Analysis Of Log Rate Noise In Ontario's CANDU Reactors

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Abstract

In the fall of 2003, the operators noticed that in the recently-refurbished Bruce A Shutdown System #1 (SDS1) the noise level in Log Rate signals were much larger than before. At the request of the Canadian Nuclear Safety Commission (CNSC), all Canadian CANDU reactors took action to characterize their Log Rate noise.

Staff of the Inspection and Maintenance Services division of Ontario Power Generation (OPG) has collected high-speed high-accuracy noise data from nearly all 16 Ontario reactors, either as part of routine measurements before planned outages or as a dedicated noise recording. This paper gives the results of examining a suitable subset of this data, with respect to the characteristics and possible causes of Log Rate noise.

The reactor and instrumentation design is different at each station: the locations of the moderator injection nozzles, the location of the ion chambers for each system, and the design of the Log Rate amplifiers. It was found that the Log noise (source of Log Rate noise) was much larger for those ion chambers in the path of the moderator injection nozzles, compared to those which were not in the path. This "extra" Log noise would then be either attenuated or amplified depending on the transfer function (time constants) of the Log Rate amplifier. It was also observed that most of the Log and Log Rate noise is independent of any other signal measured.

Although all CANDU reactors in Ontario have Log and Log Rate noise, the Bruce A SDS1 system has the largest amount of Log Rate noise, because (a) its SDS1 (and RRS) ion chambers are at the top of the reactor in the path of the moderator injection nozzles, and (b) its SDS1 Log Rate amplifiers have the smallest time constants.

1. Introduction

In the fall of 2003, the operators noticed that the noise level in the Shutdown System #1 (SDS1) Log Rate signals[1] in the recently-refurbished Bruce A reactors (Units 3 and 4) were much larger than before. After the initial investigation of the characteristics and possible causes of this increased noise, the Canadian Nuclear Safety Commission (CNSC), requested all Canadian CANDU reactor to evaluate their Log Rate signals, using high-resolution/high-speed data, and to characterize the Log Rate noise and associated instrumentation.

The Inspection and Maintenance Services (IMS) division of Ontario Power Generation (OPG) has collected high-resolution/high-speed noise data routinely from nearly all of Ontario's reactors, as part of their pre-rundown data collection. In addition, some data was collected specifically for the purposes of characterizing the Log Rate noise. This paper gives the results of examining a representative subset of this data with respect to the characteristics

[1] The Log Rate signal is the time derivative of the logarithm of the ion chamber current.

and cause(s) of Log Rate noise, for the Bruce A, Bruce B, Pickering B and Darlington stations[2].

2. Data collection

Prior to and during every planned rundown of a reactor, IMS collects data from the Log, Linear, and Log Rate signals from the ion chambers (ICs), as well as from the in-core flux detectors (ICFDs). Depending on the station, this data comes from at least three separate channels, one RRS channel, one SDS1 channel and one SDS2 channel. The data is filtered with analog anti-aliasing filters, and sampled synchronously at 200 Hz, using custom-designed Noise Analysis Systems (NASs). The NAS units also have the capability to perform individual offset (DC voltage subtraction) and apply a separate gain on each signal, hence considerably improving the resolution of the measurements. The amplitude resolution varies depending on the signal scaling, and on the gain of the NAS channels, but typically is better than 0.1% of the peak-to-peak noise amplitude.
Such data was collected at, or very near, full power from:

- Bruce A unit 3 - February 2006
- Bruce B unit 5 - October 2005
- Pickering B unit 7 - June 2006
- Darlington unit 4 - April 2003, October 2003, and September 2005.

3. Results

An ion chamber produces a current, which is proportional to the local neutron flux at its location. Electronically, there is:

- a LOG amplifier to produce a LOG signal proportional to the logarithm of the current;
- a Log Rate amplifier to produce the time derivative of the LOG signal (Log Rate); and optionally
- a LIN amplifier to produce a LIN signal proportional to the current.

The LOG signal (and also the LIN signal, if present) from the ion chamber amplifier represents this local flux signal. Even though the reactor is in a steady-state condition, these ion chamber signals all vary slightly with time. The Auto-Power Spectral Densities (APSDs) of these signals shows how the power (square of signal) varies with frequency. The APSD has a characteristic shape, or "signature", which represents the characteristics of the small perturbations to the flux in the neighbourhood of the ion chamber. It also depends at high frequencies on the time constant of the LOG amplifier, but typically this is negligibly small when the reactor is at high power.

The Log Rate signal is basically the derivative (rate of change) of the LOG signal. However, in producing the derivative, the signal is also filtered to attenuate the high frequencies, which would otherwise dominate the signal. Thus the Log Rate noise is affected by both the underlying flux noise (the LOG signal), and the dynamic response of the Log Rate amplifier (Log Rate filtering time constants).

[2] The Pickering A (units 1 and 4) ion chamber (SDSA) and fission chamber (SDSE) signals were also measured and evaluated. However, Pickering A SDS-E is unique in this respect because it uses fission chambers and Campbelling (mean square voltage) LOG amplifiers. Hence Pickering A characteristics are not discussed in this report.

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The standard deviation of each signal (a common initial indication of noise amplitude) was calculated either in the usual manner or by taking the square root of the integral of the APSD. Table 1 gives the standard deviations of the Log Rate noise at each station. It is easily seen that the Bruce A SDS1 Log Rate noise is considerably larger than that of any other system. Co-incidentally, the Bruce A SDS2 Log Rate noise is considerably less than that of any other system.

Table 1: Standard deviations of Log Rate noise in percent present power per second [%PP/s].

Station	SDS1				SDS2			
	D	E	F	Mean STDEV	G	H	J	Mean STDEV
Bruce A	0.72	0.55	0.78	0.68	0.13	0.12	0.13	0.13
Bruce B	0.33	0.22	0.29	0.29	0.26	0.28	0.22	0.25
Pickering B	0.29	0.23	0.23	0.25	0.16	0.21	0.26	0.21
Darlington	0.24	0.23	n/a	0.24	0.31	0.35	0.27	0.31

Figures 1 through 4 show the SDS1 and SDS2 APSDs for the LOG signals the Bruce A reactor, the Bruce B reactor, the Pickering B reactor and the Darlington reactor respectively. These LOG signal APSDs represent the basic neutronic noise in the vicinity of the ion chambers, as measured by the LOG circuits. They are plotted using a common amplitude scale in $[\%PP]^2$ /Hz.

The curves are generally similar at low frequencies[3] for all stations. There is usually a minor resonant peak around 0.25 Hz caused by the Reactor Regulating System (RRS).

However, for the mid-frequency range, there is a significant difference between the SDS1 and SDS2 APSDs for all stations. For Bruce A (Figure 1), the SDS1 LOG noise in the mid-frequency range is considerably larger than that of the SDS2 LOG noise. For Bruce B (Figure 2), the situation is reversed; the SDS2 LOG noise is considerably larger in the mid-frequency range than the SDS1 LOG noise. For Pickering B (Figure 3), the SDS1 LOG noise in the mid-frequency range is also larger than the SDS2 LOG noise, while Darlington (Figure 4) is similar to Bruce B.

The maximum difference in the mid-frequency range is a factor 10 to 100 in power, representing a factor of 3 to 10 in LOG signal noise amplitude.

In the high frequency range, all signals tend to reach a low noise "floor".

[3] All frequency ranges are approximate, and there are minor subtle differences between stations in terms of these ranges. However, approximately, less than 0.3 Hz may be considered as the low-frequency range, 0.3 to 3 Hz as the mid-frequency range, and above 3 Hz as the high-frequency range.

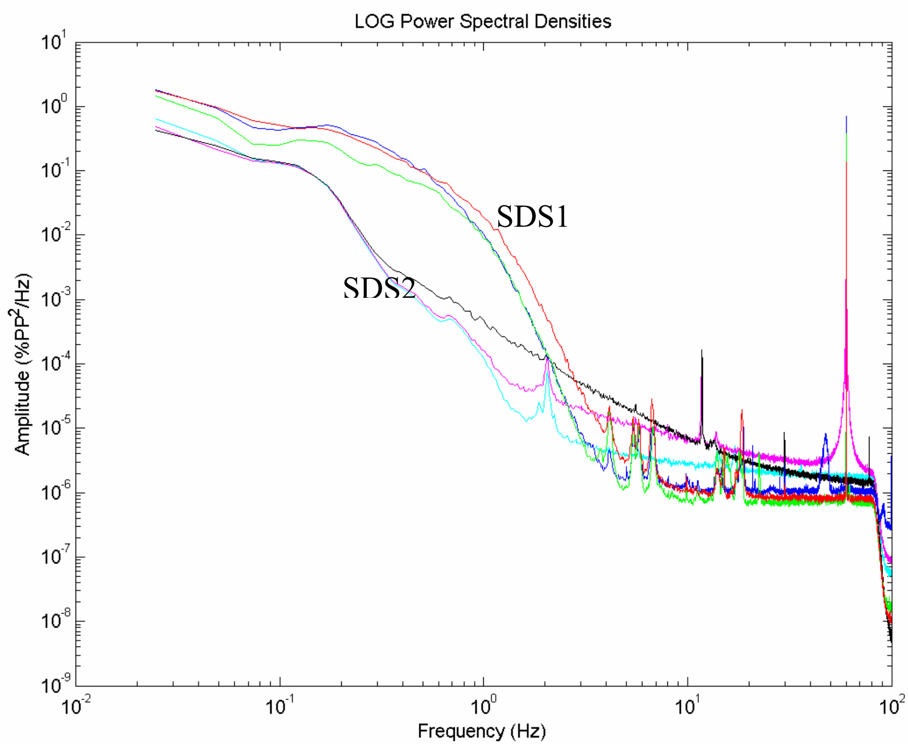

Figure 1: APSDs of Bruce A LOG noise for SDS1 and SDS2.
blue = channel D; green = channel E; red = channel F; cyan = channel G;
magenta = channel H; black = channel J

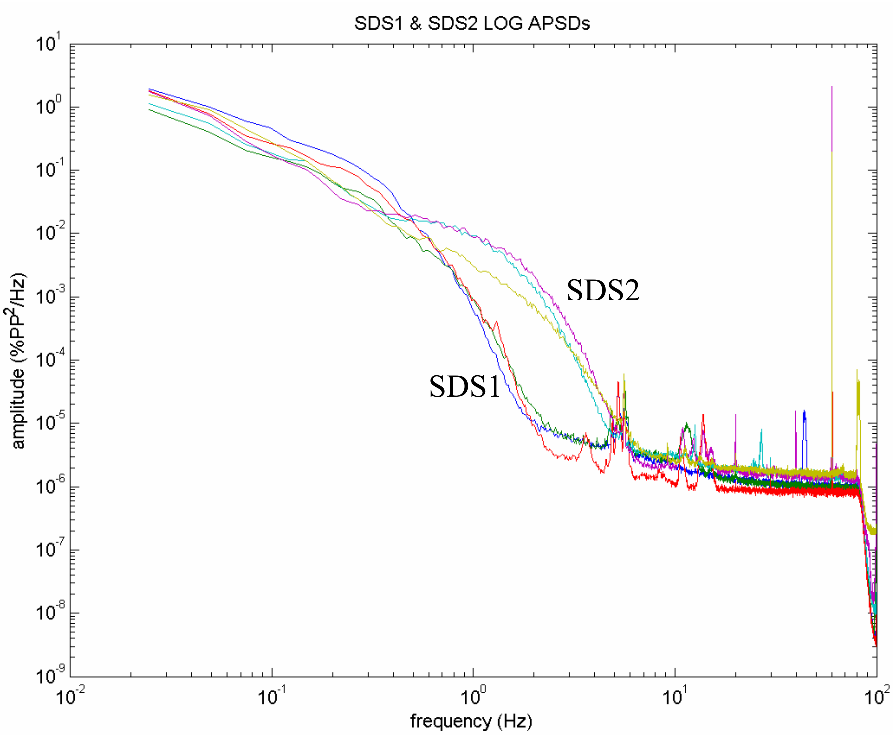

Figure 2 APSDs of Bruce B LOG noise for SDS1 and SDS2.
blue = channel D; green = channel E; red = channel F; cyan = channel G;
magenta = channel H; yellow = channel

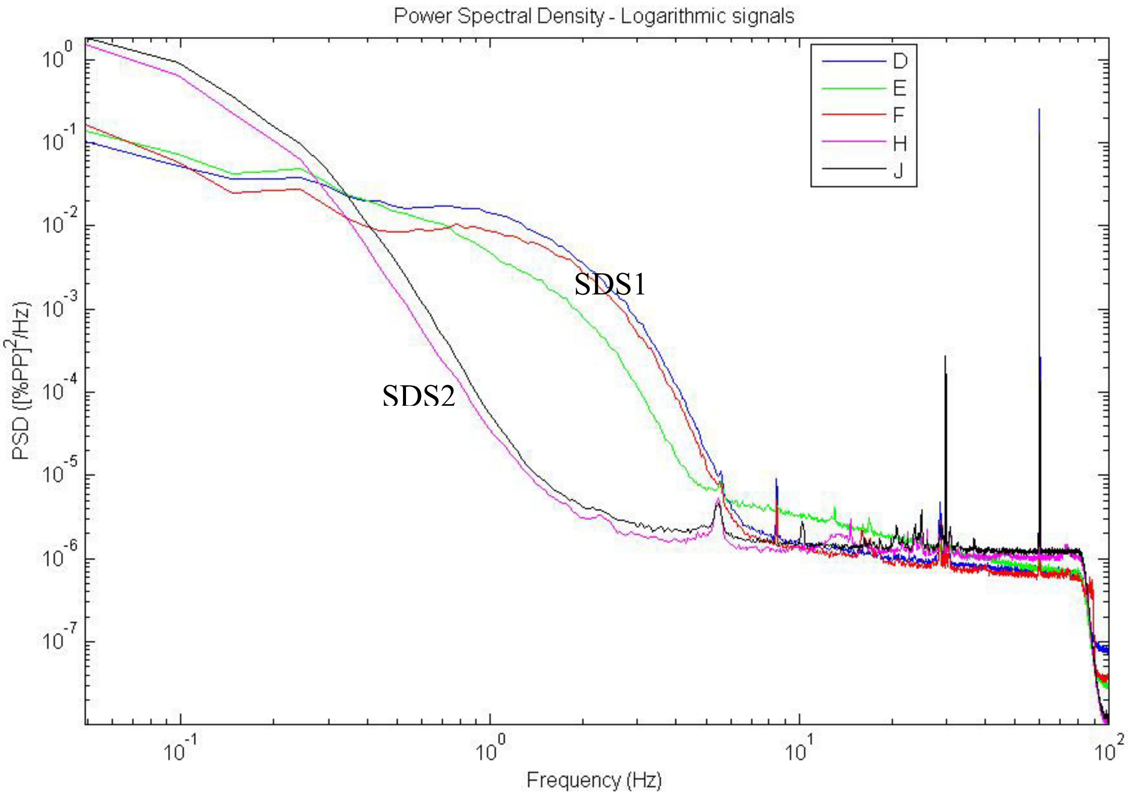

Figure 3. APSDs of Pickering B LOG noise for SDS1 and SDS2

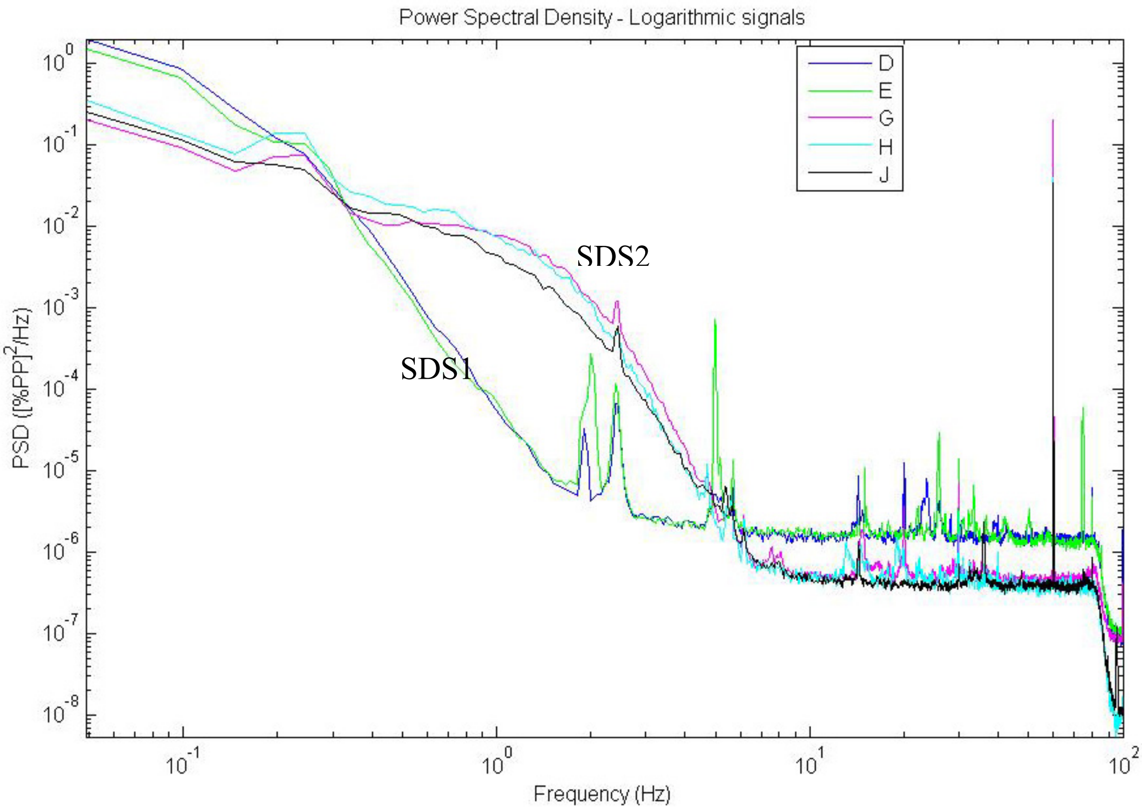

Figure 4. APSDs of Darlington LOG noise for SDS1 and SDS2

The transfer functions and coherences of the Log Rate amplifiers were computed from the derived Cross-Power Spectral Densities. Figure 5 is an example from Bruce A SDS1. The coherence in this measurement is close to unity over a wide frequency range, indicating that the Log Rate signal is directly related to that of the LOG signal, as expected. This statement equally applies to all the other systems, as well.

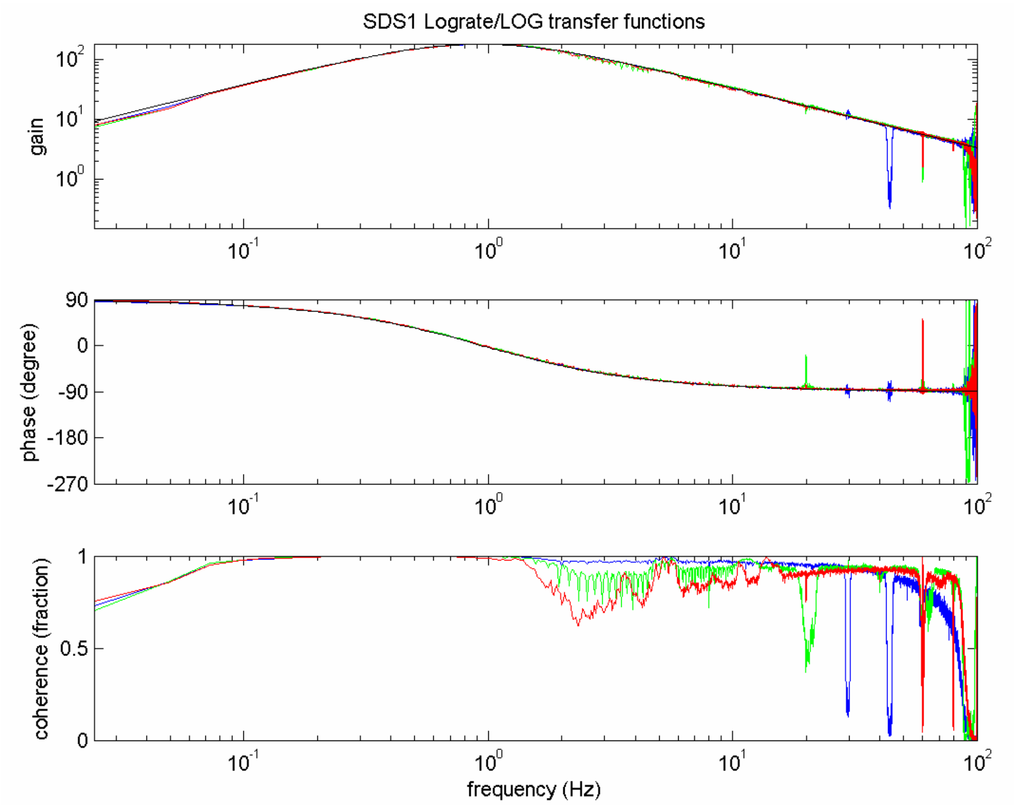

Figure 5: Measured transfer functions of the three Bruce A SDS1 IC Log Rate amplifiers.
blue = channel D; green = channel E; red = channel F; black = theory

Amplifier dynamics are given by the general transfer function:

$$F(s) = \frac{Gs}{(1+s\tau_1)(1+s\tau_2)(1+s\tau_3)}$$

where s = Laplace variable (complex frequency) (s^{-1})
τ_1, τ_2 and τ_3 = time constants of amplifier (s)
G = gain (s)

The gain G in the numerator of the transfer function, in terms of voltages, is different is every station, but, in terms of engineering units ([%PP/s] divided by [%PP]), is always 1s. The transfer functions of the Log Rate amplifiers were found to agree closely to theoretical transfer functions using the design values for the first two time constants. The third time constant (if present) was estimated by fitting the transfer function curves. Its presence, not reported in design documentation, was found during the course of this study, and, in at least some cases, its value was confirmed by examination of the manufacturer's circuit schematic. The time constants are given in Table 2 below.

Table 2: Time constants of the Log Rate amplifiers.

Station	SDS1 (ms)	SDS2 (ms)
Bruce A	125 + 125	250 + 250 + 8
Bruce B	170 + 170	250 + 250 + 8
Pickering B	250 + 250	250 + 250
Darlington	175 + 175	175 + 175 + 8

Figure 6 is a comparison of the theoretical transfer functions of the Log Rate amplifiers from all the stations. Note that all systems have the same gain in the low-frequency range (in engineering units: [%PP/s] divided by [%PP]), a peak gain in the mid-frequency range, and low gain in the high-frequency range. However, the maximum gain (in the mid-frequency range) is quite different depending on the system; those systems with smaller time constants have much more gain (e.g., Bruce A SDS1 has four times the gain of Pickering B SDS1 or SDS2 or Bruce A or B SDS2). Also, the peak gain shifts to the right (higher frequency) as the time constants are reduced.

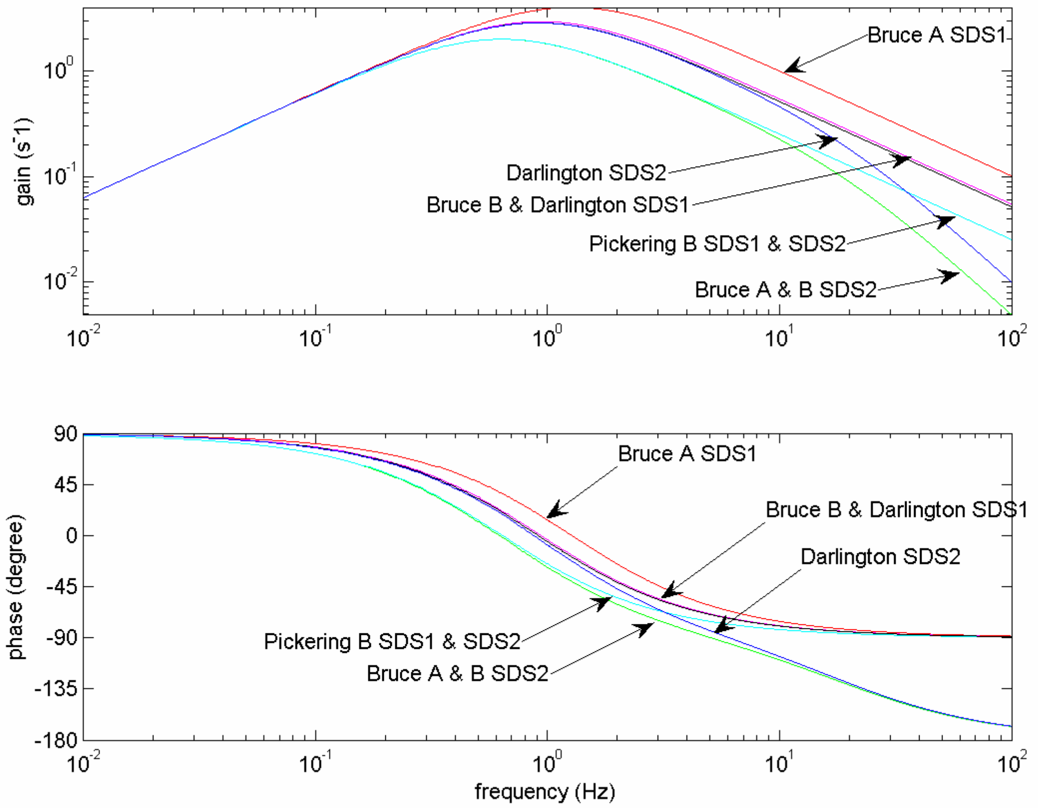

Figure 6: Transfer functions of the Log Rate amplifiers in engineering units (input in [%PP], output in [%PP/s]). Bruce A SDS1 = red; Bruce B and Darlington SDS1 = magenta/black; Bruce A & B SDS2 = green; Pickering B SDS1 & SDS2 = cyan; Darlington SDS2 = blue.

The APSDs for the Log Rate signals are basically, the APSDs of their corresponding LOG signals, multiplied by the squared gain of their Log Rate amplifier transfer function. This is illustrated for the Bruce A reactor in Figure 7. All the other reactors have Log Rate APSDs, which lie in between these two sets of curves. (For example, see Figure 8.)

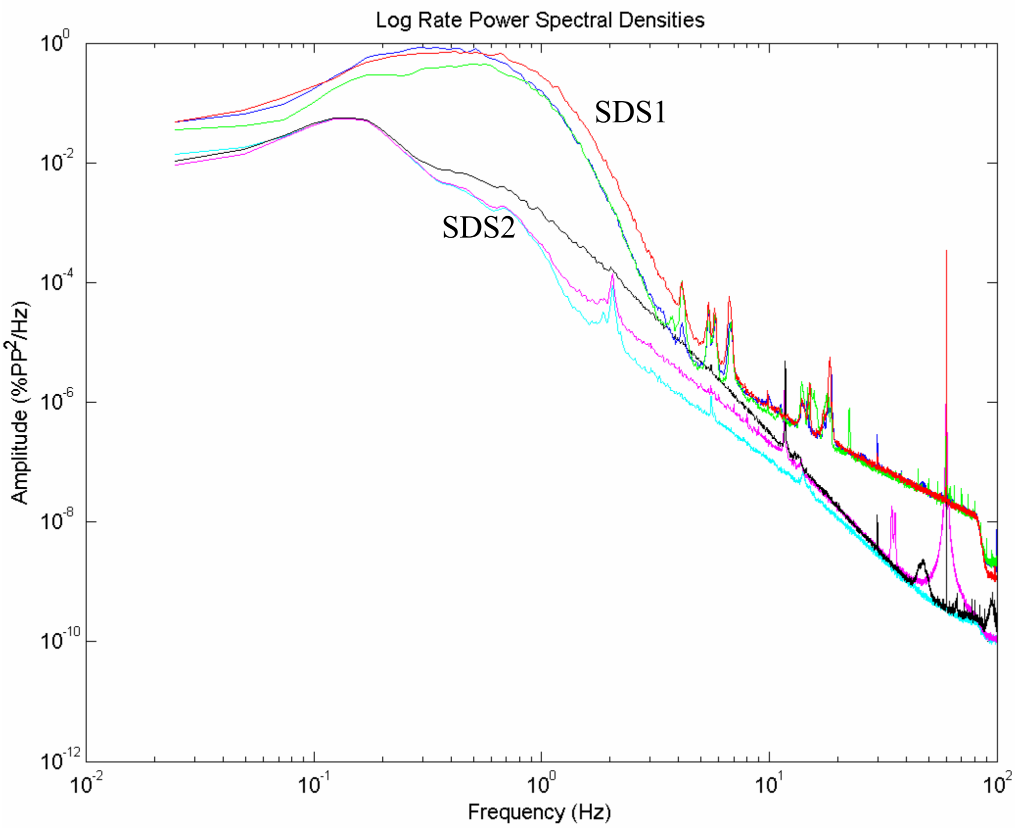

Figure 7: APSDs of Bruce A Log Rate noise for SDS1 and SDS2.
blue = channel D; green = channel E; red = channel F; cyan = channel G;
magenta = channel H; black = channel J

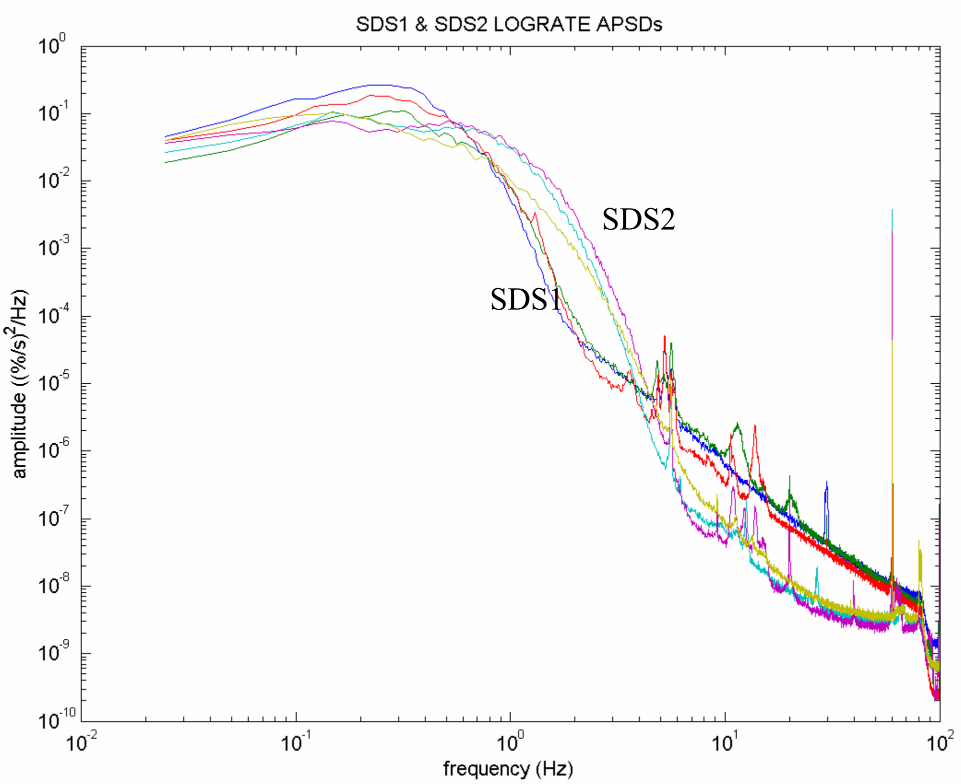

Figure 8: APSDs of Bruce B Log Rate noise for SDS1 and SDS2.
blue = channel D; green = channel E; red = channel F; cyan = channel G;
magenta = channel H; yellow = channel J

In the case of the Bruce B reactors, the system with the additional LOG noise (SDS2) has larger time constants, and hence more filtering, than that of SDS1. These two effects tend to cancel each other out, with the net result that the Log Rate noise is approximately equal in the two systems.

For some stations it was also found that, except for the low frequency range, the LOG and Log Rate signals were independent of both other LOG and Log Rate signals, even within the same system, and the adjacent ICFDs (measuring the flux inside the core). In other words, each Log Rate noise is almost an independent random signal, based on purely local effects. There is no restriction on the size of a diagram but, as a general rule, a diagram should not extend beyond the margin of the letter paper in any direction. Leave one line between the body text, the diagram and the caption.

4. Design differences

The reactor design and instrumentation at each station in Ontario are different. In particular, for the purposes of this report, the important differences are in the location of the ion chambers relative to the location of the moderator injection nozzles, and in the design of the Log Rate amplifiers (their time constants). The ICs are all located at the outer edge of the calandria. The moderator nozzles are located in the moderator area between the fuel and the calandria. The location of the ICs relative to the moderator injection nozzles are summarized in Table 3, and the time constants of the Log Rate amplifiers were summarized in Table 2.

*Table 3: Locations of the ion chambers relative to the moderator injection nozzles. Systems in the path of the moderator flow are highlighted in **bold**.*

Station	SDS1 ICs	SDS2 ICs	Moderator nozzles
Bruce A	**top, near nozzles**[4]	away from nozzles (N side)	top, flowing sideways
Bruce B	top, away from nozzles	**above nozzles** (N side)	both sides, flowing up
Pickering B	**above nozzles** (N side)	below nozzles (S side)	both sides, flowing up
Darlington	below nozzles (N side)	**above nozzles** (S side)	both sides, flowing up

It was observed that the increased LOG noise in the mid-frequency range is associated with being in the path of the moderator injection nozzles, rather than the designation (SDS1 or SDS2) of the system. This nozzle-generated "extra" LOG noise would then be either attenuated or amplified depending on the transfer function (time constants) of the Log Rate amplifier.
Although all CANDU reactors in Ontario have Log and Log Rate noise, the Bruce A SDS1 system has the largest amount of Log Rate noise because (a) its SDS1 (and RRS) ion chambers are at the top of the reactor in the path of the moderator injection nozzles[4], and (b) its SDS1 Log Rate amplifiers have the smallest time constants (high gain) in the mid-frequency region where the noise level is also high.

[4] In Bruce A Units 3 and 4, the moderator enters calandria through 16 booster lines and 6 booster bypass lines at the top of the reactor.

5. Explanation of the Nozzle-Generated Noise

When there is a jet of one fluid into another, there is, on average, a smooth transition and mixing of the two fluids, as presented on the right hand side of Figure 9. However, a significant turbulence is also created, and there is an instantaneous strong non-uniform moving field. See the left hand side of Figure 9. In our case, we interpret the light colour as cold moderator water entering the calandria and the dark colour as hot moderator water. As the local moderator temperature changes due to the turbulence, the absorption of neutrons coming from the core to the ICs also changes, thus affecting the local IC signal. As the turbulence, and its associated moderator temperature distribution, in one location is different than that in other locations, the various IC noises are mostly uncorrelated. The effect of the turbulence on the IC signal increases with the temperature difference between the incoming jet and the existing water in the calandria.

This explanation is further re-enforced by the predicted moderator temperature distributions around the calandria. The temperature distributions are non-uniform; some areas have high temperature gradients, usually accompanied by local flows in opposite directions.
In Bruce A, with 22 moderator inlets (nozzles) at the top, the highest thermal gradients also occur near the top of the reactor - a contributing factor to the SDS1 noise. All other reactors, which have their moderator nozzles on the sides, also have non-uniform temperature and flow distributions similar to those given in [2]. The calandrias do not act like simple tanks of uniform warm water. This non-uniformity in temperature/flow distributions can account for the minor differences in Log Rate noise between channels of the same shutdown system.

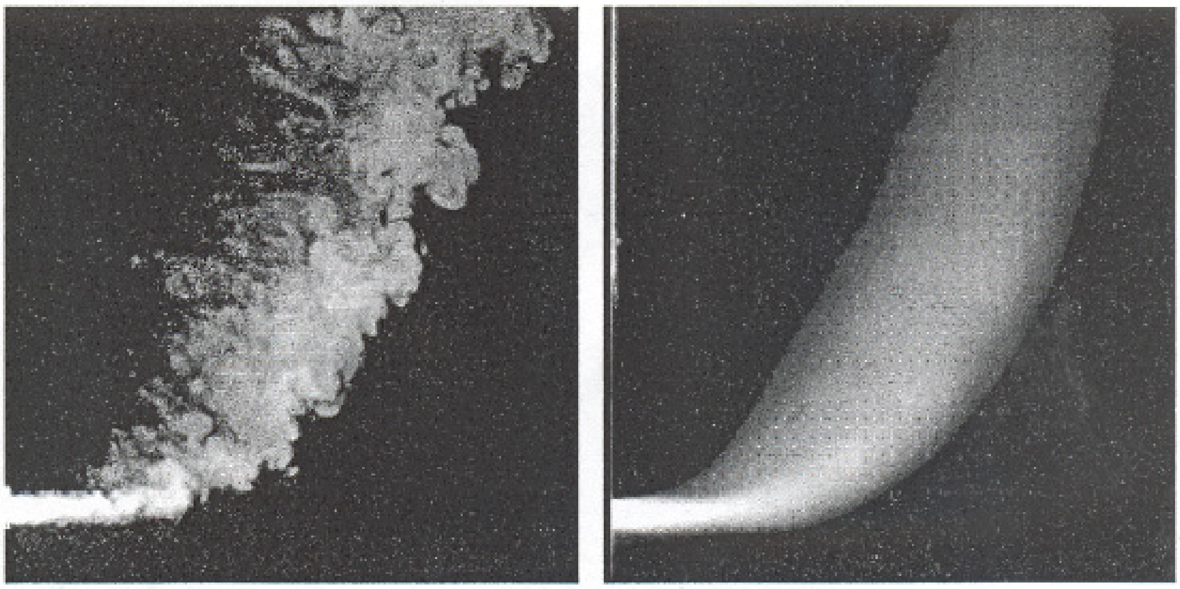

Figure 9: Instantaneous and time averaged views of a jet in cross-flow. The jet exits from the wall on the left into a stream flowing from bottom to top. Reference Figure 1.3 of [1].

6. Conclusions

The high-frequency, high-resolution data was examined to evaluate the causes of Log Rate noise in Ontario's reactors. The differences in noise characteristics are summarized as follows:

1) the LOG signal noise for ion chambers located in the path of moderator inlet nozzles is much higher in the mid-frequency range than those which are away from the effects of the nozzles.
2) the Log Rate amplifier filter dynamics may either amplify or attenuate this extra nozzle-generated LOG signal noise, depending on its time constants.

The Bruce A SDS1 IC system has the unfortunate combination of having both contributing factors: nozzle noise (with a unique arrangement of moderator entry at the top of calandria), and small time constants. No other system has this combination. Consequently, all other systems have less Log Rate noise. In particular, the Bruce A SDS2 system has the optimum combination of no nozzles, and large time constants; it has the smallest Log Rate noise, confirmed by measured data.

In conclusion, a major cause of increased LOG noise and its associated Log Rate noise in the mid-frequency range is turbulent moderator flow from the calandria inlet nozzles, which causes variations in the local temperature distribution near the nozzles, thereby producing variations in the local neutron population. Neutronic instrumentation adjacent to, and downstream of, the nozzles, will respond to these variations. This phenomenon occurs in all the reactors studied and should be considered in the design of future reactors.

7. References

[1] Durbin, P.A. and Petterson, B.A., "Statistical theory and modeling of turbulent flows", John Wiley & Sons, 2001.

[2] Kim, M., Yu, S-O and Kim, H-J, "Analysis on fluid flow and heat transfer inside Calandria vessel of CANDU-6 using CFD", *Nuclear Engineering and Design*, #236, 2006, pp 1155-1164.