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MEASUREMENT-BASED ESTIMATION OF RESPONSE TIME PARAMETERS USED IN SAFETY ANALYSIS OF CANDU REACTORS

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ABSTRACT

Reactor safety analysis determines the required values for the dynamic response of (1) safety instrumentation signals and (2) shutdown system components. The first category includes the response times of sensors, such as flow, pressure, temperature, and level transmitters, ion chambers, and in-core flux detectors. The second category represents shutdown system components and actuators, responding to a trip command.

Various accident scenarios determine the allowable values of the dynamic parameters in the form of design parameters. The actual in-situ values of these dynamic response parameters of instrumentation installed in the field can change with time due to aging, burn-up, vibration, etc. Possible drifts in dynamic parameters need to be monitored periodically by performing non-intrusive in-situ dynamic response tests throughout the lifetime of the instrumentation.

Two different techniques have been developed for the CANDU reactors of Ontario Power Generation and Bruce Power to test the dynamics of safety related instrumentation. The first technique, called reactor noise analysis, utilizes the small fluctuations (noise) of detector signals measured at steady-state full-power operation. Dynamic parameters are derived from the spectra of measured noise signals. The second technique is based on detector signals measured during an operator-initiated reactor trip at the beginning of scheduled outages.

Keywords: instrumentation response time, reactor noise analysis, reactor trip test

1. INTRODUCTION

Reactor safety analysis determines the required values for the dynamic response characteristics of (1) safety system instrumentation signals and (2) shutdown system components. The first category includes the response times and transfer functions of sensors and detectors, such as flow, pressure, and level transmitters and their sensing lines, resistance temperature detectors (RTDs), ion chambers, and the prompt/delayed components of in-core flux detectors (ICFDs), all providing measurement information on the condition of the reactor core as input to the reactor’s two independent shutdown systems. The second category represents the response times and event-timelines of shutdown system components and actuators, responding to an operator-initiated, or accident-initiated trip command. The trip response of most of the shutdown system components is directly measured by separate instrumentation, monitoring the progression and position of shutdown system components during a trip. In case of Shutdown System No.1 (SDS1), these signals include the vertical positions of all shutoff absorber rods being inserted into the core in a trip. In a second independent shutdown system (SDS2) gadolinium poison is injected into the moderator through eight in-core nozzles. In this case, the monitored trip response signals include helium tank pressure, eight poison tank levels, and poison injection valve position signals.

Safety analysis of various accident scenarios determine the required or allowable values of the dynamic parameters of instrumentation and shutdown systems components, in the forms of design parameters or factory-preset values. The actual in-situ values of these dynamic response parameters of instrumentation installed in the field may vary from system to system, and can change with time due to aging, burn-up, vibration, etc. Possible drifts in dynamic parameters need to be monitored periodically by performing non-intrusive in-situ dynamic response tests throughout the lifetime of the instrumentation.

The paper presents the two measurement/analysis techniques used regularly to estimate dynamic parameters in-situ at actual operating condition.

2. IN-SITU MEASUREMENTS OF INSTRUMENTATION DYNAMICS

Two different measurement techniques have been used in the CANDU nuclear generation stations of Ontario Power Generation and Bruce Power to test the dynamics of safety related systems and instrumentation. The first technique, called reactor noise analysis, utilizes the small fluctuations (noise) of detector signals measured at steady-state full-power operation. The measured signal fluctuations are caused by the natural fluctuations of physical processes in the reactor core (flux, flow, pressure, temperature, level fluctuations and mechanical vibrations). The frequency content of the physical noise is altered by the dynamic response characteristics of the station’s measurement instrumentation. Dynamic parameters are derived from the frequency-dependent statistics of measured noise signals, such as auto power spectral density (APSD) functions, transfer functions, coherence and phase functions.

Station signals included in the reactor noise measurements are in-core flux detectors, ion chambers, flow, pressure, and level transmitters, and resistance temperature detectors. Their frequency dependent noise signatures are regularly measured during steady-state operation, and are used for anomaly detection and parameter estimation (in-situ response time). The specific noise analysis applications include the following areas. (1) In-core flux detector and ion chamber noise measurements to monitor the vibration of fuel channels and detector tubes. (2) Pressure and flow noise measurements to estimate the in-situ response times of flow/pressure transmitters and their sensing lines installed in the reactor’s coolant loops. (3) Temperature noise measurements to estimate the in-situ response times of thermal-well or strap-on type RTDs installed in the reactor's coolant and moderator loops. The measured in-situ response time parameters provide information to validate models and assumptions on instrument response used in reactor physics and safety analysis.

The second technique is based on detector signals measured during an operator-initiated reactor trip at the beginning of scheduled outages. Measurements of ICFD and ion chamber signals responding to the insertion of shut-off rods (SDS1 trip), or to the injection of neutron absorbing poison (SDS2 trip) are regularly carried out at all stations. A reactor trip is manually initiated at high power and the trip response signals of ICFDs and ion chambers are recorded by multi-channel high-speed high-resolution data acquisition systems set up temporarily at various locations in the station. The sampling of the separate data acquisition systems are synchronized through the headset communication systems of the station. A total of 200 voltage signals can be sampled simultaneously up to 2500 samples per second. The effective prompt fractions of the ICFDs are estimated from their measured trip response. Effectiveness and the timeline of the trip mechanism responding to a trip command are assessed in the measurement as well. The measurement can identify ICFDs with abnormally slow response (under-prompt) or overshooting response (over-prompt) at the beginning of the outage. The time required for the ICFD signals to drop to predefined fractions of their pre-trip values (level crossing time) is plotted as a function of detector position and compared against safety requirements. The propagating effect of shut-off rod insertion or poison injection on the flux is monitored by the level crossing times of ICFDs and ion chambers during the trip. The measurement results are used to validate safety analysis models and parameters related to the response characteristics of shutdown systems and their instrumentation.

3. ESTIMATION OF FLOW TRANSMITTER TRANSFER FUNCTION BY PRESSURE SENSOR NOISE ANALYSIS

The transfer functions and the response times of flow transmitters can be measured in-situ (without removing them from the process) by temporarily installing high-frequency, high-sensitivity pressure sensors at the end of the high-pressure leg and the low-pressure leg sensing lines, close to the transmitter's input nozzles[1]. The temporarily installed pressure sensors record the natural pressure fluctuations in the two sensing lines, which are the differential pressure input fluctuations to the transmitter. Signal fluctuations of the pressure sensors are recorded along with the signal fluctuations of the transmitter output by a noise data acquisition system at steady-state full flow conditions. The transmitter's transfer function and the response time of the sensing line pair are calculated from the APSD and coherence functions of the measured input and output noise signals, as described below.

[1] The two sensing lines connect the up-stream and down-stream taps of the flow measurement device (orifice plate) permanently installed in the feeder pipe (inlet coolant to reactor) to the flow transmitter located outside the reactor vault. The coolant flows from the reactor inlet header tanks to the individual fuel channels through feeder pipes. 24 of the 480 feeder pipes are equipped with orifice-based flow measurements in the Darlington units, and 12 feeder pipes in the Pickering-B and Bruce-B units.

3.1 Methodology

In the frequency domain, it is assumed that the measured output noise of a differential pressure or flow transmitter, $V_{OUT}(\omega)$ is composed of two terms:

(1) the measured differential pressure input noise, $V_{IN}(\omega)$ acting through the transmitter's complex transfer function, $TRF_{IN,OUT}(\omega)$, and

(2) an unknown noise component, $N_{OUT}(\omega)$ independent of the input noise.

$$V_{OUT}(\omega) = TRF_{IN,OUT}(\omega) \times V_{IN}(\omega) + N_{OUT}(\omega) \tag{1}$$

The magnitude of the transmitter's unknown transfer function is expressed as a function of three measured frequency dependent terms

$$\left|TRF_{IN,OUT}(\omega)\right|^2 = \frac{APSD_{OUT}(\omega)}{APSD_{IN}(\omega)} \times COH^2{}_{IN,OUT}(\omega) \tag{2}$$

where

$$COH^2{}_{IN,OUT}(\omega) = \frac{\left|CPSD_{IN,OUT}(\omega)\right|^2}{APSD_{IN}(\omega) \times APSD_{OUT}(\omega)} \tag{3}$$

is the coherence function (measure of commonality) between the transmitter's input and output noise signals. APSD and CPSD denote the auto power spectral density and cross power spectral density functions of the input and output noise signals. The phase function of the complex transfer function is identical with the phase function of the complex CPSD function measured between the transmitter's input-output noise signals.

The following functional form was fitted to the measured transfer function in Eq. (2) using a non-linear iterative least-squares regression (χ^2 minimization) algorithm

$$TRF_{IN,OUT}(\omega) = \frac{(1 + i\omega\tau_4)}{(1 + i\omega\tau_1)(1 + i\omega\tau_2)(1 + 2i\omega\varsigma\tau_3 - \omega^2\tau_3^2)} \tag{4}$$

The fitted parameters are the time constants $\tau_1, \tau_2, \tau_3, \tau_4$, and damping factor ς associated with τ_3. These parameters uniquely determine the "ramp-equivalent" response time of the transmitter. It is defined as the time delay between a ramp input and the transmitter's output, after the output became parallel to the input (fully developed asymptotic response). The response time is calculated from the fitted parameters of the measured transfer function as

$$T_{ramp} = \tau_1 + \tau_2 + 2\varsigma\tau_3 - \tau_4 \quad (5)$$

The general functional form in Eq. (4) covers the transfer functions of all three types of flow transmitters used in CANDUs, Rosemount, Gould, and Bailey.

3.2 Applications

Using the above pressure sensor noise technique, the dynamic transfer functions and the response times of transmitters were estimated in-situ by noise measurements in the following applications:

- In Darlington Unit 3, the transfer functions of Rosemount, Gould, and Bailey flow transmitter were estimated, along with the assessment of their effect on sensing line resonances, response times, and signal anomaly called “flow-dips” [1,2]. The flow noise measurements were performed at various sensing line configurations at full flow and full power. The measured transfer functions of the three transmitters are shown in Figure 1.

- In Bruce-B Unit 6, the in-situ response time of all reactor outlet header pressure, coolant inlet flow and reactor core differential pressure transmitters and their sensing lines were measured [3]. The transfer function estimation was part of a “Safe Operating Envelope” project on the dynamic response of shutdown system trip parameters. Figure 2 shows the magnitude of the measured dynamic transfer functions of the six Rosemount flow transmitters installed in shutdown safety system No.1.

- In Pickering-B Unit 6, abnormally long response times of sensing lines were investigated and the in-situ transfer functions of Rosemount flow transmitters and their sensing lines were estimated [4]. Figure 3 shows the magnitude of the dynamic transfer functions of Rosemount flow transmitters installed in shutdown system flow loop FT-2D with normal response time and loop FT-4D with increased response time.

- In Darlington Unit 3, the transfer functions of new Bailey flow transmitters were estimated in-situ after installation for the purposes of validating a response time tester method (bench test) to be used in future pre-installation transmitter testing [5].

4. NOISE ANALYSIS OF FLOW TRANSMITTER OUTPUT SIGNALS

Transmitter output noise measurements, without the measurements of input pressure noise signals, were also successfully used in the estimation of in-situ response times. The estimation is based on (1) the measured APSD function of the flow transmitter output fluctuations, and (2) the measurement-based fact that the differential pressure noise (input to the transmitter) is white over the frequency range of interest, after the sensing line resonances are removed from the spectrum. This means that the APSD function of the measured transmitter output noise is a good approximation of the transmitter’s transfer function over a certain frequency range. Similarly to the previous case, the transmitter's time constants are derived by fitting a functional form with unknown time constants to the measured APSD function using a non-linear iterative curve-fit algorithm [6]. These flow noise measurements served as acceptance tests for placing new safety system flow transmitters into service after installation.

4.1 Applications

The technique was used in the following applications:

- In Darlington, the response times of all safety system flow transmitters (Rosemount and Gould types) were measured in-situ via APSD noise analysis, while the four reactor units were at 50% of full power. As a prerequisite to return to high power, the response times of all 96 flow transmitters in the four Darlington units were adjusted in noise measurements to a certain range, over a period of two months [7].

- Recently, all Gould flow transmitters were replaced with Bailey transmitters in Darlington Unit 3. The response times of the new transmitters were set to 400 msec in pre-installation bench tests. The post-installation acceptance tests of transmitter and sensing line response times were based on the measurements of the transmitter output noise APSDs [8].

- The same estimation technique was applied in the installation of new Rosemount transmitters in certain reactor inlet coolant flow loops in Pickering-B units 6, 7 and 8. New flow transmitters with increased response time were installed to reduce the effect of frequent "flow dips" causing spurious trips in certain flow channels. The response times of the transmitters were set to 500 msec by the manufacturer. The post-installation response times of the transmitters and their sensing lines were estimated in noise measurements at full-flow full-power condition [9].

Figures 4, 5, and 6 show typical measured noise APSD functions of transmitter output signals used in the above in-situ response time estimation.

5. RTD TEMPERATURE NOISE ANALYSIS

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, such as slow response and signal spikes induced by electrical effects and ground fault detectors. Similarly to the flow transmitter application, the response time of the RTD is estimated by fitting a functional form of a low-order low-pass filter to the RTD's measured noise APSD function.

The noise-based technique was used in the following applications:

- A comprehensive measurement of moderator RTD noise signals were carried out at various power levels in Bruce-B Unit 8 [10]. Signal fluctuations from the following twelve RTDs were recorded simultaneously: (a) six RTDs located at moderator core outlet, and (b) three RTDs in each of the two moderator loops located at the outlet of the two heat exchangers (inlet to the core). The response times of both thermal-well and strap-on type RTDs were estimated from the APSD functions of the RTD noise signals by curve-fit techniques. Typical APSD, coherence and phase functions of slow responding strap-on RTDs are shown in Figures 7 and 8. The curve-fit technique was applied only to the low-frequency range of the RTD noise spectrum (0 – 0.03 Hz) representing real temperature fluctuations. The sharp peaks seen above this range are caused by electrical components and were not included in the curve fit. The same spectral functions are shown for thermal-well type RTD noise signals in Figures 9 through 12. These RTDs have faster response and are located in the moderator loops at core inlet and outlet locations. Their signals are fed into the reactor's regulating system. The transit times of the moderator flow between RTDs were also estimated from the linear phase measured between RTD noise signals. The temperature fluctuations are carried by the moderator flow affecting the RTD signals in the loop with a time delay causing a linear phase difference between RTD noise signals over the frequency range of 0.015 - 0.055 Hz. Examples of linear phase functions obtained between core outlet and inlet moderator RTD noise signals are shown in Figure 13. The moderator transit times obtained for various RTD combinations were in the range of 6.9 and 13 sec.

- The response times of RTDs located at fuel channel exits were estimated at full power in pre-outage noise measurements in Pickering-B Units 6 and 8 in 2001. The purpose of the noise measurement was to identify RTDs with abnormally slow response.

6. MEASUREMENT AND ANALYSIS OF REACTOR POWER TRIPS

In the previously discussed noise-based applications, the response time of safety related instrumentation was estimated in passive and non-intrusive signal noise measurements, which took place at steady-state stationary conditions. The dynamic response of safety instrumentation is also tested in actual reactor trip measurement initiated from high reactor power at the beginning of scheduled outages.

Data acquisition systems and signal processing techniques have been developed over the years at OPG to carry out periodic reactor power trip measurements. The tests are performed on a regular basis (approx. every two years in any given reactor unit), and their purpose is

- to estimate the effective prompt fractions of the shutdown system ICFDs, relative to the trip response of the ex-core ion chambers (100% prompt reference signals),

- to assess the effectiveness of the trip mechanism (poison injection, or insertion of shut-off rods) by measuring the timing of signal changes of ICFDs and ion chambers as a function of detector location, and

- to provide trip measurement data for validating safety analysis models and assumptions on response times.

In the Darlington and Bruce CANDU stations, shutdown system No.1 utilizes the signals of three independent sets of 18 vertically located over-prompt self-powered flux detectors (Inconel) serving as neutron-overpower (NOP) protection signals. These ICFDs are sensitive to the thermal neutron flux only, and have a design prompt fraction value of 104.8%. Shutdown system No.2 has three independent sets of 17 horizontally located under-prompt self-powered flux detectors (Platinum-clad Inconel). These ICFDs have a mixed sensitivity to neutron and gamma fluxes and have a design prompt fraction value of 88.7%. In the Pickering CANDU station, both shutdown systems have under-prompt Platinum-clad Inconel self-powered flux detectors.

The effective prompt fraction of an ICFD is estimated from its measured trip response as the ratio between the normalized signal drop of the reference ion chamber and that of the ICFD signal, both measured and averaged over a 1 second interval centered around 3 sec after the start of the flux drop:

$$P_{eff} = \frac{1 - \dfrac{V_{ICFD}(t_1, t_2)}{V_{ICFD}(0)}}{1 - \dfrac{V_{IC}(t_1, t_2)}{V_{IC}(0)}} \tag{6}$$

where

- $V_{ICFD}(0)$ and $V_{IC}(0)$ are the averaged steady-state signals of the ICFD and the ion chamber, measured before the reactor trip.
- $V_{ICFD}(t_1, t_2)$ and $V_{IC}(t_1, t_2)$ are the post-trip signals of the ICFD and the ion chamber, averaged over the time interval of (t_1, t_2), where $t_1 = 2.5\,\text{sec}$ and $t_2 = 3.5\,\text{sec}$.

Additional correction terms are applied to the above ratio to remove the effects of the following components on the detector current: (1) pre-trip power changes, if trip was not initiated from steady state, (2) post-trip gamma background of fission products, and (3) delayed detector current components already active at 3 seconds after the trip. The combined effect of these three sources is in the range of 2-3%. The effective prompt fractions estimated from the trip measurements do change as detectors age. They can significantly deviate from their initial values, due to the burn-up of neutron sensitive current generating mechanism (neutron capture in the ICFD emitter). Safety model calculations establish the minimum allowable limits of ICFD prompt fractions for various accident scenarios. The reactor trip tests serve as a tool to estimate the actual ICFD prompt fractions, measured in-situ in the core under operating conditions. The ICFD prompt fractions are measured periodically, every 2 years, and are compared against the minimum allowable safety analysis values. If the required values are not met, safety analysis must be revised or the ICFDs must be replaced.

All Platinum ICFDs in Pickering-B Units 5, 6, and 7, with an initial prompt fraction of 84%, were replaced between 1996 and 2000, after more than 15 years of operation. The same trip test technique was used in the commissioning measurements of the new ICFDs. The new ICFDs are Platinum-clad Inconel detectors, with a design prompt fraction value of 92%. The actual in-situ prompt fractions of all new ICFDs were estimated in SDS1 reactor trip measurements. Their pre-trip noise signals were recorded as baselines at steady-state, followed by the measurement of their trip response. Follow-up noise measurements and trip tests are performed at the beginning of planned outages to identify possible changes in the dynamic response of ICFDs. In Unit 8, SDS1 trip test results obtained in 1993, 1998, and 2001 were used to support the deferral of the ICFD replacement project until 2004. The linear trend of prompt fraction reduction, seen in the above measurements, indicated that the worst-case predictions of all ICFDs would stay above the minimum allowable limit of 70% over the next three years [11].

ICFD noise signatures are also measured at steady-state high power before the trip. The noise analysis of ICFD signals provides information on the dynamics of the detectors, as well as, on the dynamic properties of the flux noise sources, such as fuel channel vibration, detector tube vibration, moderator density fluctuations, and the level fluctuations of "liquid zone control" compartments containing neutron absorbing light water. The measured multi-channel noise signatures of ICFD signals (auto and cross spectra, coherence and phase functions) characterize the coupled dynamics of these noise sources and the general health of the flux detector instrument lines. The measurement of signal fluctuations at steady state is followed by the trip response measurement.

In addition to estimating the ICFD prompt fractions, the measured ICFD trip response signals are also used to assess the effectiveness and timing of the poison injection system in SDS2 trips. This is required at a two-year interval, as a station commitment to the regulator (Canadian Nuclear Safety Commission).

7. COMPARING THE EFFECTS OF SHUT-OFF ROD INSERTION AND POISON INJECTION

Figure 14 shows the first two seconds of the trip response signals of 24 ICFDs and 4 ion chambers, normalized by their pre-trip values. The signals were recorded during the SDS1 trip (shut-off rod insertion) in Pickering-B Unit 8 in 2001 [11]. The ICFD response signals measured during the first two seconds after trip initiation are clearly the products of the ICFDs' prompt current generating mechanism only, since the ICFDs' delayed components do not contribute to the detectors' trip response signals at that early stage. One can make two important observations in Figure 14:

- After the SDS1 trip, the ICFD signals dropped to 20-30% of their pre-trip values, while the reference ion chambers dropped to 3-5%. This resulted in an estimated ICFD effective prompt fraction range of 75-80%. The Platinum ICFDs in Pickering-

B Unit 8 are more than 18 years old and their prompt fractions dropped from its design value (84.8%) significantly due to the neutron-capture related burn-up of the detector's emitter.

- The bulk power reduction took place over an 800-msec time interval. This is a typical flux reduction time, measured when the insertion of shut-off rods (SDS1 trip) is initiated.

Figure 15 shows the first two seconds of the trip response signals of 33 ICFDs and 2 ion chambers, normalized by their pre-trip values, in an SDS2 trip [12]. The signals were recorded in Pickering-B Unit 6 in 2001 during an SDS2 trip (poison injection). Similarly to the previous case, the ICFD signals measured during the first two seconds are generated by the ICFDs' prompt current generating mechanism, therefore the measured response can be used to estimate the ICFD prompt fraction. In comparison to the previous case, note that

- After the SDS2 trip, the ICFD signals dropped to the level of 8-15% of their pre-trip values, while the reference ion chambers dropped to 1% of their pre-trip levels. This resulted in an estimated ICFD effective prompt fraction range of 85-90%. In Pickering-B Unit 6, the old platinum ICFDs were replaced with new Platinum-clad Inconel ICFDs in 1996. Their effective prompt fractions were found to be close to their design value (88.9%).

- The bulk power reduction took place over a 400-msec time interval. This is a typical flux reduction time, measured when poison injection (SDS2 trip) is initiated.

The difference between the SDS1 and SDS2 trips is more obvious, when the SDS1 and SDS2 response signals of the same set of ICFDs are compared in the same reactor unit. Such comparison was performed for reactor units in Pickering-B, Darlington, and Bruce-B. The power reduction effect of the reactor trip on the flux is measured by the level crossing times of ICFD trip response signals. In the SDS2 trips, the poison injected from the south side of the core, and it propagates toward the north side in injection nozzles (pipes). In the SDS1 trip, shut-off rods are inserted into the core from the top. In both cases, the level crossing times of ICFD signals are used to monitor the progress of the shutdown. The times needed for the ICFD signals to drop to certain pre-defined fractions of their pre-trip values are plotted as a function of ICFD position, then they are compared against location-dependent action limits and impairment limits.

The propagation effects of the SDS1 and SDS2 trips are compared in Figure 16. It shows the 50% level crossing times of ICFD signals as a function of detector position, measured in Pickering-B Unit 6 in an SDS1 trip (1996) and in an SDS2 trip (2001), both started from 60% full power [13]. Similar comparison of the timing of SDS1 and SDS2 trip effects were performed in Darlington Unit 1 and Bruce Unit 7 [14, 15]. In all cases, the SDS2 trip was significantly faster. Comparisons of level crossing times related to other signal levels between 98% and 50% of the pre-trip values supported the finding.

8. CONCLUSION

Reactor noise analysis is routinely used for system diagnostics and in-situ response time estimation. High-performance data acquisition systems were developed and station procedures for multi-location synchronized noise measurements were established. Most of the noise measurements are required by station commitments or licensing requirements. Additional noise analysis applications are being developed as need for non-intrusive diagnostics at full power operation increases.

Reactor trip tests are performed on a regular basis to assess the health of in-core flux detectors and the effectiveness of the reactor shutdown systems. The techniques, combined with the pre-trip noise measurements carried out at full power steady-state, have provided a surveillance tool to monitor the dynamics of safety systems and to validate parameter values used in safety analysis.

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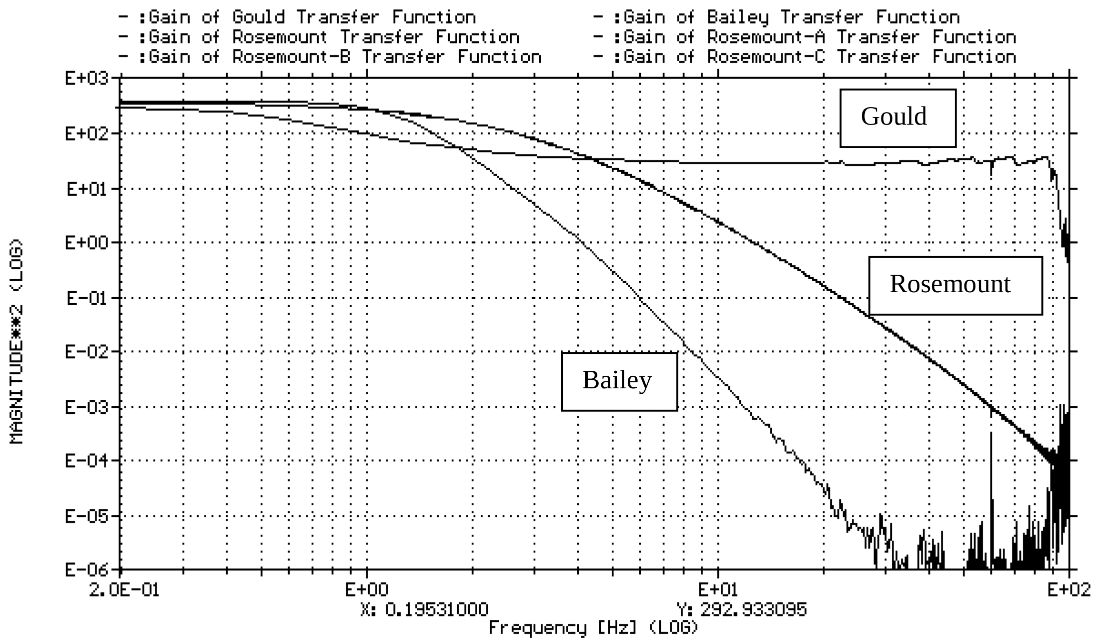

Figure 1. Magnitude of the dynamic transfer functions of Rosemount, Gould, and Bailey flow transmitters, derived from in-situ pressure sensor noise measurements in shutdown system flow loop FT-3J in Darlington Unit 3

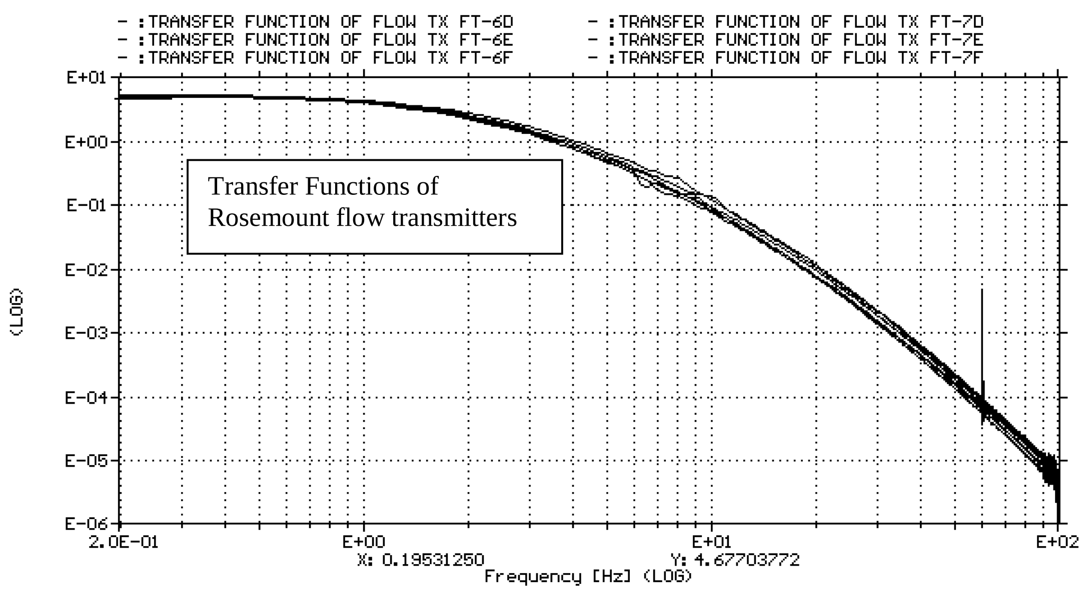

Figure 2. Magnitude of the dynamic transfer functions of Rosemount flow transmitters derived from in-situ pressure noise measurements in SDS1 flow loops in Bruce-B Unit 6

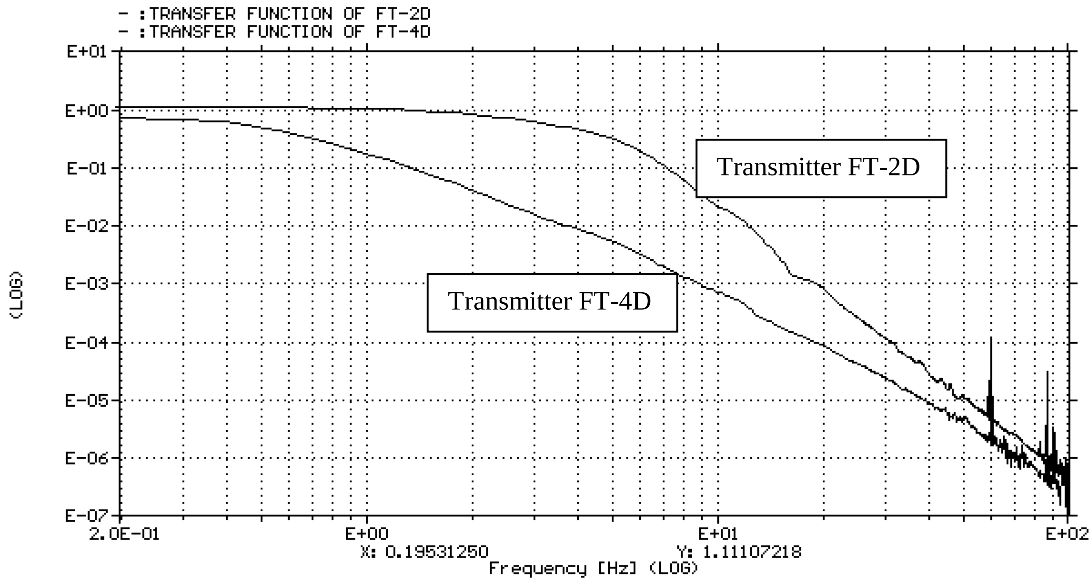

Figure 3. Magnitude of the dynamic transfer functions of Rosemount flow transmitters derived from in-situ pressure sensor noise measurements in shutdown system flow loops FT-2D and FT-4D in Pickering-B Unit 6

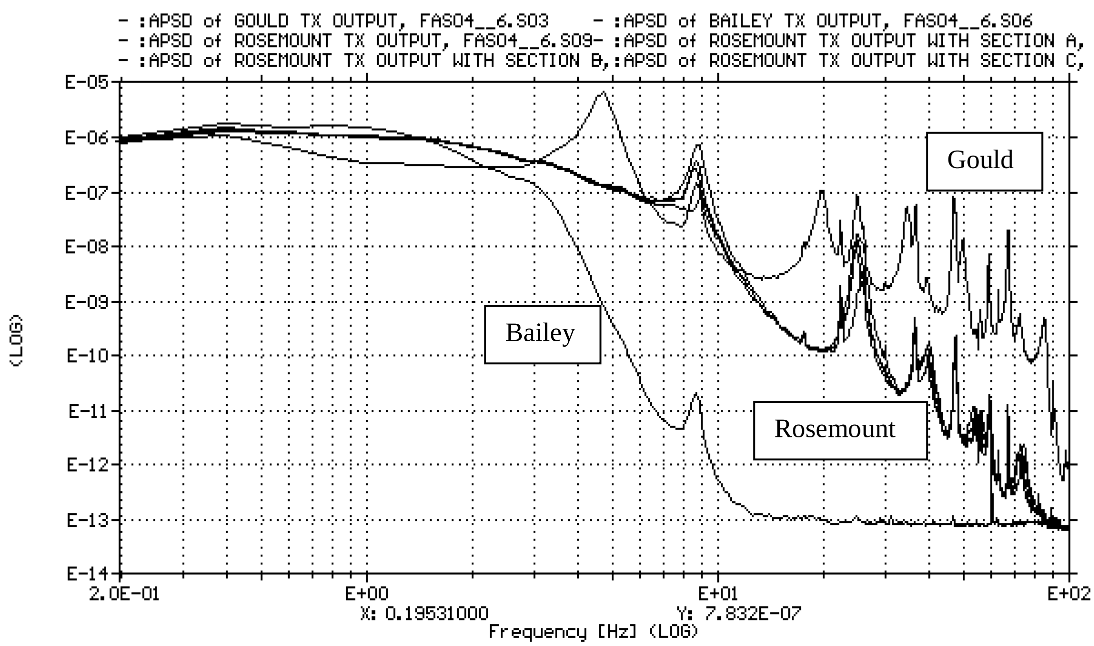

Figure 4. Comparing the normalized APSD functions of output flow noise signals of Rosemount, Gould, and Bailey flow transmitters installed on shutdown system flow loop FT-3J in Darlington Unit 3

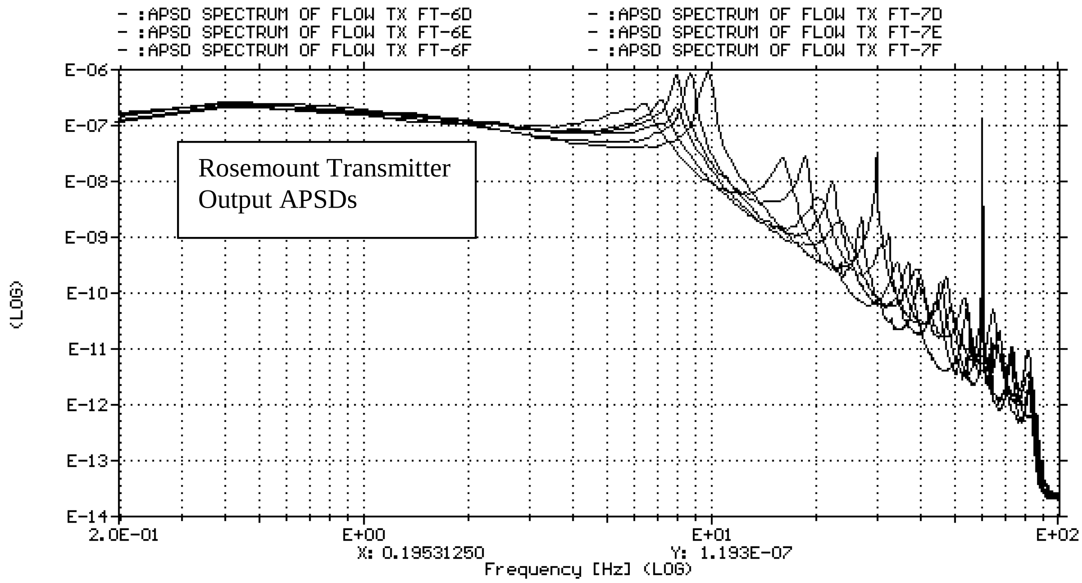

Figure 5. APSD spectral functions of the output noise signals of the six SDS1 Rosemount flow transmitters measured in Bruce-B Unit 6 at full power

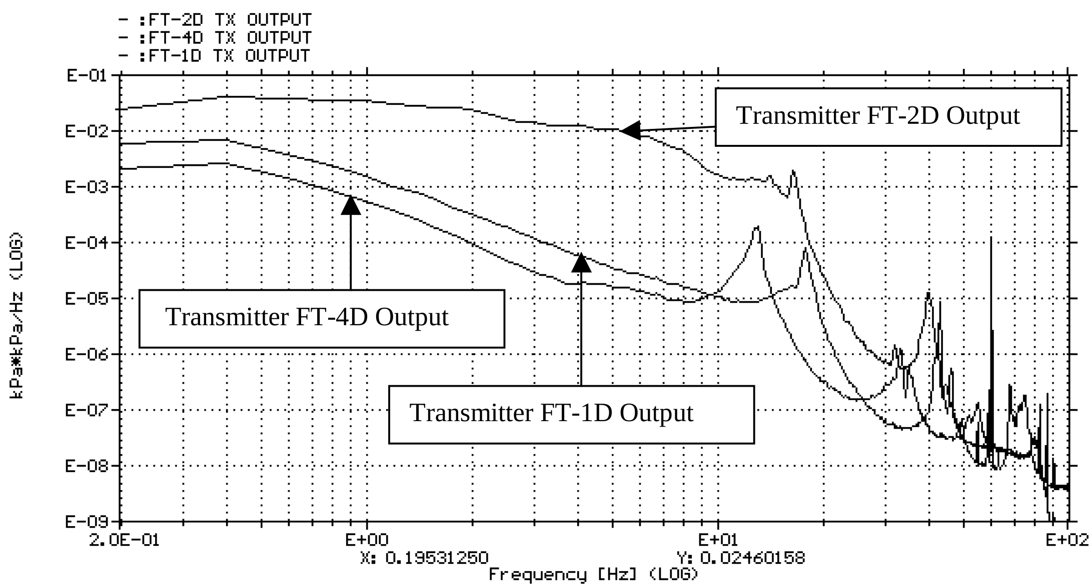

Figure 6. Comparing the APSD functions of output noise signals of Rosemount flow transmitters installed on shutdown system flow loops FT-1D and FT-4D with increased response time (500 msec), and FT-2D with shorter response time (less than 200 msec) in Pickering-B Unit 6

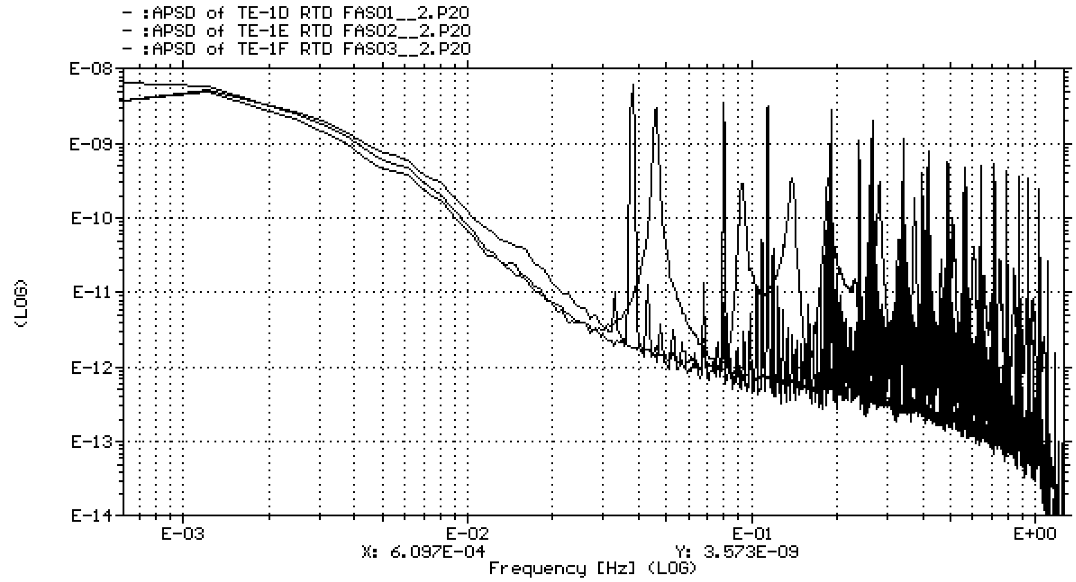

Figure 7. APSD spectra of moderator temperature fluctuations measured by three SDS1 strap-on RTDs located at core outlet in Bruce Unit 8. The noise-based response time estimates were between 60-100 sec

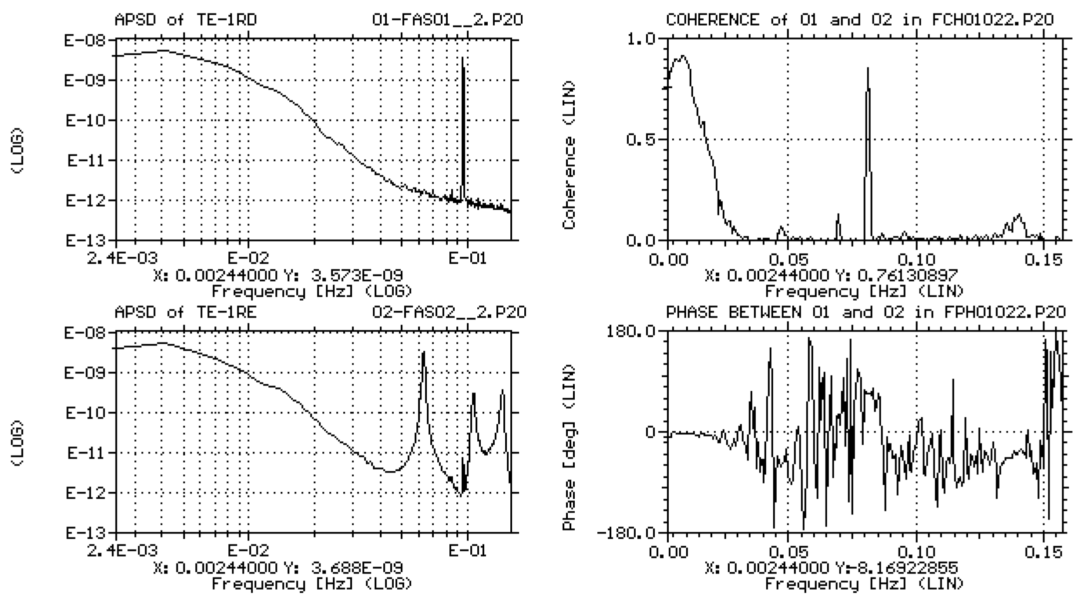

Figure 8. APSD, coherence and phase functions of moderator temperature fluctuations measured by two SDS1 strap-on RTDs located at reactor core outlet

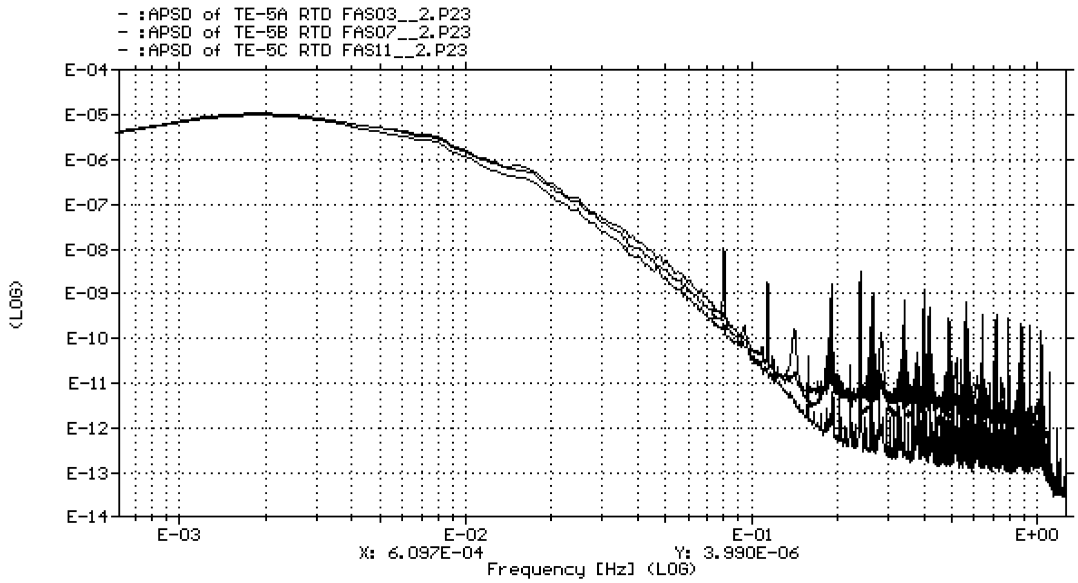

Figure 9. APSD spectra of moderator temperature fluctuations measured by three Reactor Regulating System thermal-well RTDs located at core outlet in Bruce Unit 8.
The noise-based response time estimates were between 31 and 45 sec

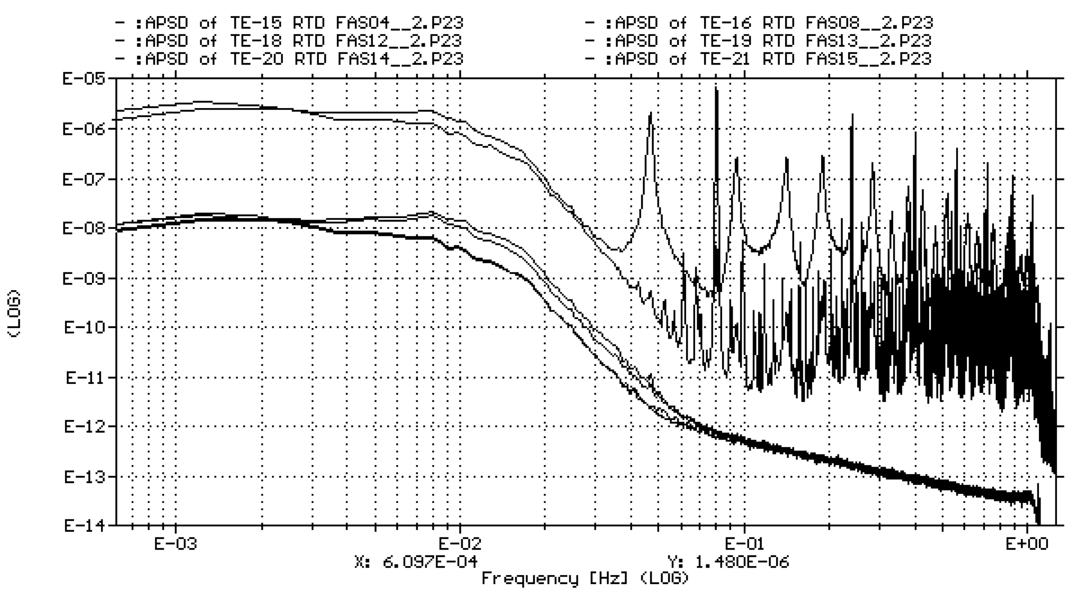

Figure 10. APSD spectra of moderator temperature fluctuations measured by six Reactor Regulating System thermal-well RTDs located at core inlet in Bruce Unit 8.
The noise-based response time estimates were between 12-22 sec

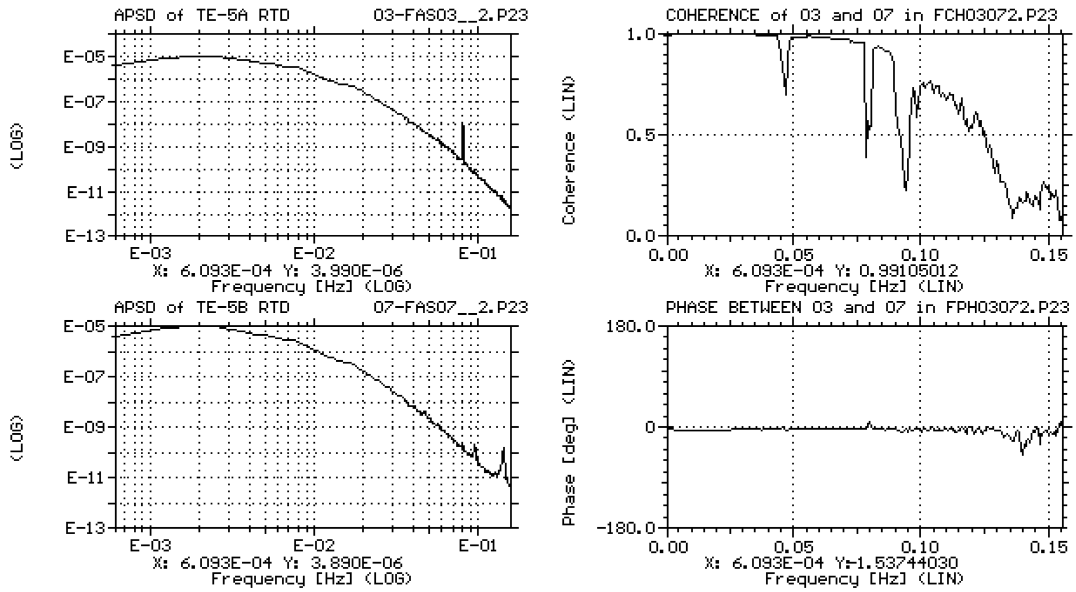

Figure 11. APSD, coherence and phase functions of moderator temperature fluctuations measured by two Reactor Regulating System thermal-well RTDs located at core outlet. The RTDs were in close proximity

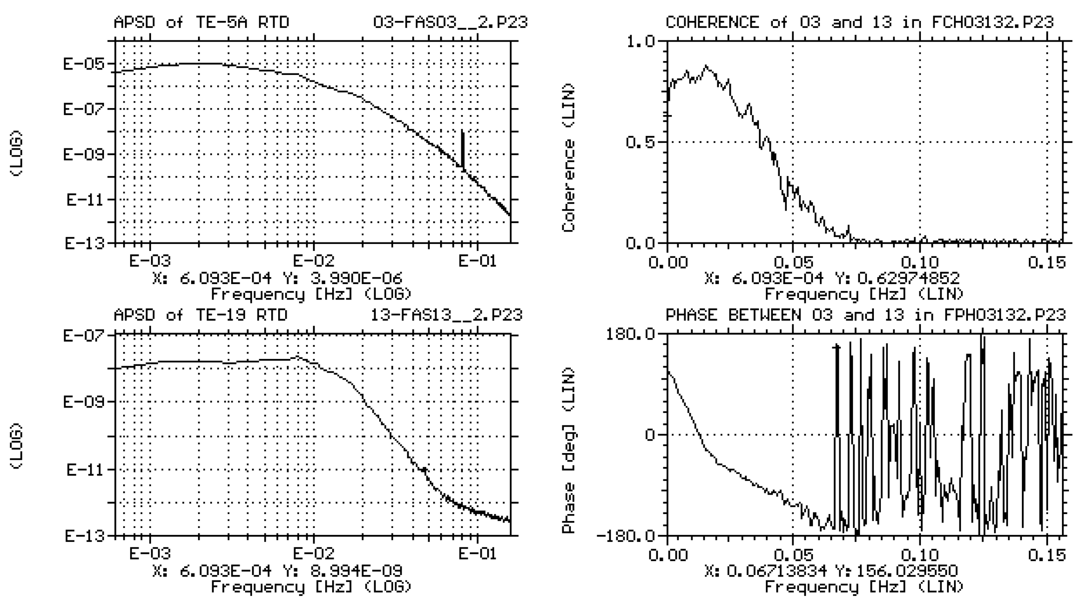

Figure 12. APSD, coherence and phase functions of moderator temperature fluctuations measured by two Reactor Regulating System thermal-well RTDs. One located at core outlet, the other at core inlet of moderator loop No.1

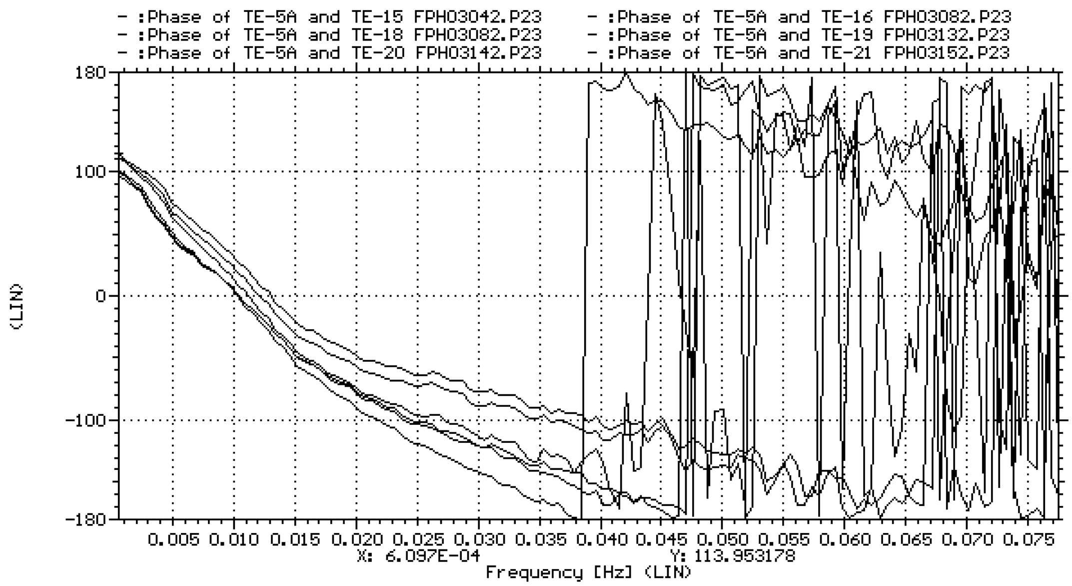

Figure 13. Phase functions between moderator temperature fluctuations measured by a core outlet RTD and six other RTDs located at core inlet. The noise-based estimates of transit times varied with distance between RTDs, and were between 6.9 and 13.0 sec

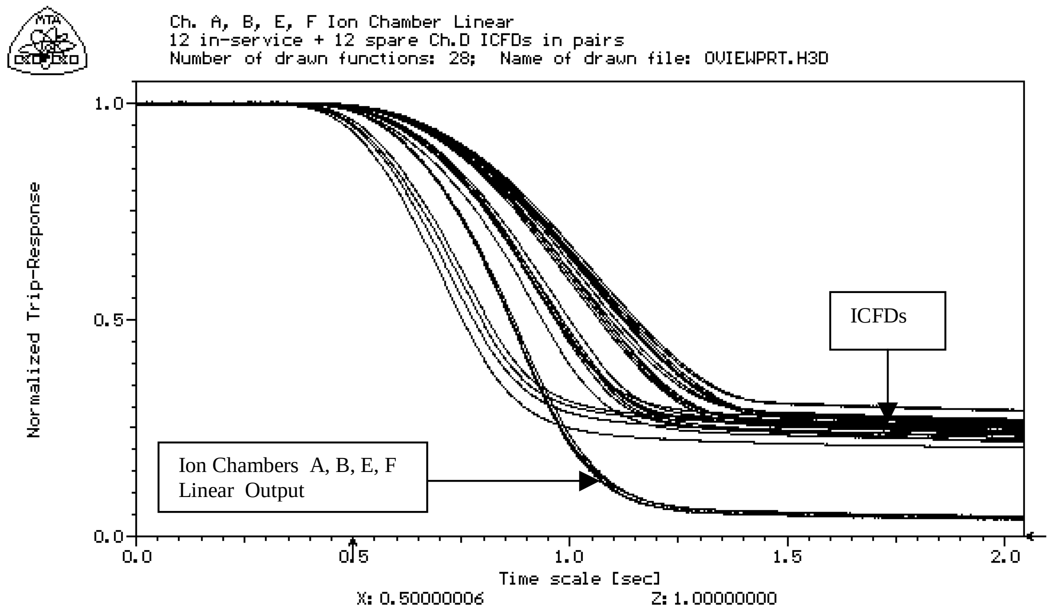

Figure 14. Normalized signals of ICFDs and ion chambers used in reactor regulating and shutdown systems responding to an SDS1 trip from 60% full power in Pickering-B Unit 8 (old ICFDs)

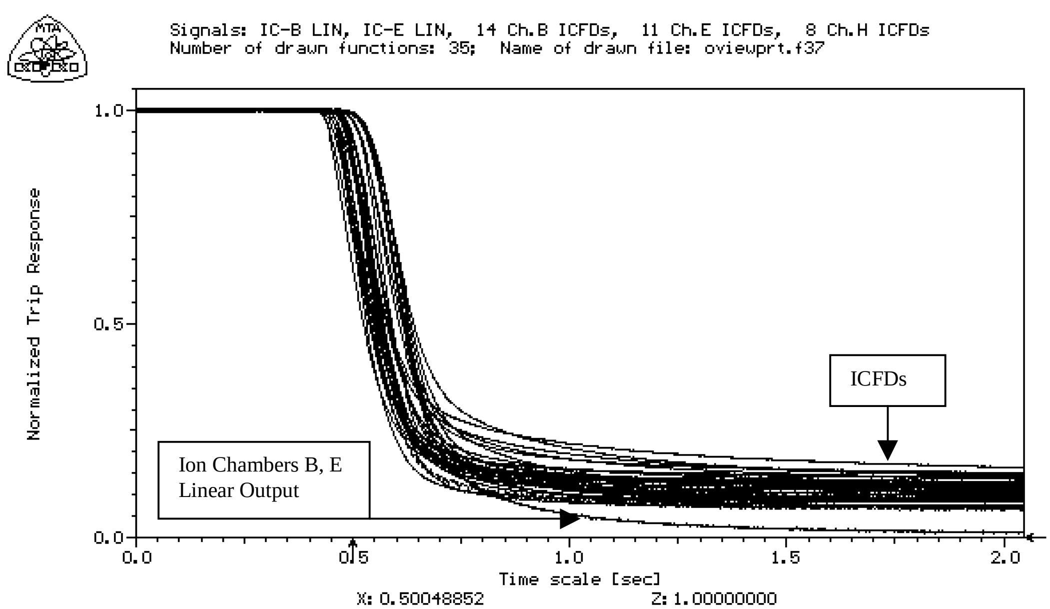

Figure 15. Normalized signals of ICFDs and ion chambers used in reactor regulating and shutdown systems responding to an SDS2 trip from 60% full power in Pickering-B Unit 6 (new ICFDs)

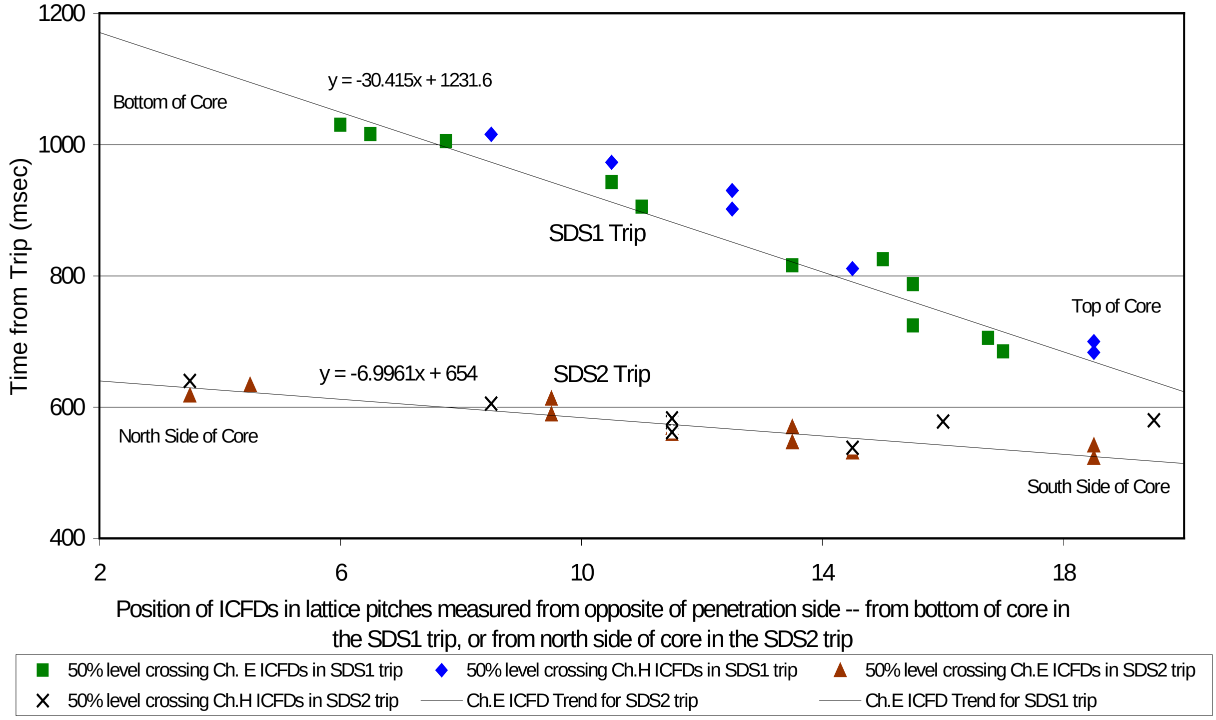

Figure 16. Comparing the 50% level crossing times of ICFD signals as a function of detector position, measured in SDS1 (1996) and SDS2 (2001) trips from 60% full power in Pickering-B Unit 6