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DEVELOPMENT AND APPLICATIONS OF REACTOR NOISE ANALYSIS AT ONTARIO HYDRO'S CANDU REACTORS

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ABSTRACT

In 1992 a program was initiated to establish reactor noise analysis as a practical tool for plant performance monitoring and system diagnostics in Ontario Hydro's CANDU reactors. 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 critical plant components, instrumentation and processes are monitored on a regular basis. Recent applications of noise analysis include (1) validating the dynamics of in-core flux detectors (ICFDs) and ion chambers, (2) estimating the prompt fraction ICFDs in noise measurements at full power and in power rundown tests, (3) identifying the cause of excessive signal fluctuations in certain flux detectors, (4) validating the dynamic coupling between liquid zone control signals, (5) detecting and monitoring mechanical vibrations of detector tubes induced by moderator flow, (6) estimating the dynamics and response time of RTD temperature signals, (7) isolating the cause of RTD signal anomalies, (8) investigating the source of abnormal flow signal behaviour, (9) estimating the overall response time of flow and pressure signals, (10) detecting coolant boiling in fully instrumented fuel channels, (11) monitoring moderator circulation via temperature noise, and (12) predicting the performance of shut-off rods. Some of these applications are performed on an as-needed basis. The noise analysis program, in the Pickering-B station alone, has saved Ontario Hydro millions of dollars during its first three years. The results of the noise analysis program have been also reviewed by the regulator (Atomic Energy Control Board of Canada) with favorable results. The AECB have expressed interest in Ontario Hydro further exploiting the use of noise analysis technology.

INTRODUCTION

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. This is 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. Although reactor noise analysis techniques usually offer an indirect way of diagnostics and require expert knowledge, often they are the only diagnostic indicators of processes inaccessible to direct plant testing.

In 1992 an extensive program of reactor noise analysis was initiated in Ontario Hydro to develop CANDU-specific noise-based statistical techniques for monitoring process and instrumentation dynamics, diagnostics and early fault detection. 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 three years at various operating conditions. Also, recommended standards and procedures for regular station 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 statistical 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 simultaneous 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. Table 1 shows the typical instrumentation used in the noise analysis surveillance program in Pickering-B. Week long 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 is being developed in AECL Chalk River Laboratories, which will eventually replace the current system [1] and will transfer the technology to the stations. Application areas in which reactor noise analysis has been successfully used are discussed in the following sections.

VALIDATING IN-CORE FLUX DETECTOR DYNAMICS

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 (ICFDs) 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 1995. 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 0-10 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 in 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 validated 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.

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 (SDS1-initiated reactor trip from full power), or to the ion chamber noise characteristics, assuming in both cases that the ion chambers are 100% prompt and truely 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 the latest measurement 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 is used to estimate the ICFD's prompt fraction. The cause of the apparent lack of broad-band coherence expected between ion chambers and ICFDs is under investigation.

Typically, reactor rundown tests can be performed every two years for a limited number of ICFD detectors only. A typical set of power-rundown response curves are shown in Figure 3. The first curve is an ion chamber response signal, while the rest shows the slower response of the ICFDs. These rundown curves also marked the end of 894-day continuous operation of the current world record holder Pickering-B Unit 7. Once the ICFD noise signatures are calibrated to the results of the reactor rundown test or 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.

MONITORING DETECTOR TUBE VIBRATIONS

Evidence of mechanical vibration of horizontal detector guide tubes has been found in the spectral functions of certain noise signals of horizontal SDS2 and vertical SDS1/RRS ICFDs. 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 detector tubes, induced by the moderator flow, resulted in strong peaks in the APSD and coherence functions of ICFD noise signals 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. Higher harmonic frequencies of the detector tube vibrations were also observed in the ICFD noise spectral functions as smaller and narrower peaks with 180 degree phase difference. As an example, Figure 4 shows the spectral functions of two ICFDs located in horizontal detector tube No.8 in Pickering-B Unit 5. The vibration peaks in the noise spectra at 3.8 Hz result in 100% coherence and zero phase difference in the ICFD noise signals. The first harmonics of the tube vibration at 7.0 Hz has a smaller coherence peak and the phase difference in the two ICFD noise signals is 180 degree at that frequency (not shown in Figure 4). Similar spectral functions of another ICFD pair housed in horizontal detector tube No.9 are shown in Figure 5. The in-phase vibration peak occurs at 3.7 Hz (fundamental vibration mode).

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 6 with two ICFDs from two different horizontal detectors tubes. 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 shift 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 6 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.

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 [3]. The long term monitoring of these vibration peaks is useful for early detection of mechanical damages in the reactor core caused by vibrations.

ESTIMATING RTD RESPONSE TIME

Noise analysis also provides a non-intrusive method for monitoring and estimating the dynamic response of RTDs installed in the process. The technique has been applied to both thermo-well and strap-on RTDs used in temperature measurements of moderator, reactor inlet-outlet header, channel-outlet and FINCH fuel channels of various reactor units. Measurable and physically reasonable fluctuations of RTD signals have been analyzed in Darlington, Pickering-B and Bruce-B units, and their noise signatures have been learned. Based on the established noise database, RTDs with degraded dynamic response can be identified.

Signal fluctuations of SDS1 heat transport high temperature (HTHT) RTDs were recorded in PNGS-B Unit 8 for 15 hours with the reactor operating at full power. The objective of the noise measurement was to estimate the response time of the newly installed RTDs and to identify possible anomalies in the RTD signals. The RTD response time derived from the APSD of noise signals was in the range of 14-16 sec for all the SDS1 HTHT safety RTDs. The APSD functions exhibited a clear corner frequency on log-log scale at around 1.1×10^{-2} Hz with linear attenuation. Irregular bi-level changes were found in some of the RTD signals. Earlier noise measurements of FINCH channel RTDs, reactor inlet/outlet header RTDs, moderator inlet/oulet RTDs and fuel channel outlet RTDs in Bruce-B and Darlington units also showed that the temperature fluctuations sensed by the RTDs are in the frequency range below 0.5 Hz for both the thermo-well and the strap-on RTDs.

Additional RTD noise measurements in the frequency range of 0-100 Hz were carried out in Pickering-B Unit 6 in 1993, in order to identify the source of a strong electrical noise in the SDS2 HTHT RTD temperature signals which has already tripped the reactor once. Based on our measurements, a design fault in the circuit of one of the ground fault detectors was positively identified as the source of signal transients. In fact, in 1989, one of the Pickering B units tripped on high temperature. Diagnosis at the time could not confirm the cause of the trip, but a faulty ground fault detector was suspected. Based on the conclusive results of the 1993 Unit 6 noise measurements, a surveillance program has been put in place at the station to monitor ground fault detector integrity. This program has already prevented a reactor trip in 1994 (on the current world record holder for continuous production, Unit 7 at Pickering-B) by early detection of a fault in the ground fault detector.

INVESTIGATING PRESSURE NOISE AND FLOW SIGNAL ANOMALIES

Noise analysis is being 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 pressure and flow transmitters and validating their dynamics, (2) identifying the resonance frequencies of pressure sensing lines, (3) validating FINCH flow and SDS1 safety flow signals, and (4) separating anomalies in flow from instrument noise.

Transient alarms on SDS1 Low Gross Flow (LGF) safety signals were investigated, which involved simultaneous noise measurements of four SDS1 flow signals, two reactor inlet and two outlet header pressure signals and seven FINCH inlet flow noise signals in the PHT system of Pickering-B Unit 6 at full power operation. The objective was to investigate the characteristics and the root cause of the strong signal dips detected in the SDS1 LGF flow signals, and to determine whether the signal dips represented real flow transients in the PHT system (induced by pumps or process abnormalities), or if the dips were generated locally in the flow measuring elements/instrumentation. The spurious alarms (dipping below 90% flow) caused by the dips in the Low Gross Flow loops has been a problem on PNGS-B units for some time. In Unit 6 the SDS1-D Low Gross Flow F4D-FT1 signal was spuriously alarming at a rate of up to 30 times per 12-hour shift. The typical time width of a signal dip was 70 msec.

The analysis proved that the signal dips in SDS1-D signals did not represent global flow reductions in the process. Most likely, the dips are generated locally and independently by the flow (Δp) measurement elements (orifice plate and impulse lines). Similar flow (Δp) measurements in FINCH channels do not show any dips, only the normal flow fluctuations. In those channels a much smoother flow element (Venturi tube) is applied to achieve a measurable Δp signals. No reactor inlet and outlet header pressure signals showed any dips similar to those found in SDS1-D flow signals. The fundamental frequencies and their higher harmonics of pressure sensing line resonances were also identified in all the pressure and flow signals as resonance peaks in the noise spectra. These peaks are well-known and are considered as normal components of the measured noise signals. They can be separated from the effect of the random dips on the flow noise spectra.

Fluctuations in the FINCH and SDS1-D flow signals are totally uncorrelated even if they were connected to the same reactor inlet header. The lack of coherence can be explained by the dominance of the independent and random dips in the SDS1-D flow signals superimposed on the normal and correlated fluctuations of the flow signals. The occurrence of dips in SDS1-D flow signals is random, resulting in a white noise contribution to the flow noise spectra. Also, the dips are uncorrelated between the four SDS1-D flow signals, indicating that the dips are generated independently. A subsequent study showed that by applying a minimum necessary filtering (dampening) to the SDS1-D Δp transmitter signals, the signal dips causing spurious alarms can be greatly reduced. Since the noise measurements proved that the signal dips do not represent real physical flow reductions in the PHT system, applying low-pass filtering to the transmitter signals would not corrupt the signal dynamics. Similar flow dips were found in the LGF safety signals of other Pickering-B units. The problem seems to be generic in all orifice-based flow measurements.

Further pressure and flow noise measurements were made in the low frequency range (0-1.0 Hz). A sharp and strong peak in the pressure noise spectra was found at 0.025 Hz in all the measured inlet and outlet header pressure noise signals with zero phase difference and maximum coherence (see Figures 7 and 8). This slow and correlated in-phase oscillation of pressure signals with about 40 sec time period can be clearly seen in the raw time series as well. Most likely the pressure oscillation is caused by a periodic "feed-and-bleed" control. Also, a smaller and wider pressure peak was found around 0.3 Hz in the inlet and outlet header pressure signals with high coherence. The 0.3 Hz oscillation between two reactor header pressure signals is in-phase or opposite phase depending on whether the two reactor headers are in the same coolant loop or in different loops (see Figures 7 and 8). These low-frequency pressure fluctuations have no effect on the measured FINCH and SDS1 flow fluctuations, since the latters are based on differential pressure measurements, in which both legs of the differential pressure transmitter are equally affected by the pressure oscillations. However, the same pressure oscillations can be identified in the in-core neutron flux fluctuations.

VALIDATING ZONE CONTROL SIGNALS

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 multi-channel spectral analysis of noise 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 zone level indicator signal and the in-core neutron flux detector located in the same zone (Zone 1) in Pickering-B Unit 6 is shown in Figure 9. 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. The corresponding spectral functions of zone level and control valve position signals of Zone 1 can be seen in Figure 10. 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 neutron 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 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 inferred from noise can be decomposed into a local zone component and an overall reactor core component. Once these complex 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.

VALIDATING ION CHAMBER SIGNAL DYNAMICS

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. Ion chamber noise signals from both SDS1 and SDS2 systems are being continuously recorded in the current Unit 5 outage. The purpose of these measurements is 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 5 and 7. 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 changing 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.

DETECTING BOILING IN FINCH FUEL CHANNELS BY FLOW NOISE ANALYSIS

The detection of coolant boiling in FINCH fuel channels can be based on the measurement of 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 [4]. The coolant is incompressible in non-boiling state, therefore the inlet and outlet flow fluctuations occur simultaneously, in phase. This results in high coherence and zero phase-shift between inlet and outlet flow fluctuations. Figure 11 shows the statistical coupling between inlet and outlet flow fluctuations in FINCH channel H05 with outlet temperature 305^0C, which indicates that the coolant is in non-boiling state (one-phase flow). The coherence is high over the entire 0-1.25 Hz frequency range, and the phase difference is zero.

In boiling FINCH channels the coolant becomes compressible, therefore the inlet flow fluctuations propagate to the outlet with some time delay, which leads to a linear phase function and a characteristic structure in the coherence function. In Figures 12 and 13, FINCH channels R17 and E14 with higher outlet temperatures (305.5^0C and 306^0C, respectively) show smaller coherence and phase difference deviating from zero in a characteristic way. Other FINCH channels with similar outlet coolant temperature exhibited the same behaviour of inlet/outlet flow noise coupling. In Figure 14 the noise signatures of inlet/outlet flow in FINCH channel L20 with outlet temperature 309^0C can be seen. This channel is most likely in boiling. Both the coherence and the phase functions are significantly different from the previous cases: (a) structured coherence function and linear phase as a function of frequency, (b) very high coherence and opposite phase below 0.05 Hz. The above dependency of phase and coherence functions on the channel power is typical and well-studied in light water reactors (in BWR, and in certain PWR), where strong coolant density fluctuations are carried by the coolant flow.

These observations give an independent way of detecting coolant boiling in FINCH channels using flow noise measurements (as opposed to outlet temperature and flow DC readings). The detection is based on the shape of the coherence and phase functions between inlet/outlet flow fluctuations. Since these functions have a relative amplitude scale, they are invariant to signal scaling factors and signal DC-offset bias. Therefore, the noise-based method can be applied even if the flow meter is miscalibrated (conversion factors and DC-readings are biased).

CONCLUSION

CANDU noise measurements carried out in the past three 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. 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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Table 1. Typical CANDU Instrumentation Used in Noise Analysis (Pickering NGS "B" shown)

System	**Type of Sensor**	**Number per System**	**Location of Sensor**
Neutron Power Measurement, Reactor Regulating System (RRS), SDS1 & 2	Platinum / Inconnel in-core flux detectors.	RRS: 28 SDS1: 34 + 34 Spare SDS2: 23 + 23 Spare	Distributed throughout the core to measure local neutron flux.
Neutron Power Measurement, Reactor Regulating System (RRS), SDS1 & 2	Boron Impregnated Ion Chambers	RRS: 3 SDS1: 3 SDS2: 3	At the edge of the neutron reflector to measure bulk neutron power and rate.
Pressure Measurement, Heat Transport Pressure Control System (HTPCS), Emergency Core Injection System (ECIS) and SDS1 & 2	DP Cell	HTPCS: 6 (Outlet Header) ECIS: 4 (Inlet header) 4 (Outlet Header) SDS1: 8 (Outlet Header) SDS2: 12 (Outlet Header)	Distributed throughout the four reactor outlet headers and four reactor inlet headers.
Channel Flow Measurement, RRS and SDS1	DP Cell	RRS: 22 SDS1: 12	Selected inlet feeders
Liquid Zone Level (a system used to control zonal powers within the reactor core)	DP Cell	RRS: 14	Distributed throughout the core.
Temperature Measurement, heat Transport process indication (Process) RRS, SDS1 & 2.	Platinum RTD	RRS: 380 (Outlet Channels) 22 (Inlet Channels) SDS1: 6 (Outlet Header) SDS2: 6 (Inlet Header) Process: 6 (Outlet Header) 4 (Inlet Header)	

NOTE: The 22 channels with full instrumentation, flow, inlet and outlet temperatures, are referred to in this paper as "FINCH" (fully instrumented) channels. In the case of the Darlington and Bruce reactors, FINCH channel instrumentation also includes outlet flow measurement. The inlet and outlet flow measurements are used in a steam quality calculation as these reactors allow some degree of boiling. The Pickering reactors operate sub-cooled in all channels.

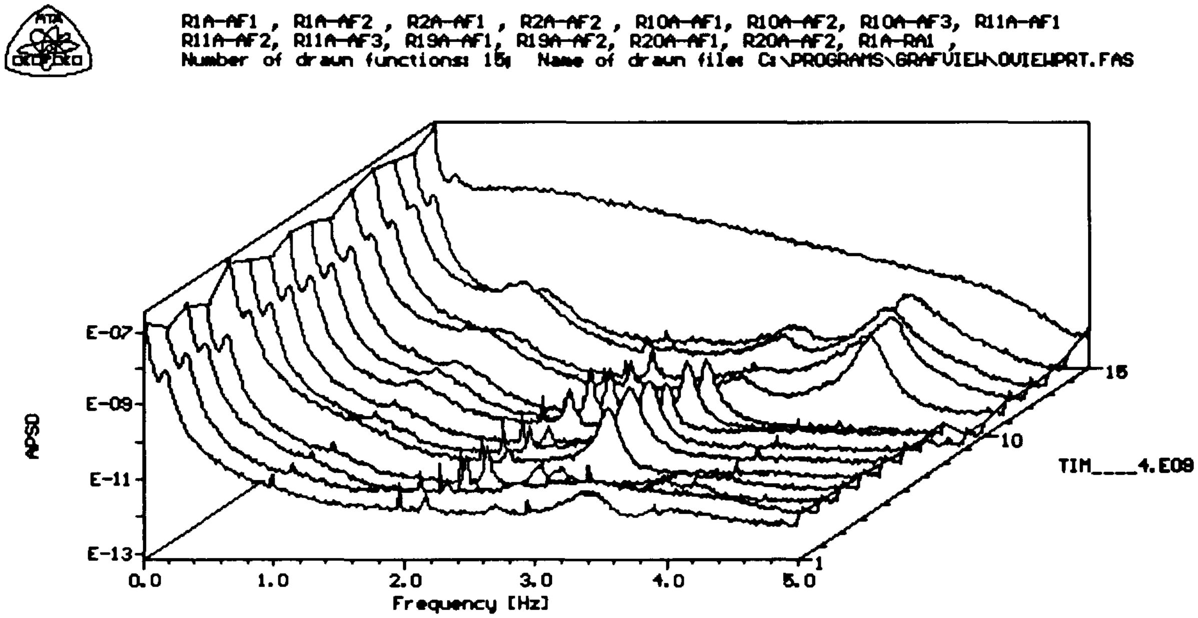

Figure 1. Normalized APSD functions of fourteen ICFD and an ion chamber noise signals from RRS Channel A in PNGS-B Unit 5, February 24, 1995

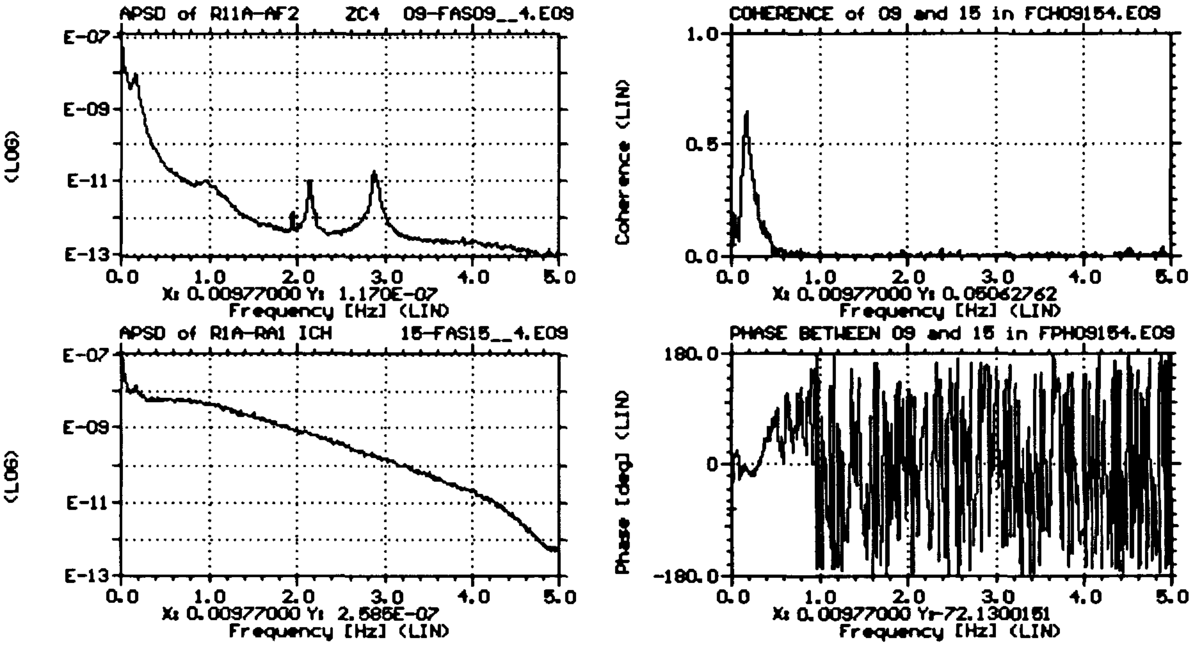

Figure 2. Normalized APSD, coherence and phase functions of neutron noise signals from ICFD R11A-AF2 and RRS-A ion chamber.
The peak at 0.2 Hz is a global reactivity oscillation
(PNGS-B Unit 5, February 24, 1995)

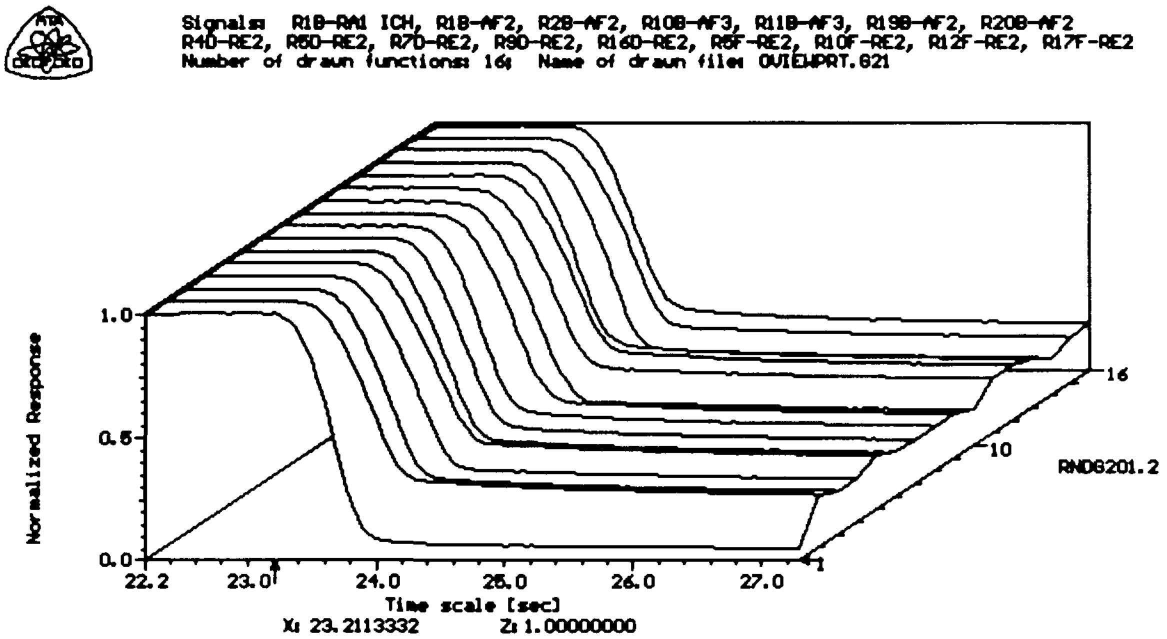

Figure 3. Normalized rundown response curves of RRS-B ion chamber and fourteen ICFDs (PNGS-B Unit 7, October 7, 1994)

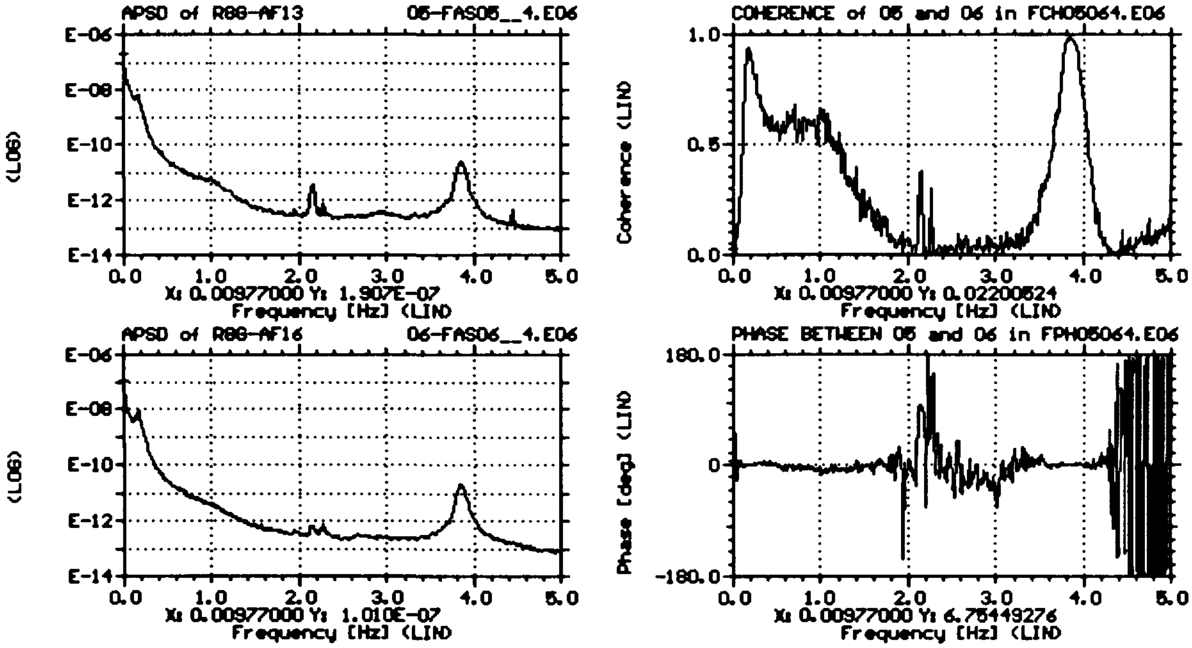

Figure 4. Normalized APSD, coherence and phase functions of neutron noise signals from two SDS2-G ICFD in-service detectors located in the same horizontal detector tube (HFD8)
The peak at 3.8 Hz is the fundamental vibration of tube HFD8
(PNGS-B Unit 5, February 24, 1995)

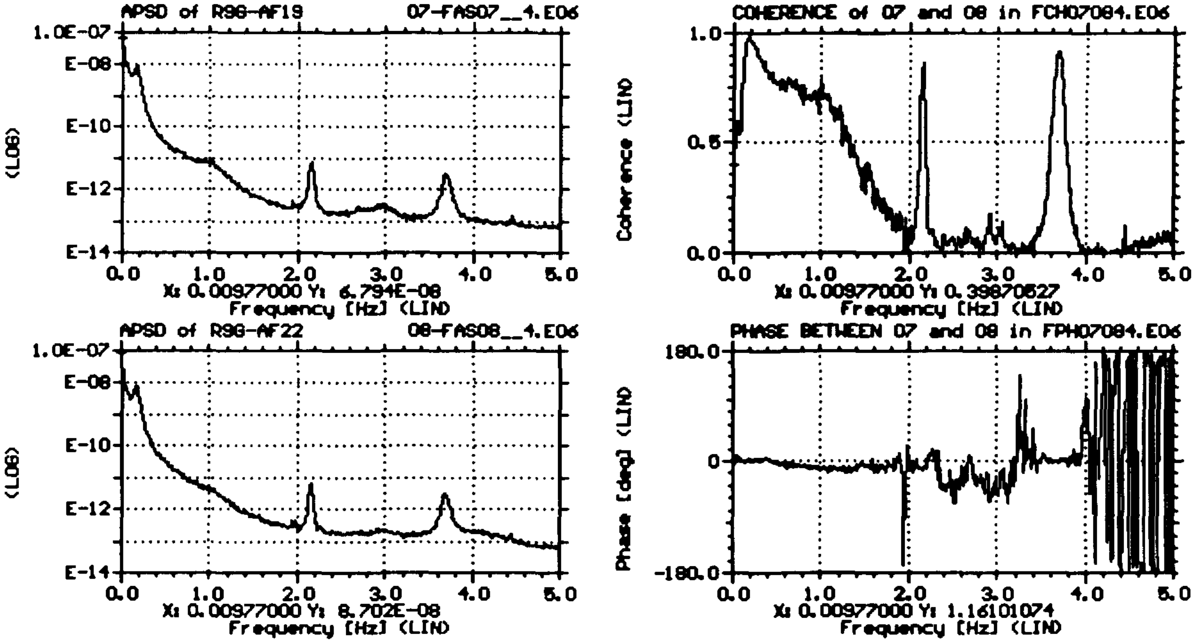

Figure 5. Normalized APSD, coherence and phase functions of neutron noise signals from two SDS2-G ICFD in-service detectors located in the same horizontal detector tube (HFD9) The peak at 3.65 Hz is the fundamental vibration of tube HFD9 (PNGS-B Unit 5, February 24, 1995)

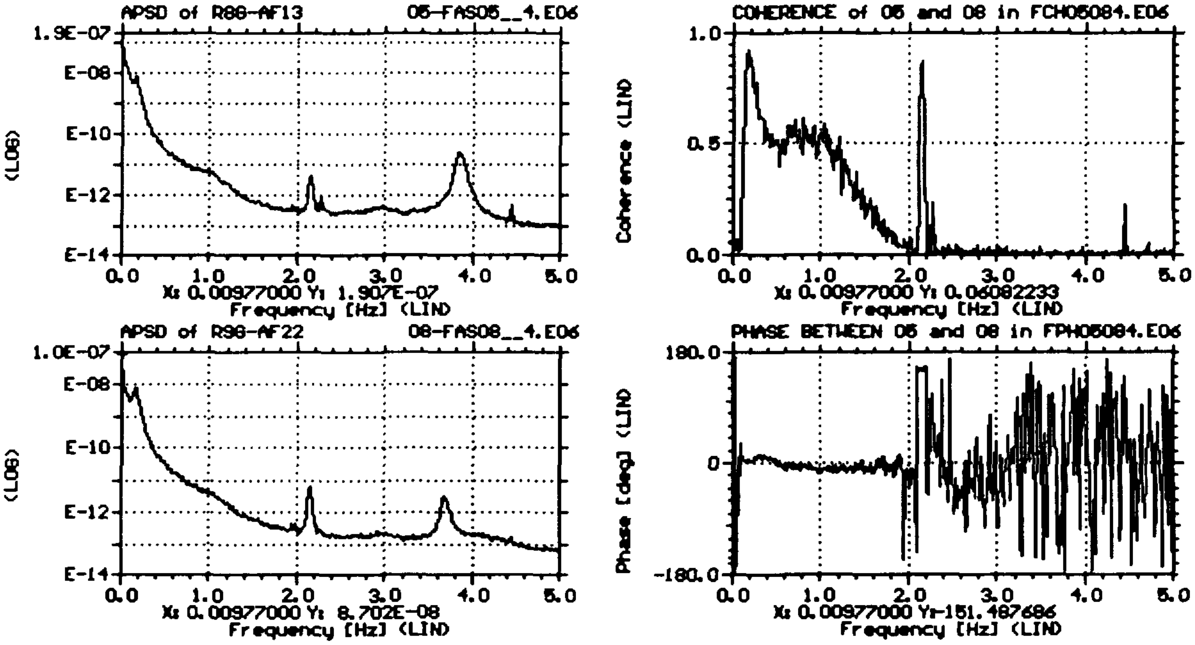

Figure 6. Normalized APSD, coherence and phase functions of neutron noise signals from two SDS2-G ICFD in-service detectors located in different horizontal detector tubes HFD8 and HFD9 in PNGS-B Unit 5, February 24, 1995

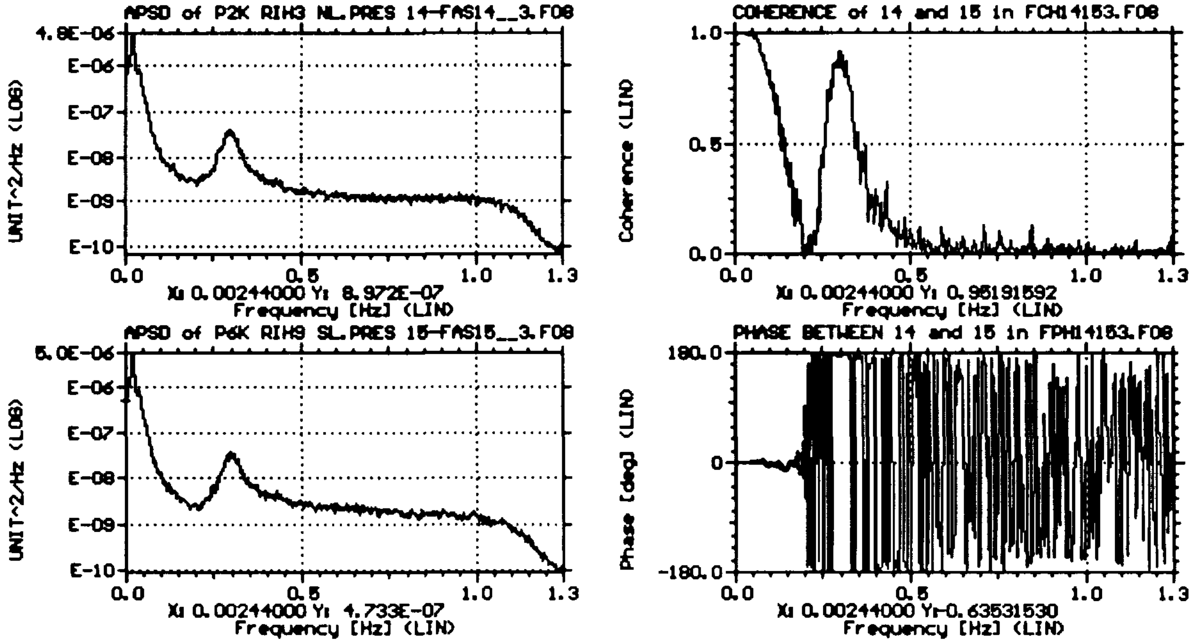

Figure 7. APSD, coherence and phase functions of pressure fluctuations of reactor inlet headers RIH3 and RIH9 located in different loops (north-south loops, PNGS-B Unit 6, November 1993)

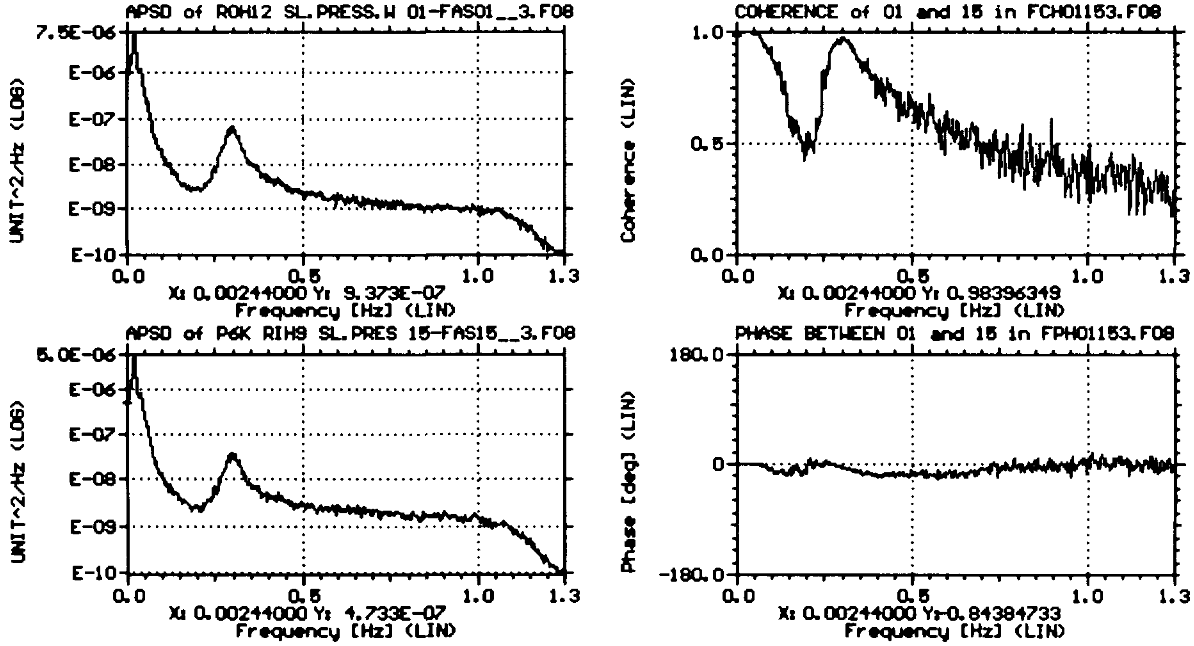

Figure 8. APSD, coherence and phase functions of pressure fluctuations of reactor inlet header RIH9 and outlet header ROH12 located in the same loop (south loop, east-west flow, PNGS-B Unit 6, November 1993)

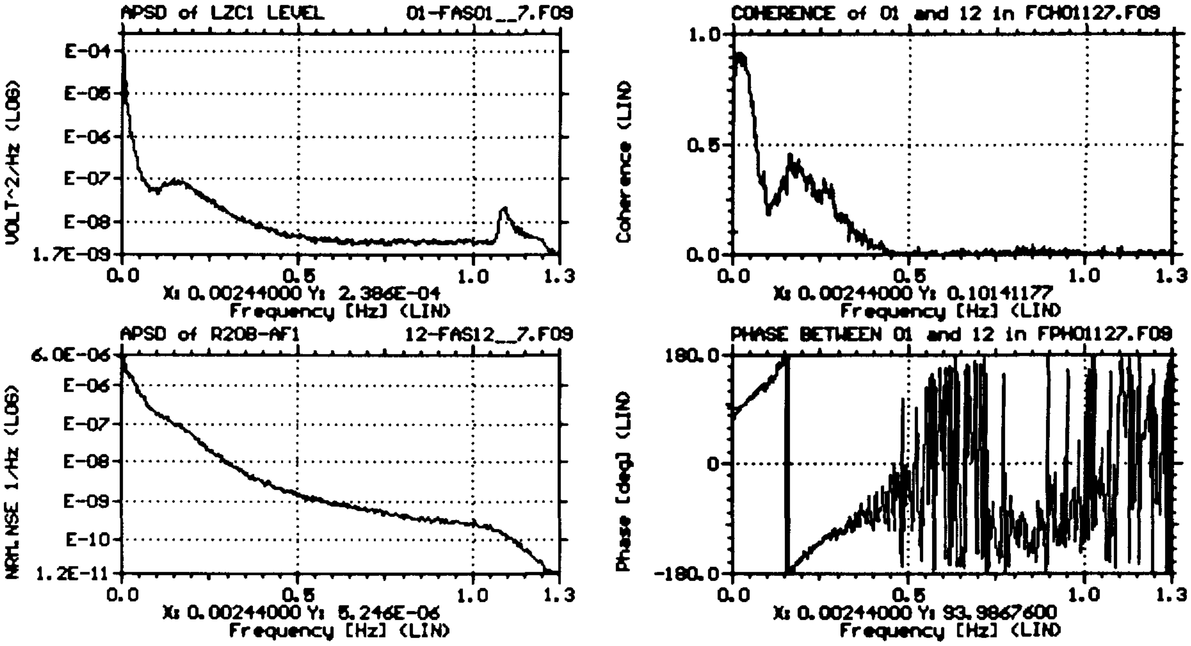

Figure 9. APSD, coherence and phase functions of Liquid Zone Level signal and In-Core Flux Detector signal in Zone 1 of PNGS-B Unit 6, August 25, 1994

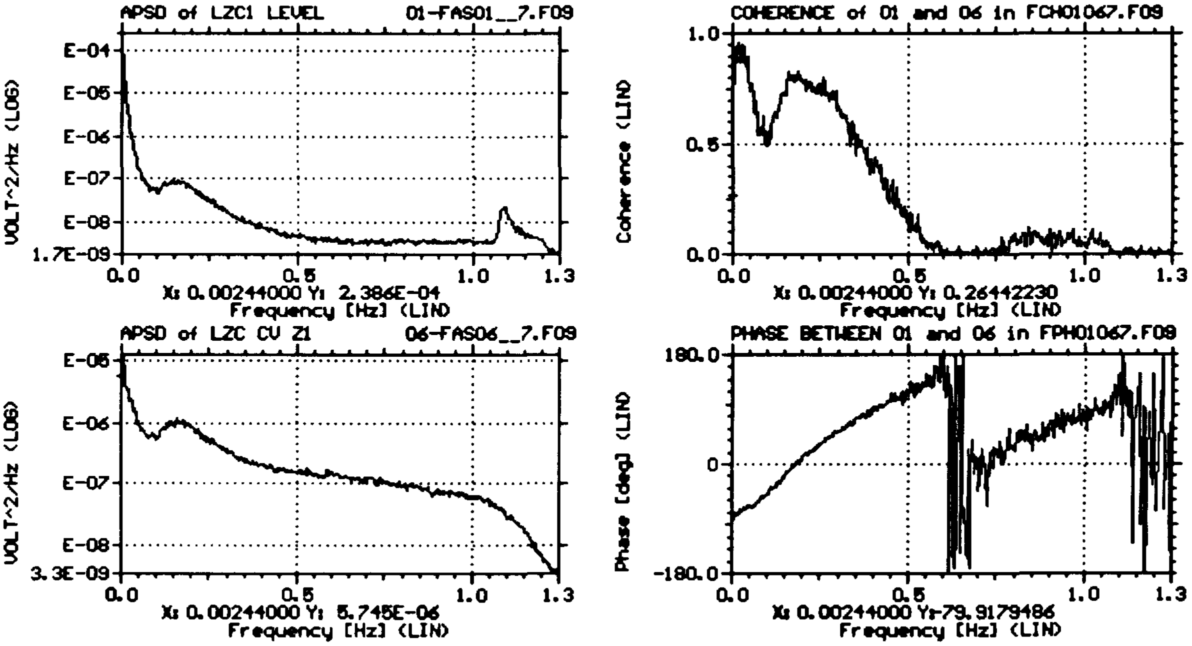

Figure 10. APSD, coherence and phase functions of Liquid Zone Level signal and Control Valve Position signal in Zone 1 of PNGS-B Unit 6, August 25, 1994

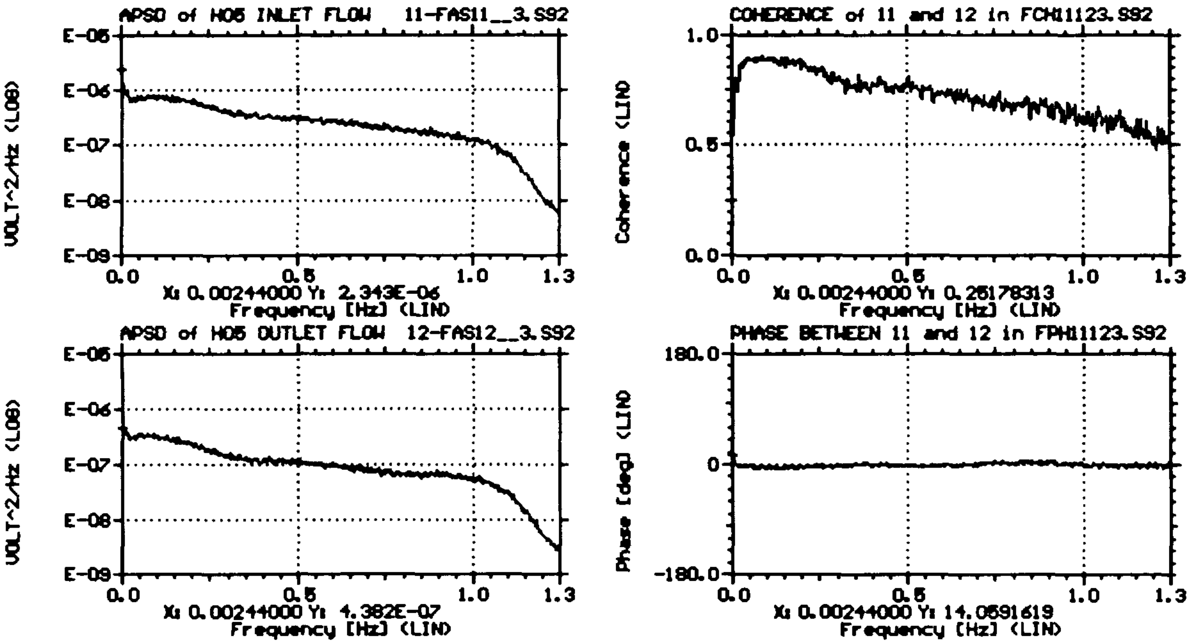

Figure 11. APSD, coherence and phase functions of inlet and outlet flow fluctuations in FINCH channel H05 with outlet temperature 304.5^0C (non-boiling channel, DNGS Unit 3, 1993)

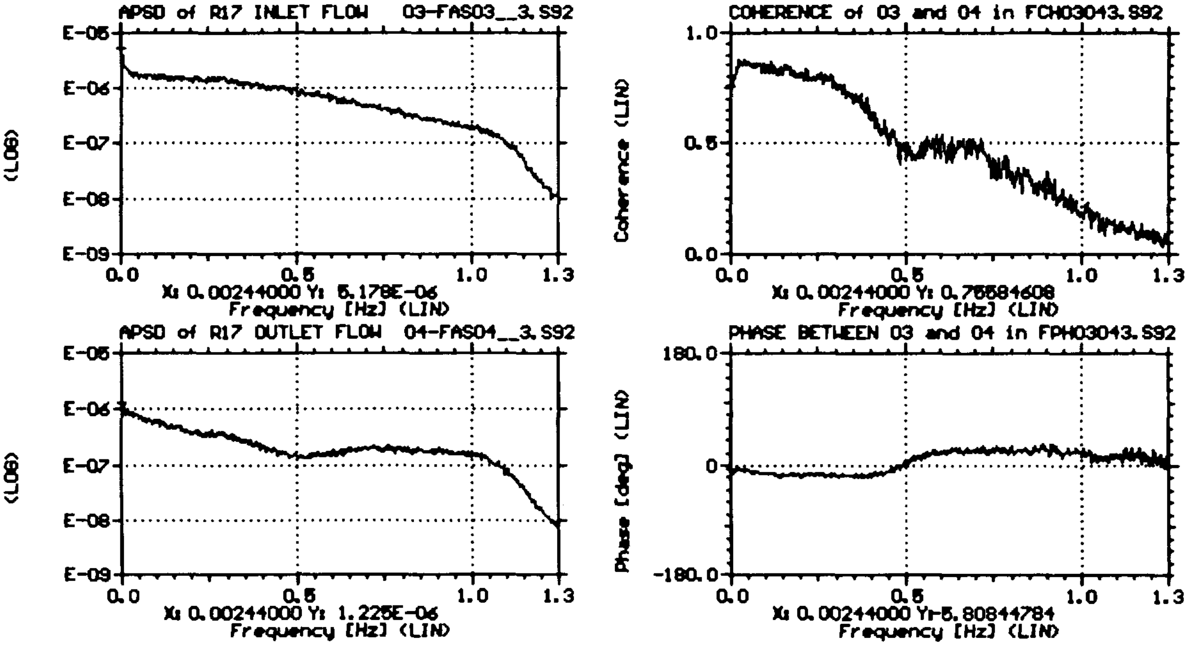

Figure 12. APSD, coherence and phase functions of inlet and outlet flow fluctuations in FINCH channel R17 with outlet temperature 305.5^0C (intermediate channel, DNGS Unit 3, 1993)

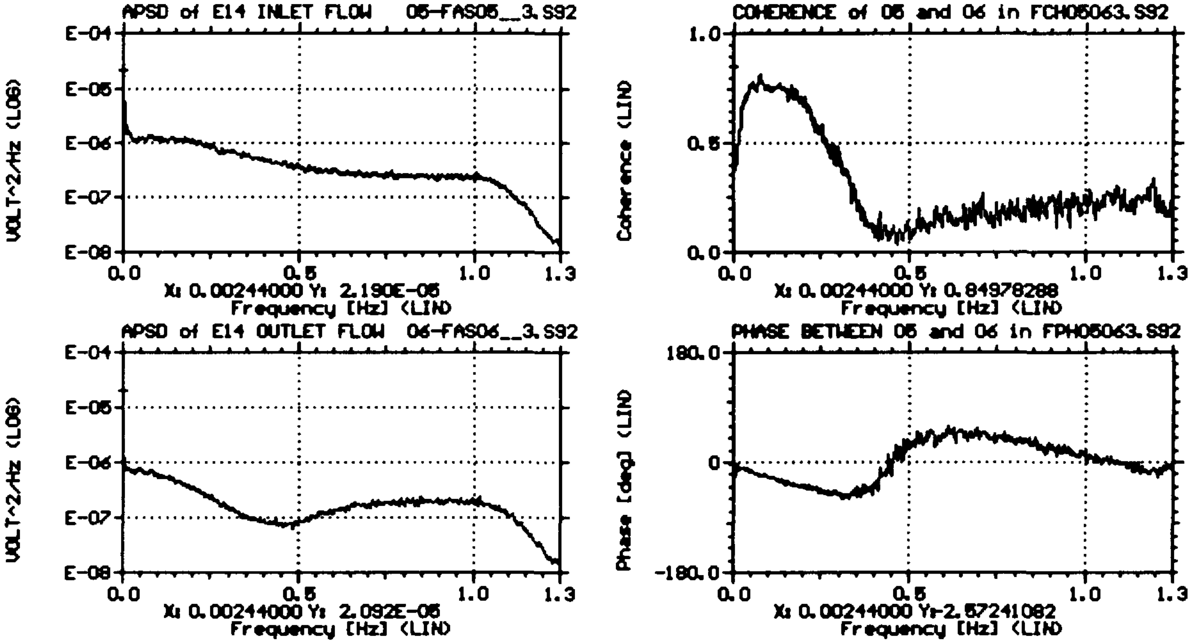

Figure 13. APSD, coherence and phase functions of inlet and outlet flow fluctuations in FINCH channel E14 with outlet temperature 306^0C (intermediate channel, DNGS Unit 3, 1993)

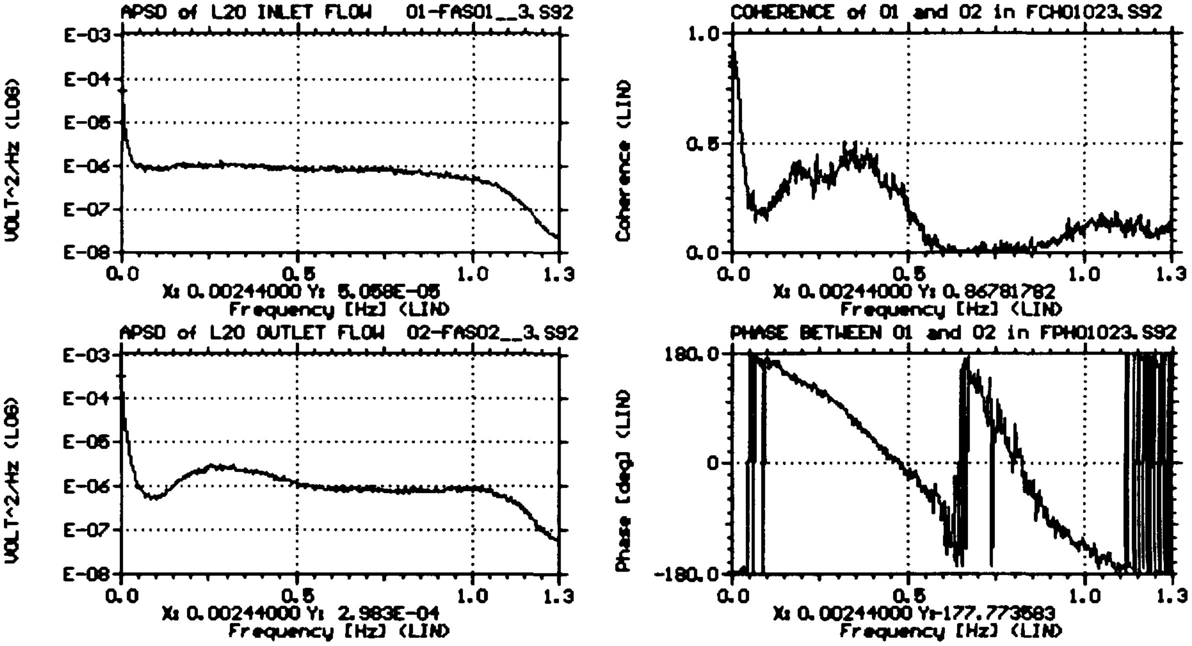

Figure 14. APSD, coherence and phase functions of inlet and outlet flow fluctuations in FINCH channel L20 with outlet temperature 309^0C (boiling channel, DNGS Unit 3, 1993)