI6	−1.0	+0.69	2.4	−3.6	+2.4	−1.2
NI4	−1.2	+0.86	2.1	−4.9	+2.6	−2.3
NI10	−1.3	+0.92	2.4	−4.9	+3.3	−1.6
NI8	−1.1	+0.84	2.8	−4.0	+3.0	−1.0
NI7-5	−0.23	+0.20	2.4	c	c	c
NI42-5	−0.20	+0.18	2.2	c	c	c
NI6-5	−0.20	+0.17	2.2	c	c	c

[a]Signal is between these amplitudes 80% of the time.

[b]rms values obtained from Table 1.

[c]Not computed.

The preceding APD analysis was performed on the 12 available detector signals, and the results are summarized in Table 3. The preferred direction of motion results seem to indicate that the barrel's natural resting point is the side of the vessel where detectors NI6, NI8, NI4, and NI10 are located and is randomly pushed toward detectors NI5, NI9, and NI3. The magnitude of movement could be calculated using numerical neutron transport computer codes. However, these calculations are beyond the scope of our present investigation.

5. SUMMARY AND RECOMMENDATIONS

The objective of this investigation, namely a documentation of abnormal noise signatures for Palisades, was accomplished. The signatures in this report serve as references with which to compare data taken after the Palisades plant resumes operation.

We recommend that follow-up data acquisition and analysis be performed after plant operation is resumed, using the same techniques and normalizations described in this report. The purpose would be to determine whether or not the core barrel motion has been eliminated.

We also believe that the neutron noise signatures associated with the movement of the core barrel in this PWR will be helpful in diagnosing similar abnormalities if they should occur in other PWR's.

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6. APPENDIX

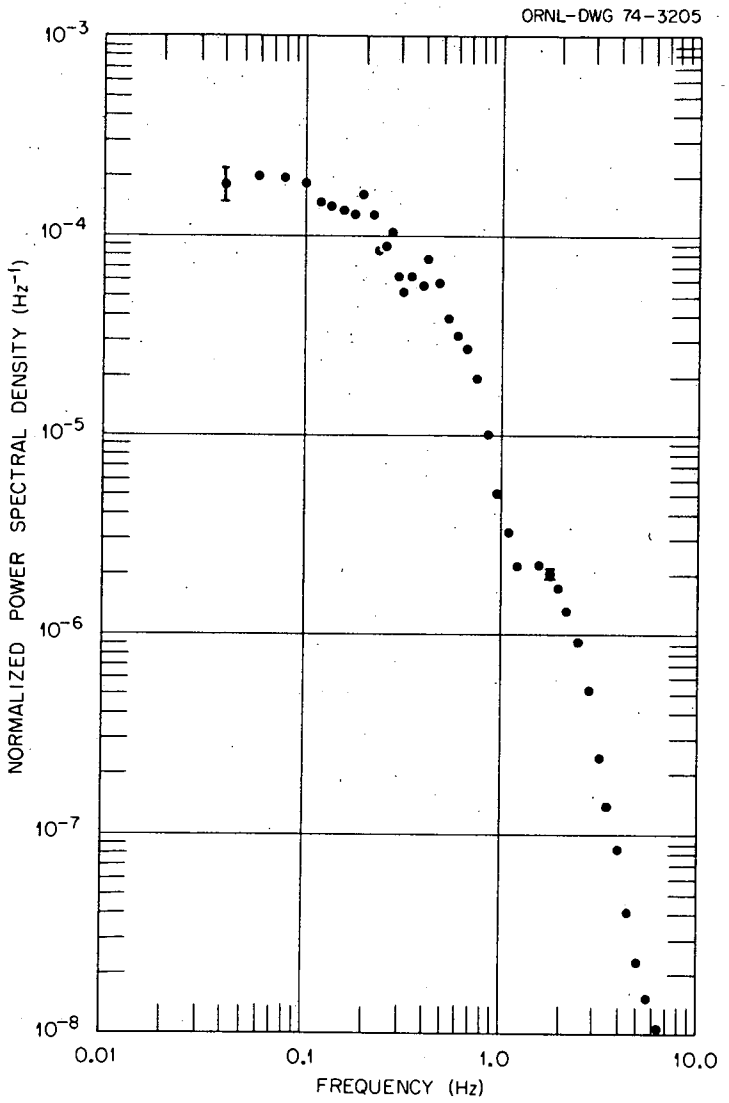

Fig. A1. Power spectrum of ex-core detector NI5 upper.

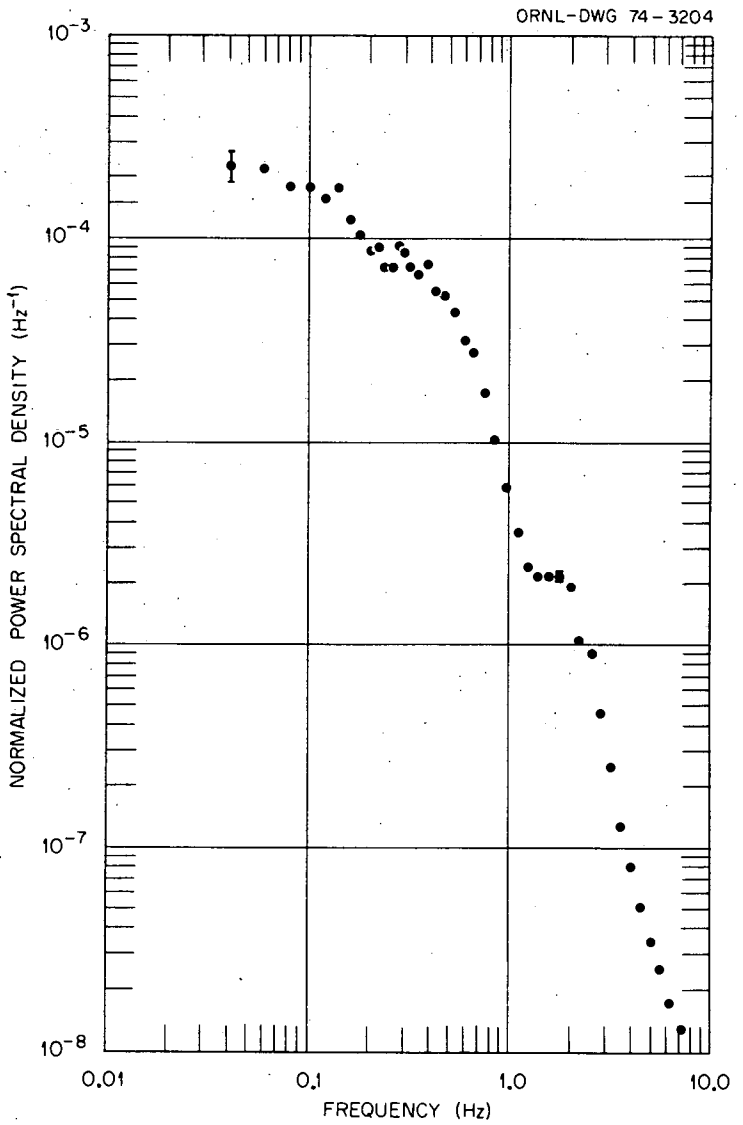

Fig. A2. Power spectrum of ex-core detector NI5 lower.

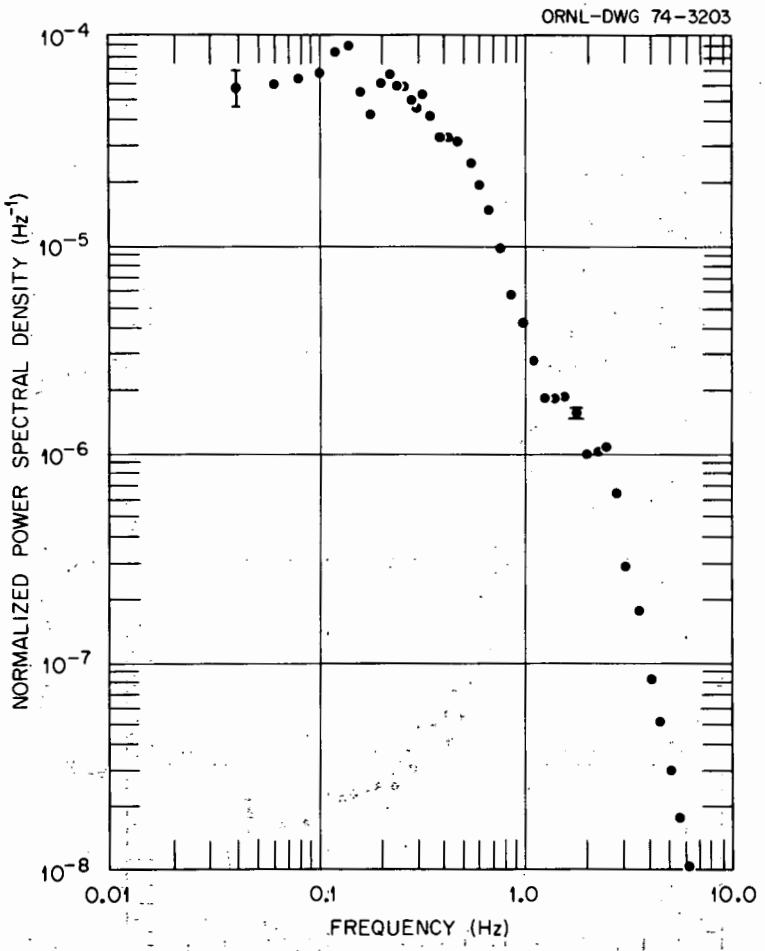

Fig. A3. Power spectrum of ex-core detector NI7.

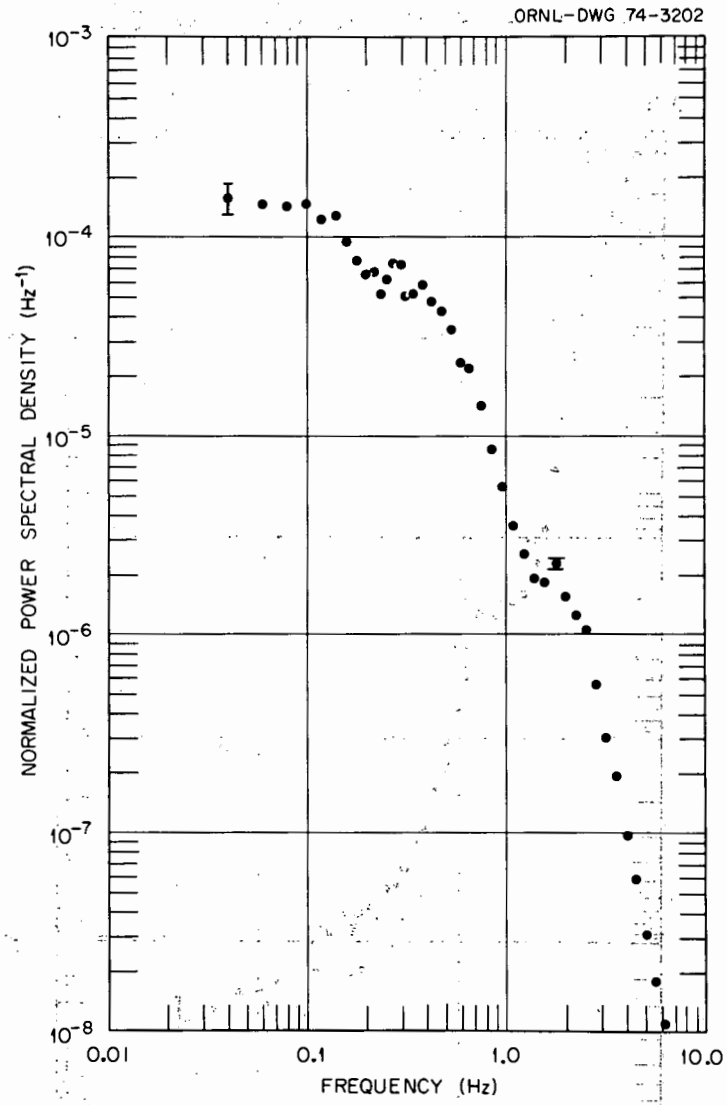

Fig. A4. Power spectrum of ex-core detector NI8.

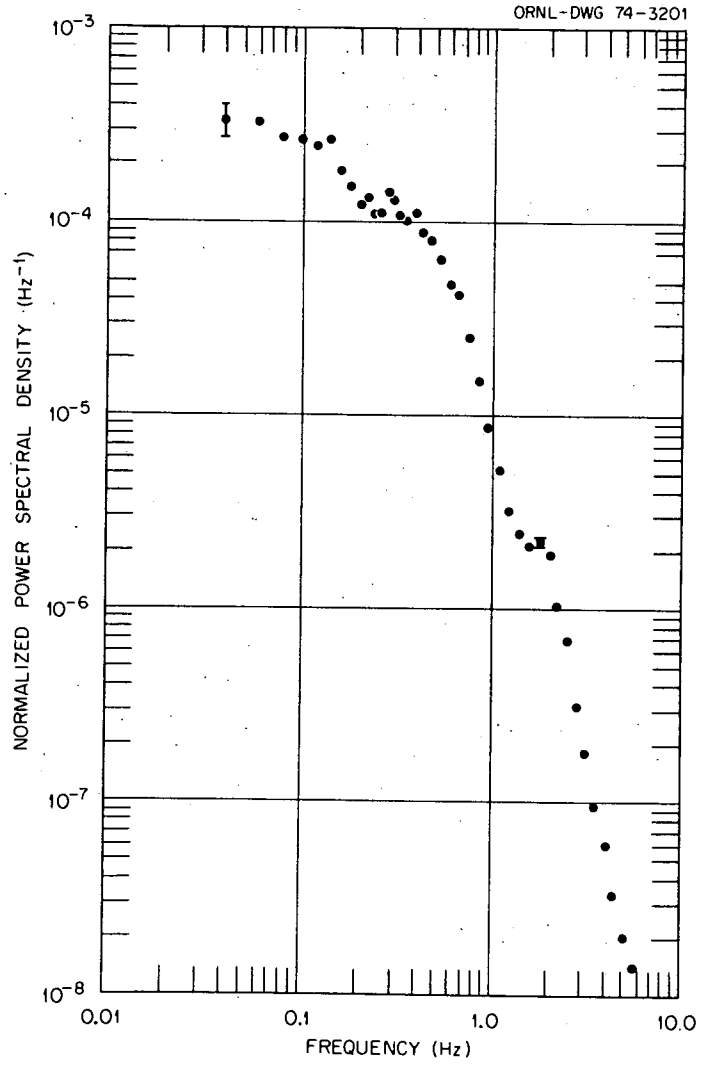

Fig. A5. Power spectrum of ex-core detector NI9.

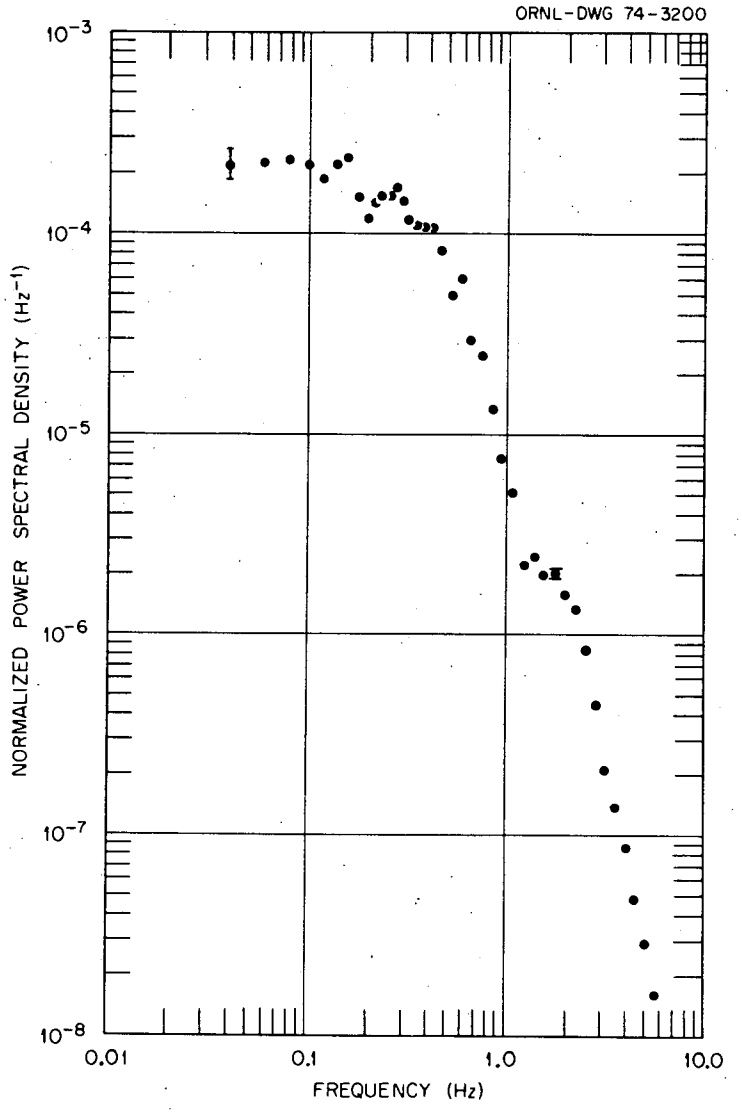

Fig. A6. Power spectrum of ex-core detector NI10.

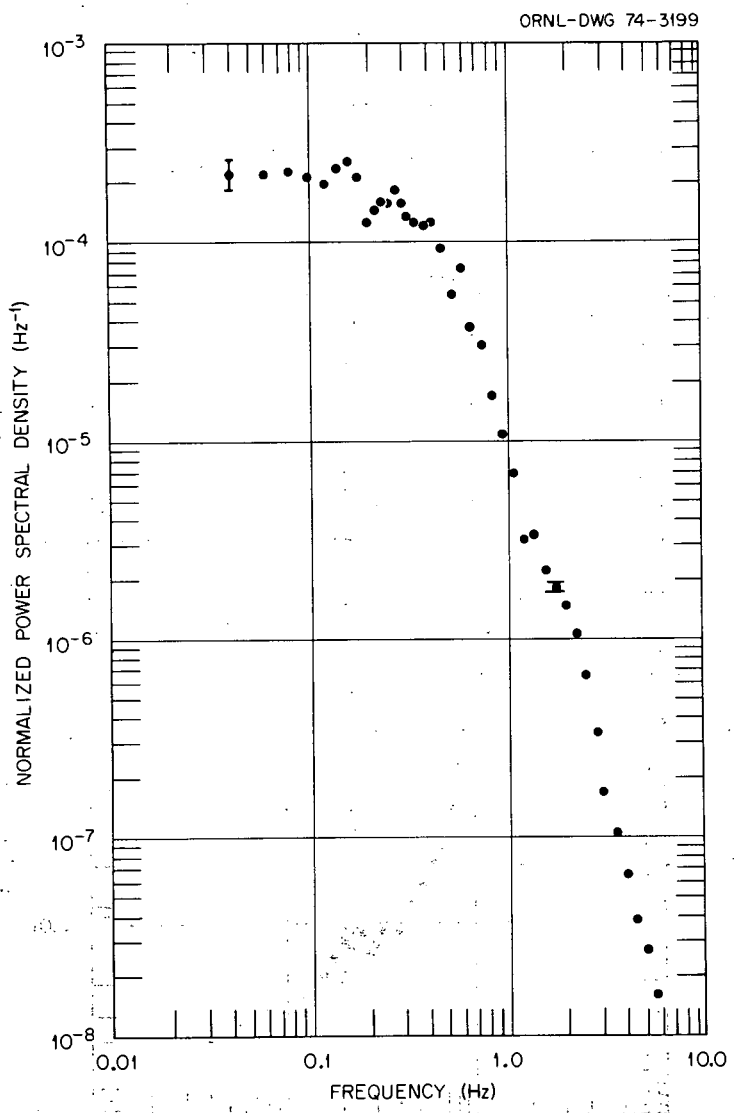

Fig. A7. Power spectrum of ex-core detector NI3.

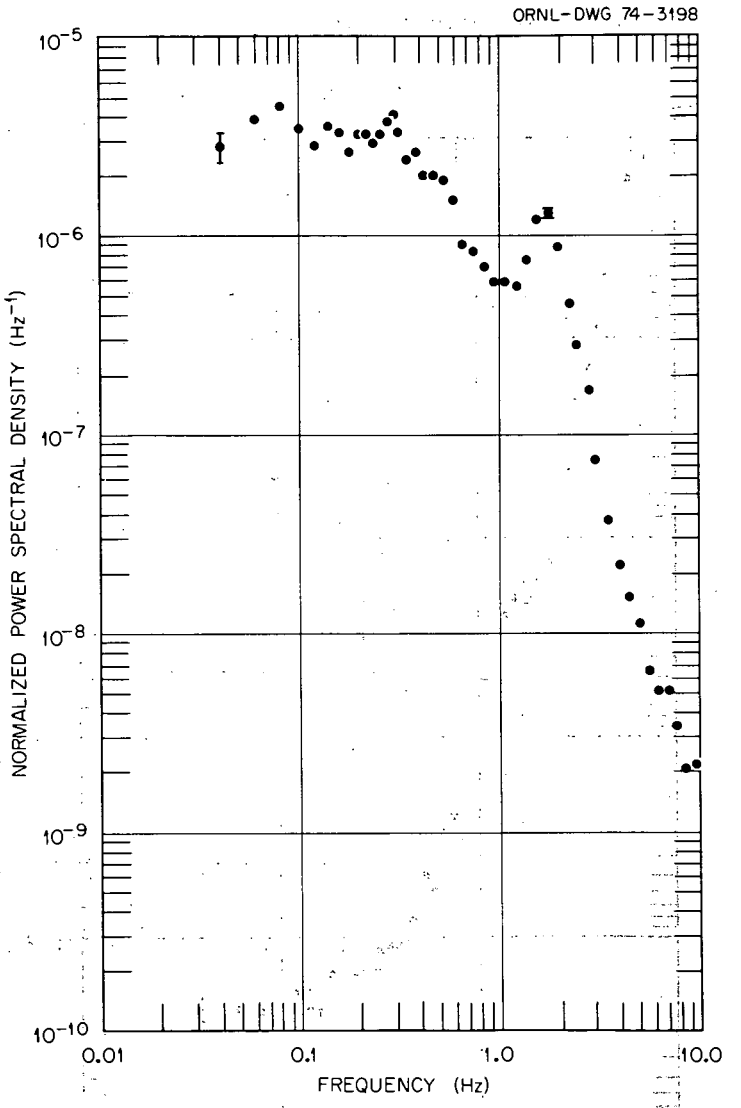

Fig. A8. Power spectrum of in-core detector NI7-5.

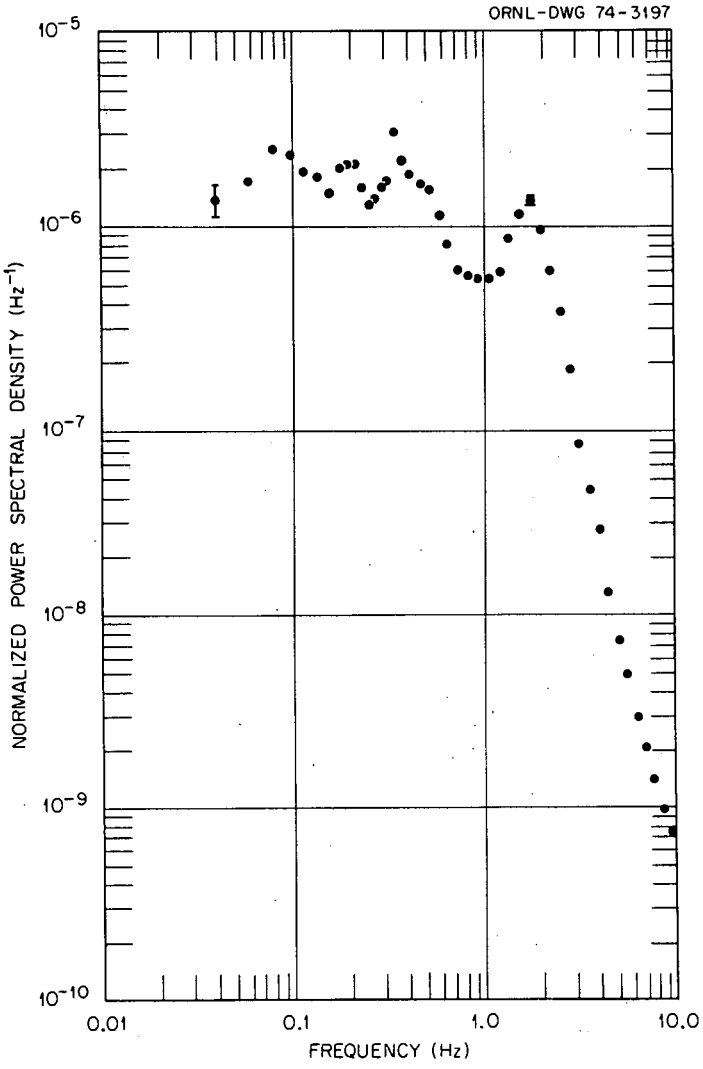

Fig. A9. Power spectrum of in-core detector NI6-5.

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