Thermal gradients caused by the CANDU® moderator circulation

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Presented at the 29th Annual Conference of the Canadian Nuclear Society (CNS)
June 1st – 4th, 2008 in Toronto, Ontario, Canada.

Abstract

The heavy water moderator circulation system of a CANDU® reactor, maintains calandria moderator temperature at power-dependent design values. The temperature differentials between the moderator and the cooler heavy water entering the calandria generate thermal gradients in the reflector and moderator. The resultant small changes in thermal neutron population are detected by the out-of-core ion chambers as small, continuous fluctuations of the Log Rate signals. The impact of the thermal gradients on the frequency of the High Log Rate fluctuations and their amplitude is relatively more pronounced for Bruce A as compared to Bruce B reactors. The root cause of the Log Rate fluctuations was investigated using Bruce Power operating plant information data and the results of the investigation support the interpretation based on the thermal gradient phenomenon.

1. Introduction

The four reactor units of Bruce A nuclear power station are natural uranium fuelled, heavy water (D_2O) cooled and heavy water moderated CANDU® reactors. The heavy water moderator, in addition to thermalizing the fast neutrons, is also used as a reflector and acts as a heat sink under some transient conditions. The CANDU® moderator system is a safety related system and an important process system. The moderator temperature in the reactor is power dependant and is maintained at specified temperatures by the Moderator Temperature Control (MTC) system. It is important to note that changes in moderator temperature affect its moderating properties [1].

In Bruce A reactor Units 3 and 4, restarted in years 2004 and 2003 respectively, the High Log Rate (HLR) trip system exhibited fluctuations in the Log Rate signal. This paper summarizes the results of analyses using Plant Information (PI) data and site observations, to zero in on the root cause of the Log Rate signal fluctuations.

2. Thermal gradient theory

The Bruce A moderator circulation system is made up of two main moderator pumps, P1 and P2, and two heat exchangers, HX1 and HX2, as shown in Figure 1[1] and Figure 2. The heavy water is drawn from the bottom of the reactor calandria, cooled by the heat exchangers and returned to the calandria via sixteen booster assemblies and six booster bypass lines that feed the calandria moderator at the top of the calandria. Note that the booster assemblies no longer contain booster rods and have been modified to keep the same moderator flow profile.

[1] There are also three auxiliary pumps and an expansion tank.

A theory was proposed that the Log Rate signal fluctuations were caused by the thermal effects within the reflector and the moderator in the top part of the calandria, directly below the SDS 1 and RRS ion chambers. These thermal effects are responsible for the formation of temperature gradients and other localized turbulences like buoyancy effects. The basis of the thermal gradient theory hinges on the design basis that the thermal neutron fluxes at the ion chamber locations are proportional to the reactor power. Thus the basis points to the origin/source of the fluctuations to be in the reactor, that is, the reflector plus the moderator at the top of the calandria. H.W. Hinds and al [2] supported the thermal gradient phenomenon as the major cause of the Log Rate fluctuations in Bruce Units 3 and 4, referring to the fluctuations as "noise".

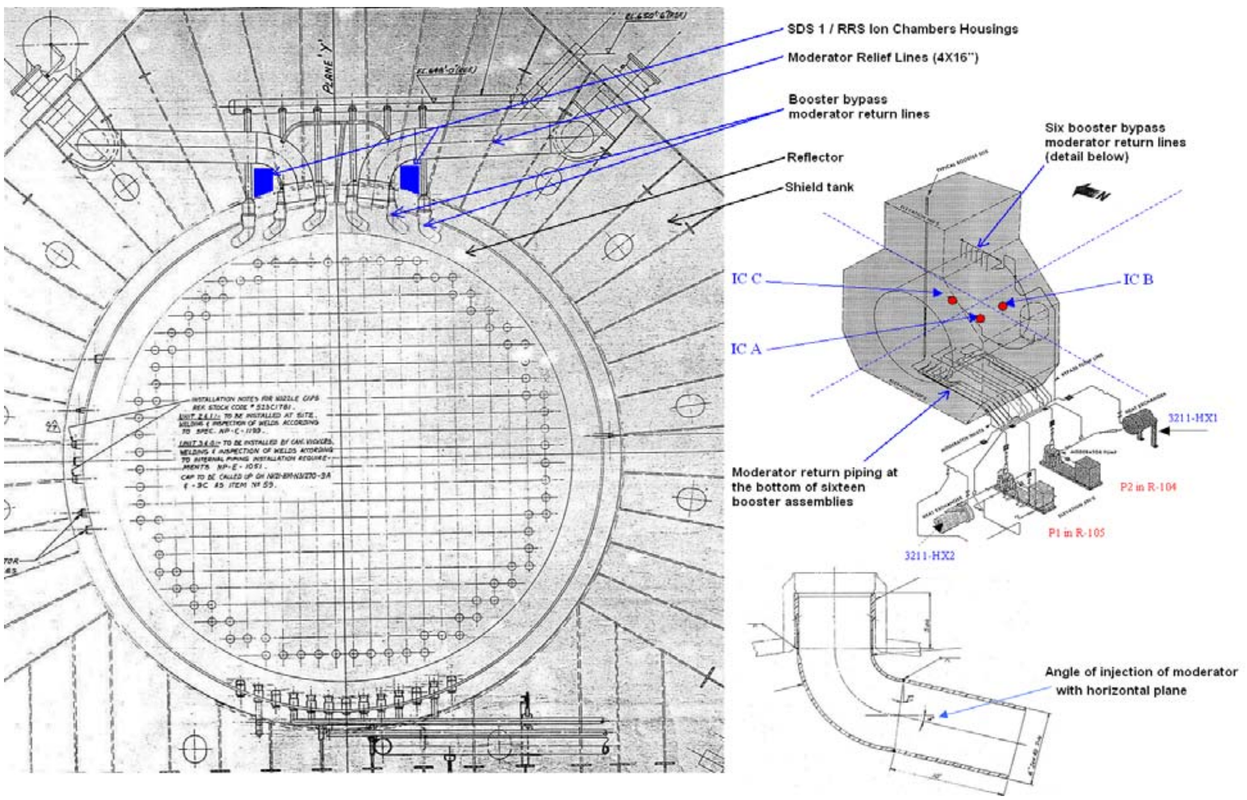

Figure 1: Reactor calandria, reflector, and shield (view from East) with booster lines orientation / View from South-West of reactor, with Pumps P1 and P2, Heat Exchangers 3211-HX1 and 3211-HX2, moderator inlet lines and booster lines

The thermal gradient phenomenon is caused by the local changes in the moderating or slowing down properties of the moderator with changes in its temperature[2] as a result of cold and relatively warm moderator mixing. The changes in the moderator temperature affect the local thermal neutron population (or reactivity) as a result of thermal gradients. The change in temperature changes the mean energy of the thermal neutrons and hence their absorption cross section. The neutron cross section varies with neutron energy or velocity. The magnitude of the thermal gradients depends on the moderator temperature coefficient [4], [5]. The moderator reactivity coefficient has the following properties that play an important role in the Log Rate fluctuation characteristics:

[2] The change in moderator reactivity per degree change in temperature is called "moderator temperature coefficient".

- The changes in the moderation or slowing down.
- The absolute value and possibly the sign of the moderator temperature coefficient are strongly dependent on the fuel irradiation (mostly build up of plutonium), but it is definitively negative with fresh fuel and clean moderator in the reactor core.
- The effect of the poison in the moderator is to make the reactivity coefficient more positive.

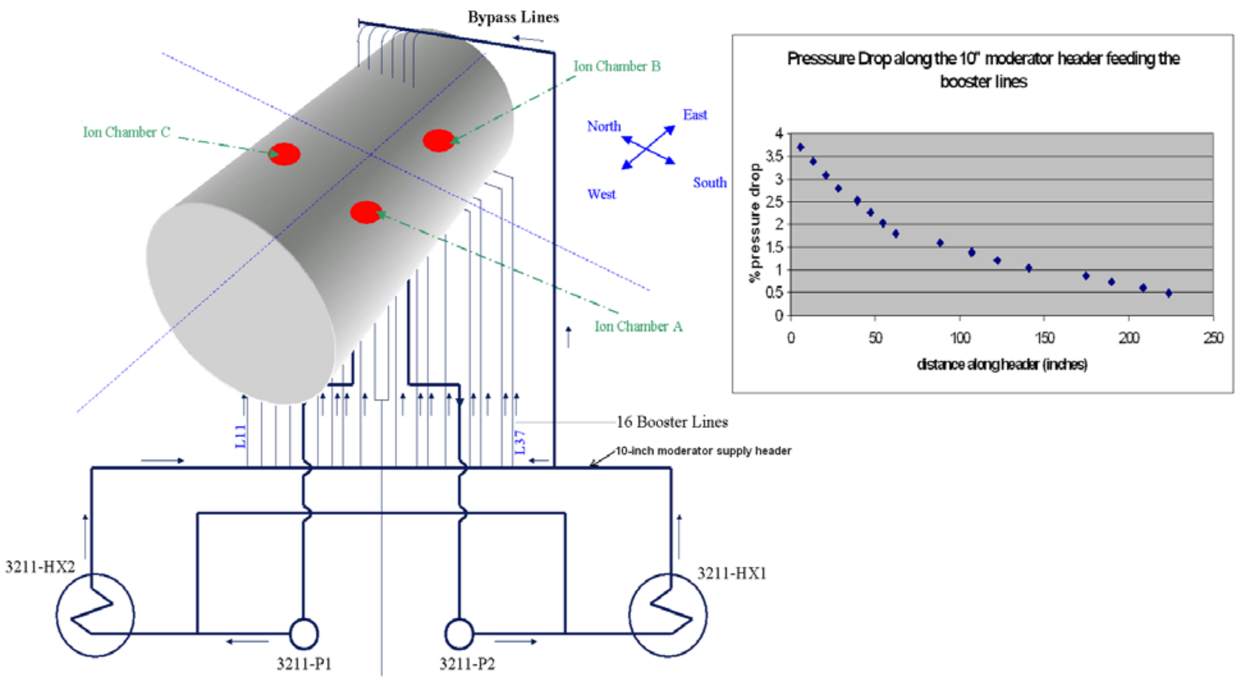

Figure 2 Moderator flow discharge in booster lines and pressure drop along the 10-inch moderator header feeding the booster lines

3. Log Rate signals

The Log Rate signals are generated by the ion chamber amplifiers, based on the current signals from the uncompensated ion chambers located in lead housings, just outside the reactor calandria. In Bruce A reactor units, the Shutdown System Number One (SDS 1) Channels D, E and F and the Reactor Regulating System (RRS) Channels A, B and C use vertical ion chambers, located above the reactor calandria, in their lead housings, as shown in Figure 1 and Figure 3. In other CANDU® reactors, the ion chambers are located on the two sides of the reactor calandria. The moderator relief ducts and booster guide tubes, which are a part of the moderator circulation system, are also present in the shield tank with some of them in close proximity of the vertical ion chambers, as shown in Figure 3. The shield tank contains light water, which is a weak (gray) absorber of thermal neutrons and good scatterer of fast neutrons.

3.1 General characteristics of ion chamber Log Rate signal fluctuations

The PI data from Bruce A reactors Units 3 and 4 was collected over a total period of 3 years, mainly between 2004 and 2006. The data included readings from the In-core Flux Detectors (ICFD), Zone Levels, Lin and Log signals, as well as Log Rate signals.

The data was analyzed and it became evident that:

- The reactor power is steady.
- The signal fluctuations are of low frequency (0.5 to 2 Hz band).
- The fluctuations are random in nature and show no fixed pattern.
- The fluctuations are process related.
- The amplitudes of the fluctuations are reactor power dependent.
- The fluctuations are apparent only in the SDS 1 vertical ion chambers.
- The fluctuations are dependent on ion chamber location, relative to the booster bypass moderator inlet nozzles.

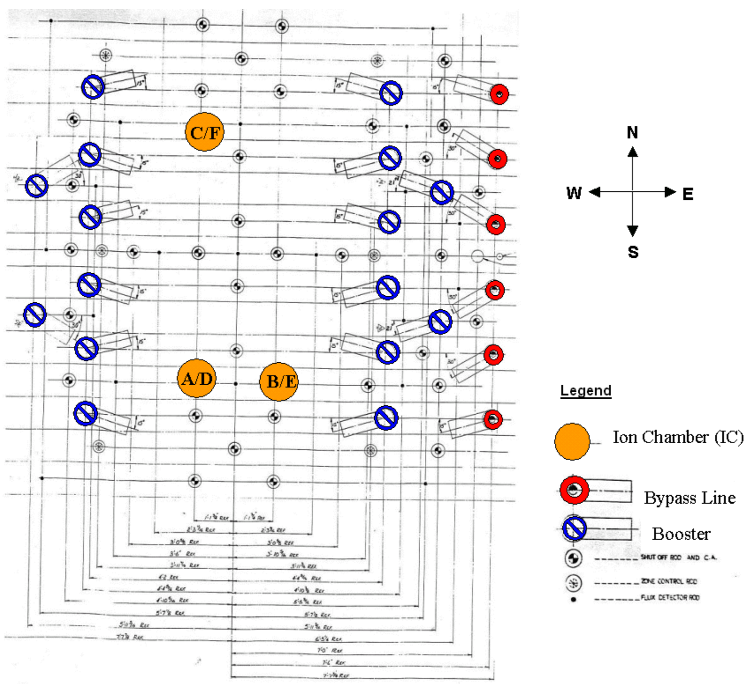

Figure 3 Orientation of the Moderator Inlet Boosters and Bypass Lines Nozzles

4. Thermal gradient formation

For Bruce A reactor Units 3 and 4, at full power the moderator inlet temperature is 33°C and outlet temperature is 66°C. The moderator circulation pattern, especially in the top of the calandria (i.e. reflector plus the top part of the core), is complex [3]. The relatively cool inlet moderator mixes with warmer moderator forming turbulent temperature gradients near the calandria inlet nozzles.

The moderator inlet is from the top via a multi-port system involving sixteen boosters and six booster bypass inlet nozzles as shown in Figure 1. Figure 1 shows the orientation of the cold moderator injection nozzles, designed to prevent damage to the in-core components from moderator flow pressure through the booster bypass inlet lines. In addition to the effect of forced moderator circulation, there are buoyancy effects due to the density differences between the cold (relatively heavy) and hot (relatively lighter) moderator in the top regions of the calandria.

Consequently, there are spatial and temporal moderator temperature variations occurring continuously. As discussed below, these temperature gradients are the root cause of the Log Rate signal fluctuations observed at the Units 3 and 4 SDS 1 High Log Rate (HLR) signals.

On the other hand, in Bruce B reactors, the cooler moderator enters from the side of the calandria through fan-type diffusers, which generate less turbulence at the SDS 2 Ion Chambers location. It may be noted that these fluctuations are of low frequency because they are not electrical or electronic in nature but process related.

4.1 Explanation of Log Rate fluctuation characteristics

The characteristics of the Log Rate fluctuations depend on a number of factors. The moderator inlet nozzles are designed to inject cold water in the 70 cm reflector region and along the calandria shell as shown in Figure 1. The reflector plays a very important role, because the epithermal neutrons (neutrons with above-thermal energy values of about 0.025 eV) entering the reflector thermalize in the reflector. Portions of the thermalized neutrons escape the calandria and affect the signal of the out-of-core ion chambers. Therefore, the non-stationary thermal gradients, which cause small changes in neutron population in the reflector region, have small but measurable effect on the output of the ion chambers.

The amplitude of the fluctuations depends on two primary factors[3]:

- The change in neutron population as a result of thermal gradients, and
- The rate of change of the neutron population.

Any poison, i.e. negative reactivity added, to the moderator and thus to reflector, affects the number of thermal neutrons escaping into the shield tank and thus the ion chambers Log Rate signals. The moderator temperature coefficient varies with moderator poison concentration and thus the impact of thermal gradients on the amplitude of the Log Rate signal.

The magnitude of the moderator thermal gradients or differentials is a function of the reactor power. At zero power, generally the moderator temperature is invariant and there are no thermal gradients to affect the ion chambers signal. As the reactor power increases, more and more heat is deposited in the moderator, therefore, “delta (Δ) T” between the cooler moderator entering the calandria and the calandria moderator changes.

The ion chambers signals are affected by the global and local flux perturbations taking place in the reactor. The complexity of the thermal gradient patterns generated by the booster and booster bypass lines affects the response of the individual ion chambers differently depending on their location relative to thermal gradients. The local thermal neutron population variations caused by the thermal gradients relative to the location of the individual ion chambers are responsible for the differences in the signals of the individual ion chambers, as shown in Section 5.3. For the same reason, the signals due to local perturbations cannot be coherent, except as shown in [2], where a minor coherence of the ion chamber signals in the frequency range 0.2 Hz to 0.25 Hz is an example of global response, caused by the RRS system.

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[3] This is in a way similar to the change in thermal neutron population caused by the shutter mechanism at the location of the ion chambers to test the SDS 1 and SDS2 Log Rate trip function.

5. Operational support of the thermal gradient theory

5.1 Shim operation

Thermal neutron absorbers (like boron or gadolinium) added to the moderator, during fresh fuel core conditions, to suppress excess reactivity is called “shim”. The shim hardens the thermal neutrons spectrum, thus decreases their contribution. The amplitude of the Log Rate fluctuations increased as the shim was burned by destruction of shim atoms by neutron bombardment, as expected. The moderator temperature affects ion chamber response by virtue of its effect on the number and rate of scattering reactions in the reflector. The presence of shim reduces the ratio of scattering/absorption reactions and, hence, also reduces the relative perturbation component in the overall neutron signal.

5.2 Power dependence

The moderator inlet temperature is maintained[4] at a fixed temperature (T_{fixed}), the calandria moderator temperature varies ($T_{variable}$), as it is proportional to the reactor power due to normal thermal leakage from the fuel channels and radiation heat deposition in the moderator. The ΔT between the calandria moderator and moderator inlet varies with reactor power:

$$\Delta T = T_{variable} - T_{fixed} \qquad (1)$$

This ΔT, through the moderator temperature coefficient, is responsible for the thermal gradients. The phenomenon is mostly responsible for the power dependence of the Log Rate signal fluctuations.

Site observations showed that the amplitude of the log rate fluctuations is power dependent. The number of fluctuations of the Log Rate signal as the reactor is brought from 50% FP to ~90% FP is shown in Figure 4, Figure 5 and Figure 6. The number of fluctuations between ±0.004% Dec/sec and ±0.005% Dec/sec, between ±0.005% Dec/sec and ±0.006% Dec/sec, and above ±0.006% Dec/sec are plotted.

The amplitude of the fluctuations is very small below 50% full power (FP), increasing noticeably in the 50% FP to 80% FP range and then increasing only minimally above 80 % FP. Figure 7 shows the variations in the number of Log Rate signal fluctuations increasing, both above +0.002% Dec/sec and below -0.002% Dec/sec. The analysis of the PI data supports the above-mentioned observation.

5.3 Differences in responses of individual ion chambers

The Bruce A vertical ion chambers for SDS 1 and RRS are located in three physically separated ion chamber housings, located as shown in Figure 3. There are observed inter-channel

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[4] The MTC system maintains the moderator inlet temperature at a required setpoint. This is accomplished by controlling the flow of Service Cooling Water to the heat exchangers. The calandria moderator outlet temperature is maintained below a maximum and the maximum temperature depending on the reactor power.

differences in the fluctuations, as each channel displays a different Log Rate fluctuations pattern. This is a direct reflection of the turbulent temperature gradients in the reflector and the core at the top of the calandria. The magnitude and frequency of fluctuations gives a picture of the thermal gradient patterns relative to the location of the individual ion chambers.

Measurements and 3D simulations of moderator temperature for 600 MW reactors show that moderator temperature can vary significantly within the reactor core due to two forces: a mix of momentum force by inlet jets and buoyancy by heat load [3].

5.4 Log Rate fluctuations not detected by the SDS2 horizontal ion chambers

In Bruce A reactors Units 3 and 4, the SDS2 ion chambers for channels G, H and J are located on the North side of the reactor calandria in the shield tank. The SDS2 ion chamber Log Rate signals did not show any measurable fluctuations: this clearly shows that the SDS 1 and RRS ion chamber signals are affected by the thermal gradients generated in the reflector and the core in the upper regions of the calandria.

Bruce B observations strongly support the Bruce A observations and explanations. For Bruce B, the calandria moderator inlets are on both the North and South sides of the calandria. The SDS2 ion chambers are closer to the North side. The moderator injection close to the ion chambers, whether located on the top or side of the calandria, is the key factor responsible for the relatively HLR fluctuations.

It is important to note that:

- Bruce B SDS2 ion chambers HLR amplitude has characteristics similar to Bruce A SDS 1 ion chambers HLR amplitude.
- The amplitude of the Bruce B HLR fluctuations is also relatively smaller because the time constant of the Log Rate trip electronics and the response time of the indicating meters are larger than that of Bruce A electronics, as explained in Section 6.
- The Bruce B fan-type diffusion nozzles are superior to Bruce A round-pipe nozzles for reducing moderator thermal gradients at the discharge points.

5.5 Pump swap test

A test was conducted on Bruce Unit 4 on November 3rd and 4th, 2005. The purpose of the test was to perturb the moderator process conditions by swapping the moderator pumps P1 (normally ON) and P2 (back-up pump, normally OFF), with a small period of time (around 1 minute) when both pumps would be ON. The swapping process reversed the direction of the moderator flow in the 10-inch moderator supply header and thus the sequence of the discharge pressure drops, as shown in Figure 2, along the header via booster lines into the calandria. The flow reversal caused the change in the pattern of the thermal gradients resulting in, as expected, very small changes in the localized reactivity perturbations due to pressure drop along the header, as shown in Figure 2.

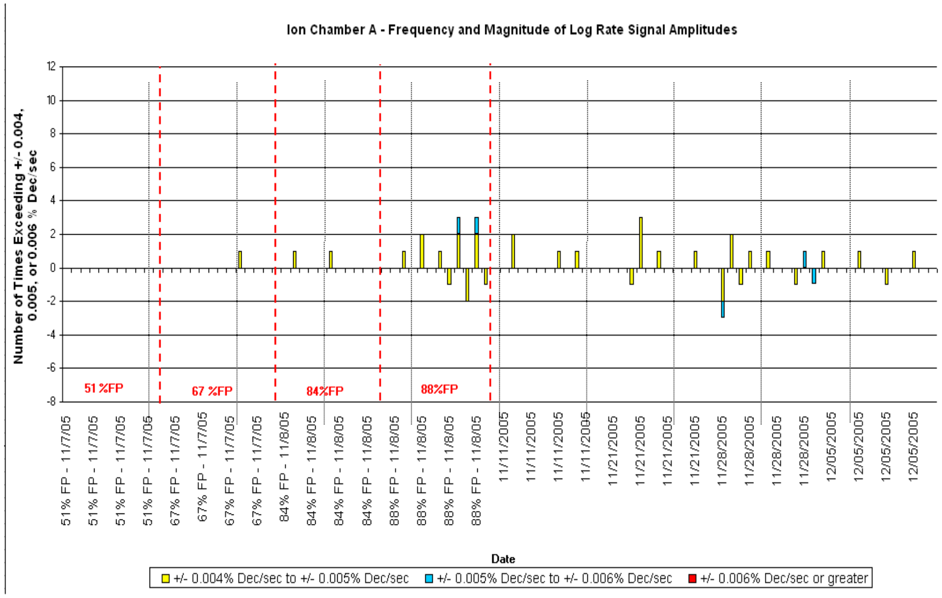

Figure 4 Ion Chamber A Frequency and Magnitude of Log Rate Signal Amplitudes

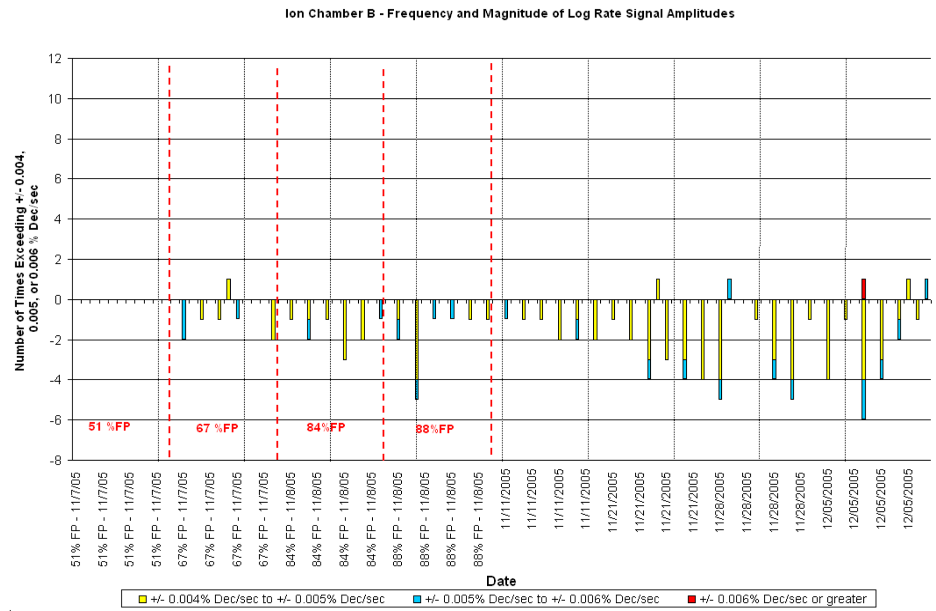

Figure 5 Ion Chamber B Frequency and Magnitude of Log Rate Signal Amplitudes

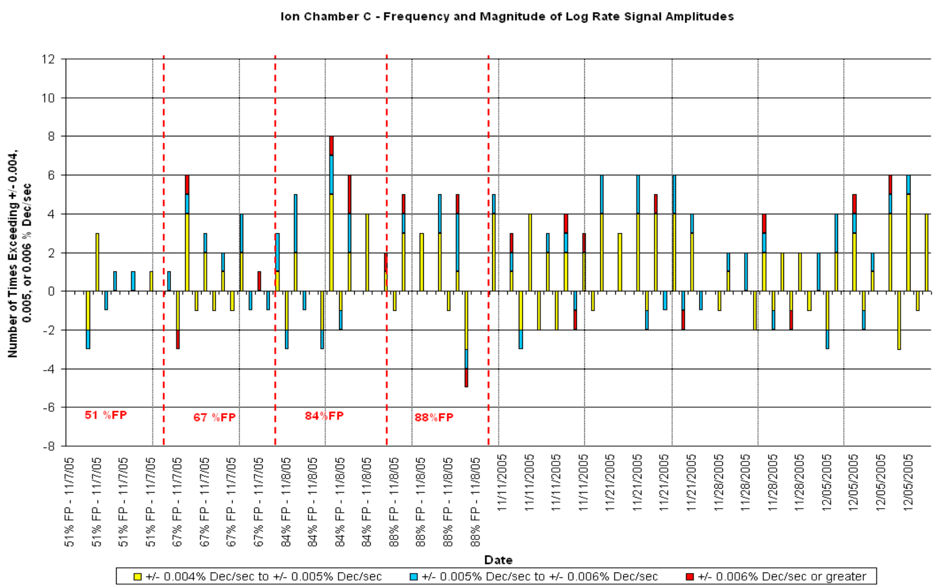

Figure 6 Ion Chamber C Frequency and Magnitude of Log Rate Signal Amplitudes

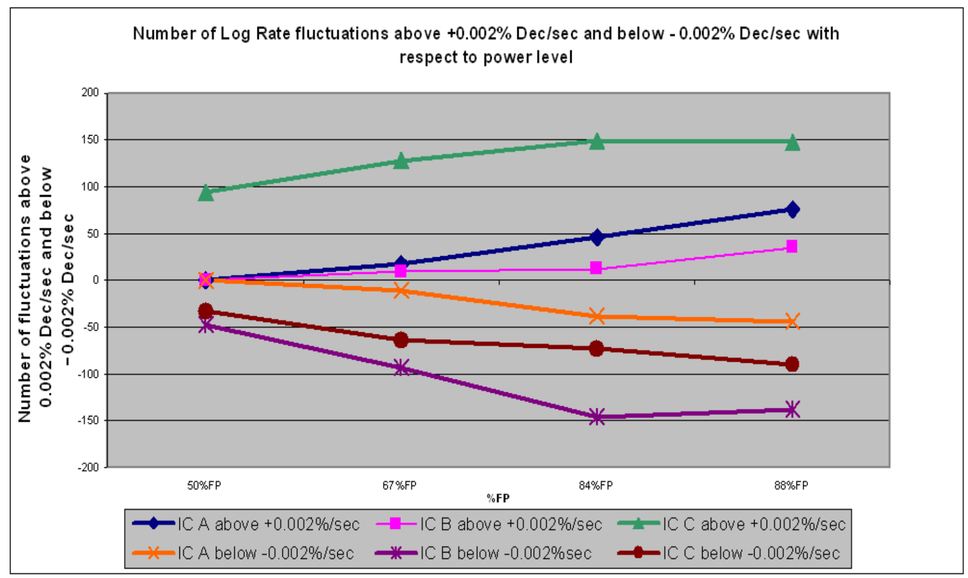

Figure 7 Number of Log Rate fluctuations above +0.002% Dec/sec and below –0.002% Dec/sec with respect to reactor power (%FP)

The fluctuations recorded by the ion chambers A, B and C are shown in Figure 8, Figure 9 and Figure 10 during the pump swap test. The frequency and magnitude of the Log Rate signal amplitudes at the individual ion chamber locations during the pump swap operation are shown in Figure 11, Figure 12 and Figure 13. The figures show the number and frequency of variations in the Log Rate signals between ±0.004% Dec/sec and ±0.005% Dec/sec, between ±0.005% Dec/sec and ±0.006% Dec/sec and above ±0.006% Dec/sec. The figures show that the variations in the frequency and magnitude of the Log Rate signals depend on the relative position of the ion chambers with respect to the moderator inlet nozzles.

It is important to note that:

- Changes in the moderator thermal gradients (and resulting variations in thermal neutron flux) due to the reversal in moderator pump discharge were expected to be very small,
- CANDU® in-core and out-of-core neutron monitoring systems are sensitive enough to detect those small changes in the neutron population as a result of the changes in thermal gradients pattern.

6. Log Rate signal generation and indicating electronics in Bruce A Units 3 and 4

The side effect of faster response time required of SDS 1 Log Rate circuit for out-of-core large Loss of Coolant Accident (LOCA) coverage necessitated changes to signal generation and indicating electronics.

6.1 Ion chamber amplifier with trip function

The old API COMPACK indicating alarm meter, which included the Log Rate Trip function, was replaced with a new Sartrex 903015 ion chamber amplifier and Log Rate circuit. The Sartrex amplifiers have a dual time constant of 0.125 seconds, as compared to the old Keithley 25014 ion chamber amplifiers with time constants of 0.2 seconds and 0.325 seconds. The Keithley amplifiers attenuated the low frequency (0.5 to 2 Hz) signal fluctuations to a greater degree than the new Sartrex amplifiers. The frequency response of the Keithley and Sartrex amplifiers is shown in Figure 14.

The significant reduction in the time constants of the Log Rate circuits resulted in shifting the peak of the low frequency response to a slightly high frequency bandwidth and increasing the low frequency bandwidth of low frequency fluctuations (that results in a larger bandwidth for low frequency fluctuations and consequently relatively larger amplitude variation at the output of the amplifiers).

6.2 Indicating meter

A new Versatile indicating meter, for the Log Rate signal and trip set point, also replaced the old API COMPACK alarm meter. The new Versatile meter does not carry any safety function. The response time of this new meter is faster (less than one second) than the response time of the indicating meter portion of the old API indicating meter. That is why, the fluctuations in the Log Rate signal for Bruce A Units 3 and 4 were not as evident before the equipment replacement, due to the slower response time of the old API meter movement.

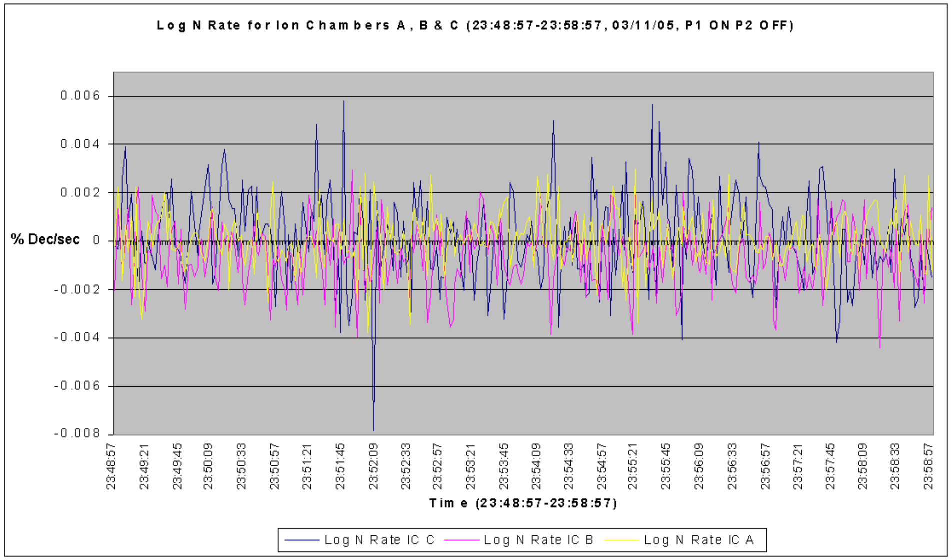

Figure 8 Log N Rate for Ion Chambers A, B & C (Main Pump Swap Test: P1 ON, P2 OFF)

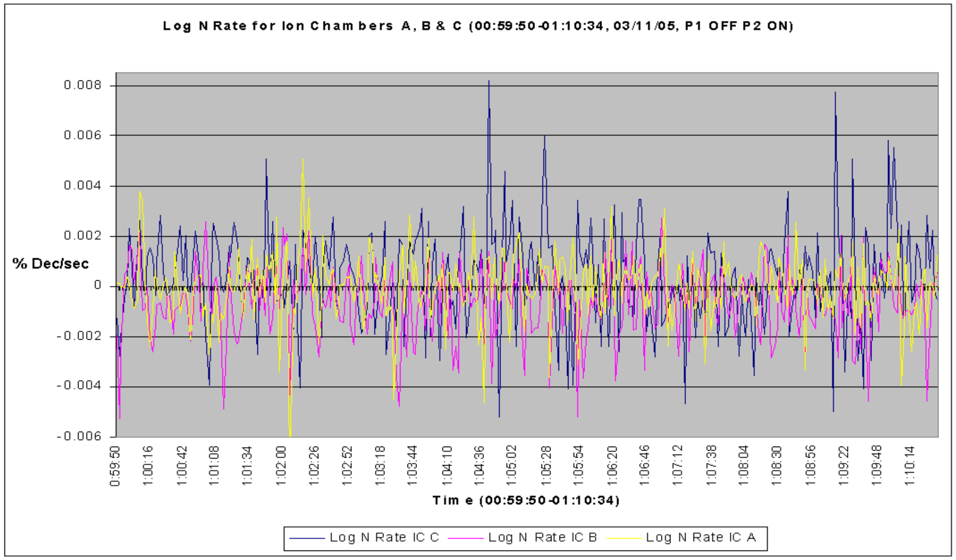

Figure 9 Log N Rate for Ion Chambers A, B & C (Main Pump Swap Test: P1 OFF, P2 ON)

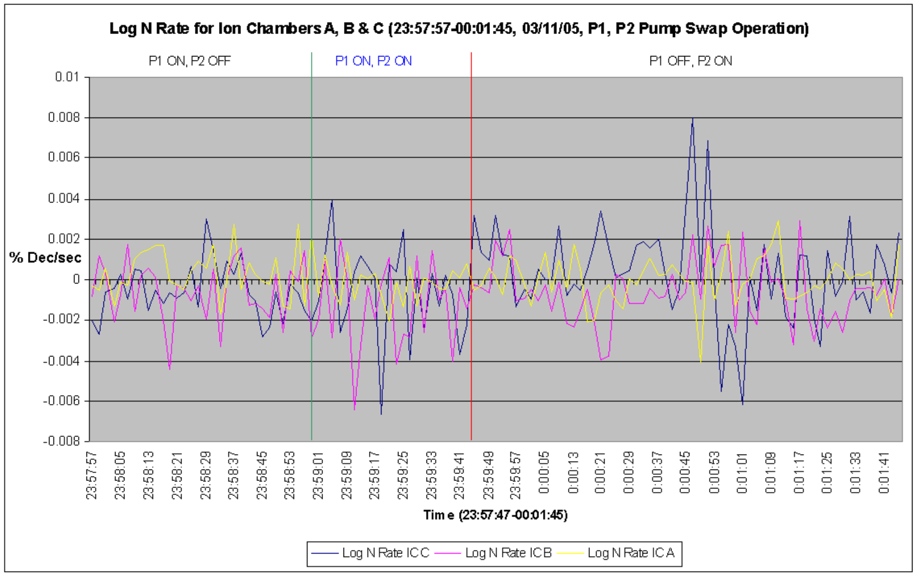

Figure 10 Log N Rate for Ion Chambers A, B & C (Main Pump Swap Test: P1, P2 Swap)

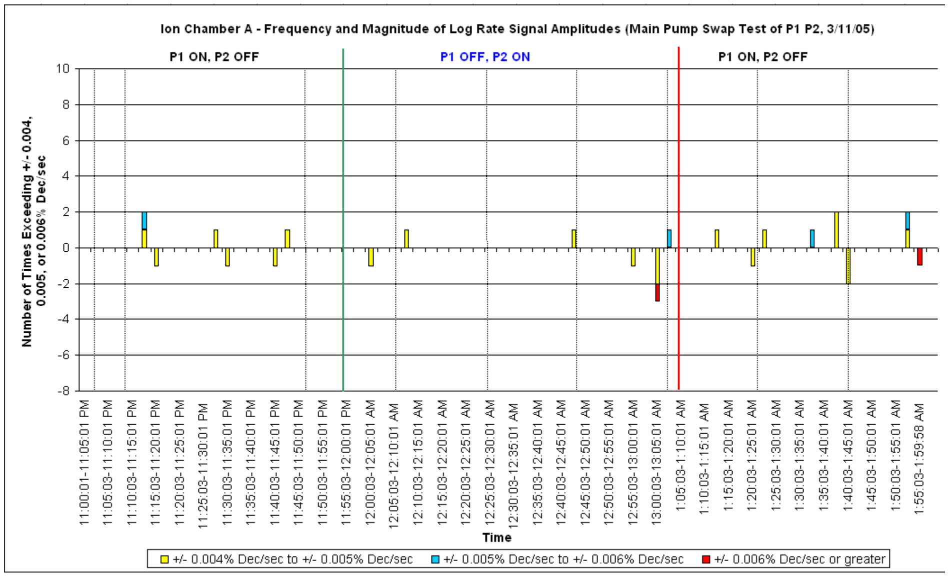

Figure 11 Ion Chamber A - Frequency and Magnitude of Log N Rate Signal Amplitudes (Main Pump Swap Test of P1 and P2)

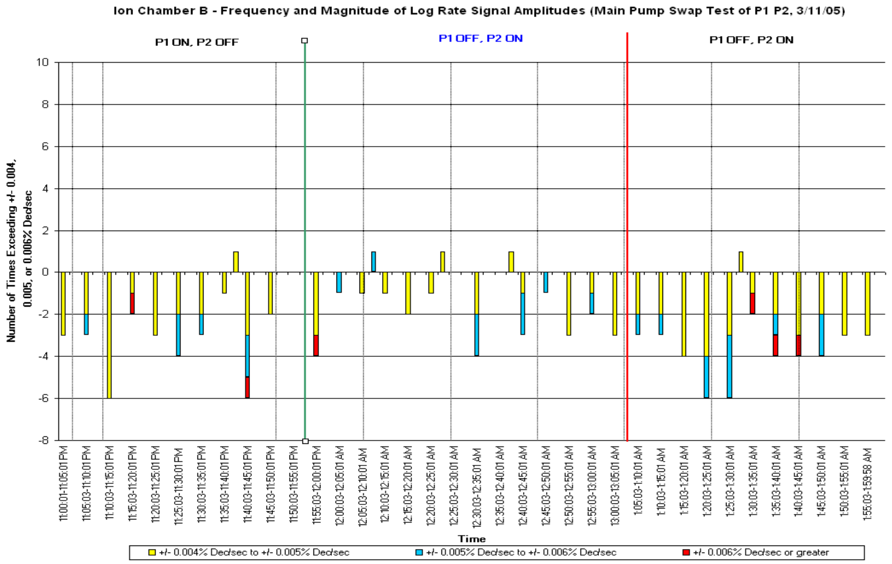

Figure 12 Ion Chamber B - Frequency and Magnitude of Log N Rate Signal Amplitudes (Main Pump Swap Test of P1 and P2)

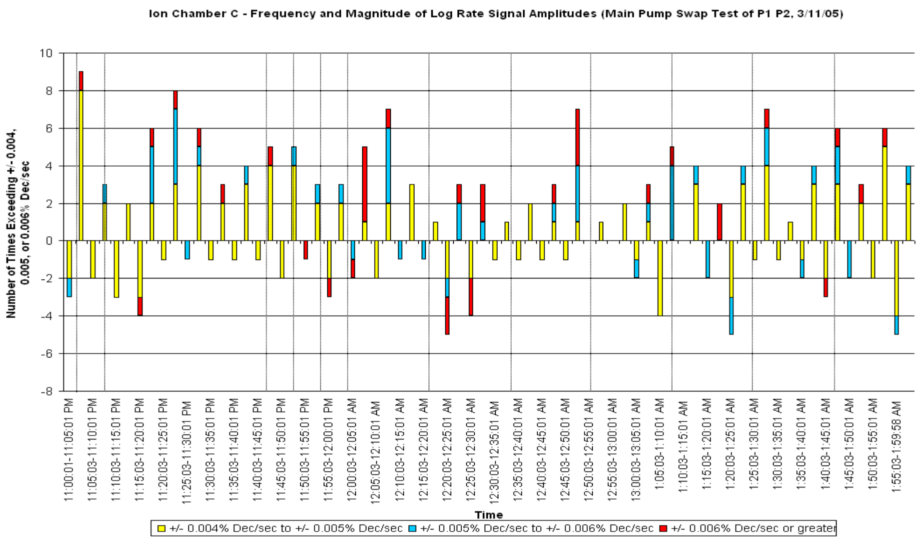

Figure 13 Ion Chamber C - Frequency and Magnitude of Log N Rate Signal Amplitudes (Main Pump Swap Test of P1 and P2)

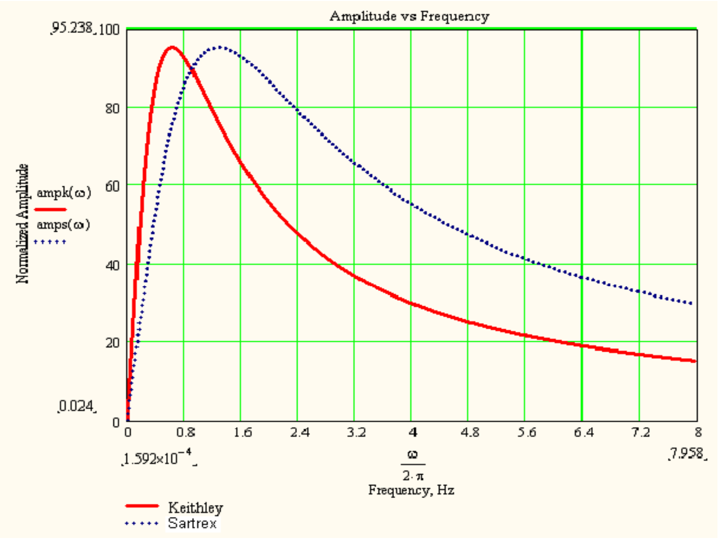

Figure 14 Amplitude vs. Frequency for Keithley and Sartrex Ion Chambers Amplifiers

7. Conclusion

The Bruce A reactor Units 3 and 4 moderator inlet nozzles geometry is unique because of the original design requirements for booster rods cooling, as compared to Bruce B and other CANDU® reactors. The unique moderator circulation system through the unique nozzle design produces turbulent temperature gradients in the reflector and upper part of the reactor core. These temperature gradients cause small but detectable variations in the local neutron population in the reflector and at the top of the reactor core.

Therefore, the root cause of the Log Rate signal fluctuations, observed in the Bruce A reactor Units 3 and 4, is the turbulent moderator temperature gradients generated by the moderator circulation patterns in the reactor. The thermal gradients are generated by the moderator circulation system where cold moderator enters the reactor calandria through the booster inlet nozzles and the booster bypass inlet nozzles, as well as the buoyancy effects in the reflector and moderator at the upper part of the calandria.

The ion chamber signals show the impact of the turbulent thermal gradients and of the wider bandwidth of the new ion chamber amplifiers. Plant observation and analyses of the PI data provide solid confirmation that the thermal gradient phenomenon is the root cause of the ion chambers Log Rate fluctuations.

8. References

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9. Acknowledgments

The work presented in this paper was made possible through the efforts of Bruce Power staff Jorgen Hertzum Larsen and Bernie Alvarez. A major part of the initial analyses were carried out with the help of AECL summer student Ashley Pope.

The authors also want to thank Gord Spielman for the many valuable comments and discussions throughout the progress of this work.