REACTOR NOISE ANALYSIS APPLICATIONS IN ONTARIO HYDRO: A STATISTICAL MEASUREMENT TECHNIQUE FOR VALIDATING INSTRUMENTATION DYNAMICS

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ABSTRACT

Reactor noise analysis is a non-intrusive statistical technique regularly used in surveillance and diagnostics tasks. Valuable information on reactor system dynamics can be extracted from the fluctuations of instrumentation signals measured during steady-state operation. The small and measurable fluctuations of process signals are the results of stochastic effects inherent in physical processes, such as heat transfer, boiling, coolant flow turbulence, fission process, structural vibrations and pressure oscillations. The goal of reactor noise analysis is to monitor and assess the conditions of technological processes and their instrumentation in the nuclear reactor in a non-intrusive passive way. The reactor noise measurements are usually performed at steady-state operation, while the availability of the signals in their respected systems (e.i. shutdown systems, regulating system) is not interrupted.

This paper discusses some of the recent applications of reactor noise analysis in Ontario Hydro's CANDU stations, related to the dynamics of in-core flux detectors (ICFDs) and ion chambers. These applications include (1) detecting anomalies in the dynamics of ICFDs and ion chambers, (2) estimating the effective prompt fractions of ICFDs in power rundown tests and in noise measurements, (3) detecting the mechanical vibration of ICFD instrument tubes induced by moderator flow, (4) detecting the mechanical vibration of fuel channels induced by coolant flow, (5) identifying the cause of excessive signal fluctuations in certain flux detectors, (6) validating the dynamic coupling between liquid zone control signals, (7) estimating the response time and the dynamic transfer functions of flow transmitters and temperature detectors.

INTRODUCTION

In 1992 an extensive program of reactor noise analysis was initiated in Ontario Hydro to develop noise-based statistical techniques for monitoring process and instrumentation dynamics, diagnostics and early fault detection. Since then, various CANDU-specific noise analysis applications have been developed and validated. The noise-based statistical techniques are being successfully applied as powerful troubleshooting and diagnostic tools to a wide variety of actual operational I&C problems. The dynamic characteristics of certain plant components, instrumentation and processes are monitored on a regular basis. A comprehensive "noise survey" of detector signals from the standard instrumentation of Pickering-B, Bruce-B and Darlington units have been carried out in the past six years at various operating conditions. Also, recommended standards and procedures for regular noise measurements have been developed. In these measurements the feasibility of applying noise analysis techniques to actual operating data has been clearly demonstrated. The results indicated that the detection and characterization of instrument and process failures, and validation of process signals and instrument functionality can be based on the existence of certain multi-channel complex patterns of statistical noise signatures derived from the measured reactor noise signals.

Multi-channel PC-controlled analog data acquisition hardware and signal processing software capable of carrying out 48-channel noise measurements have been developed and regularly used in station noise measurements. The custom-built signal conditioning and data acquisition hardware (isolation buffer amplifiers, filters, DC-compensators. noise amplifiers, ADC boards) are fully software-controlled. The procedure for safely connecting analog station signals from the two shutdown safety systems (SDS1 and

SDS2), the reactor regulating system (RRS) and the fully instrumented fuel channels (FINCH) to the noise measuring hardware has been established. Long term noise measurements can be carried out with no interference with the normal operation of the plant. The PC-based off-line signal processing software includes FFT-based multi-channel spectral analysis, multivariate autoregressive (MAR) modelling for cause-and-effect analysis and response time estimation, and sequential probability ratio tests (SPRT) of MAR-based residual time series for fault detection. A newly designed portable noise analysis system has been developed in AECL Chalk River Laboratories, which will eventually replace the current system and will transfer the technology to the stations [1]. In the present configuration, the new noise analysis system consists of two identical data acquisition units. Each unit is capable of sampling 16 signals simultaneously at a maximum sampling frequency of 2.4 kHz with 16-bit ADC resolution. The two units have optically isolated inputs, and they can be run in synchronized modes. The built-in analysis software offers a user friendly access to statistical spectral calculations and graphical presentation of results.

VALIDATING IN-CORE FLUX DETECTOR DYNAMICS BY NOISE ANALYSIS

One of the most important applications of reactor noise analysis in Ontario Hydro's CANDU units is the confirmation of the functionality and dynamic response of in-core flux detectors and their amplifiers. The validation is based on the signatures of intersignal spectral functions characterizing the statistical coupling between detector signal fluctuations measured simultaneously. The first in-core neutron flux noise measurements in Ontario Hydro's power plants at full-power operation were performed in early 1992 at Units 6, 7 and 8 of Pickering-B [2]. Further in-core neutron noise measurements were carried out in all units of Darlington and Pickering-B and in two units of Bruce-B between 1992 and 1998 [3,4]. Noise signals from regular in-service and spare ICFDs (self-powered flux detectors with Platinum, Inconel or Vanadium emitters) of SDS1, SDS2, RRS and Flux Mapping systems were measured at full-power normal operation before scheduled reactor outages. The results showed that neutron noise signals contained process related dynamic information in the frequency range of 0-20 Hz. This indicates that the detectors are "alive" and capable of following the small but fast fluctuations in the neutron flux around its static value, even after 12 years of continuous service in the Pickering-B units.

In Pickering-B periodic and systematic noise measurements of all in-core flux detectors used in the shutdown systems and the reactor regulating system are carried out on a regular basis to confirm that the detectors meet their transient response requirements. The statistical noise signatures characterizing the normal detectors were learned for all vertical and horizontal detectors, regular and spare detectors in all reactor units. A large database of signatures has been established in terms of auto power spectral density (APSD), coherence and phase functions, and MAR-models of detector noise signals. Abnormal signatures indicating the degradation of detectors/instrumentation dynamics can be readily identified. In 1992 one of the in-core flux detectors of RRS channel B in Pickering-B Unit 6 was identified as degraded based on its unusual noise characteristics and low coherence with other ICFD noise signals. The same detector was found to be degraded in the subsequent reactor rundown test as well. In 1994, two more detectors were found to have degraded dynamics through the noise analysis surveillance program. Based on the noise analysis results, the detectors have been declared failed by the station's engineering staff. In other cases, detectors previously declared to be unavailable, were cleared by noise analysis and put back in service. Also, in-core flux detectors with low insulation resistance ($<$ 100 kOhm) were confirmed to be still operational.

The multi-channel statistical characteristics of noise signals from specific groups of normal ICFDs display certain patterns, which can be learned from noise measurements under normal conditions. Each of the following groups of detectors has specific statistical coupling between their noise signals, in terms of coherence and phase functions: (1) ICFDs located in the same vertical detector tube, (2) ICFDs located in the same horizontal detector tube, (3) ICFDs lined up along the same set of fuel channels, and (4) ICFDs and liquid zone level indicator located in the same zone. The known spatial dependency of normal noise coupling signatures is used to detect anomalies and validate the dynamics of newly installed instrumentation.

Noise measurements were used in the recent commissioning of new HESIR in-core flux detectors installed in Pickering-B Unit 6 in March 1996. Noise signals of SDS2 ICFDs were recorded at 60% of full power and were analyzed off-line. The multi-channel noise signatures of all SDS2 ICFDs were found to be normal. Evidence of a normal level of detector tube vibrations and fuel channel vibrations were also detected in the ICFD noise statistics [5]. After the noise measurements, the response signals of all SDS1/SDS2 HESIR in-core flux detectors and SDS1/SDS2 ion chambers to an SDS1-induced trip from 60% of F.P. were recorded and processed. The effective prompt fractions of all ICFDs, estimated from their trip response signals, were found to be above 90%. Detailed results of the rundown test are given in [6].

Multi-channel measurements of ICFD and ion chamber noise signals are also used to estimate the relative prompt fraction of ICFDs. The noise-based estimation of ICFD relative prompt fractions can be calibrated either to the absolute prompt fraction of ICFDs derived from a subsequent reactor rundown test, or to the ion chamber noise characteristics, assuming in both cases that the ion chambers are 100% prompt and truly represent the global flux changes in the core over the frequency range of interest. Figure 1 shows the normalized APSD functions of fourteen ICFDs and an ion chamber, all used in channel A of the reactor regulating system. The noise signals were recorded in Pickering-B Unit 5 on February 24, 1995. The coherence and phase functions of an ICFD and the ion chamber noise signals can be seen in Figure 2. The narrow high coherence range around 0.2 Hz with zero phase difference can be used to estimate the ICFD's prompt fraction. The apparent lack of broad-band coherence between ion chambers and ICFDs is typical in CANDU reactors.

Similar results of noise measurements in Bruce-B Unit 7 are shown in Figures 3 and 4. In-core flux detector and ion chamber noise signals show a global (in-phase) reactivity fluctuation at 0.2 Hz with high coherence across the core. In Figure 3 the flux fluctuations of the RRS-A ICFD in zone 8 (south side) and the RRS-A ion chamber (north side) are highly correlated at 0.2 Hz, despite their large physical distance. Figure 4 shows similar functions of the noise signals of the RRS-A ICFD in zone 13 and the RRS-A ion chamber (both are on north side). Since the two detectors are closer, there are other common noise components below 0.5 Hz, superimposed on the in-phase reactivity peak at 0.2 Hz. If no sufficient coherence can be found between ICFDs and the ion chamber, the relative promptness of ICFDs can be still assessed. This requires the existence of high coherence and zero phase between the ICFD noise signals in the frequency range of 0.1-1.5 Hz.

POWER RUNDOWN TESTS OF IN-CORE FLUX DETECTORS

The dynamics of in-core flux detectors are also tested in power rundown tests performed on a regular basis during planned reactor trips. The objective of these measurements is to confirm the compliance of ICFD response dynamics with design conditions. Time series of ICFD and ion chamber signals used in the shutdown and reactor regulating sytems are recorded simultaneously during the reactor trip and analyzed off-line. The linear output signals of ion chambers serve as 100% prompt reference signals.

Reactor rundown tests can be performed before planned outages for a limited number of ICFD detectors and ion chambers. The purpose of the test is to check and compare the transient signals of ICFDs and ion chambers responding to an operator-initited reactor trip. These response signals can be also used (1) to estimate the effective prompt fraction (EPF) of the in-core flux detectors, (2) to assess the spatial distribution and effectiveness of the trip mechanism (shut-off rod drop or poison injection), and (3) to determine the accuracy and the limiting factors of the above EPF estimation [6,7,8,9]. Anomalies in the dynamics of ICFDs and ion chambers, as well as, in the trip mechanism can be detected by analyzing the recorded transient response signals of ICFDs and ion chambers.

A typical set of power-rundown response curves in an SDS1-induced trip in Pickering-B Unit 7 are shown in Figure 5. The first curve is the measured response of the RRS-B ion chamber (linear output), while the rest shows the slower response of the coiled platinum ICFDs from channels RRS-B and SDS1-D/F. These rundown curves also marked the end of the 894-day continuous operation of the current world record holder Pickering-B Unit 7. In all four Pickering-B units, ICFD rundown tests are carried out as part of the pre-outage workplan. The latest ICFD rundown test was completed in Pickering Unit 5 in April 1998 in an SDS1 trip from 60% of FP. The lowest prompt fraction value found was 74.1%, which was still well above the 70% minimum acceptance value. Comparison to rundown results obtained in 1994 and 1995 in Unit 5 showed a decrease of 0.3-0.7% per year in the average prompt fraction [10,11]. Based on the favourable results, the program of replacing the coiled ICFDs with new HESIR ICFDs in Unit 5 was deferred until 1999.

SDS1 and SDS2 induced rundown tests are also performed regularly in Darlington before scheduled outages [7,8,9]. The purpose of the measurements is to estimate the effective prompt fractions of SDS1 and SDS2 ICFDs, and to assess the spatial distribution and effectiveness of the trip mechanisms (rod drop vs. poison injection). In the SDS1-induced rundown test in Unit 1 the average prompt fraction of the vertical Inconel ICFDs was 103%, while the horizontal Platinum-clad ICFDs had an average value of 90%. In the SDS2-induced rundown test in Unit 2 these values were 102% and 89%, respectively. In the SDS1-induced trip test, the response curves of both vertical and horizontal ICFDs showed a clear top-to-bottom spatial dependency (delay), in correlation with the insertion of the shut-off rods. ICFDs at the same elevation had similar response curves to SDS1-trip (see Figure 6). This observation can be used to identify possible degradation of ICFDs or shut-off rods. In the SDS2-induced trip test, the response curves of both vertical and horizontal ICFDs displayed a time delay along the south-to-north line, following the pattern of the poison propagation inside the injection nozzles. This indicates that the poison propagation inside the nozzles is the main reason of time delays, as opposed to the poison propagation in the moderator. The south-to-north propagation of poison inside the nozzle can be looked at as the insertion of a set of "horizontal shut-off rods" over a time period of approx. 100 msec. The maximum south-to-north time difference measured between the first and the last responding ICFDs was approx. 120-130 msec. In the SDS2-trip all signals went down from their pre-trip value to a low level within 400 msec. In the SDS1-trip in Unit 1, this transient time interval was 1 second.

Once the ICFD noise signatures are calibrated to the results of the reactor rundown test or to the ion chamber noise, changes in the prompt fraction can be detected by noise analysis any time between rundown tests. The noise-based monitoring of detector performance can reduce the need for further rundown tests.

VIBRATIONS OF DETECTOR TUBES DETECTED BY NOISE ANALYSIS

Evidence of mechanical vibration of horizontal detector guide tubes has been found in the spectral functions of noise signals of certain horizontal SDS2 and vertical SDS1/RRS in-core flux detectors. Detectors vibrating in an inhomogenious static flux sense virtual flux fluctuations, and the mechanical vibration is mapped into detector current fluctuations. Increase in the vibration amplitude or possible impacting on surrounding calandria tubes can be detected indirectly by neutron noise analysis. The vibration of the horizontal detector tubes, induced by the moderator flow, resulted in strong peaks in the APSD and coherence functions of noise signals of vibrating ICFDs in the frequency range of 3-5 Hz. Noise signals of detectors located in the same vibrating detector tube have high coherence and zero phase difference at the fundamental frequency of tube vibration. Figure 7 shows the APSD, coherence and phase functions of two SDS2-G ICFDs located in the same horizontal tube HFD8 in Unit 5 of Pickering-B. The huge coherence peak at 3.8 Hz with zero phase difference is a clear indication of detector tube vibration. Higher harmonic frequencies of detector tube vibrations were also observed in the ICFD noise spectral functions as small and narrow peaks with 180 degree phase difference.

Noise signals from detectors located in different tubes have zero coherence at the vibration frequencies since the vibration of different tubes are not correlated, even if they had the same vibration frequency. Such a case is shown in Figure 8 with two ICFDs from two different horizontal detectors tubes in Pickering-B Unit 5. The peaks at 3.5 Hz and 3.2 Hz in the respective APSD functions are caused by the vibrations of detector tubes. The wide peak centered around 1.1 Hz in the coherence functions with zero phase was found in all detector pair combinations. This peak is typical only in the Pickering-B units. A narrow coherence peak at 0.2 Hz with zero phase was also found in all detector pairs. The flux oscillation at

0.2 Hz has been observed in all CANDU units of Ontario Hydro measured so far. It was especially dominant in Bruce-B units. The 0.2 Hz and 1.1 Hz in-phase coherence peaks represent a global reactivity fluctuation affecting signals of all in-core flux detectors in both horizontal and vertical guide tubes. The third common component found in Unit 5 detector noise signals is a narrow vibration peak at 2.1 Hz. In Figure 8 the phase difference between the two detectors at the 2.1 Hz vibration frequency is close to 180 degree, a strong indication of core internal vibration. The fact that this peak can be found in ICFDs located in different tubes excludes the possibility of detector tube vibration as a source of flux fluctuations at that frequency. Both the magnitude and the phase of the vibration peak exhibit a spatial dependency on detector locations. Further analysis is being carried out to identify the source of vibration.

The APSD functions of noise signals from ICFDs located in vertical guide tubes show signs of guide tube vibration too, although the vertical detector tubes are less susceptible to mechanical vibration. The 0.2 Hz and 1.1 Hz global in-phase fluctuations are present in the noise signals of vertical detectors too. Also, the 2.1 Hz core internal vibration can be seen in the spectral functions of some vertical ICFDs in Pickering-B Unit 5.

By monitoring the trend of vibration peaks in the noise spectral functions of the measured detector signals, the mechanical condition of the detector tube can be assessed based on the following simple principles: (1) increase in the magnitude of the peak in the noise APSD indicates increasing vibration of the detector tube, (2) shift in the location of the APSD peak indicates changes in the mechanical conditions/support of the detector tube, (3) widening of the APSD peak indicates increasing impacting with the surrounding structures [12]. The long term monitoring of these vibration peaks is useful for early detection of mechanical damages in the reactor core caused by vibrations.

VIBRATIONS OF FUEL CHANNELS DETECTED BY ICFD NOISE ANALYSIS

Recent ICFD noise measurements detected the flow-induced vibration of fuel channels at frequencies around 4.5 - 6 Hz and at 25 Hz in Darlington and Pickering-B units. In-core flux detectors lined up along the same group of fuel channels showed common vibration peaks with high coherence. At these frequencies, the phase difference between the ICFD noise signals was either 0 or 180 degree, depending on whether the detectors were on the same side, or different sides of the vibrating fuel channel(s). In many cases, multiple vibration peaks at slightly different frequencies were seen in the coherence functions, indicating that there were several vibrating fuel channels among the common neighboring channels of the two in-core flux detectors. Similar noise measurements were performed in a CANDU-600 reactor, where evidence of similar fuel channel vibrations was also found in the same frequency range [13].

A typical result of ICFD noise measurements performed in Darlington U1 is shown in Figure 9. Two vibration peaks can be seen in the coherence and APSD functions at frequencies 4.6 Hz and 5.6 Hz. The two in-core flux detectors, VFD11-1E and VFD18-1E, have six common neighboring fuel channels, at locations rows H, J, K and columns 4 and 5. The double peak in the coherence function with zero phase shows that the signals of the two ICFDs are affected in the same way, by the vibration of at least two neighboring fuel channels. The spectral functions of the same two in-core flux detectors in Darlington Unit 2 are shown in Figure 10. The same set of fuel channels are vibrating at frequencies slightly different from the previous case. There are five distinct in-phase vibration peaks in the coherence function over the frequency range of 4-6 Hz, indicating that five of the six neighboring fuel channels vibrate and affect the signals of the two ICFDs in the same way.

Higher modes of fuel channel vibrations were found in many cases. In Figures 11 and 12 the spectral functions of RRS-A Zone 6 and Zone 8 in-core flux detector noise signals are shown for Darlington Unit 1 and Unit 2, respectively. In both cases, a strong and relatively wide (multiple) peak was found in the coherence function centered around 15 Hz. The phase difference between the two detectors at 15 Hz is 180 degree, which is typical for second mode vibrations. In both reactor units the fundamental modes of fuel channel vibration can be also seen in the coherence functions as in-phase peaks between 4 Hz and 6 Hz.

ICFDs lined up along the same set of fuel channels, but separated by a relatively large distance (e.g. zone 3 ICFD in VFD1 and zone 10 ICFD in VFD27), may exhibit in-phase coherence peaks at the above frequencies, due to the common effect of fuel channels vibrating nearby. Monitoring the vibration of fuel channels via ICFD noise analysis should be done periodically as part of the regular ICFD dynamic response noise test. Changes in the above vibration patterns may indicate structural changes in the fuel channels.

VALIDATING ION CHAMBER SIGNAL DYNAMICS BY NOISE ANALYSIS

Noise components of log N and log N Rate signals of the three ion chambers used in the reactor regulating systems were continuously recorded during the startup of Darlington Unit 4 in 1993. Similar noise measurements of three ion chambers used in SDS2 were carried out during the entire three-month outage of Pickering Units 5 and 7 in April-June and October-December of 1994, respectively. By using two separate noise data acquisition systems, ion chamber noise signals from both SDS1 and SDS2 systems were continuously recorded and analyzed before and during the outage of Pickering Units 5 and 6 in 1995. The purpose of these measurements was to monitor the functionality of ion chambers and their instrumentation at low power ($10^{-2} - 10^{-5}$ % of F.P.). Should anomalies occur, corrective actions still could be taken before the startup. In the Pickering-B applications, noise analysis identified faulty ion chamber amplifiers. Also, the noise measurement provided supporting data for the relatively frequent SDS1 spurious Log N Rate trips in Pickering units. Both the Darlington and the Pickering-B noise measurements showed that the multi-channel noise signatures of the Log N and Log N Rate signals of the ion chambers had a certain pattern, which changed with reactor power. By analyzing these patterns the ion chamber signals can be validated during the outage. The validation of the dynamics did not require any step change in power or the temporary isolation of the tested instrumentation.

Figure 13 shows the normalized APSD, coherence and phase functions of SDS2 channel J ion chamber Log N and Log N rate noise signals sampled at 10 Hz at full power. In the low frequency range (0-1.0 Hz), the high coherence and the linear phase starting from 90 degree are typical characteristics of the normal dynamics of SDS2 ion chamber log N noise signal and its time derivative (log N rate) noise signal. At low power (10^{-4}% of F.P.) the coherence is close to unity over the whole frequency range, with a phase function similar to the one shown in Figure 13. At full power the global flux fluctuations sensed by all three SDS2 ion chambers are in phase and have high coherence. Figure 14 shows the normalized APSD, coherence and phase functions of channel G and J log N rate noise signals sampled at 10 Hz at full power. The in-phase coherence peak at 1.1 Hz is typical in all Pickering-B units, in both the ion chamber and the in-core flux detector noise signals. At low power the coherence function is zero between any two ion chambers. Results of a comprehensive noise survey of the dynamics of SDS1 and SDS2 log N and log N rate signals performed in Pickering-B Unit 6 at both full power and at low power (10^{-4}% of F.P.) at various sampling rates are discussed in [14]. Typical anomalies, such as deviations in the time constants and gains of ion chamber electronics, excessive background noise, irregular spikes and transients were identified in some of the ion chamber signals occuring at certain power levels.

VALIDATING ZONE CONTROL SIGNALS BY NOISE ANALYSIS

The objective of this application is to validate the cause-and-effect relationships between the ICFDs signals, liquid zone level signals and their control valve position signals. The flux in the 14 zones of CANDU reactor core is controlled by constantly adjusting the level of light water in 14 liquid zone compartments located inside the core. The demand positions of inlet control valves of the liquid zones are calculated by the control computer based on the readings of the 14 in-core flux detectors assigned to the 14 zones. Faulty level transmitters, hunting control valves and possible instabilities in the coupling between neutron flux and liquid zone level signals can be identified by the multi-channel spectral analysis of the noise components of these signals. Based on these measurements, the sensitivity of RRS in-core flux detector signals to the changes in the individual liquid zone levels can be estimated as a frequency dependent complex transfer functions derived from the spectra of the measured neutron flux and liquid zone level noise signals.

Dynamic coupling between fluctuations in the zone level indicator signal and the in-core flux detector located in the same zone (Zone 1) is shown in Figure 15. The very high coherence (90%) and the 90 degree phase difference at zero frequency indicate that the slow changes (below 0.1 Hz) in the liquid zone level and neutron flux signals are coupled through a time integral with a delay time of 1.5 sec. Similar phase analysis showed that the zone level noise is the time integral of the control valve position fluctuations. The former lags behind the latter by a time delay of 1.5 sec, derived from the phase slope. Liquid zone level fluctuations are also coupled with in-core flux fluctuations and control valve fluctuations at 0.25 Hz, even if the signals were measured in different zones. This wide peak represents a global and correlated coupling between zone control signal fluctuations in the whole reactor core. The flux fluctuations in different zones are also correlated in phase, except below 0.1 Hz, where the slow flux changes are driven by the independent control actions in the 14 zones. The slow zone level fluctuations (below 0.1 Hz) in different zones are independent (zero coherence), while level fluctuations around 0.25 Hz are in phase and correlated between any two zones (broad peak in coherence). In-core flux detector and control valve position noise signals are also strongly correlated below 0.5 Hz with a constant phase shift of 180 degree. The above complex coupling patterns of ICFD, level and valve position fluctuations were found in all combinations of zone pairs. Similar zone control noise measurements in Darlington (1993) and Bruce-B (1994) showed the same statistical coupling under normal conditions. The frequency dependent dynamic coupling derived from noise can be decomposed into a local zone component and an overall reactor core component. Once these complex spatial patterns have been learned, they can be used to validate process/instrumentation dynamics. If these patterns are reproduced in subsequent noise measurements, it indicates that the process and its instrumentation is in normal condition.

OTHER APPLICATIONS OF NOISE ANALYSIS

Noise analysis has been successfully used in pressure and flow measurements of the primary heat transport (PHT) system too. The application includes the following areas: (1) estimating the response time of flow transmitters and validating their dynamics, (2) identifying the resonance frequencies of pressure sensing lines, (3) validating FINCH flow and SDS safety flow signals, and (4) characterizing anomalies in flow, such as signal dips and oscillations [15,16]. In 1997 the technique was successfully used in Darlington in a large scale project of estimating and adjusting the time constants of all coolant flow transmitters in all four units. The signals of the flow transmitters (Rosemount and Gould) are used in the SDS1 and SDS2 shutdown systems. The estimation was based on the spectral functions of flow fluctuations obtained in in-situ flow noise measurements at full flow [17]. Typical spectra of flow fluctuations used in the estimation are shown in Figure 16. In June 1998, flow and sensing line pressure noise measurements were performed on the SDS2 flow loop FT-3J, in-situ at 98% of FP in Darlington Unit 3 to investigate the effect of various flow transmitters (Gould, Rosemount, Bailey) and sensing line modifications on the statistical signatures (resonance frequencies, noise amplitude, flow-dip amplitude distributions, time constants, etc.) of the sensing line pressure signals, differential pressure input signal and transmitter output signal. The analysis of measurement data is underway, and the results will be reported soon.

Noise analysis also provides a non-intrusive method for monitoring and estimating the dynamic response of RTDs installed in the process, and for isolating the cause of RTD signals anomalies (spikes induced by ground fault detectors). The applications include RTD signals from reactor outlet headers, FINCH channels, moderator inlet and outlet locations. Boiling in FINCH fuel channels can be also detected by flow noise analysis. The detection of coolant boiling in FINCH fuel channels is based on the measurement of the channel inlet and outlet flow fluctuations. Noise measurements in Darlington showed strong correlation between the occurrence of boiling (indicated by fuel channel outlet temperature) and the coherence and phase functions of inlet and outlet flow fluctuations in the frequency range of 0-1 Hz [3].

CONCLUSION

CANDU noise measurements carried out in the past six years proved that fault detection and validation of process/instrumentation dynamics can be based on the existence of multi-channel complex patterns of statistical noise signatures. These signatures can be obtained from the time series measurements at steady state operating conditions. The technique is being successfully applied now in a wide variety of actual station problems as a powerful troubleshooting and diagnostic tool.

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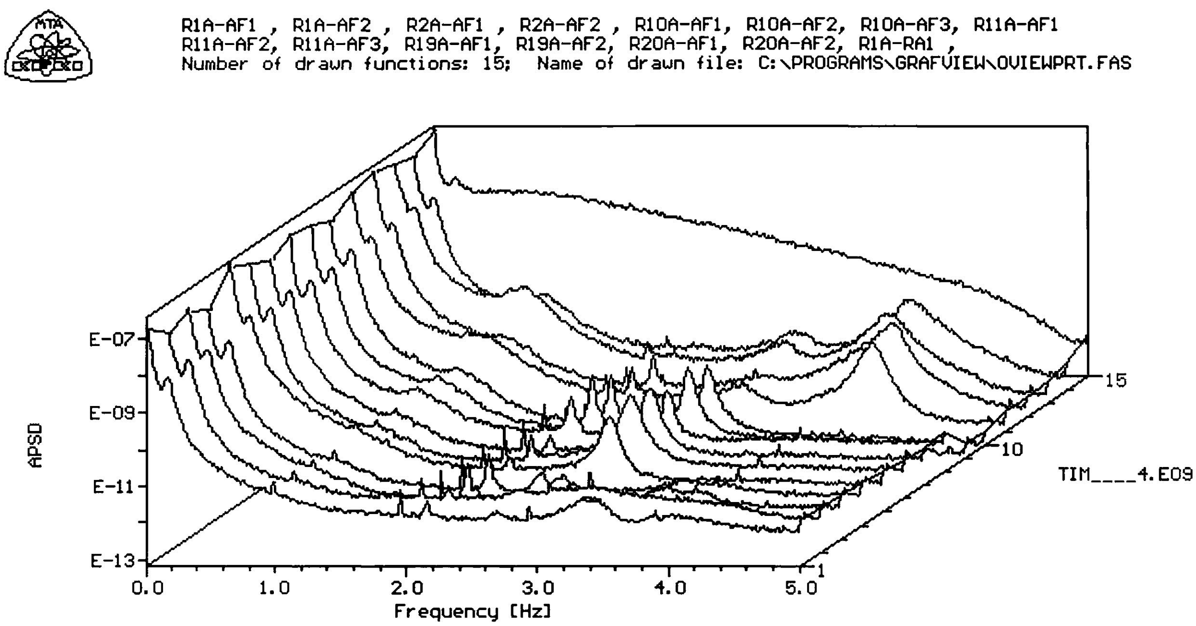


Figure 1. Normalized APSD functions of fourteen ICFD and ion chamber noise signals from channel RRS-A in Pickering-B Unit 5, February 24, 1995

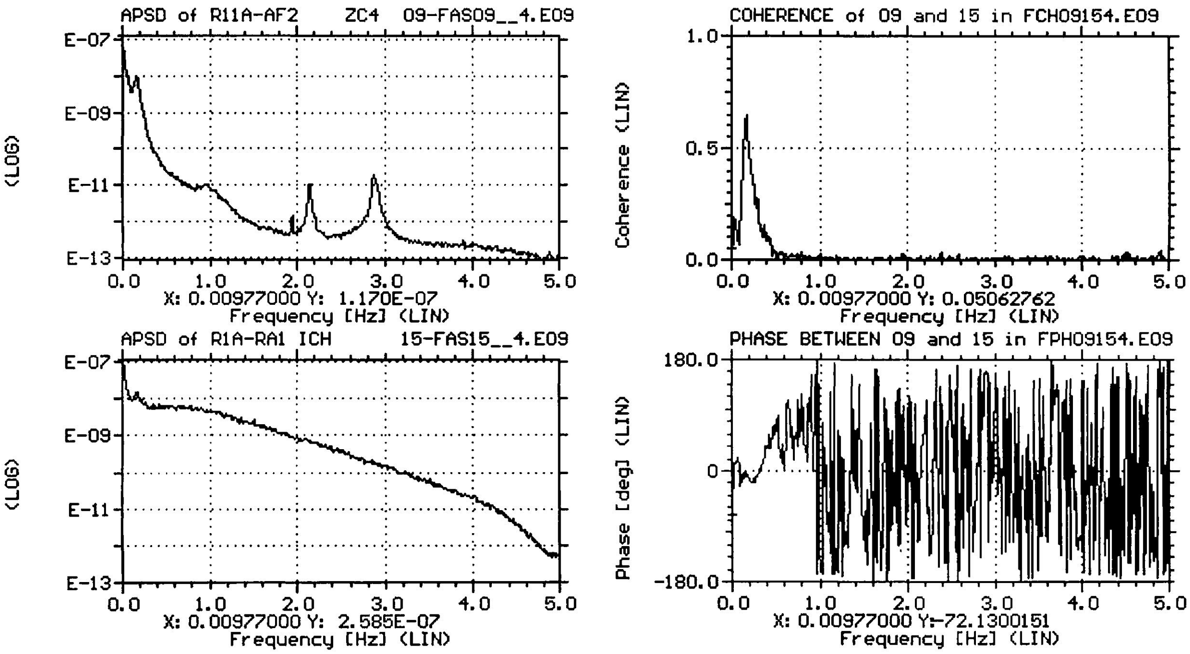


Figure 2. Normalized APSD, coherence and phase functions of neutron noise signals from ICFD R11A-AF2 and RRS-A ion chamber.
The peak at 0.2 Hz is a global reactivity oscillation
(Pickering-B Unit 5, February 24, 1995)

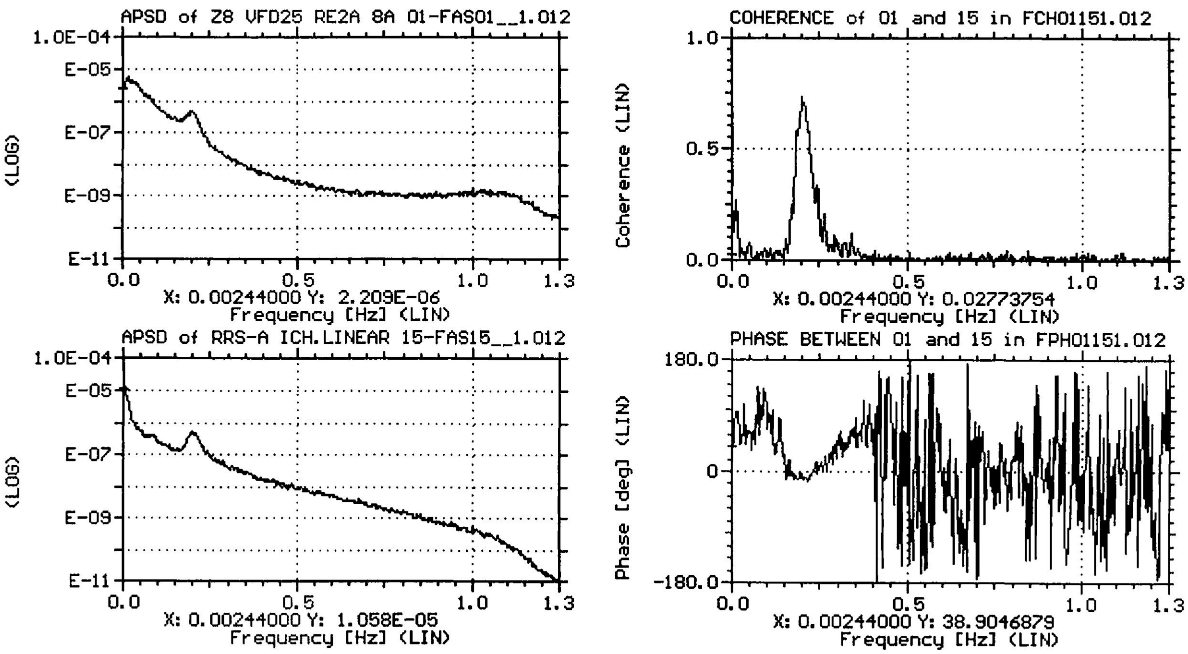


Figure 3. Normalized APSD, coherence and phase functions of neutron noise signals from Zone 8 ICFD VFD25-RE2A and RRS-A ion chamber linear output. The peak at 0.2 Hz is a global reactivity oscillation (Bruce-B Unit 7, August 9, 1994)

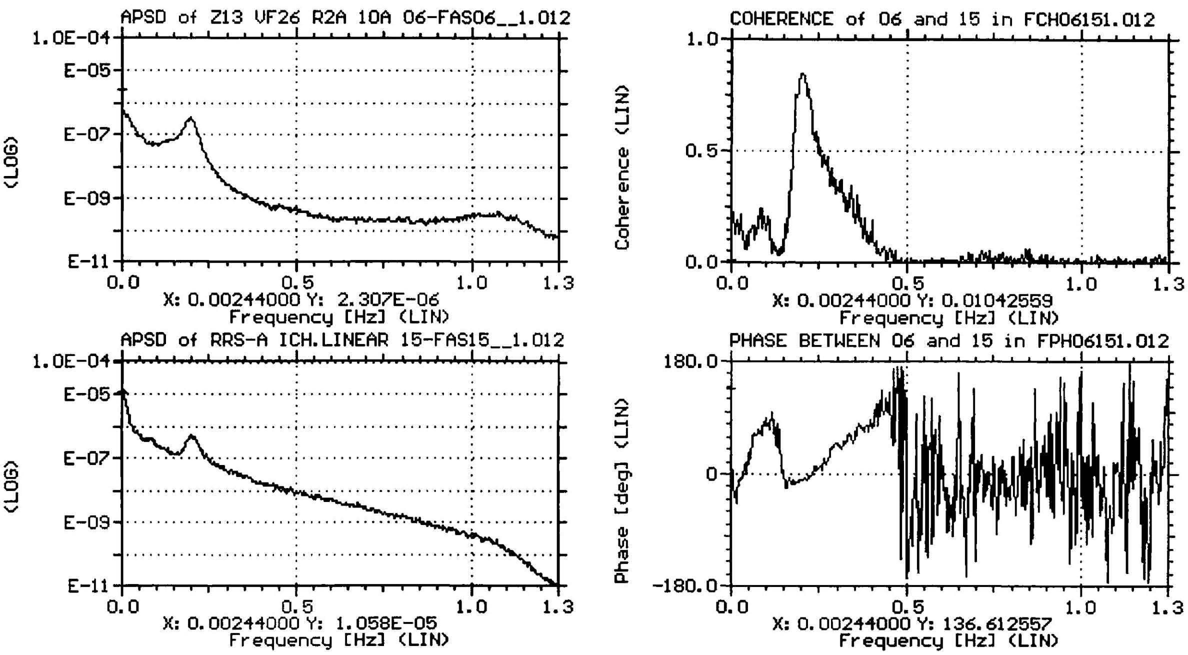


Figure 4. Normalized APSD, coherence and phase functions of neutron noise signals from Zone 13 ICFD VFD26-RE2A and RRS-A ion chamber linear output. The peak at 0.2 Hz is a global reactivity oscillation (Bruce-B Unit 7, August 9, 1994)

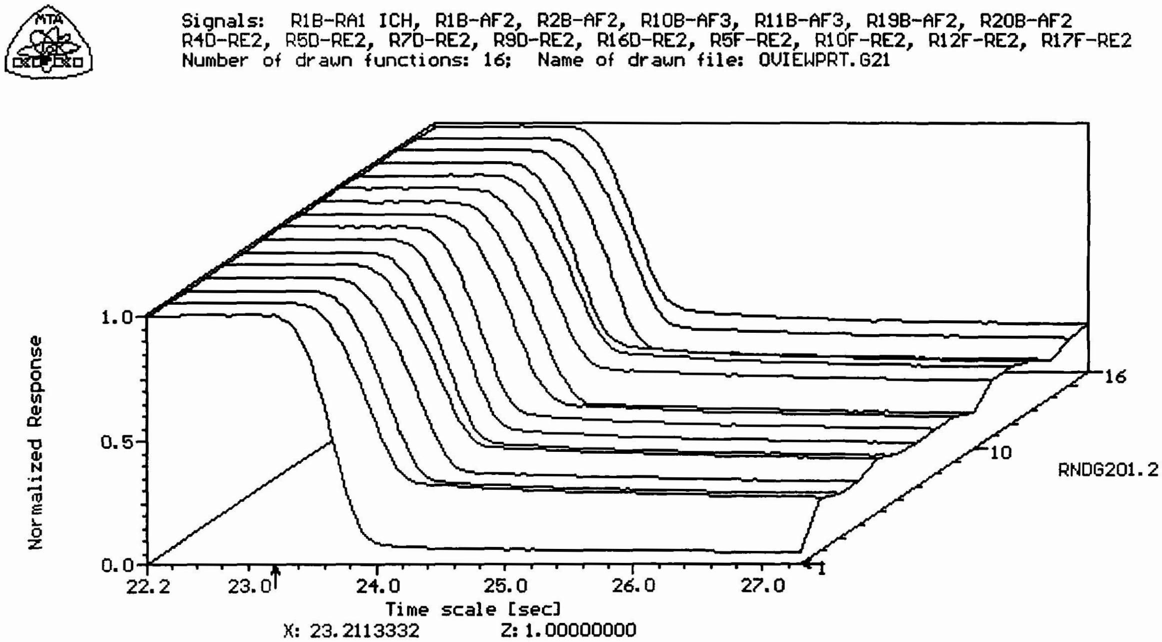
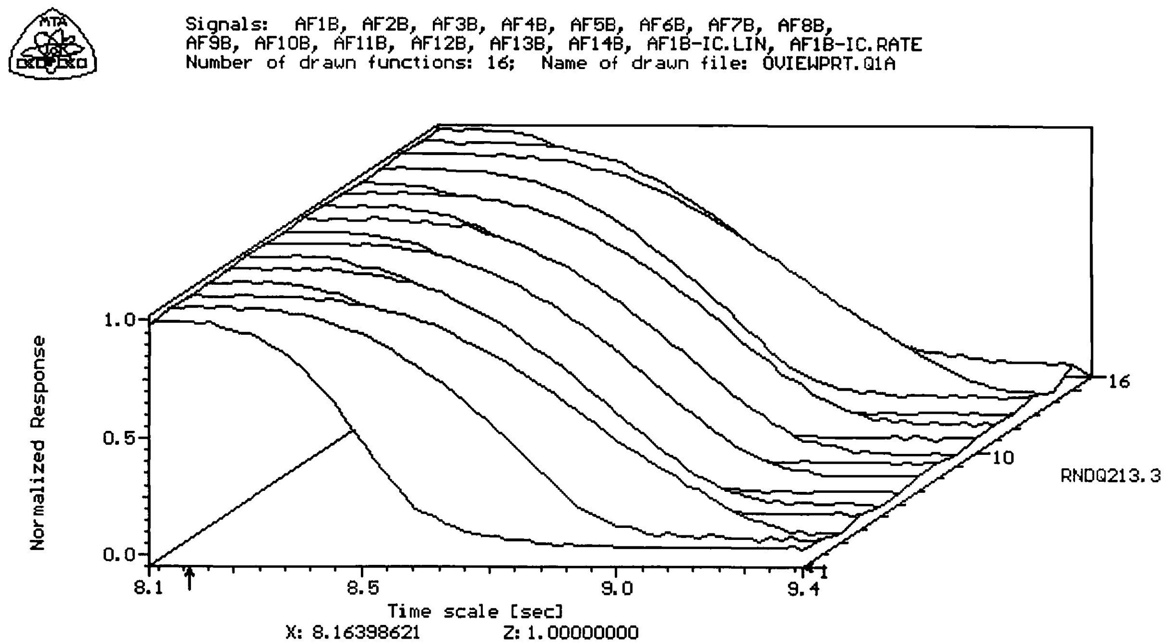


Figure 5. Normalized rundown response curves of RRS-B ion chamber and fourteen ICFDs from channels RRS-B and SDS1 D/F
(Pickering-B Unit 7, October 7, 1994)



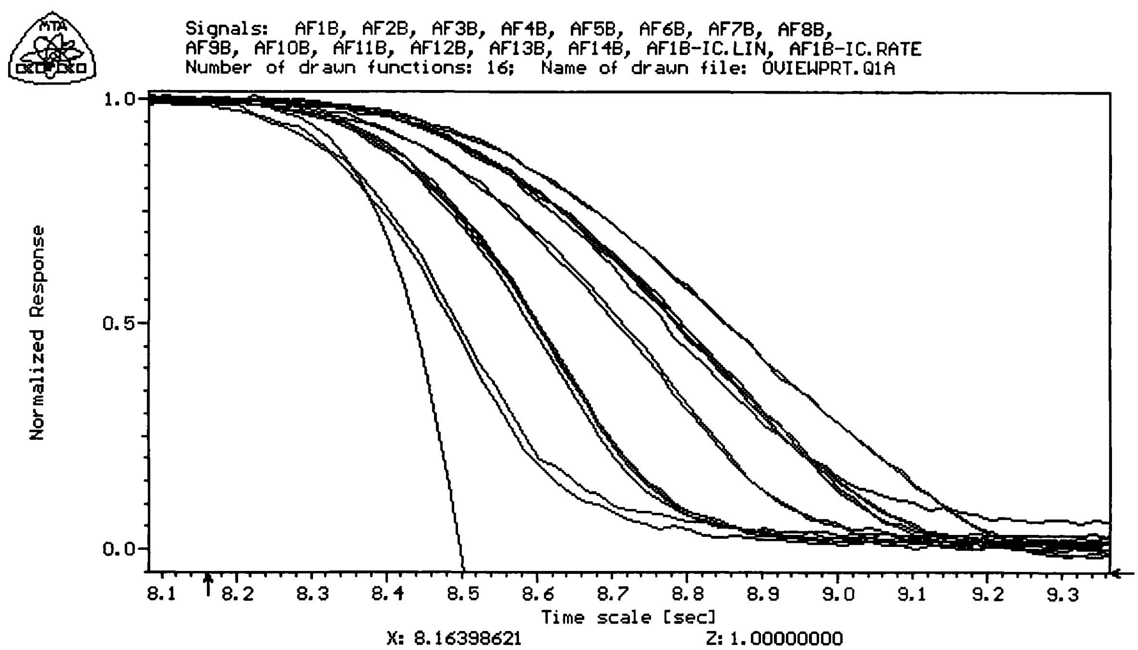


Figure 6. Rundown response signals of RRS-B ICFDs (AF-1B through AF14B), RRS-B ion chamber linear output and log rate signals normalized to their pre-trip values and displayed over 1 sec SDS1-initiated trip from 60% of F.P. in Darlington Unit 1, on August 28, 1995

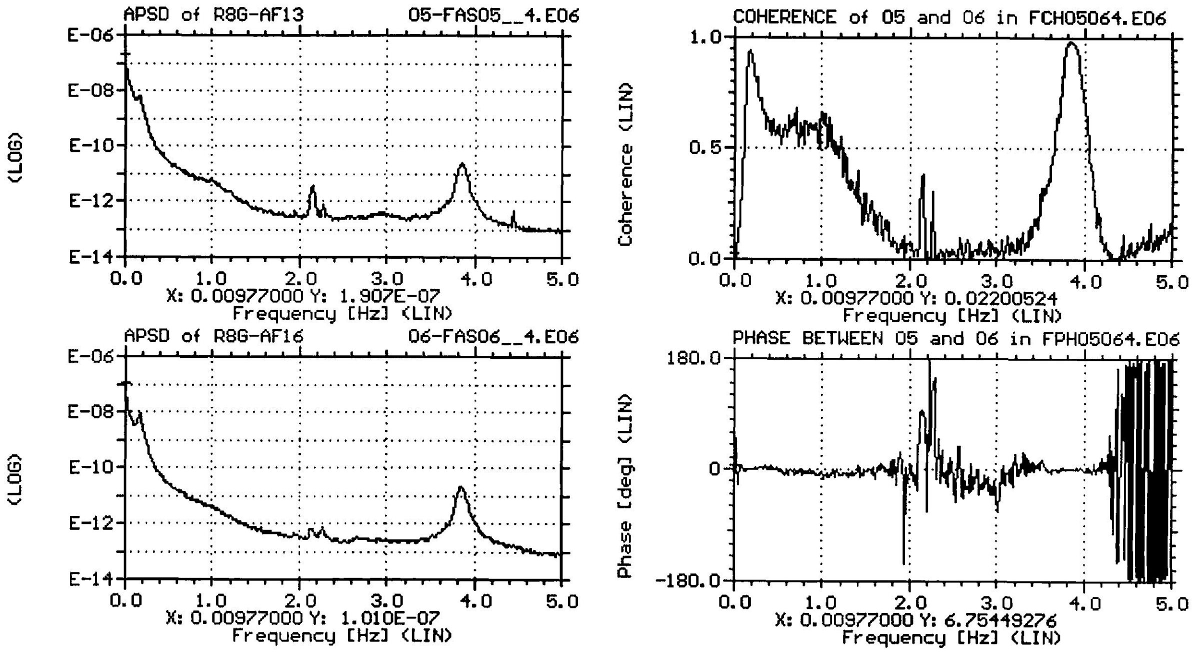


Figure 7. Normalized APSD, coherence and phase functions of neutron noise signals from two SDS2-G ICFD in-service detectors located in the same horizontal detector tube HFD8 in Pickering-B Unit 5, February 24, 1995

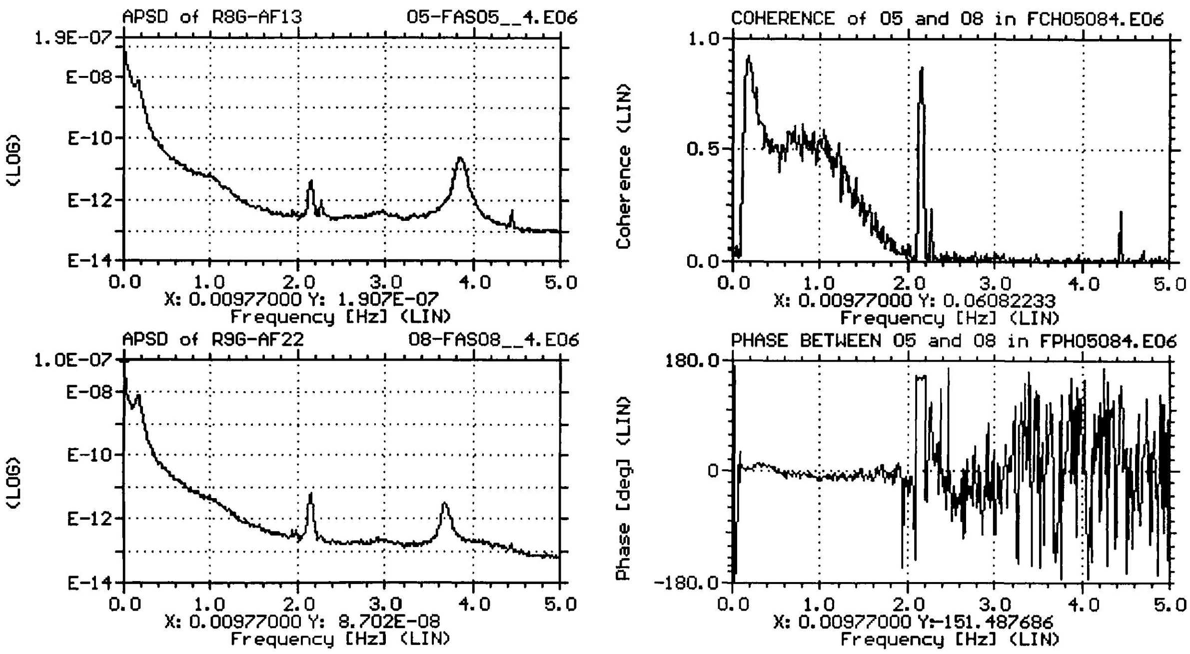


Figure 8. Normalized APSD, coherence and phase functions of neutron noise signals from two SDS2-G ICFD in-service detectors located in different horizontal detector tubes HFD8 and HFD9 in Pickering-B Unit 5, February 24, 1995

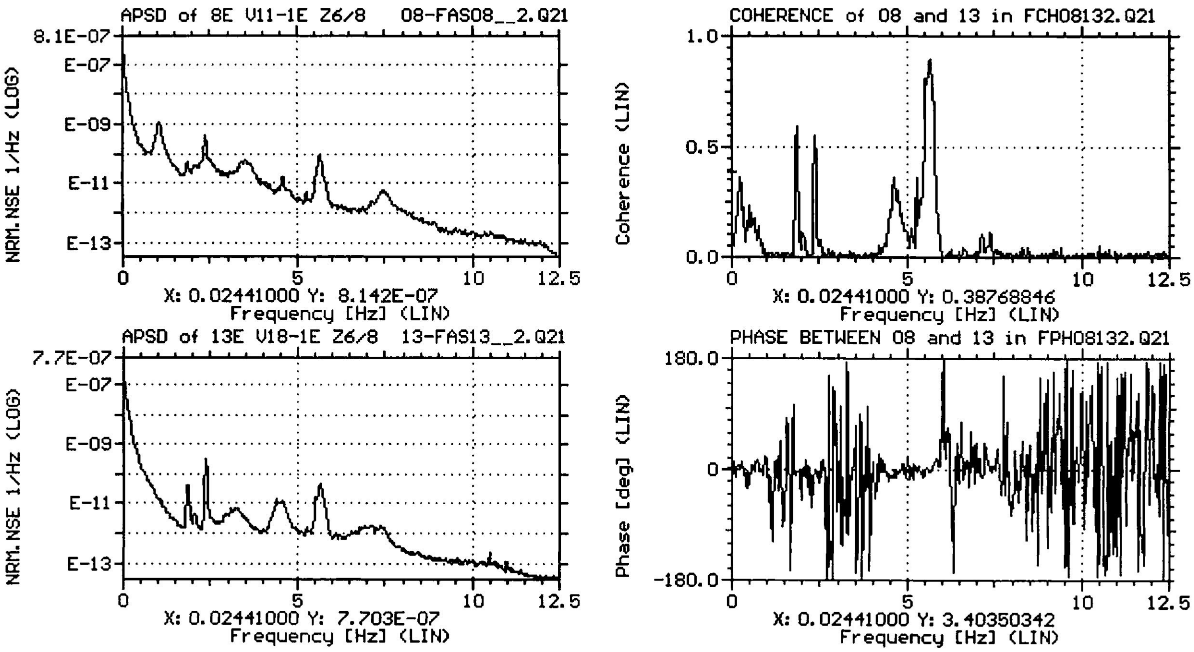


Figure 9. Normalized APSD, coherence and phase functions of noise signals from ICFDs VFD11-1E and VFD18-1E in Darlington **Unit 1**
Adjacent fuel channels: H J K L - 4/5 and G H J K - 4/5 in zones 6 and 8
(frequency range: 0 - 12.5 Hz)

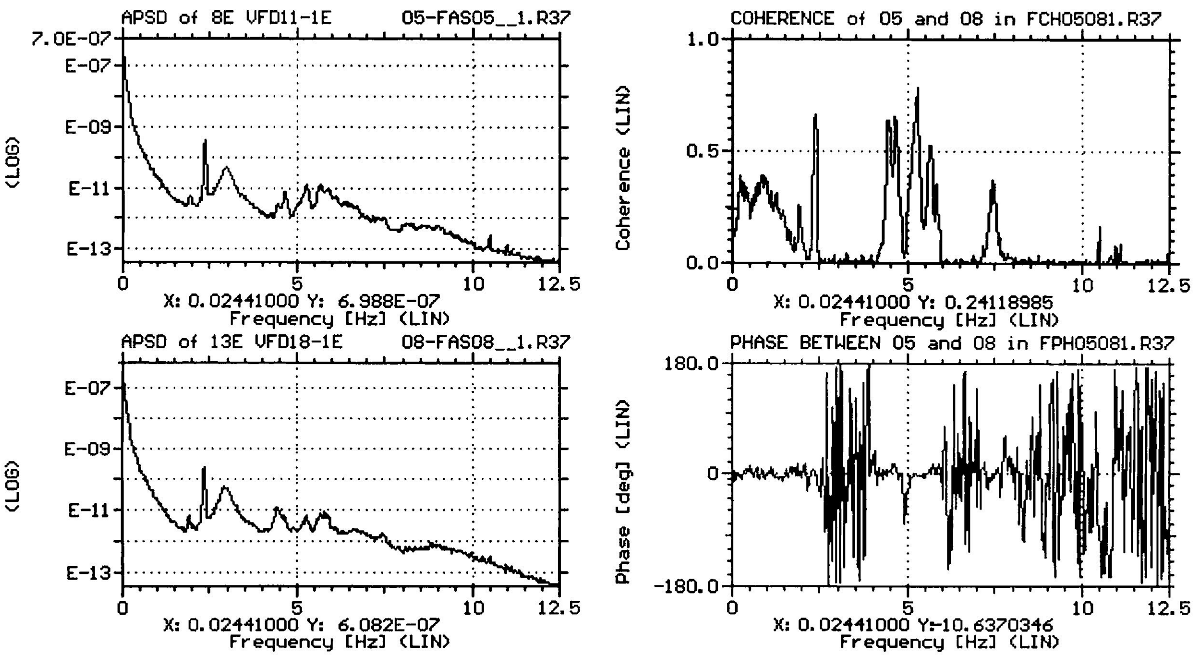


Figure 10. Normalized APSD, coherence and phase functions of noise signals from ICFDs VFD11-1E and VFD18-1E in Darlington **Unit 2**
Adjacent fuel channels: H J K L - 4/5 and G H J K - 4/5 in zones 6 and 8
(frequency range: 0 - 12.5 Hz)

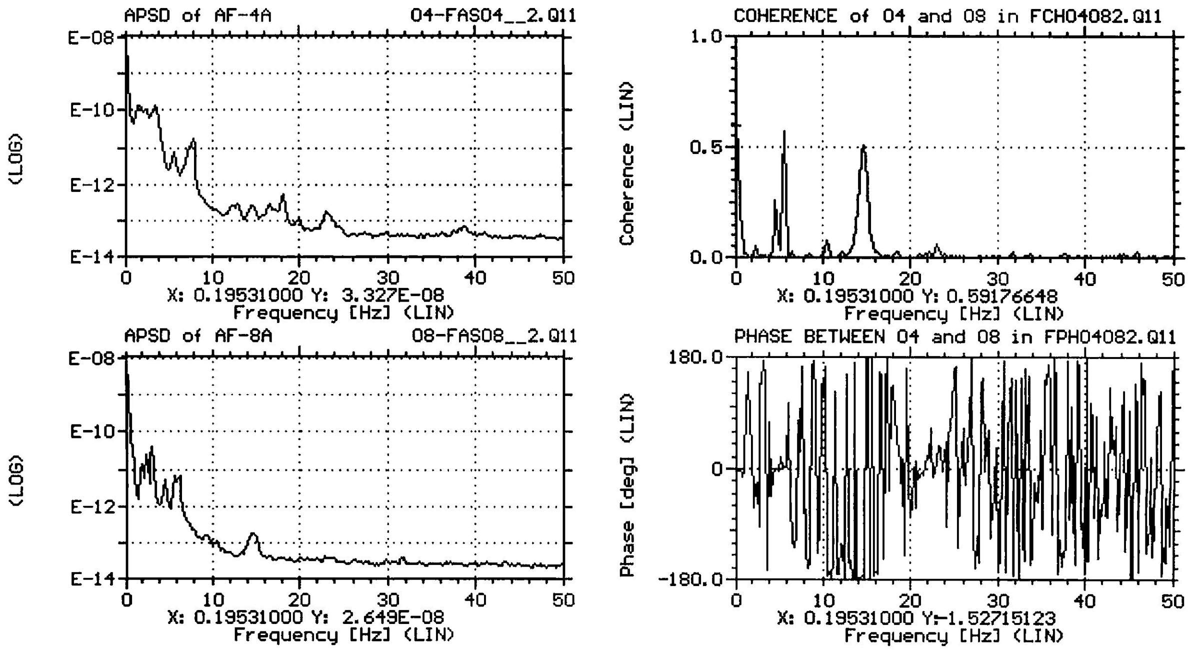


Figure 11. Normalized APSD, coherence and phase functions of Zone 6 and Zone 8 RRS-A ICFD noise signals in Darlington **Unit 1**
Adjacent fuel channels: G H J K - 4/5
(frequency range: 0 - 50 Hz)

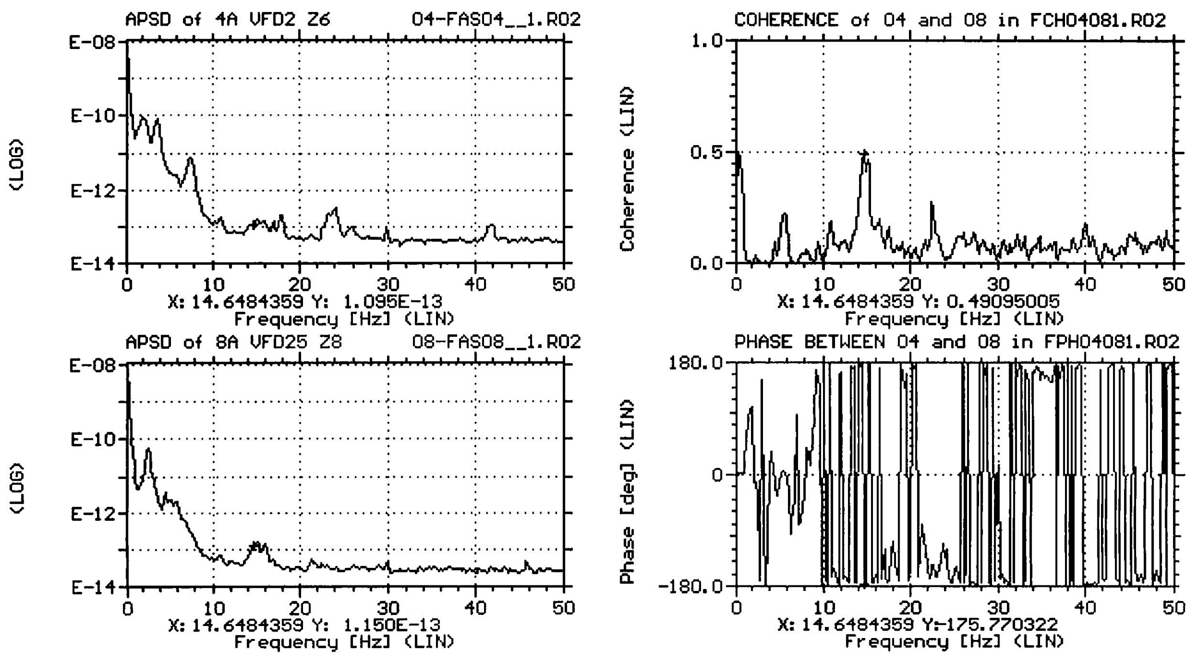


Figure 12. Normalized APSD, coherence and phase functions of Zone 6 and Zone 8 RRS-A ICFD noise signals in Darlington **Unit 2**
Adjacent fuel channels: G H J K - 4/5
(frequency range: 0 - 50 Hz)

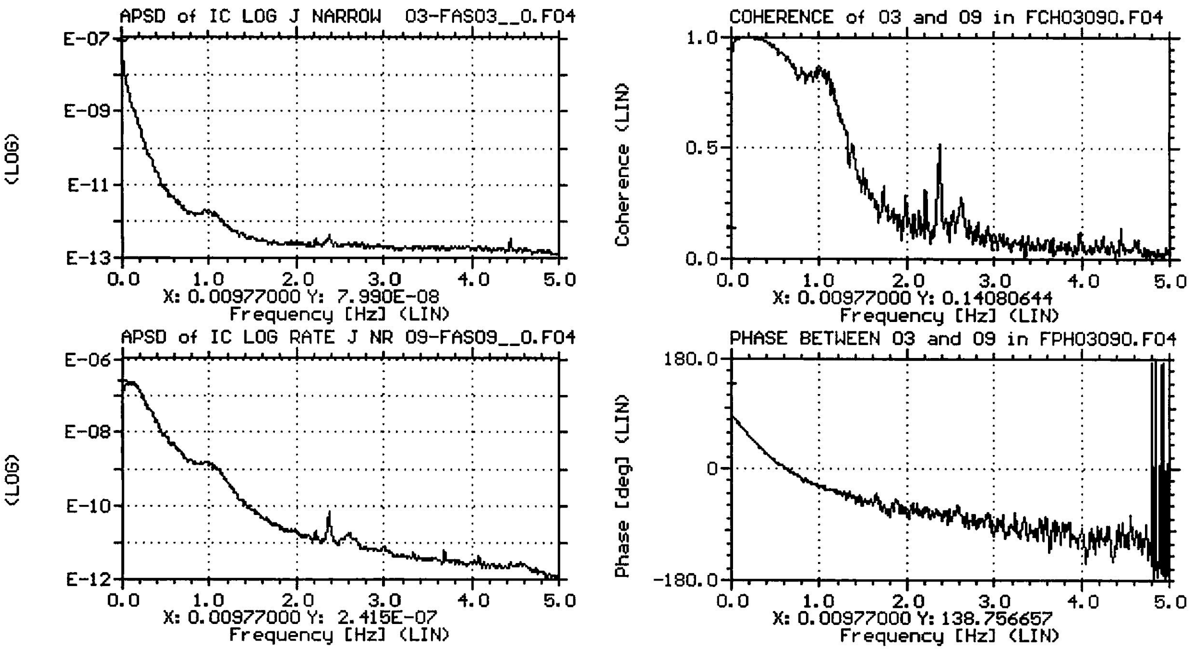


Figure 13. Normalized APSD, coherence and phase functions of SDS2 channel J ion chamber Log N and Log N rate noise signals sampled at 10 Hz at full power (Pickering-B Unit 6, October 26, 1995)

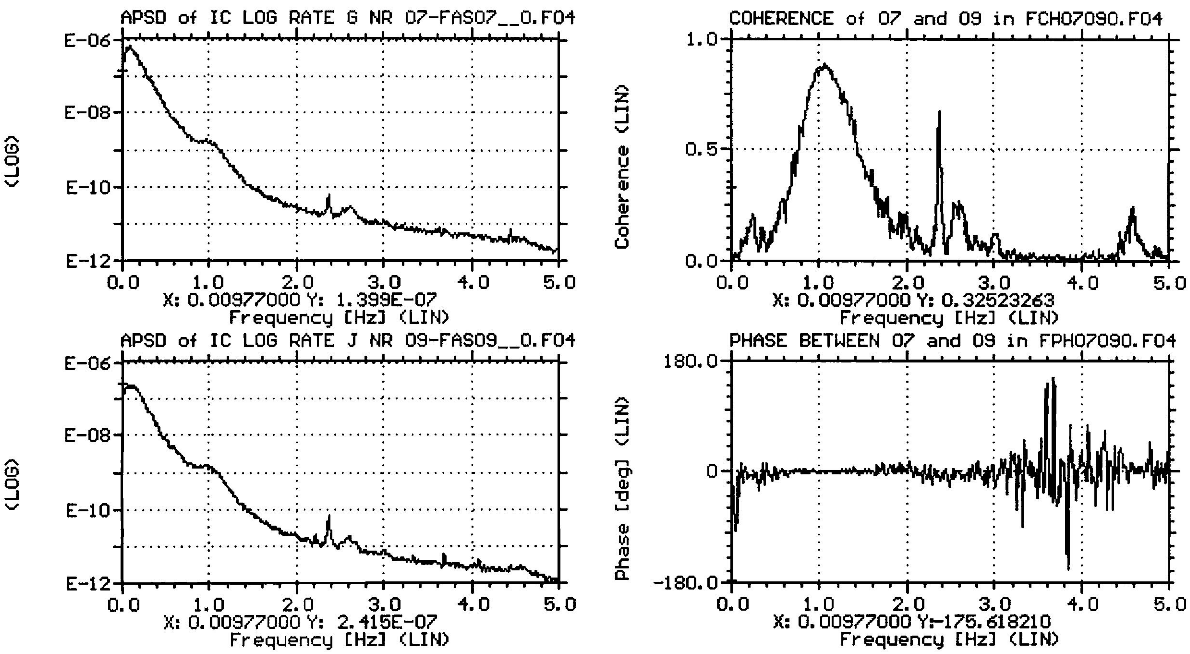


Figure 14. Normalized APSD, coherence and phase functions of SDS2 channel G and J ion chamber Log N rate noise signals sampled at 10 Hz at full power (Pickering-B Unit 6, October 26, 1995)

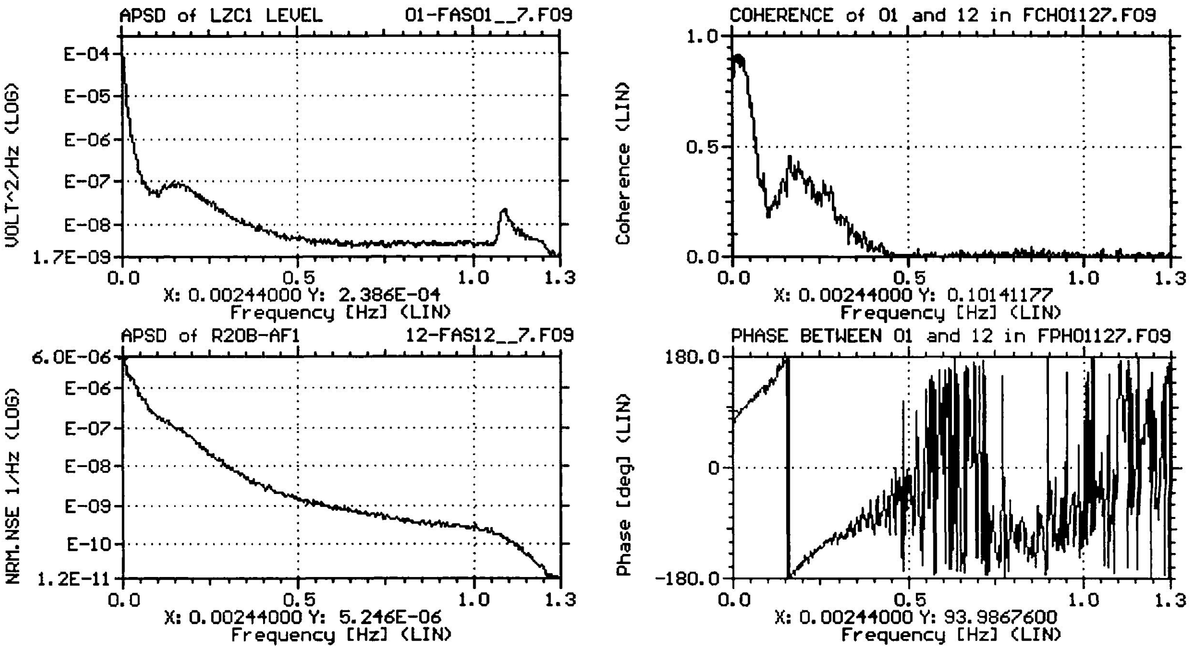


Figure 15. APSD, coherence and phase functions of Liquid Zone Level signal and In-Core Flux Detector signal in Zone 1 of Pickering-B Unit 6, August 25, 1994

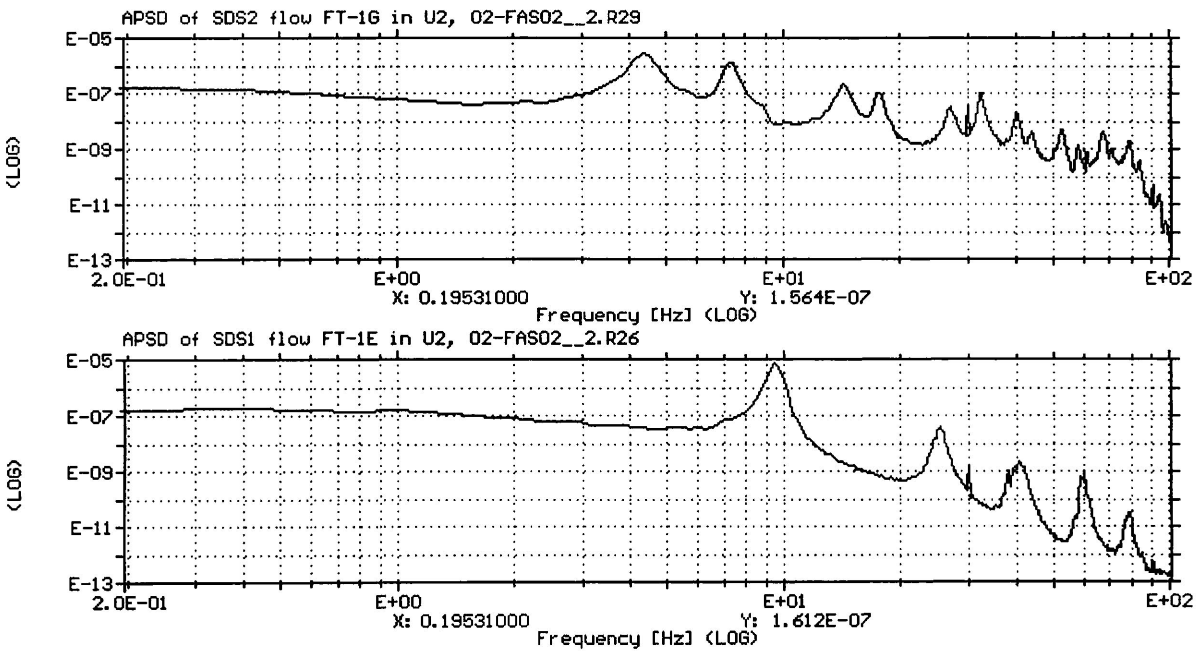


Figure 16. Typical APSD functions of coolant flow fluctuations measured by Gould and Rosemount transmitters used in the SDS2 and SDS1 safety systems
(Darlington Unit 2, September 24, 1997)