MEASUREMENT AND ANALYSIS OF THE DYNAMIC RESPONSE OF REACTOR INSTRUMENTATION OF SAFETY AND REGULATING SYSTEMS

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ABSTRACT

The dynamics of safety and control related instrumentation is regularly tested in the CANDU nuclear power stations of Ontario Power Generation (OPG). Two different measurement techniques are being used regularly to test the dynamics of processes and their instrumentation. In both cases, voltage signals of standard station instrumentation are recorded by portable multi-channel high-speed high-resolution data acquisition systems. Safety related dynamic parameters are derived from the multi-channel time series measurements.

The first inspection technique is used at steady-state full power operation. It utilizes the dynamic information carried by the small fluctuations (noise) of station signals measured around their steady-state mean values. The validation of signal dynamics is based on the frequency-dependent statistics of fluctuations (noise signatures) obtained in time series measurements.

The specific applications include the following areas:

- Flux noise measurements to detect and characterize (a) possible anomalies of in-core flux detectors (ICFDs), ion chambers and their electronics, (b) mechanical vibration of fuel channels and in-core detector tubes induced by coolant/moderator flow.
- Pressure and flow noise measurements (a) to estimate the resonance frequencies and response times of flow/pressure transmitters and their sensing lines, (b) to identify the root cause of flow oscillations and “flow dips” found in orifice-based reactor coolant inlet flow signals.
- Noise measurements of the level signals of the light-water liquid zones and ICFDs to detect (a) oscillating control valves, (b) instabilities in local flux control.

The second technique is called the rundown test, which includes the measurement of in-core flux detectors and ion chambers responding to a reactor trip from steady-state high power. The reactor trip is initiated manually at the beginning of planned outages by firing shutdown system No.1 (SDS1 – shut-off rods), or shutdown system No.2 (SDS2 - poison injection). The recorded trip response signals of ICFDs and ion chambers are used to derive the effective prompt fractions of ICFDs, and to assess the dynamics/effectiveness of the trip mechanism: speed of shut-off rod insertion in SDS1 trips, and poison

propagation inside the injection nozzles/moderator in SDS2 trips. In addition to the regular rundown tests performed in the reactor units of Darlington, Pickering-B and Bruce-B stations, the same technique was used to commission new ICFDs installed in Pickering-B Units 5 and 6.

Results provided by the two inspection techniques are used in the following areas: (a) safety calculations and modeling, (b) instrument commissioning projects, (c) compliance with regulatory requirements and (d) troubleshooting anomalies in detector and instrument dynamics.

1. INTRODUCTION

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 manner. The noise measurements are usually performed at steady-state operation, while the availability of the signals in their respective system (shutdown systems, regulating system) is not interrupted.

In 1992, an extensive program of reactor noise analysis was initiated 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 in 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 over the past eight years at various operating conditions. Also, station procedures for performing 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 have indicated that the detection and characterization of instrument and process failures, as well as, the 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 and signal processing systems, capable of carrying out synchronized measurements of six nodes of 16-channel signal groups, have been developed and regularly used in station measurements. The custom-built signal conditioning and data acquisition hardware (isolation buffer amplifiers, anti-aliasing filters, DC-compensators, noise amplifiers, 16-bit analog-to-digital converter 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 data acquisition 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 modeling for cause-and-effect analysis and response time estimation, and curve fitting to measured noise signatures for the purpose of deriving signal time constants. The typical frequency-dependent statistical functions calculated from the multi-channel time series measurements are (a) the auto power spectral density (APSD) functions of noise signals, (b) coherence function, and (c) phase functions between noise signals.

Additional functions in the time domain, such as amplitude probability density functions and auto and cross correlation functions are calculated.

Newly designed portable noise analysis systems with optically isolated inputs have been developed in AECL Chalk River Laboratories [1]. In the present configuration, the new noise analysis system consists of two identical 16-channel 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.

2. VALIDATING IN-CORE FLUX DETECTOR DYNAMICS BY NOISE ANALYSIS

Three different types of in-core flux detectors (self-powered flux detectors) are used in OPG's CANDU reactors for safety and control purposes. A prompt fraction can be assigned to each detector, which gives the prompt response of the detector current to an initial change in thermal neutron flux. In addition to the prompt response, a series of delayed current components are included in the detector response.

In Darlington and Bruce-B, the in-core flux detectors used in SDS1 are Inconel ICFDs located in vertical guide tubes. The Inconel ICFDs are overprompt (104%), and are almost entirely neutron sensitive. Their main current producing process is the prompt (n, γ, e) neutron-capture interaction. The small delayed detector current with negative amplitude arises from (n, β) decay and from the delayed reactor γ-field through the (γ, e) prompt interaction.

The in-core flux detectors used in SDS2 in Darlington and Bruce-B are Platinum-clad Inconel ICFDs located in horizontal guide tubes. The Platinum-clad Inconel ICFDs are underprompt (89%) and they have a mixed neutron/gamma sensitivity (60% vs. 40%). The relatively large delayed current is caused by (n, β) decay and by the delayed portion of the reactor γ-field. Approximately one third of the reactor γ-field is delayed with respect to the thermal neutron flux (delayed γs are emitted by fission products). The reactor regulating system in Darlington is equipped with Inconel overprompt ICFDs, while in Bruce-B, Platinum-clad Inconel underprompt ICFDs are used in RRS.

In Pickering-B, both shutdown systems and the reactor regulating system use the same type of ICFDs. In unit 7 and 8, all ICFDs are coiled Platinum underprompt detectors with an original prompt fraction of 85%. The prompt fractions of most of these ICFDs decreased significantly over the years. Their average value is 80%. In units 6 and 5, the entire ICFD system was replaced in 1996 and 1999, respectively. The new HESIR in-core flux detectors are Platinum-clad underprompt ICFDs.

The ICFD signal fluctuations measured and processed in the noise analysis applications are small but relatively fast changes. The frequency range of interest in noise analysis is from 0.01 Hz to 100 Hz. Since the delayed components of the ICFD current are too slow to contribute to the above frequency range, the entire ICFD noise spectrum is produced by the prompt component of the detector's current generating mechanisms. Therefore, the deterioration of the ICFD prompt fractions can be directly detected in the measured noise signatures. The noise analysis of ICFD signals gives a direct, still non-intrusive way of monitoring the prompt fractions of ICFDs.

One of the most important applications of reactor noise analysis in OPG's CANDU units is the confirmation of the functionality and dynamic response of in-core flux detector signals. The validation is based on the statistical signatures of signal fluctuations characterizing the frequency content and the dynamic coupling between detector signal fluctuations.

The first in-core flux detector noise measurements at full-power were performed in early 1992 at Units 6, 7 and 8 of Pickering-B [2]. Further in-core noise measurements were carried out in Darlington and Bruce-B in the same year [3, 4].

The results showed that flux noise signals contained process related dynamic information in the frequency range of 0-20 Hz. This indicates that the in-core flux detectors are "alive" and capable of following the small but fast fluctuations in the neutron/gamma flux around its static value, even after 12-15 years of continuous service.

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 dynamic 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, coherence and phase functions of detector noise signals. Having established the station-specific baseline noise signatures, abnormal noise patterns indicating incipient degradation of detectors/instrumentation dynamics now 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 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 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.

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 couplings between their noise signals:

- ICFDs located in the same vertical detector tube,
- ICFDs located in the same horizontal detector tube,
- ICFDs lined up along the same set of fuel channels, and
- ICFDs and liquid zone level indication signals located in the same zone.

The known spatial dependency of normal noise signatures is used to detect anomalies and validate the dynamics of newly installed instrumentation.

Noise measurements were used in the commissioning of new HESIR in-core flux detectors installed in Pickering-B Unit 6 in March 1996, and in Unit 5 in June 1999. Noise signals of the new ICFDs were recorded at 60% of full power and were analyzed off-line. The multi-channel noise signatures of all 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. After the noise measurements, the response signals of all in-core flux detectors and 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 the measured signals, were found to be above 90%.

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 fractions 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 (RRS-A). The noise signals were recorded in Pickering-B Unit 5 at full power on February 24, 1995. The coherence and phase functions of the noise signals from the ICFD in Zone 4 (east side) and the RRS-A ion chamber (north side) can be seen in Figure 2. The narrow high-coherence range around 0.2 Hz with zero phase-difference indicates the presence of a global (in-phase) reactivity fluctuation, which is common in all ICFD and ion chamber noise signals. This frequency range is used to estimate the ICFD's relative prompt fraction.

Similar results of noise measurements in Bruce-B Unit 7 are shown in Figures 3 and 4. As in the previous case, the in-core flux detector and ion chamber noise signals show a global 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 (north side) and the RRS-A ion chamber are highly correlated at 0.2 Hz, despite their large physical distance. Figure 4 shows a similar coupling between the noise signals of the RRS-A ICFD in Zone 13 (south side) and the RRS-A ion chamber. If no sufficient coherence can be found between an ICFD and the reference ion chamber, the relative promptness of the ICFD can be still assessed by comparing its noise spectrum to that of other ICFDs. 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.

3. VIBRATIONS OF DETECTOR TUBES DETECTED BY NOISE ANALYSIS

Evidence of mechanical vibration of both horizontal and vertical 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.

A detector vibrating in an inhomogeneous static flux senses virtual flux fluctuations and it produces an oscillating current component at the vibration frequency via its prompt response channel. In this way, the movement of the detector in a non-zero flux gradient is directly mapped into detector current fluctuations. Increase in the vibration amplitude or possible impacting on surrounding structures can be detected indirectly by ICFD noise analysis.

The vibration of detector tubes, induced by the moderator flow, results in strong peaks in the spectra and coherence functions of noise signals of 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. Depending on the locations of the ICFDs inside the guide tube, the detectors may have zero or 180 degree phase differences at the frequencies of the higher harmonics, with high coherence.

Figure 5 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 vibrations 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 detector tubes in Pickering-B Unit 5. The peaks at 3.8 Hz and 3.7 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 Power Generation measured so far. It was especially dominant in the 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.

The APSD functions of noise signals from ICFDs located in vertical guide tubes in Pickering-B 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 also present in the noise signals of vertical detectors. Also, the 2.1 Hz core internal vibration can be seen in the spectral functions of some vertical ICFDs in Pickering-B units.

Flow-induced vibrations of the long vertical detector guide tubes (VFD1 and VFD27) were observed in all four Darlington units. The frequency spectra of ICFDs located in the vertical flux detector tube VFD27 in Unit 1 is shown in Figure 7. The fundamental vibration peak is at 2.5 Hz, followed by three equally-spaced peaks of higher vibration modes. Similar results obtained in Unit 4 are shown in Figure 8. The noise spectra of ICFDs in VFD27 have a series of relatively wide peaks at regular frequencies 2.7 Hz apart. The regular series of wide vibration peaks is an indication of detector tube impacting.

By monitoring the trend of vibration peaks in the noise spectral functions of the measured ICFD signals, the mechanical condition of the detector tube can be assessed based on the following simple principles.

- Increase in the magnitude of the peak in the noise spectra of the ICFD indicates detector tube vibration with increasing amplitude.
- Shift in the frequency location of the spectral peak indicates changes in the mechanical conditions/support of the detector tube.
- Widening of the spectral peak and the occurrence of higher harmonics in the ICFD noise spectra indicate increasing impacting with the surrounding reactor internals [5].

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

4. VIBRATIONS OF FUEL CHANNELS DETECTED BY ICFD NOISE ANALYSIS

ICFD noise measurements detected the flow-induced vibration of fuel channels at frequencies around 4.5 - 6 Hz and at 15 Hz in the Darlington, Pickering-B and Bruce-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 found in the same frequency range [6].

A typical result of ICFD noise measurements performed in Darlington Unit 1 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 pair of in-core flux detectors in Darlington Unit 2 are shown in Figure 10. The same group of fuel channels is vibrating at frequencies slightly different from the previous case in Unit 1. 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 phase.

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 ICFD 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. Similar results were obtained in routine ICFD noise measurements in the Pickering-B and Bruce-B reactor units as well.

Noise measurements clearly showed that ICFDs lined up along the same set of fuel channels, but separated by a relatively large distance, 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 is done routinely as part of the regular noise-based ICFD surveillance. Changes in the above vibration patterns may indicate impacting or structural changes in the fuel channels.

5. 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 System 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 3-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 (minimum of –7 decades). Should anomalies occur, corrective actions still could be taken before the startup. In the Pickering-B applications, noise analysis identified faulty ion chamber amplifiers, and it provided supporting data for the relatively frequent SDS1 spurious Log N Rate trips in Pickering-B 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 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.

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 (-4 decades) 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. A comprehensive noise survey of the dynamics of Lin N, Log N and Log N Rate signals of SDS1 ion chambers were performed at both full power and at low power in Pickering-B Unit 6 and Unit 8 in 1996 and 1999. Typical anomalies, such as excessive background noise, irregular spikes, transients, and EMI sensitivity were identified in the ion chamber signals at low power levels.

6. VALIDATING ZONE CONTROL SIGNALS BY NOISE ANALYSIS

The goal of this application is to validate the cause-and-effect relationships between the ICFDs signals, the 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 the measured 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 the 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 15. The 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 s, 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 individual 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 in the 14 zones are driven by the independent control actions of the reactor regulating computer.

The slow zone level fluctuations (below 0.1 Hz) in different zones are independent (zero coherence), while the 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 and Bruce-B showed the same statistical coupling under normal conditions. A typical zone control coupling in Darlington Unit 3, shown in Figure 16, is remarkably similar to that of Pickering-B Unit 6, shown in Figure 15.

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 spatial patterns have been learned, they can be used to validate process/instrumentation dynamics of the zone control system. If these patterns are reproduced in subsequent noise measurements, it indicates that the process and its instrumentation are in normal condition.

7. OTHER APPLICATIONS OF NOISE ANALYSIS

Noise analysis has also been successfully used in pressure and flow measurements of the primary heat transport system. The application includes the following areas: (1) estimating the response time of flow and pressure transmitters and validating their dynamics, (2) estimating the resonance frequencies and the time constants of pressure sensing lines, (3) validating FINCH flow and SDS safety flow signals, and (4) characterizing the root cause of flow anomalies, such as “signal dips” and oscillations found in orifice-based reactor coolant inlet flow signals [7, 8]. Most of the SDS safety flow channels exhibit large, negative, aperiodic flow-signal transients, called “flow dips”. The signal transients are random in occurrence. Their width is less than 100 msec, and their amplitude could be as big as 10% of full flow.

In the fall of 1997, the technique was successfully used in the Loss-of-Flow (LOF) trip-coverage project at Darlington. In collaboration with AECL Chalk River Laboratories, the response times of the PHT safety system flow transmitters were measured, re-adjusted to a specific value, and validated across all four reactor units with non-intrusive, in-situ flow-noise measurements. The signals of the flow transmitters (Rosemount and Gould) are used in the SDS1 and SDS2 shutdown systems. The response time estimation was based on the spectral properties of the fluctuations of the flow transmitter output signal obtained in in-situ measurements at full flow [9].

In June 1998, flow and sensing line pressure noise measurements were performed in-situ on the SDS2 flow loop FT-3J in Darlington Unit 3 at 98% of full power. The goal of the measurement was to investigate the effect of various flow transmitters (Rosemount, Gould, and Bailey) and various sensing line modifications on the statistics of “flow dips”. The statistical signatures of the sensing line pressure signals, the differential pressure input signal to the flow transmitter, and the transmitter output signal were measured and analyzed. The noise signatures evaluated in the study included the frequencies and noise amplitudes of sensing line resonances, amplitude distribution of flow-dips, attenuation of frequency components, time constants, and overall response time [10-12]. Typical frequency spectra of the flow fluctuations measured by the three different flow transmitters in loop FT-3J are shown in Figure 17. The magnitudes of the corresponding transmitter transfer functions, derived from the in-situ pressure/flow noise measurements in loop FT-3J, are shown in Figure 18.

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). Boiling in FINCH fuel channels can be also detected by noise analysis. The detection of coolant boiling in FINCH fuel channels is 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 [3].

8. 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 systems 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 at the beginning of planned outages for a limited number of ICFD detectors and ion chambers. The validation of their dynamics is based on the their response to an operator-initiated reactor trip. These response signals are also used (1) to estimate the effective prompt fractions of the in-core flux detectors and (2) to assess the spatial distribution and effectiveness of the trip mechanism (drop of shut-off rods, or poison injection). 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. SDS1 and SDS2 induced rundown tests are carried out regularly in Darlington and Pickering-B at the beginning of scheduled outages as part of the ICFD surveillance program [13, 14].

In a typical SDS1-induced rundown test in Darlington Unit 1, the average prompt fraction of the vertical Inconel ICFDs was 103%, while the horizontal Platinum-clad Inconel ICFDs had an average prompt fraction of 90%. In a typical 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 19). This observation can be also used to identify possible degradation of the shut-off rod mechanism.

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 SDS1-trips, this time interval is 1 second).

Figures 20 and 21 show the normalized trip response signals of the SDS1 Channel F ICFDs (overprompt Inconel) and the SDS2 Channel H ICFDs (underprompt Platinum-clad Inconel), along with the Channel H and F ion chamber linear output signals.

SDS1-trip measurements were also used in the commissioning of new HESIR in-core flux detectors installed in Pickering-B Unit 6 in March 1996, and in Unit 5 in June 1999, to test the dynamic response of the new ICFDs and to estimate their effective prompt fractions [15, 16]. The trip response signals of all safety system ICFDs were recorded and analyzed off-line. Typical ICFD commissioning results are shown in Figure 22. The estimated prompt fractions and the 50%-level crossing times of the ICFD signals are plotted as functions of the vertical locations of the ICFDs.

Once the ICFD noise signatures are calibrated to the results of the reactor rundown test or to the ion chamber noise signatures, changes in the ICFD prompt fraction can be detected by noise analysis any time between rundown tests. The noise-based monitoring of detector performance can complement the information on detector dynamics inferred from the rundown tests.

CONCLUSION

CANDU noise measurements carried out over the past eight years have 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 are obtained from the multi-channel time series measurements performed 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. CANDU reactors provide a unique opportunity, in that the amount of detailed information contained in their neutron spectra far surpasses that typically observed in light water reactors. There is significant potential to develop many more sophisticated and useful core surveillance tools by exploiting this information using noise analysis technology.

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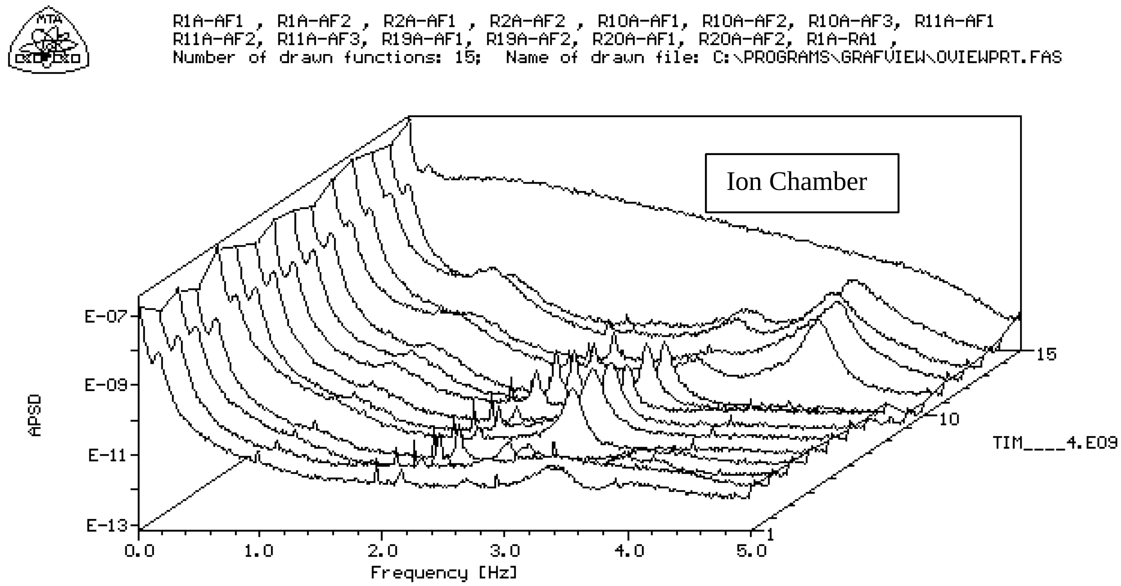


Figure 1. Normalized APSD functions of fourteen ICFD noise signals and the ion chamber noise signal from Channel A of the Reactor Regulating System (RRS-A), measured in Pickering-B Unit 5.

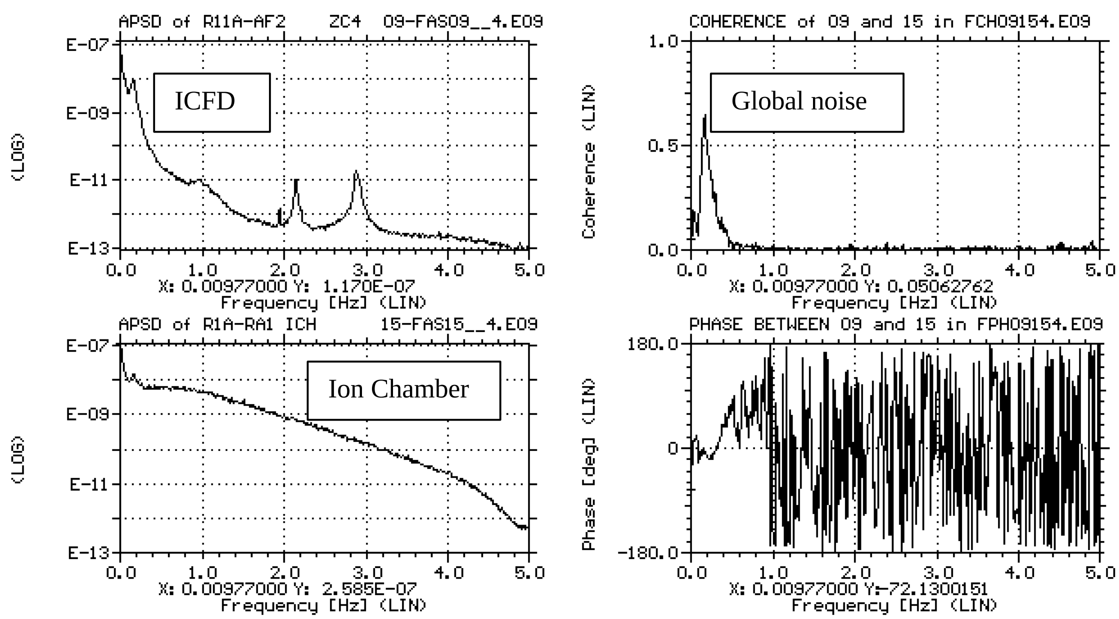


Figure 2. Normalized APSD, coherence and phase functions of noise signals of ICFD R11A-AF2 from Zone 4 and the linear output of the ion chamber from RRS-A. The peak at 0.2 Hz is a global reactivity oscillation caused by the global oscillations of liquid zone levels in the 14 light water compartments in Pickering-B Unit 5.

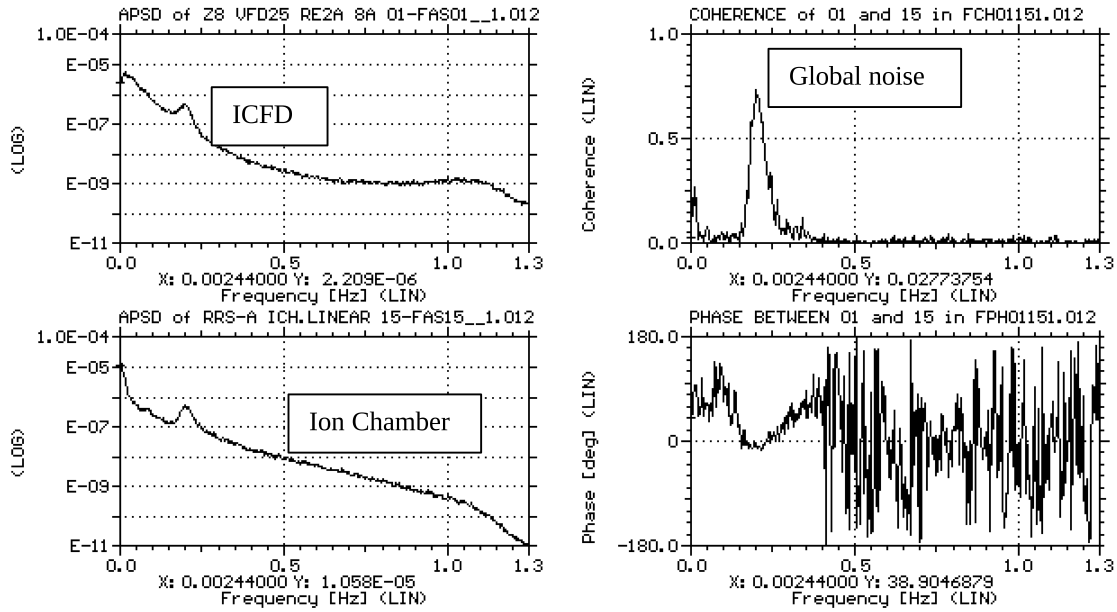


Figure 3. Normalized APSD, coherence and phase functions of flux noise signals from Zone 8 ICFD VFD25-RE2A and RRS-A ion chamber. The peak at 0.2 Hz is a global reactivity oscillation caused by the global oscillations of liquid zone levels in the 14 light water compartments in Bruce-B Unit 7.

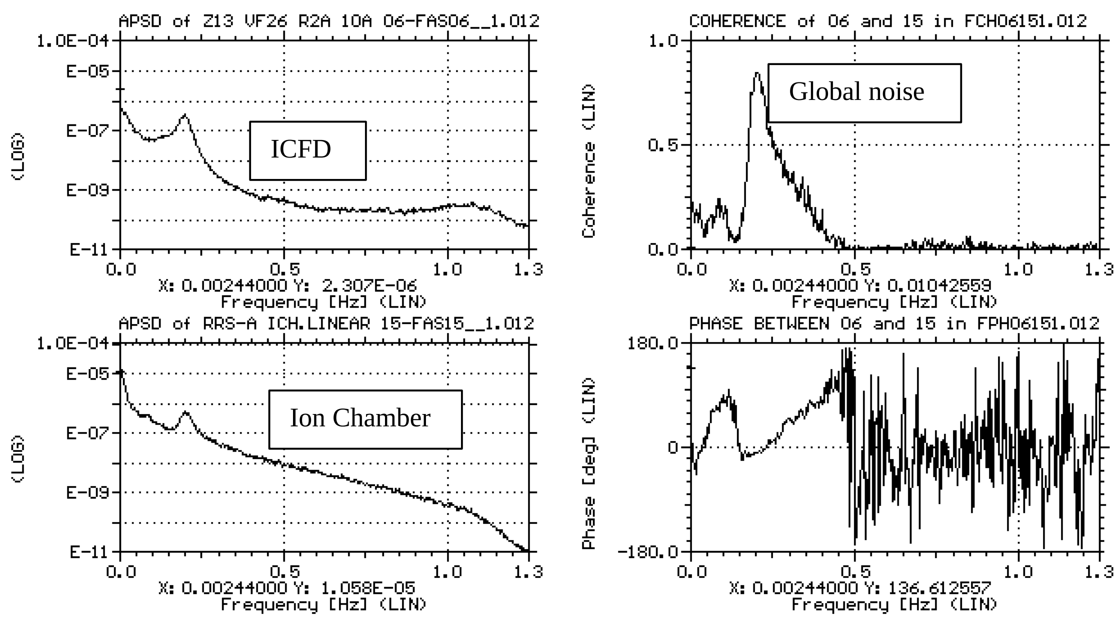


Figure 4. Normalized APSD, coherence and phase functions of flux noise signals from Zone 13 ICFD VFD26-RE2A and RRS-A ion chamber. The peak at 0.2 Hz is a global reactivity oscillation caused by the global oscillations of liquid zone levels in the 14 light water compartments in Bruce-B Unit 7.

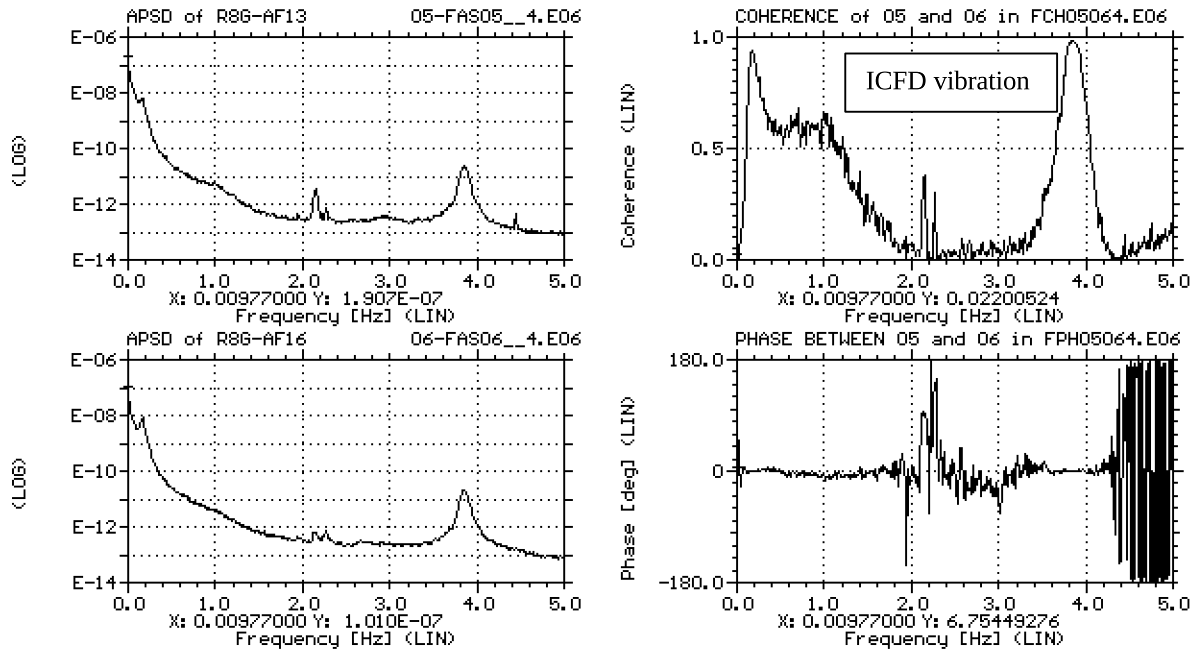


Figure 5. Normalized APSD, coherence and phase functions of flux noise signals from two SDS2-G ICFDs located in the same horizontal detector tube, HFD8, measured in Pickering-B Unit 5.

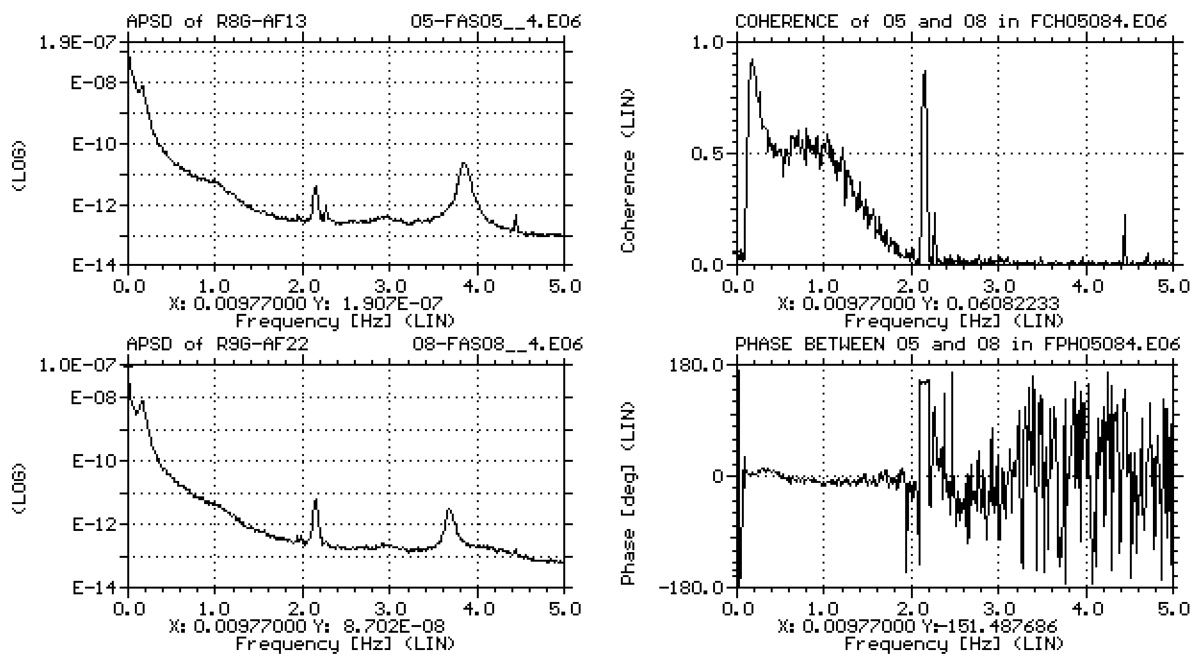


Figure 6. Normalized APSD, coherence and phase functions of flux noise signals from two SDS2-G ICFDs located in different horizontal detector tubes, HFD8 and HFD9, measured in Pickering-B Unit 5.

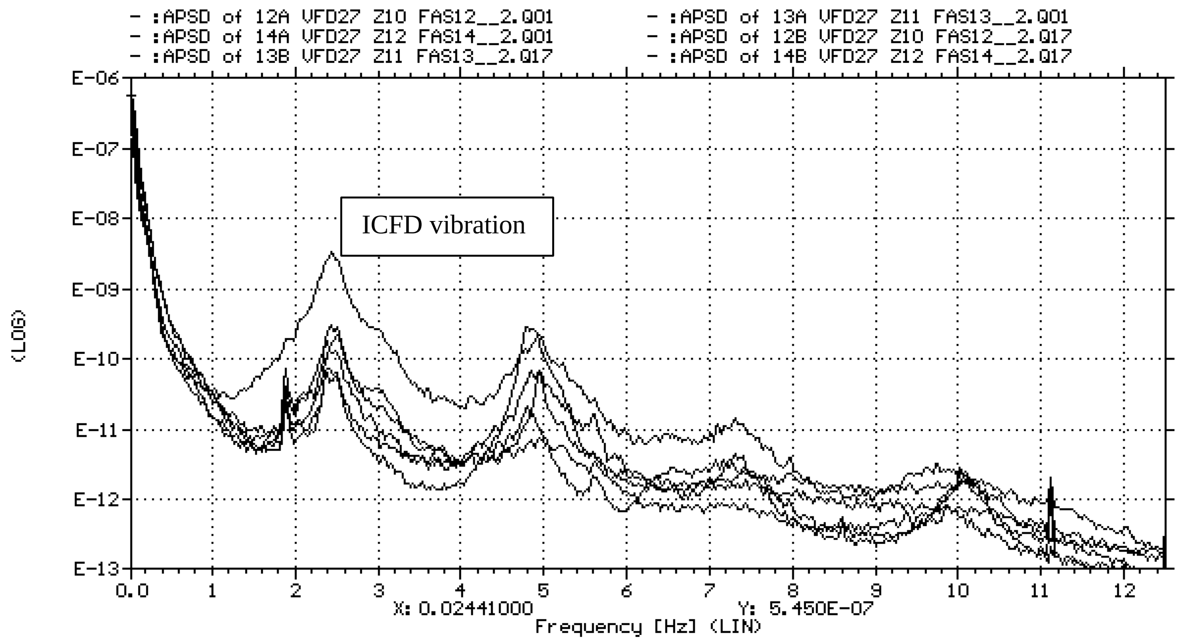


Figure 7. Normalized APSD functions of flux noise signals from ICFDs located in the same vertical flux detector tube, VFD27, measured in Darlington Unit 1 at full power operation.

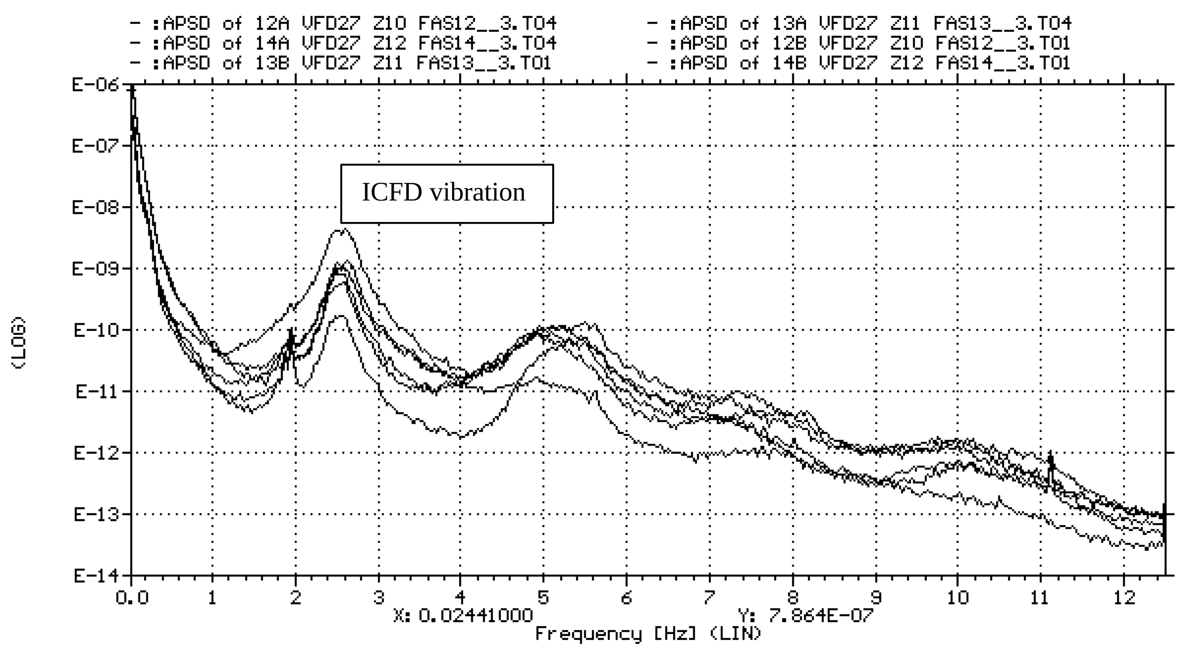


Figure 8. Normalized APSD functions of flux noise signals from ICFDs located in the same vertical flux detector tube, VFD27, measured in Darlington Unit 4 at full power operation.

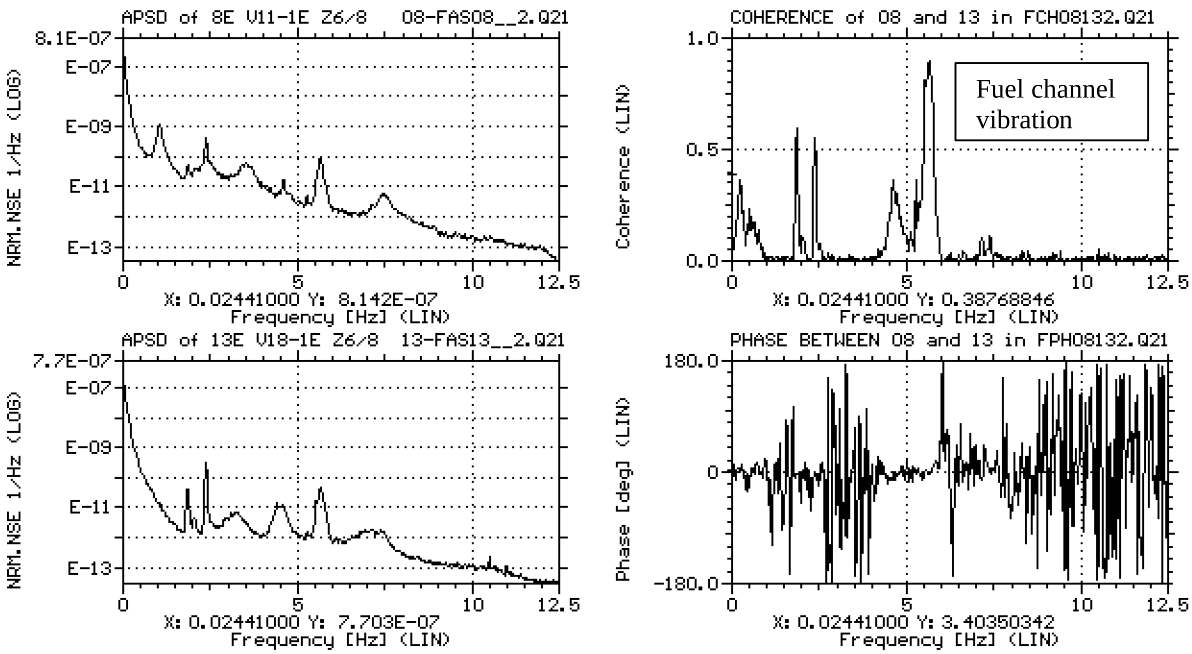


Figure 9. Normalized APSD, coherence and phase functions of flux noise signals from ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 1.**

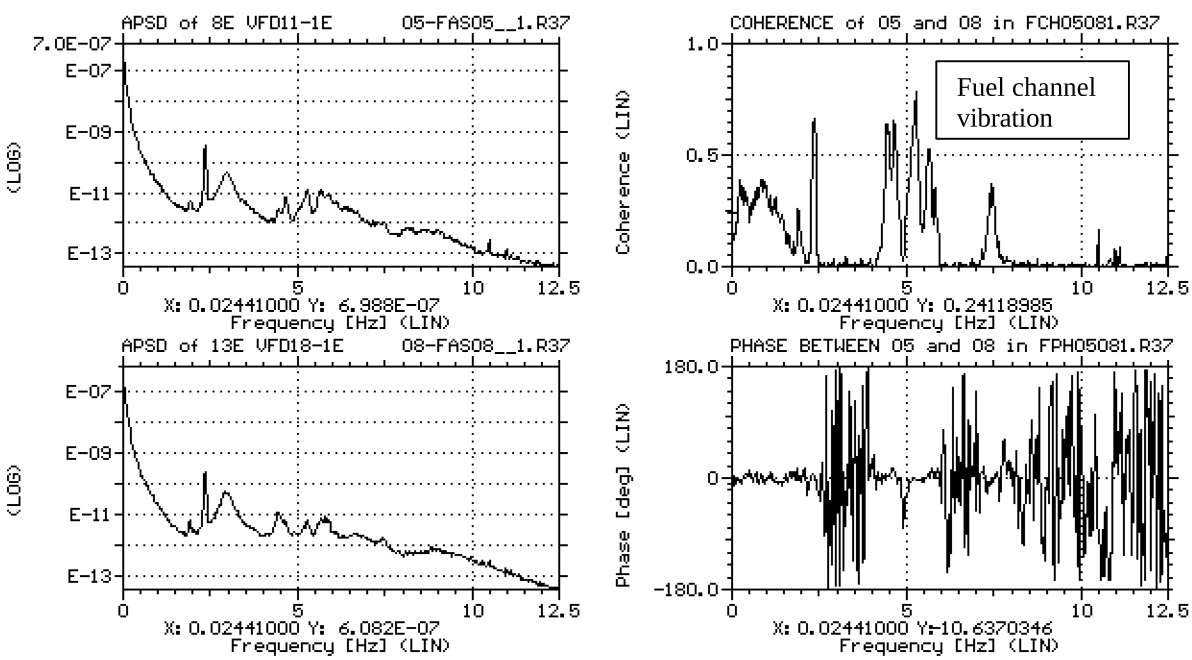


Figure 10. Normalized APSD, coherence and phase functions of flux noise signals from ICFDs VFD11-1E and VFD18-1E lined up along the same set of fuel channels in Zones 6 and 8 in Darlington **Unit 2.**

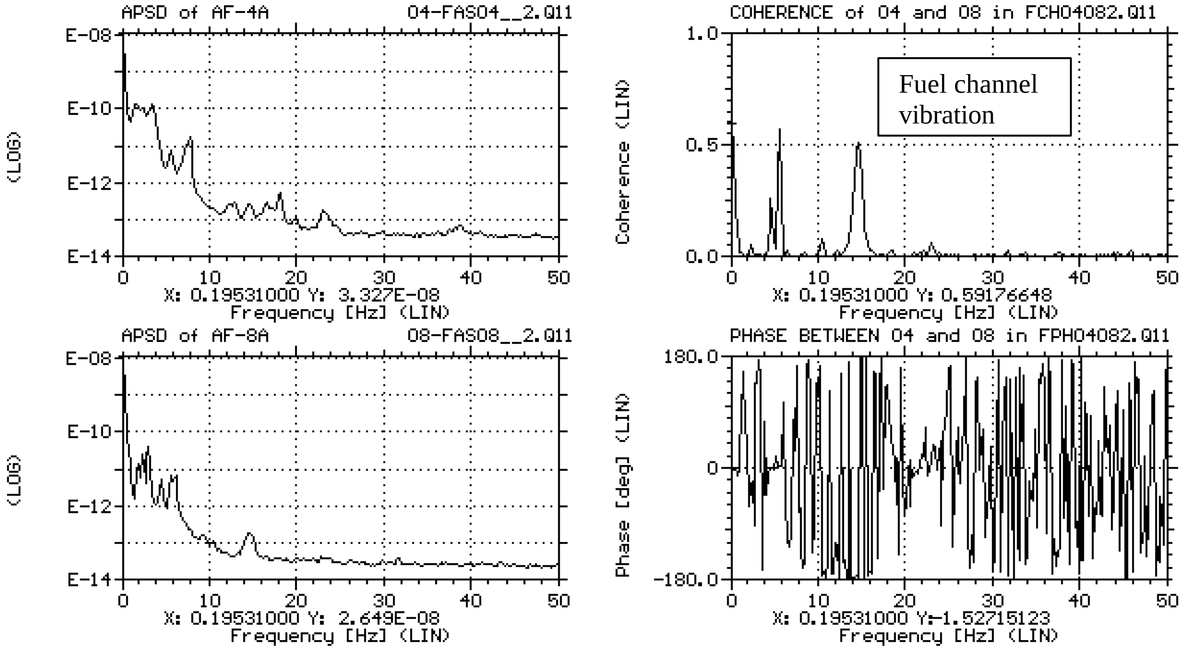


Figure 11. Normalized APSD, coherence and phase functions of flux noise signals from RRS-A ICFDs in Zones 6 and 8, lined up along the same set of fuel channels in Darlington **Unit 1.**

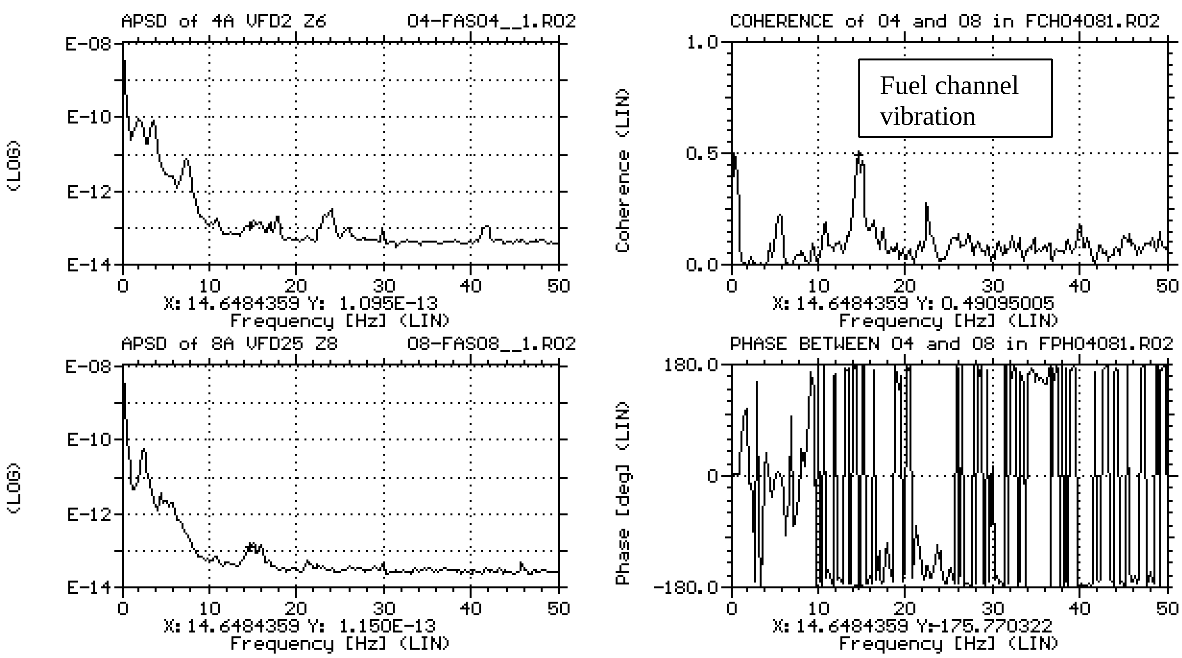


Figure 12. Normalized APSD, coherence and phase functions of flux noise signals from RRS-A ICFDs in Zones 6 and 8, lined up along the same set of fuel channels in Darlington **Unit 2.**

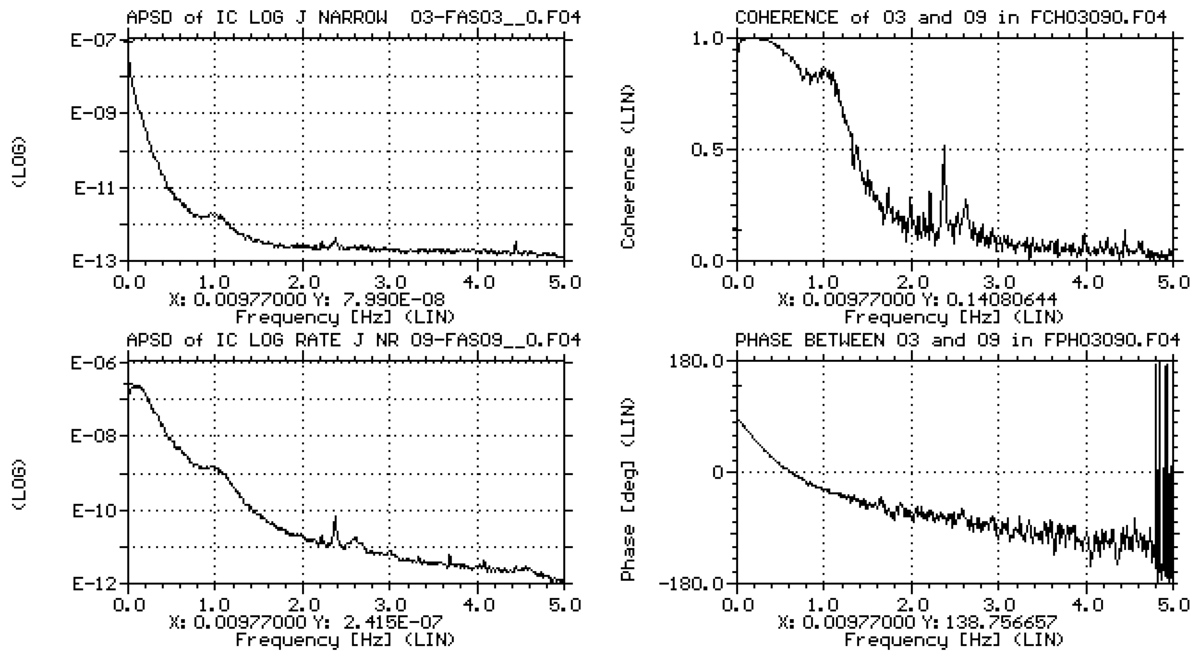


Figure 13. Normalized APSD, coherence and phase functions of Ion Chamber Log N and Log Rate noise signals from SDS2 Channel J, sampled at 10 Hz at full power in Pickering-B Unit 6.

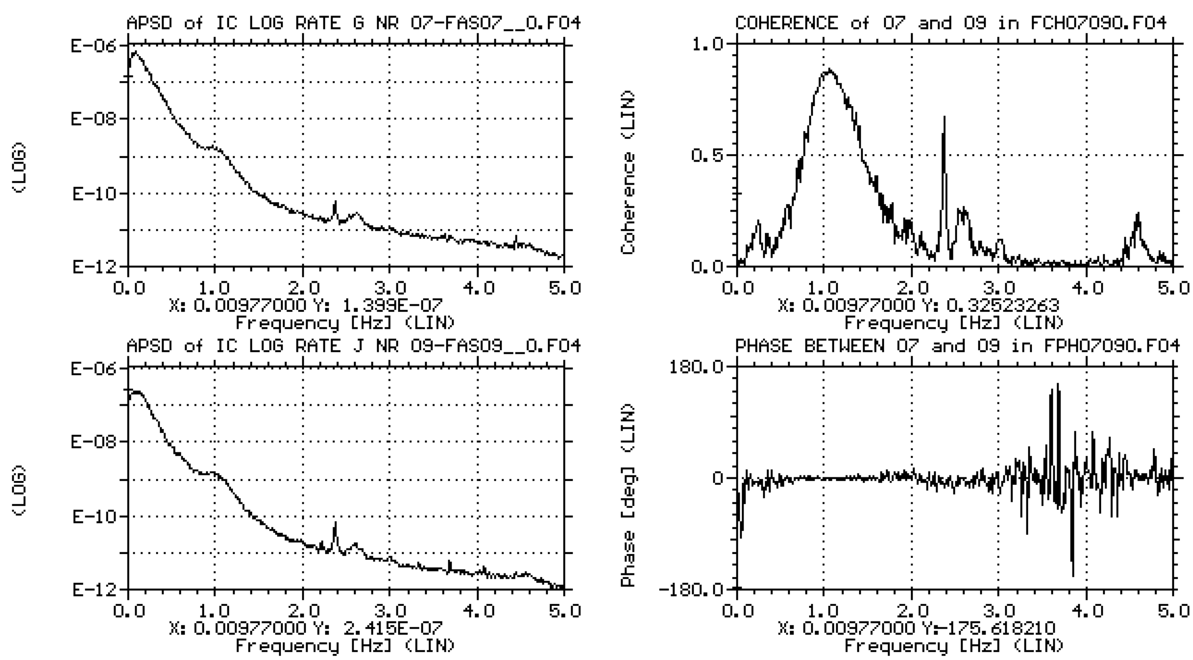


Figure 14. Normalized APSD, coherence and phase functions of Ion Chamber Log Rate noise signals from SDS2 Channels G and J, sampled at 10 Hz at full power in Pickering-B Unit 6.

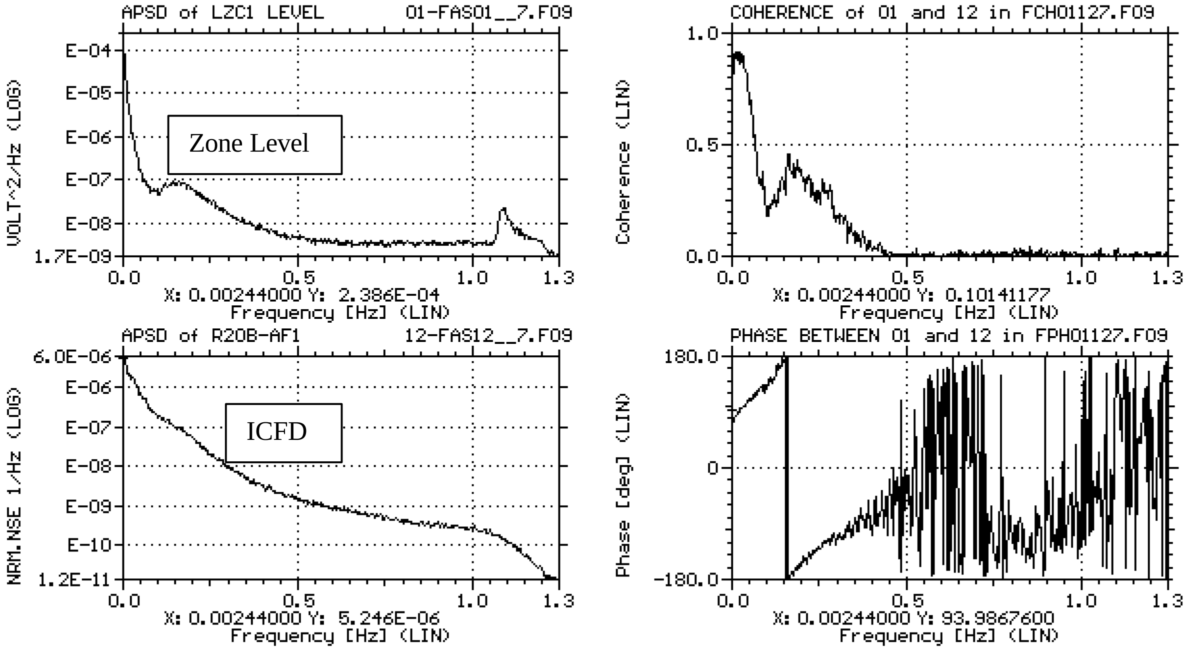


Figure 15. Normalized APSD, coherence and phase functions of the Liquid Zone Level noise and the RRS-B ICFD noise measured in Zone 1 in Pickering-B Unit 6.

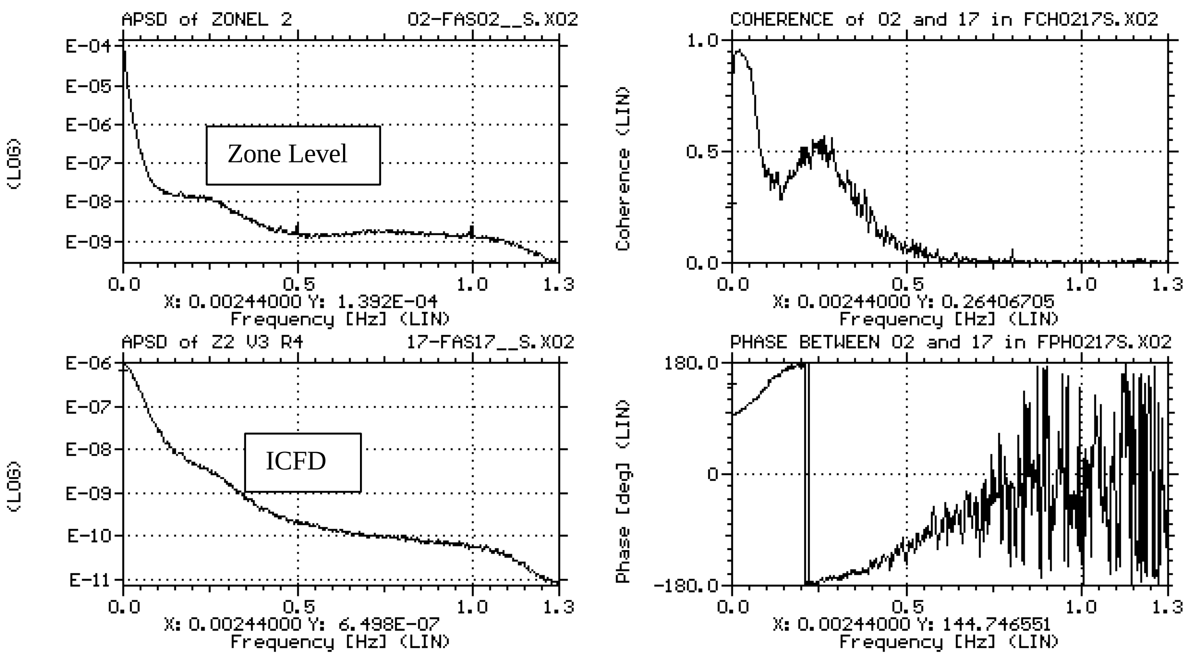


Figure 16. Normalized APSD, coherence and phase functions of the Liquid Zone Level noise and the RRS-A ICFD noise measured in Zone 2 in Darlington Unit 3.

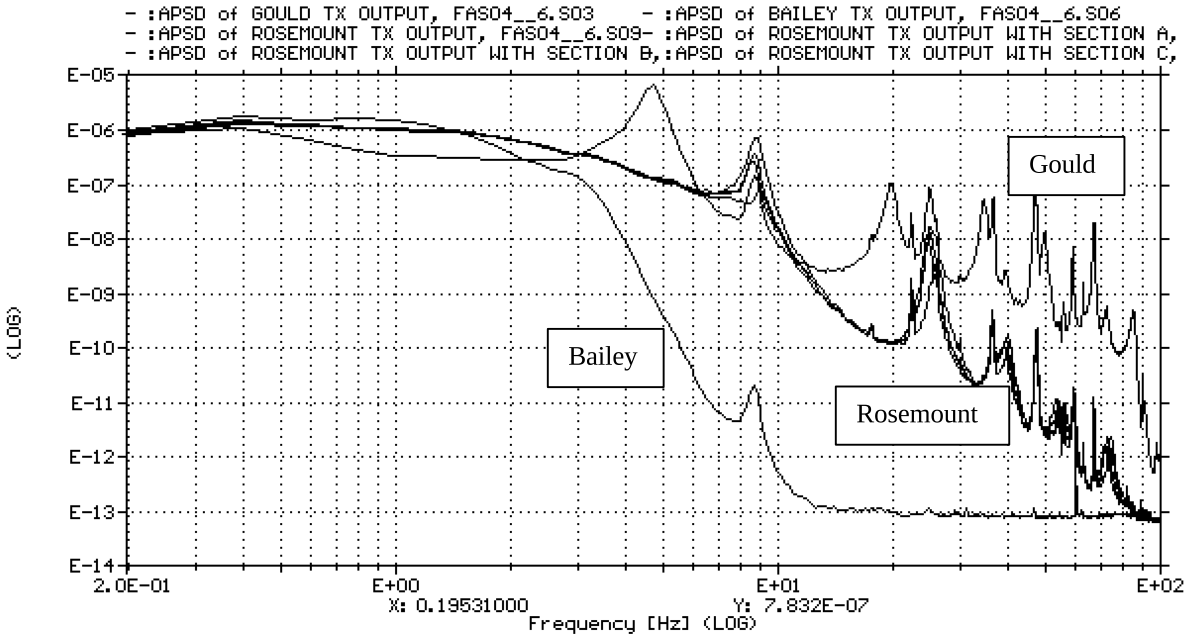


Figure 17. Normalized APSD functions of flow noise signals from Rosemount, Gould, and Bailey flow transmitters installed on safety system flow loop FT-3J in Darlington Unit 3.

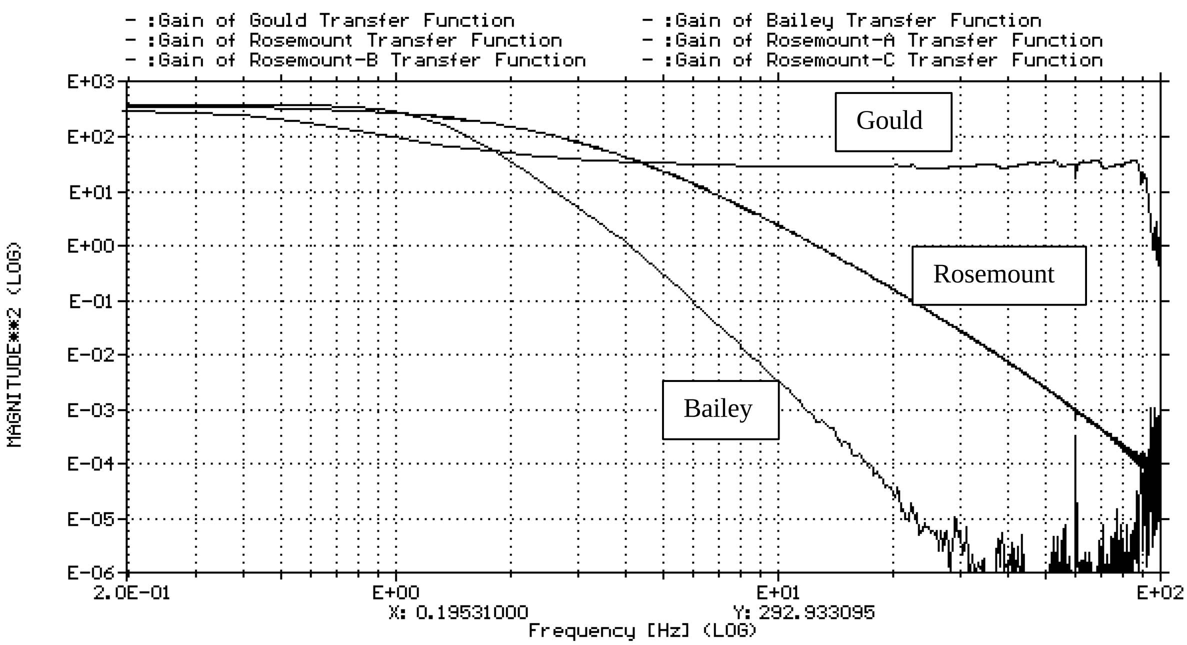
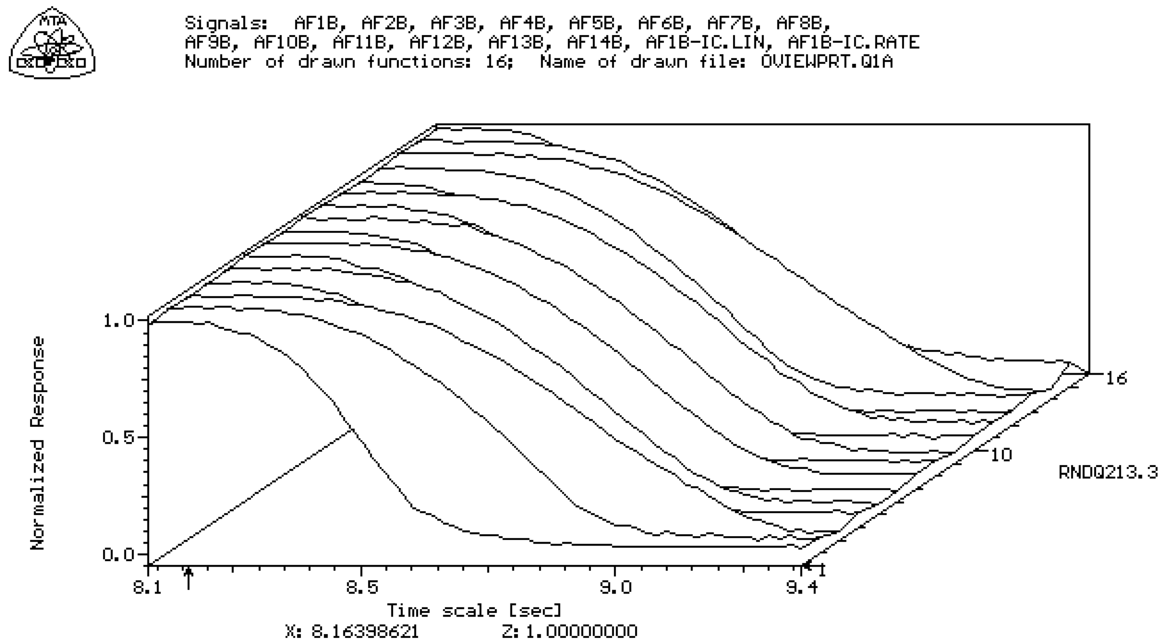


Figure 18. Magnitude of the dynamic transfer functions of Rosemount, Gould, and Bailey flow transmitters derived from in-situ noise measurements in safety system flow loop FT-3J in Darlington Unit 3.



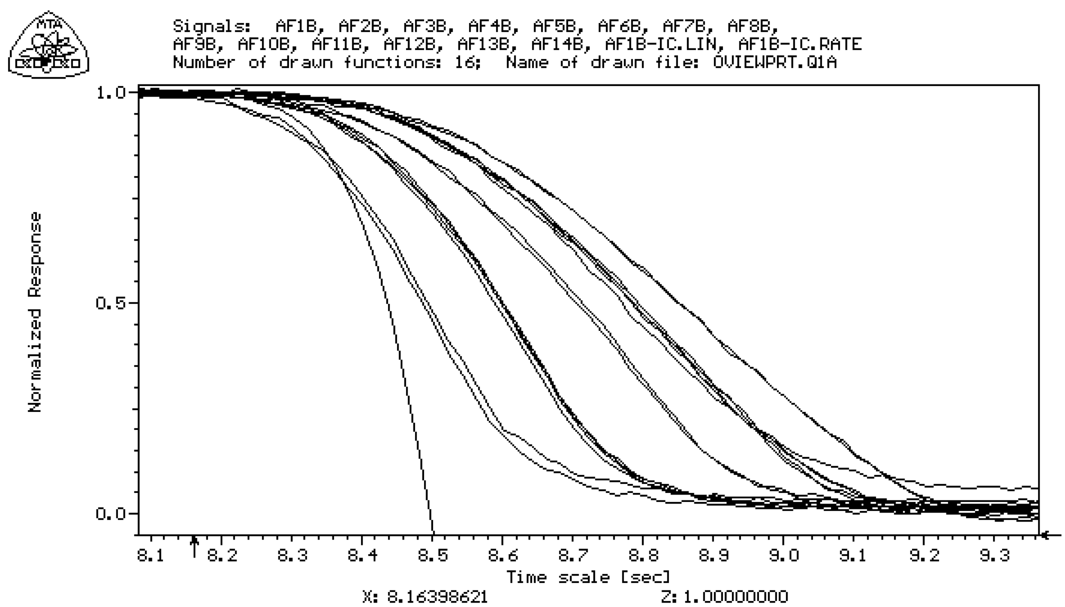
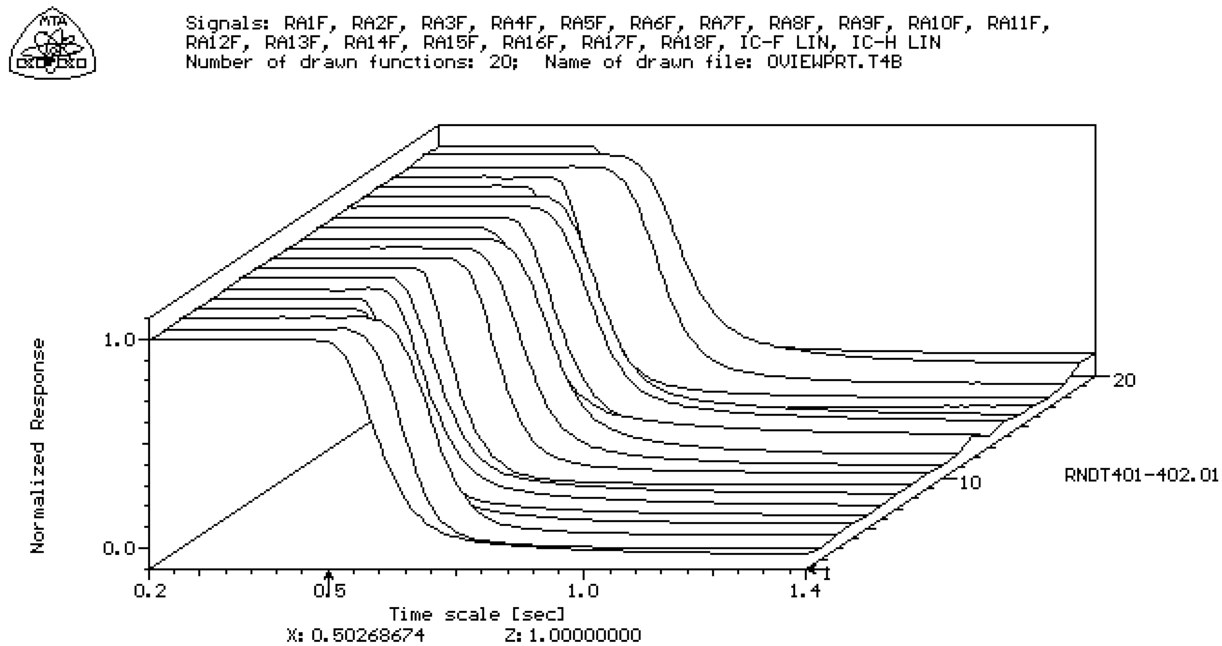


Figure 19. Rundown response signals of RRS-B ICFD and ion chamber signals normalized by their pre-trip signals in an SDS1-initiated trip from 60% of full power in Darlington Unit 1.



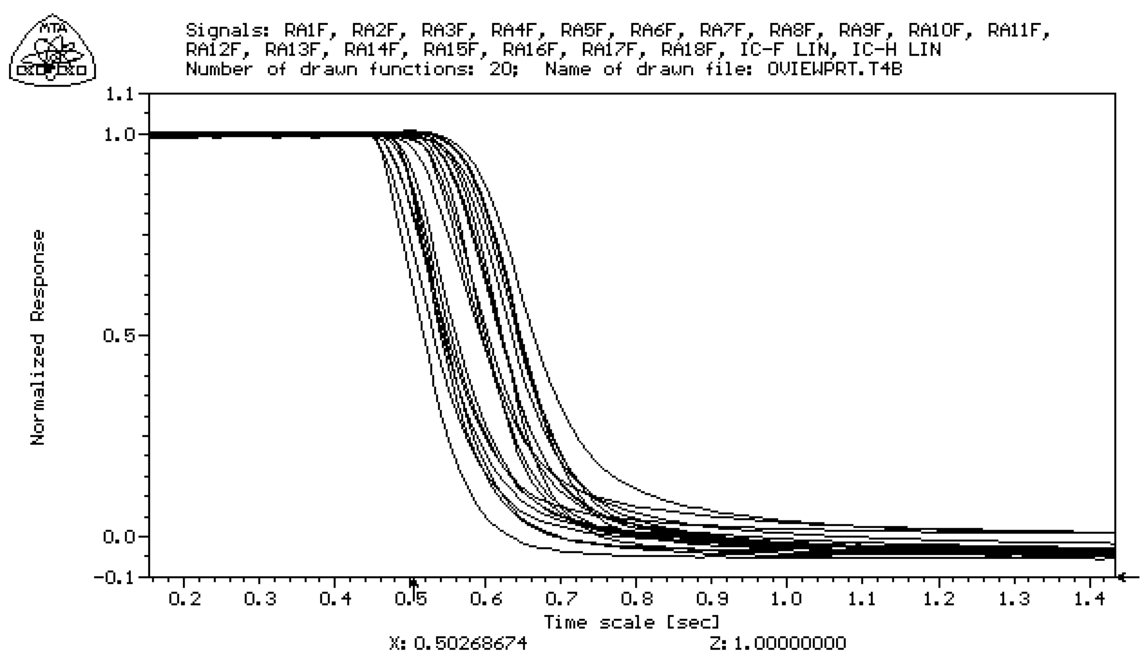
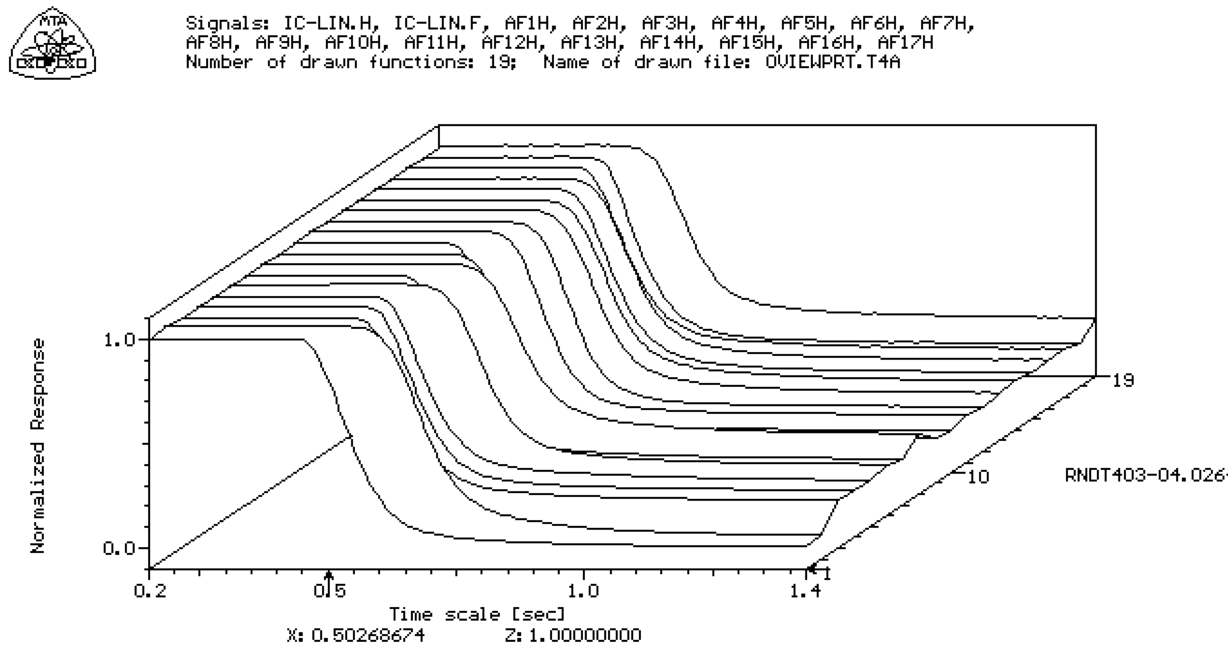


Figure 20. Normalized rundown signals of SDS1 Channel F overprompt ICFDs and Channel F/H ion chambers measured in an SDS2 trip in Darlington Unit 4 in April 1999.



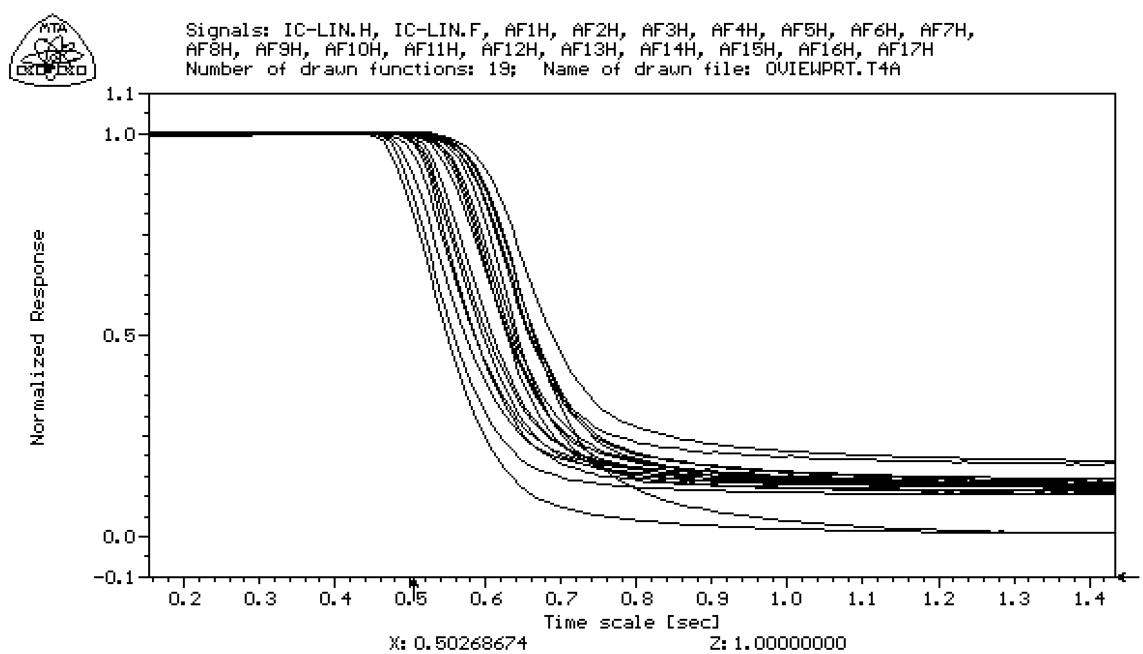
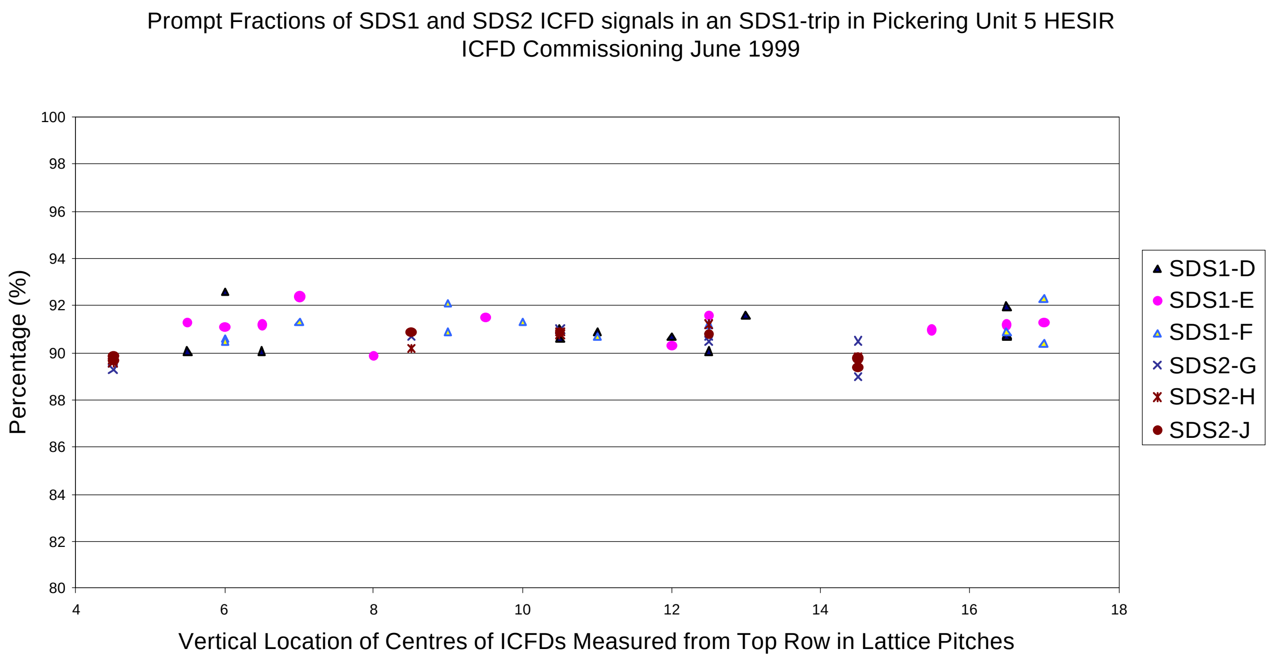


Figure 21. Normalized rundown signals of SDS2 Channel H underprompt ICFDs and Channel F/H ion chambers measured in an SDS2 trip in Darlington Unit 4 in April 1999.



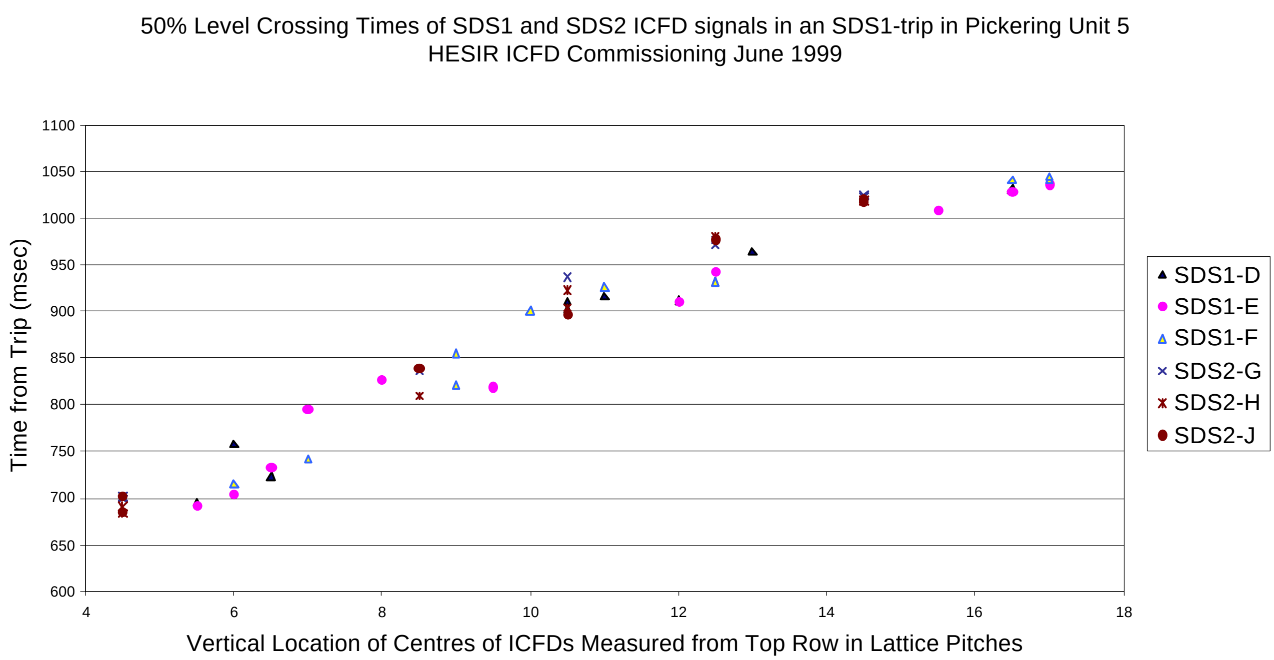


Figure 22. Prompt fractions and 50%-level crossing times of the new ICFDs in an SDS1-initiated trip in Pickering Unit 5 (ICFD commissioning test in June 1999).