SEPTEMBER 1996

ECN-R--96-011

NL97F3981

energy innovation

POWER-LAW SPECTRA FOUND IN PLANT SIGNAL OF THE BORSSELE NPP

An Analysis Using Wavelet

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SEPTEMBER 1996

KS002143174
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ECN-R--96-011

DE009714542

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Application of Wavelet for wide-frequency range investigation and investigation (spectrum) for the secondary system signals.

Revisions		
A	Draft for internal verification	
B	Draft for internal review	
1	Final	
Made by: E. Türkcan Author	**Approved by:** H. Gruppelaar	ECN-Nuclear Energy Section Applied Physics (TF)
Checked by: W.P. Voorbraak Section Leader	**Issued by:** E. Türkcan	

Acknowledgement

The authors would like to thank N.V. Electriciteits-Productiemaatschappij Zuid-Nederland EPZ for permission of releasing the operating NPP's data used in this presentation for research purposes.

Abstract

Power-law spectra were found in the temperature signals of the secondary loop in the Borssele Nuclear Power Plant, a PWR in the Netherlands. The coolant temperature before the steam generator inlet was found to fluctuate such that its power spectrum density S, follows $S \sim f,^{-\alpha}$ where α is ~4/3. Analyses using PSD suggested that the value of α is roughly constant over years. Detailed analyses were conducted using wavelet, with the discovery that that the power-law appears constantly only at around 0.1 Hz, and the estimated α was found between 1.26 and 1.36. The feedwater pressure signal and feedwater flow rate signal in the same frequency range were white noise and Brownian motion respectively, and the indication of $\alpha = 4/3$ was not found from them.

Keywords

Borssele Nuclear Power Plant, Wavelet analysis, Power-law spectra, Feedwater temperature

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1. INTRODUCTION

The random process with a power-law spectrum can be observed in various forms, such as; electric current and voltage in electronic equipment, electric resistance of certain materials, traffic flow, economic and meteorological data, and even in music. Constructing those models has been a nontrivial problem and has met with little success so far.

This report introduces another example of the process in thermohydraulic flow. The coolant temperature of the secondary loop in a nuclear power plant (NPP) was found to fluctuate following a power-law. Needless to say, the plant was properly regulated with constant generator output and, therefore, the temperature should have been regulated as its signal would be composed of a constant value and small amplitude of stochastic noise.

In this report the temperature signal is roughly illustrated in Chapter 2, and the power-law of interest is identified. Wavelet methodology which is suitable for wide-frequency range exploration, is applied for the detailed analysis in Chapter 3, and concluding remarks given in Chapter 4.

2. OUTLOOK OF THE TEMPERATURE SIGNAL

The Borssele NPP, the pressurized water reactor (PWR) plant in the Netherlands was built by KWU in 1974, and has a nominal electrical power of 477 MW. See Table 1 for more detailed information on the plant.

Figure 1 is a schematic of the plant; there are two cooling systems (Loop 1 and Loop 2) of the reactor and two steam generators (SG 1 and SG 2) which feed steam to the turbine. The condenser feeds water back to the two steam generators. In these feedwater lines, the feedwater temperature (FWT) fluctuated with the peculiar characteristics shown below.

Table 1: *Borssele PWR System Information*

Electrical power rating	477 MW
Thermal power rating	1370 MW
Number of fuel assemblies	121
Active core height	2.65 m
Core diameter	2.68 m
U-235 enrichment	
41 assemblies	2.5 %
40 assemblies	2.8 %
40 assemblies	3.1 %
Prompt neutron lifetime	2.2 x 10-5 s
Delayed neutron fraction	0.007
Boron concentration	
at beginning of the cycle	2200 ppm
Coolant inlet temperature	295.4°C
Coolant outlet temperature	319.4°C
Total fuel-to-coolant heat transfer area	219.93 m^2
Fuel specific heat capacity	340 J/kg°C
Fuel-to-coolant heat transfer coefficient	3.04 W/(cm^2°C)
Core coolant flow rate	9200 kg/s
Average core coolant flow velocity	4.28 m/s
Water volume	8.937 m^3
Specific gravity of water	0.795
Mass of UO_2 per assembly	355 kg
Total mass of one assembly	500 kg
Fuel temp. coef. of reactivity	max -1.7 pcm/°C min -3.2 pcm/°C
Moderator temp. coef. of reactivity	max -5 pcm/°C min -40 pcm/°C

Figures 2 and 3 display the time-series data for the FWT signal in different time scales; the upper graph shows data ten times longer than the lower graph. The two graphs with different time scales can hardly be distinguished, that is, the data has a self-similar (or fractal) character. In other words, characteristics of the signal do not change with respect to the cut-off frequency of the low-pass filter. Consequently its power spectral density (PSD) has a power-law such as

$$S \sim f^{-\alpha} \qquad (2.1)$$

where S is a PSD, f is a frequency and α is a certain positive value. Figure 4 shows the PSDs of FWT signals. The value of α is , in this case, $\sim$4/3, and is evaluated in more detail in Chapter 3.

For detailed analyses five sets of the NPP operation signals recorded on different dates were chosen, and are labelled Record A, B, C, D and E in the following. Each was recorded under full power and normal conditions. See Table 2 for information on the records.

Table 2: *Operation data sets used for the analyses*

Record	date	fuel cycle	data length (s)
A	94-DEC-30	21st	32768
B	95-MAR-23	22nd	4096
C	95-MAY-3	22nd	4096
D	95-AUG-11	22nd	32768
E	95-OCT-16	22nd	32768

Unfortunately the analyzer setting of FWT for SG1 was not properly adjusted, and so the signals of FWT, only for SG2 in the Records are analyzed, but we believe there should not be much difference from the signals measured in a different feedwater line as seen in Fig. 4.

The PSDs of the FWT signal for each Record are shown in Figs. 5-9. All graphs look almost linear, and their α-values are close to 4/3. The power law, consequently, seems to appear almost constantly.

3. EXAMINATION OF POWER-LAW USING A WAVELET SPECTRUM

It is also possible to achieve smoother PSDs than those shown in Figs. 5–9, by using a smaller lag-window for the FFT calculation, but in that case the frequency range of graphs gets narrower. Therefore it is always necessary to compromise some smoothness of the PSD graph which bars accurate evaluation of the power-law. The wavelet spectrum introduced below, however, can overcome this problem.

The wavelet spectrum E_j, is defined as

$$E_j = \sum_k |\alpha_{j,k}|^2 \quad , \tag{3.1}$$

where $\alpha_{j,k}$ is a wavelet coefficient. The subscript j is an index for frequency (or for resolution) , and E_j can be rewritten as a function of f; say $E(f)$. If $E(f)$ has a power law such as

$$E(f) \propto f^{-\beta} \quad , \tag{3.2}$$

then

$$\alpha = \beta + 1 \tag{3.3}$$

is satisfied. Then it is accordingly possible to estimate α by calculating the wavelet spectrum of time-series data. The technique used here is exactly the same as the one introduced in Ref. [1], and briefly explained in Appendix A.

The wavelet spectra for Records A-E are shown in Figs. 10–14. The most remarkable point learned from these graphs is that the spectra are not as linear as would be expected from the PSDs (see also Figs. 5–9). A comparison of the two methodologies therefore suggests that small deviations from linearity are not noticeable in the PSD graphs because of roughness. For example, the wavelet spectrum for Record C (Fig. 12) has a fairly narrow frequency range of power-law, which exists only around 0.1 Hz. Another remarkable evidence from Figs. 10–14, is that the dynamics at ~0.1 Hz always gives a power-law spectrum.

The estimated β values are displayed in each graph with fitted line, and change between 0.26 – 0.36, i.e., 1.26 – 1.36 for α. The change of the α-value does not seem systematic with respect to time.

Finally, the feedwater pressure (FWP) and feedwater flow rate (FWF) signals, which are the two closest signals to FWT were examined in the hope of finding a physical explanation of the power-law. For this purpose Record A was selected, because it has the widest power-law range and should include dynamics typical for the power-law, if any. The PSDs of FWP signal for SG 1 and 2 are shown in Fig. 15; Both signals look almost white around the frequency range of ~0.1 Hz. More exact values of α are estimated by the wavelet spectrum in Fig. 16; they are -0.04 (β = -1.04) and 0.09 (β = -0.91) for SG 1 and SG 2 respectively. The PSDs for the FWF signal in the same frequency range has the power of ~-2 (see Fig. 17). Their wavelet spectra show α = 2.00 and 2.01 for the FWF signals of SG 1 and SG 2 respectively.

White noise can be ascribed to a pure random process and the noise with $\alpha = 2$ is called Brownian motion explained by a time-integral of white noise; hence these two kinds of noise can be understood in mathematical terms. It is not possible to compose the signal with $\alpha = 4/3$ of white noise and Brownian motion, and the explanation of FWT dynamics is probably complicated.

4. CONCLUDING REMARKS

The feedwater temperature of the secondary loop fluctuated such that the power spectrum satisfies a power-law. Analyses using wavelet spectrum showed that the power law appears constantly at around 0.1 Hz, and estimated the power between -1.26 and -1.36, something which cannot be explained by simple stochastic process. The feedwater pressure signal and feedwater flow rate signal also have a PSD with a power-law in the same frequency range, but these powers were estimated at zero and two, which can be explained by simple stochastic process.

REFERENCES

[1] M. Yamada and K. Ohkitani: *An Identification of Energy Cascade in Turbulence by Orthonormal Wavelet Analysis*, Prog. Theor. Phys. 86, 4, 799(1991).

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APPENDIX A. POWER-LAW WAVELET SPECTRUM

In a Fourier analysis, the time function $u(t)$ is decomposed into the sum of sinusoidal functions, which is localized in the frequency domain, such as

$$u(t) = \sum_s a_s e^{2\pi i f s t} \quad , \tag{A.1}$$

where a_s is the Fourier coefficient. In wavelet analysis, however, $u(t)$ is decomposed into the wavelet $\Psi_{j,k}(t)$, which is localized in both time and frequency domain, such as

$$u(t) = \sum_j \sum_k \alpha_{j,k} \Psi_{j,k} \quad , \tag{A.2}$$

where $\alpha_{j,k}$ is called a wavelet coefficient. Unlike a sinusoidal function, it is possible to define many kinds of wavelets, and Meyer's wavelet is adopted in this study. In the case of Meyer's wavelet

$$\Psi_{j,k}(t) = 2^{j/2}\Psi(2^j t - k) \tag{A.3}$$

is satisfied, where $\Psi(t)$ is called a mother wavelet (of Meyer's wavelet): $\Psi(t)$ cannot be expressed explicitly and its detail is found in Ref. [1]. For Meyer's wavelet, $\Psi_{j,k}(t)$ is localized in the frequency domain between $2^j/3$ and $2^{j+2}/3$ Hz (see Ref. [1]). Therefore the wavelet spectrum E_j expressed by Eq. (3.1) is understood as an integral of the signal's power between $2^j/3$ and $2^{j+2}/3$ Hz:

$$E_j = S(f)\left(\frac{2^{j+2}}{3} - \frac{2^j}{3}\right) = 2^j S(f) \quad . \tag{A.4}$$

The center frequency of $\Psi_{j,k}(t)$ is

$$f = \left(\frac{2^{j+2}}{3} + \frac{2^j}{3}\right)/2 = 2^j \frac{5}{6} \approx 2^j \quad . \tag{A.5}$$

By substituting 2^j with f in Eq. (A.4), we have

$$E(f) \approx f S(f) \quad . \tag{A.6}$$

By using Eq. (2.1), we finally have

$$E_j \propto f^{-(\alpha-1)} \quad , \tag{A.7}$$

which leads to Eq. (3.3).

APPENDIX B. FIGURES

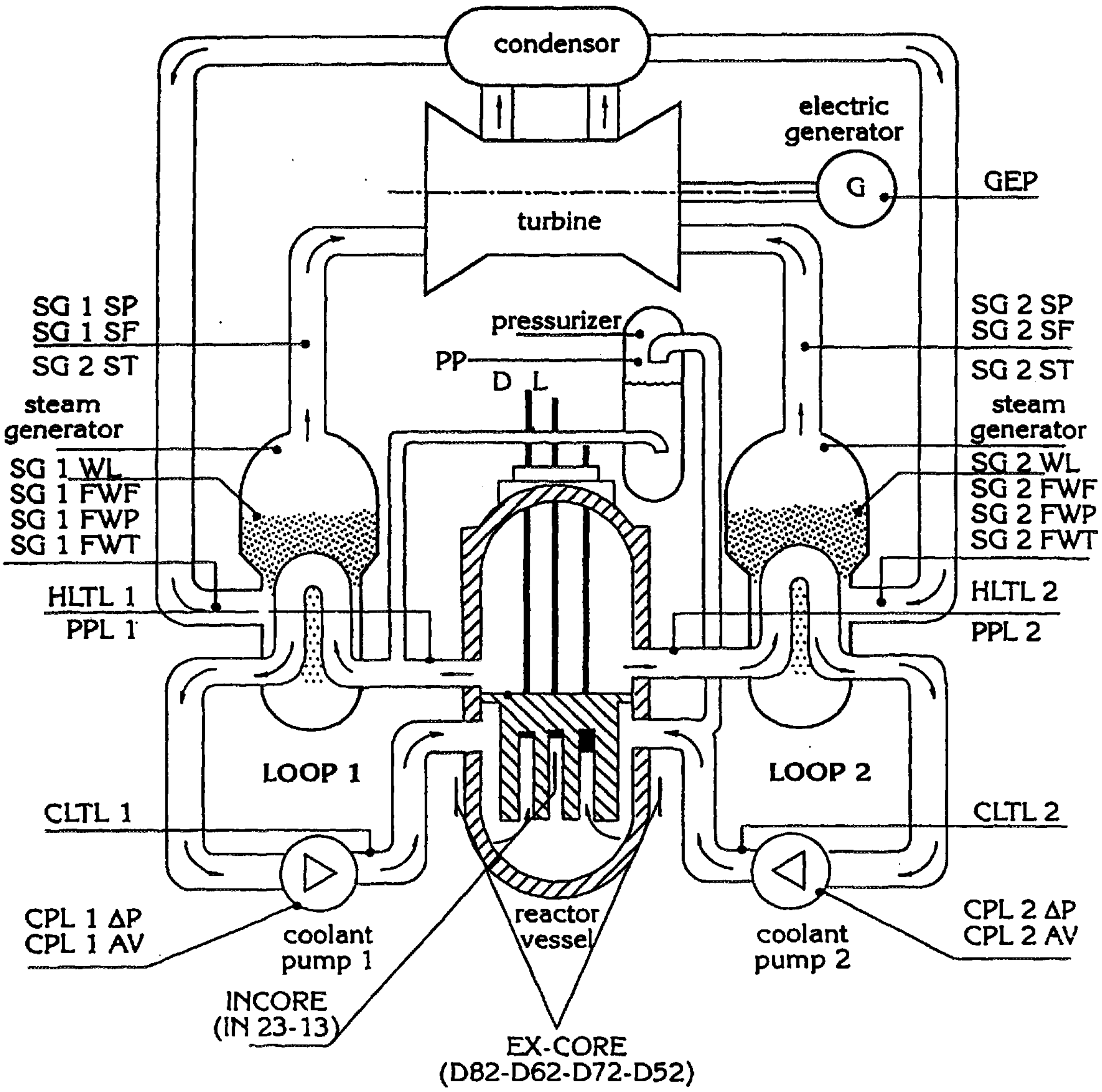

Fig.1: *Schematic of the Borssele NPP and measured signals*

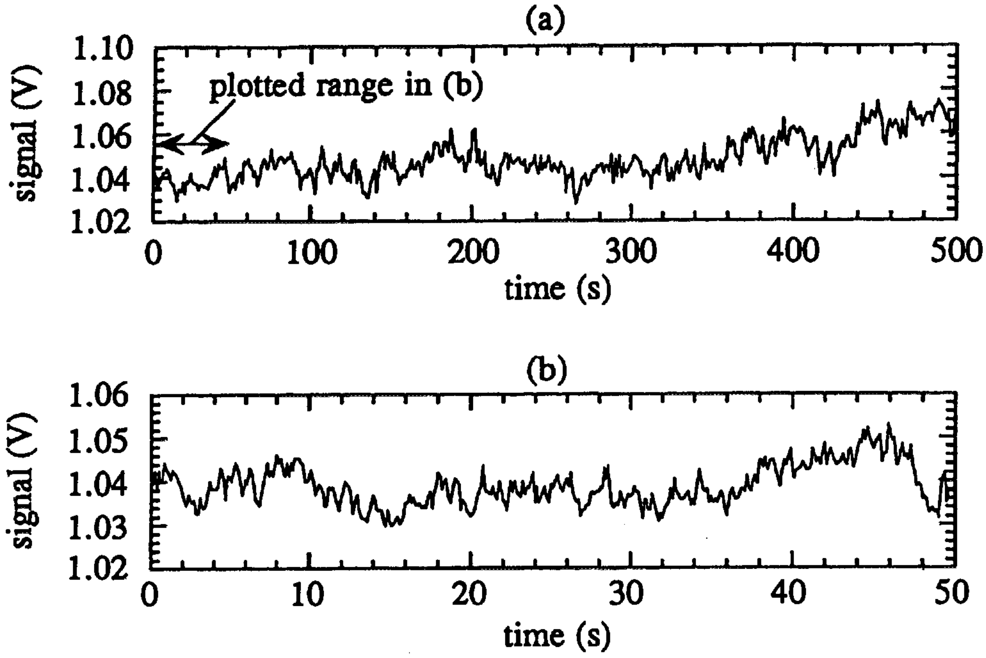

Fig.2: *Self-similarity of the temperature signal measured at feedwater to SG 1*

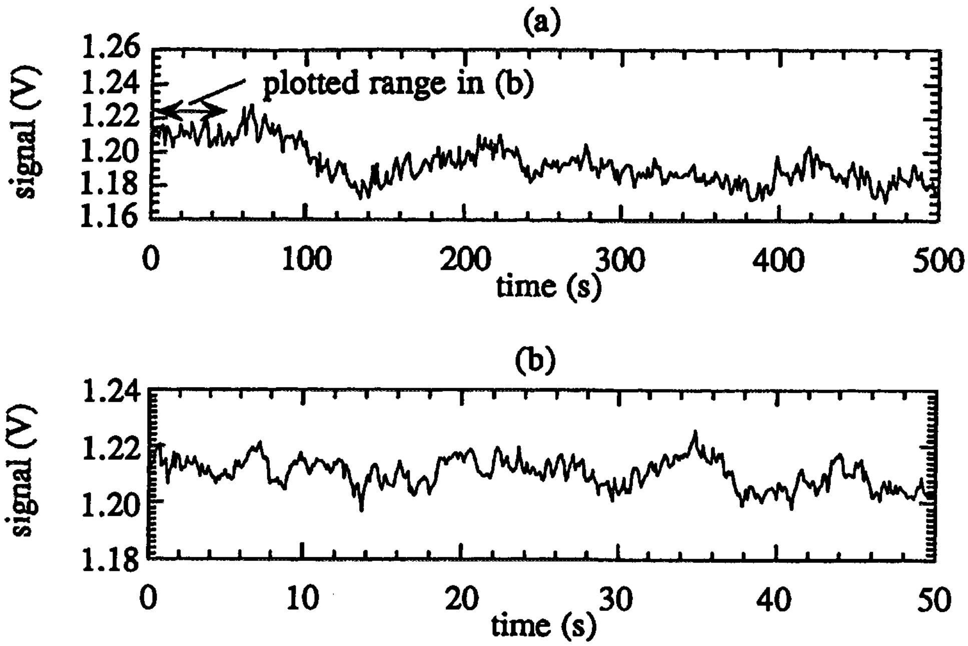

Fig.3: *Self-similarity of the temperature signal measured at feedwater to SG 2*

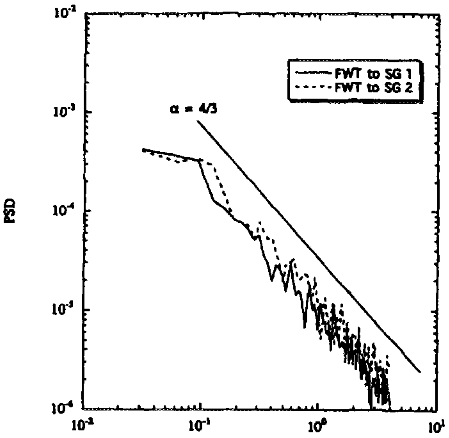

Fig.4: *PSD of the feedwater temperature (FWT) signal*

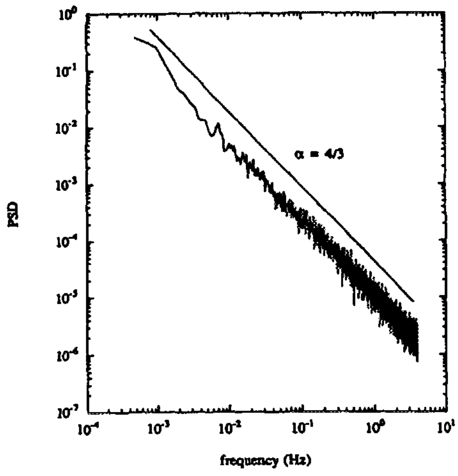

Fig.5: *PSD of feedwater temperature signal for Record A*

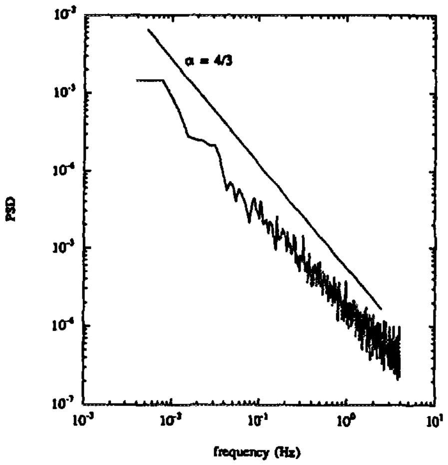

Fig.6: *PSD of feedwater temperature signal for Record B*

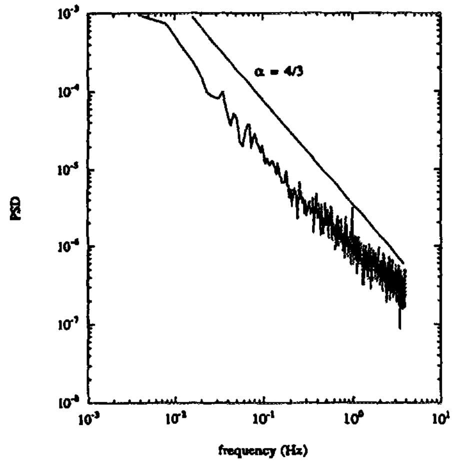

Fig.7: *PSD of feedwater temperature signal for Record C*

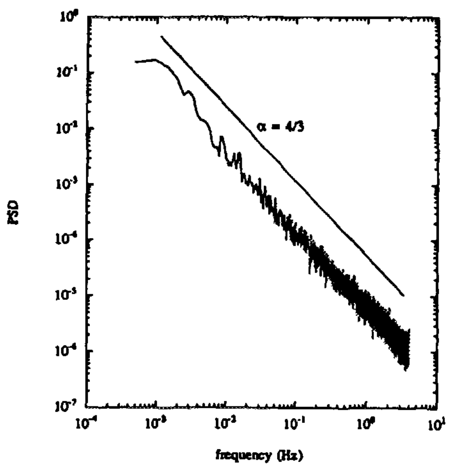

Fig.8: *PSD of feedwater temperature signal for Record D*

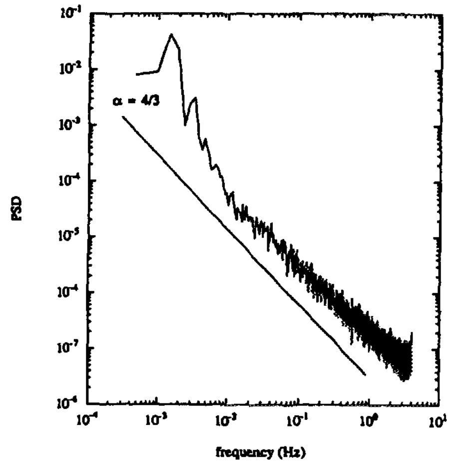

Fig.9: *PSD of feedwater temperature signal for Record E*

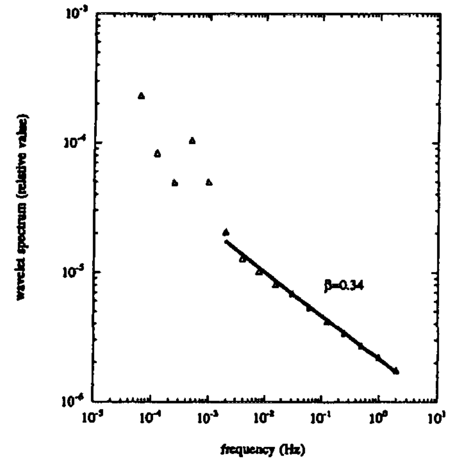

Fig.10: *Wavelet spectrum of feedwater temperature signal for Record A and its fitted line*

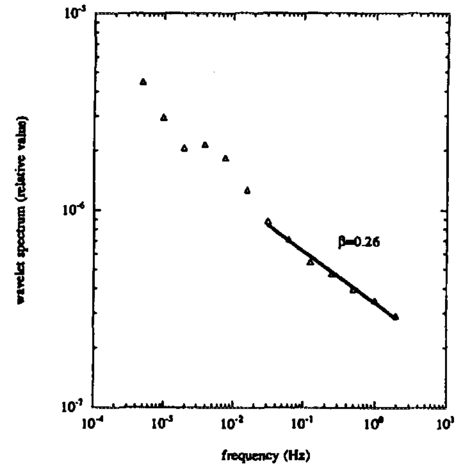

Fig.11: *Wavelet spectrum of feedwater temperature signal for Record B and its fitted line*

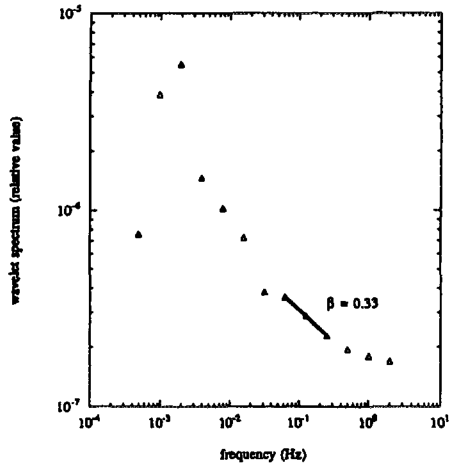

Fig.12: *Wavelet spectrum of feedwater temperature signal for Record C and its fitted line*

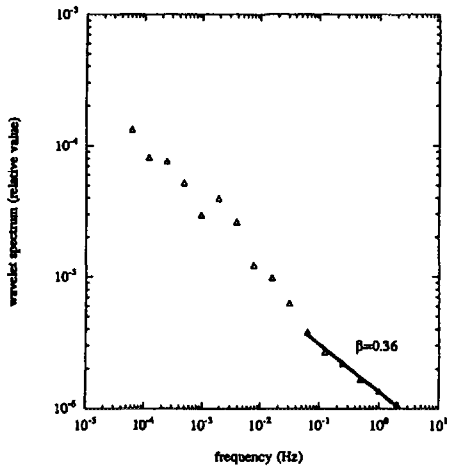

Fig.13: *Wavelet spectrum of feedwater temperature signal for Record D and its fitted line*

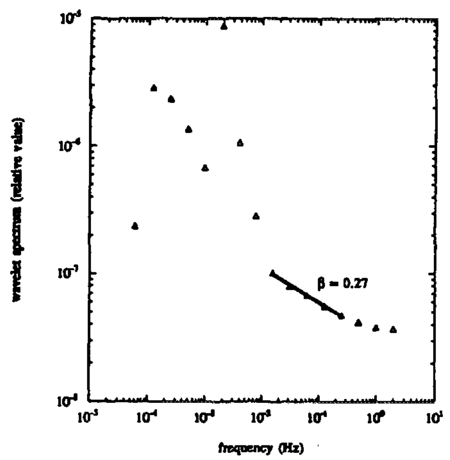

Fig.14: *Wavelet spectrum of feedwater temperature signal for Record E and its fitted line*

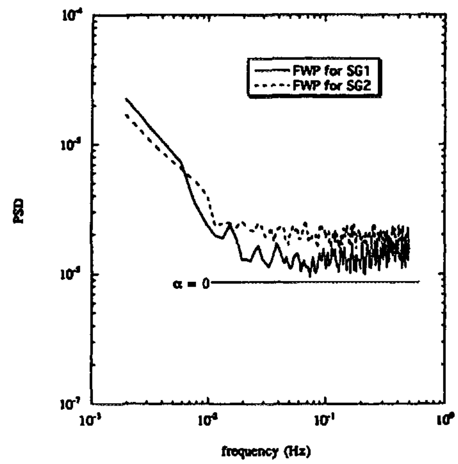

Fig.15: *PSD of the feedwater pressure (FWP) signal*