RANGE EXTENSION FROM -7.0 to -7.2 DECADES FOR FLUX MONITORING USING REACTOR REGULATING SYSTEM (RRS) ION CHAMBERS AT BRUCE POWER

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Abstract

In CANDU reactors, neutron flux must be monitored at all power levels. Operation of the permanent ion chamber systems at low power is limited by background gamma radiation which causes a small current to flow in the ion chamber. This residual current becomes a significant portion of the total current during outages.

The low end of the ion chamber range was originally -7.0 decades (10^{-7} full power) when the current due to neutrons was estimated to equal the residual current. Start-up instrumentation was required at this point.

A range extension to -7.2 decades has been supported for Bruce Power RRS ion chambers by showing from outage and approach to critical data and theoretical calculations that the neutron component of the current and residual current become equal at about -7.4 decades such that SUI installation may now be avoided for many outages with significant reduction in dose to maintenance staff.

1.0 Introduction

Operating Policies and Principles requires that neutron flux be monitored at all power levels. Under shutdown conditions, current procedures at Bruce Power require the installation of start-up instrumentation (SUI) when the lowest RRS ion chamber signal indicates power is -7.0 decades (and decreasing).

The objective of this paper is to summarize a study to assess the feasibility of using the RRS ion chamber signals for flux monitoring below -7.0 decades. The study was based on operating data from outages and subsequent Approach to Criticals (ATCs), and included data from boral shutter movements when at very low power.

The benefit of extending the range of the RRS ion chambers is that SUI installation would not be needed for many outages reducing overall outage times and the associated work and dose uptake required to install and remove SUI.

2.0 Background Information

At the low end of the flux range, the operation of the ion chamber is limited by the gamma radiation caused by activated nuclei in the ion chamber and in the surrounding structure. This causes a small residual current to flow from the ion chamber which becomes a significant portion of the total current after the reactor is shutdown.

Original design calculations estimated that when the power had decayed to -7 decades, 50 percent of the ion chamber current was due to neutrons. At this point, the ion chamber was deemed to be no longer sufficiently neutron-sensitive and responsive to fission power. The low end of the flux range for the ion chambers was set at -7 decades and installation of SUI detectors would be required at less than -7 decades to continue flux monitoring and for the restart after the outage.

Fig. 1 shows the location of the vertical and horizontal ion chamber housings and the position of one of the three RRS ion chambers in the vertical housing. Each vertical housing contains one RRS ion chamber, one SDS1 ion chamber and a boral shutter for testing. The ion chambers are surrounded by high purity lead to attenuate gamma-radiation from the reactor.

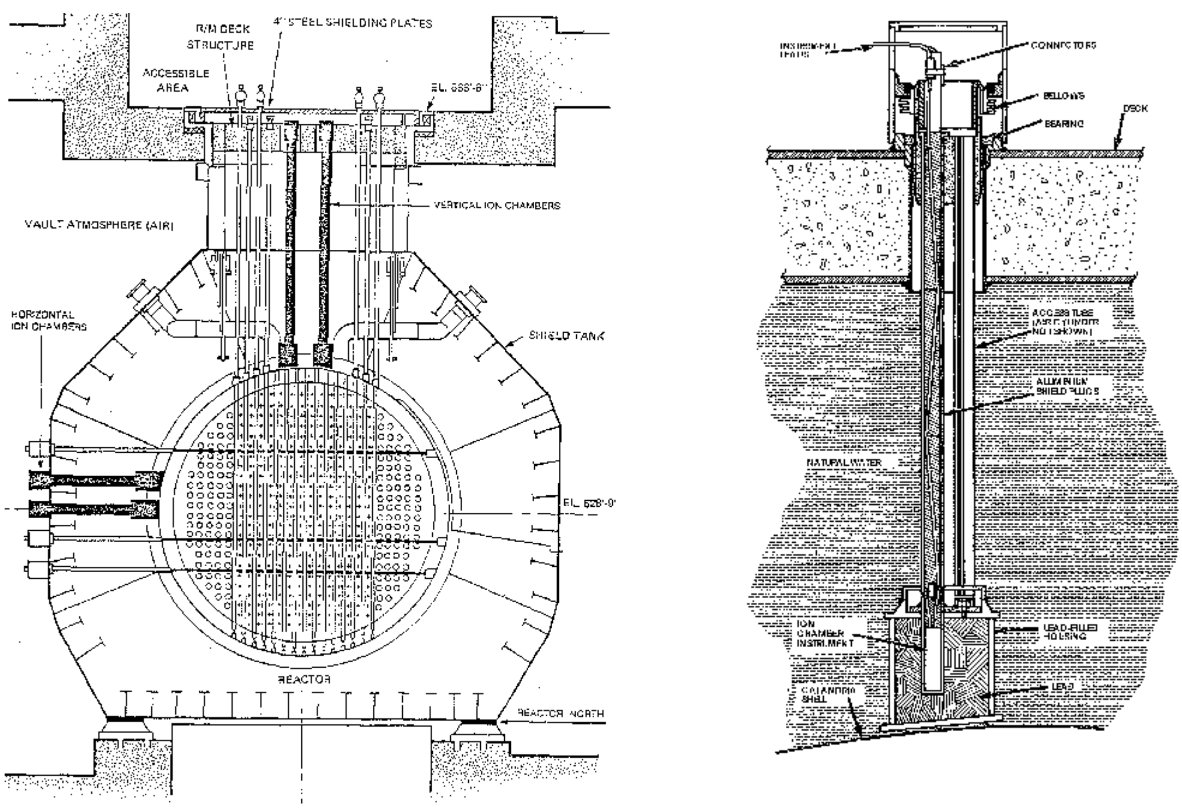

Figure 1 Ion Chamber Locations

When needed, SUI detectors are installed in the horizontal ion chamber housings. For most outages at Bruce Power, BF_3 detectors are used but for very long outages, higher sensitivity ^{3}He detectors are sometimes used.

The feasibility study was composed of two sets of data analyses:

a) Analysis of approach to critical data for both Bruce A and Bruce B;
b) Analysis of shutter test data during the Bruce B vacuum building outage in 2015

During an ATC evolution, the flux at the ion chamber and SUI sites changes for three reasons:

- Increase in core reactivity from gadolinium removal.
- Change in ion chamber shading due to the reduction of gadolinium.
- Shifts in the neutron spectrum as the gadolinium is removed.

During each outage, after the overpoisoned guaranteed shutdown state (OPGSS) has been established, the moderator gadolinium concentration is constant and the ion chamber signals decrease as the local gamma precursors and photo-neutron precursors decay.

3.0 Models for Data Analysis

Two models developed to assess the ATC and shutter movement data are summarized in this section.

3.1 Model for ATC Data

During an ATC after an extended outage with SUI installed, the initial flux at the ion chamber and SUI sites is less than -7 decades of full power. It is gradually increased during the ATC evolution by gadolinium removal and the ion chamber current at time t is determined by the following equation:

$$I_t^{RRS} = I_t^N + I^R \qquad (1)$$

where

I_t^{RRS} is the total ion chamber current,

I_t^N is the component of the ion chamber current due to neutrons, and

I^R is the residual current in the ion chamber over the ATC period due to the activation products in the ion chambers and nearby structures.

The activation products which cause the residual current are the longer-lived isotopes created in the ion chamber and surrounding structures during high power operation before shutdown, but which are still present at the time of the ATC. They are assumed to be constant over the ATC period of approximately 20 hours. The contribution from gamma radiation from the reactor to the residual current when shutdown is negligible as it is screened out by the lead which surrounds the ion chambers.

The ratio, κ, of the ion chamber neutron reaction based current to the total ion chamber current at any time t is defined as:

$$\kappa_t = \frac{I_t^N}{I_t^{RRS}} \qquad (2)$$

It can be shown that the functional relationship between κ and the ion chamber amplifier log output (signal in decades), V and the residual current can be described as follows:

$$\kappa \quad = 1 - \frac{\tilde{I}^{R}}{10^{V}} \tag{3}$$

The tilde indicates that the residual current is a normalized value in decades consistent with the log amplifier output. Based on the ion chamber considerations outlined in design, with κ set to 0.5 with the ion chamber output at -7.0 decades, the residual current would be -7.3 decades (i.e. 0.5×10^{-7} FP).

The solution to Eq. (3) is plotted in Fig. 2 for values of the residual current of 0.5×10^{-7} FP (Design) and 0.2×10^{-7} FP. As shown, the flux at the ion chamber site and the amplifier output voltage increase as the ATC proceeds. κ approaches 1 asymptotically as the neutron component of the ion chamber current increases and the residual current becomes more and more negligible. At the lower end of the x-axis when κ is equal to zero, the total current is attributed to the residual current.

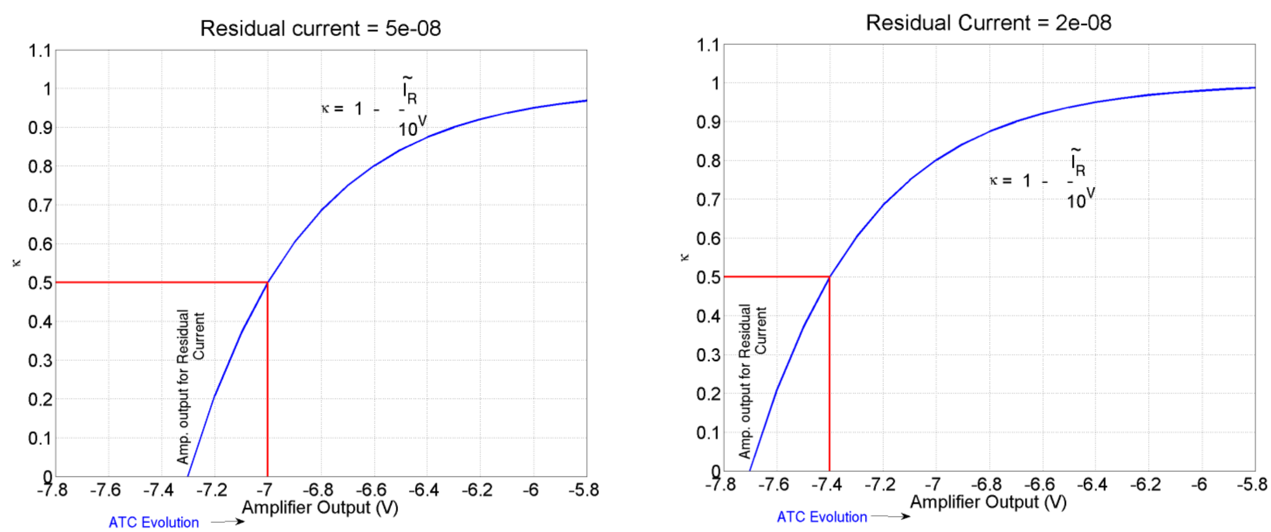

Figure 2 Theoretical Curves for κ vs. Amplifier Output

Assumptions for ATC Analysis

The main assumptions for the extraction of κ from the ATC data are:

i. The change in neutron flux at the RRS ion chamber sites in the vertical housings is the same as the change in flux at the SUI sites in the horizontal housings. We take the SUI signal as a surrogate for the neutronic component of the ion chamber signal. Substituting the SUI signal into Eq. (2), we have:

$$\kappa_t = \frac{\tilde{I}_t^{SUI}}{\tilde{I}_t^{RRS}} \tag{4}$$

The SUI count rates are normalized to the linearized ion chamber log outputs when the reactor power is greater than -6.8 decades during the ATC. The normalized SUI count rates and ion chamber reading track as power is raised confirming that κ can be taken as being close to 1.

ii. The change in SUI readings are always directly proportional to change in thermal neutron flux at the SUI detector sites.

iii. The residual current is assumed to be constant over the ATC period. This is deemed to be an appropriate assumption given the number of days after shutdown at which the ATC (greater than 25 when SUI has been installed) as well as the fact that the evolution only spans 20-25 hours.

3.2 Model for Shutter Movement Data

Within the ion chamber housing, the boral shutter is located adjacent to the ion chambers (RRS and SDS1). The shutter is fully inserted during normal operation and is used to test the rate log trip function. Under shutdown conditions the shutter is sometimes withdrawn, depending on the anticipated length of the outage. The neutron flux in the vicinity of the ion chambers increases as a result allowing the ion chambers to sustain a higher amplifier log output and hence delaying the SUI installation time.

Shutter tests for neutron flux monitoring were initiated during the Bruce B station outage in 2015. The tests involved moving the shutter from the withdrawn position to the inserted position and observing the decrease in the amplifier log output after waiting a sufficient time for the amplifier output to reach steady state. At relatively high power early in the outage (between -6 and -7 decades), the change in ion chamber current is directly proportional to the change in the flux at the ion chamber sites as the residual current is small compared to the neutronic component of the ion chamber signal. Later in the outage, the residual current becomes a larger fraction of the ion chamber current because the photo-neutron precursors in the fuel decay at a faster rate than the longer lived gamma precursors at the ion chamber sites. The response of the ion chamber to the movement of the shutter will therefore gradually decrease as the outage progresses until there would be no response when the ion chamber current is essentially all from the local gamma flux.

κ defined in Eq. (2), can be determined from the response of the ion chamber when the shutter is moved from the withdrawn position to the inserted position using the following relationship:

$$\kappa = \frac{\text{observed fractional decrease during test}}{\text{reference observed fractional decrease}} \quad (5)$$

The reference fractional decrease is the amplifier log output decrease obtained early in the outage when κ can be considered as close to 1 and the shutters are in the extracted positions.

For the purposes of checking ion chamber functionality during an extended outage, the withdrawn position of the shutter is taken as normal (or the initial position) and the test is based on how much the signal *decreases* when the shutter is inserted for about 30 seconds. The size of the decrease depends upon the relative portions of the total ion chamber current from the local neutron and gamma fluxes.

3.3 Monte Carlo Simulations

While not a part of the feasibility study, Monte Carlo simulations were performed to better understand the phenomena which influence the neutronic component of the ion chamber signal.

Assumptions for these simulations include:

i. The power history for all bundles, and consequently, the input photo-neutron source, was derived assuming photo-neutron precursors were at equilibrium prior to the outage.

ii. There are no other significant neutron or gamma sources within the model. Sources from irradiation of the calandria shell or other core or device structures are ignored.

4.0 Results

4.1 Approach to Critical Data

Table 1 shows the amplifier output signal for the median RRS ion chamber signal at which the estimate of κ was 0.5 for 10 ATCs performed on Bruce Power Units. It was observed that output signals were in the range -7.37 decades to -7.8 decades, and all estimates were substantially less than the original design estimate of -7.0 decades.

Table 1 Results for Approach to Critical Data

Unit	Outage Duration (Days)	ATC Date	Median RRS Ion Chamber Output for κ = 0.5
7	61	Jun-2011	-7.55
7	57	Apr-2014	-7.44
8	58	Jun-2009	-7.37
8	43	Feb-2012	-7.8
5	42	Oct-2004	-7.52
3	54	Apr-2010	-7.37
3	193	Aug-2012	-7.53
4	206	Feb-2013	-7.42
4	92	Apr-2014	-7.47
4	103	Jul-2015	-7.37

Fig. 3 illustrates how κ was extracted from each ATC data set. The figure shows SUI and RRS ion chamber trends in decades plotted against time for the Bruce B Unit 7 ATC on 7-Apr-2014 following an outage of 57 days. The ion chamber readings are available from the Plant Information (PI) system. The SUI trends are obtained from the count rates during the ATC which were then normalized to the linearized ion chamber readings towards the end of the outage when the residual current can be taken as negligible compared to the total current (i.e. κ is close to 1). The normalization point circled on the ATC trends is at an amplifier voltage of -6.4 decades when the ion chamber trends are observed to track the SUI trends.

The graph on the right of the figure shows κ calculated using Eq. (4) plotted against the amplifier output voltage. κ had increased to 0.5 when the amplifier output was -7.42 decades.

The trends in the graph at the bottom left of the figure show the moderator purification flow and measured gadolinium concentrations for this ATC.

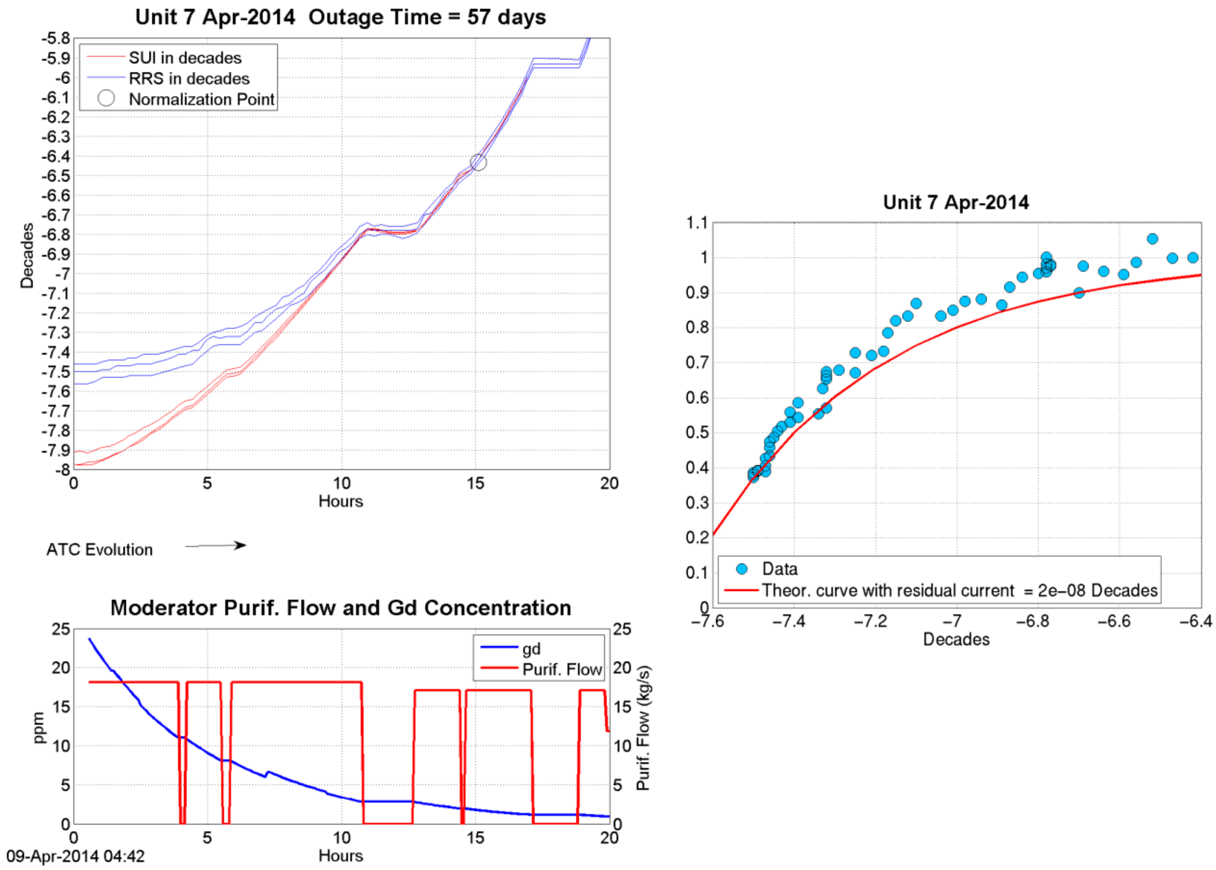

Figure 3 Sample Results – ATC Data for Unit 7 Apr-2014

While the data displayed in Fig. 3 is for the ATC of a reactor which has been operating at high power such that activation products are present in the ion chambers and surrounding structures and give rise to a significant residual current when shutdown, it is of interest to show data from a first start-up when no residual current is expected.

Figure 4 compares the reactor power measured by in-core SUI fission chambers to the RRS ion chamber readings over the range -7.9 decades to -5.9 decades for the First ATC for Unit 2 following refurbishment and a shutdown period of approximately 16 years.

The ion chamber readings track the fission chamber reading throughout this range confirming there was negligible residual current present. It is evident that any activation products in the ion chambers and surrounding structures which would have existed at shutdown in 1996 had long since decayed away. The ion chambers were neutron-sensitive and responsive to fission power even at -7.9 decades at this time.

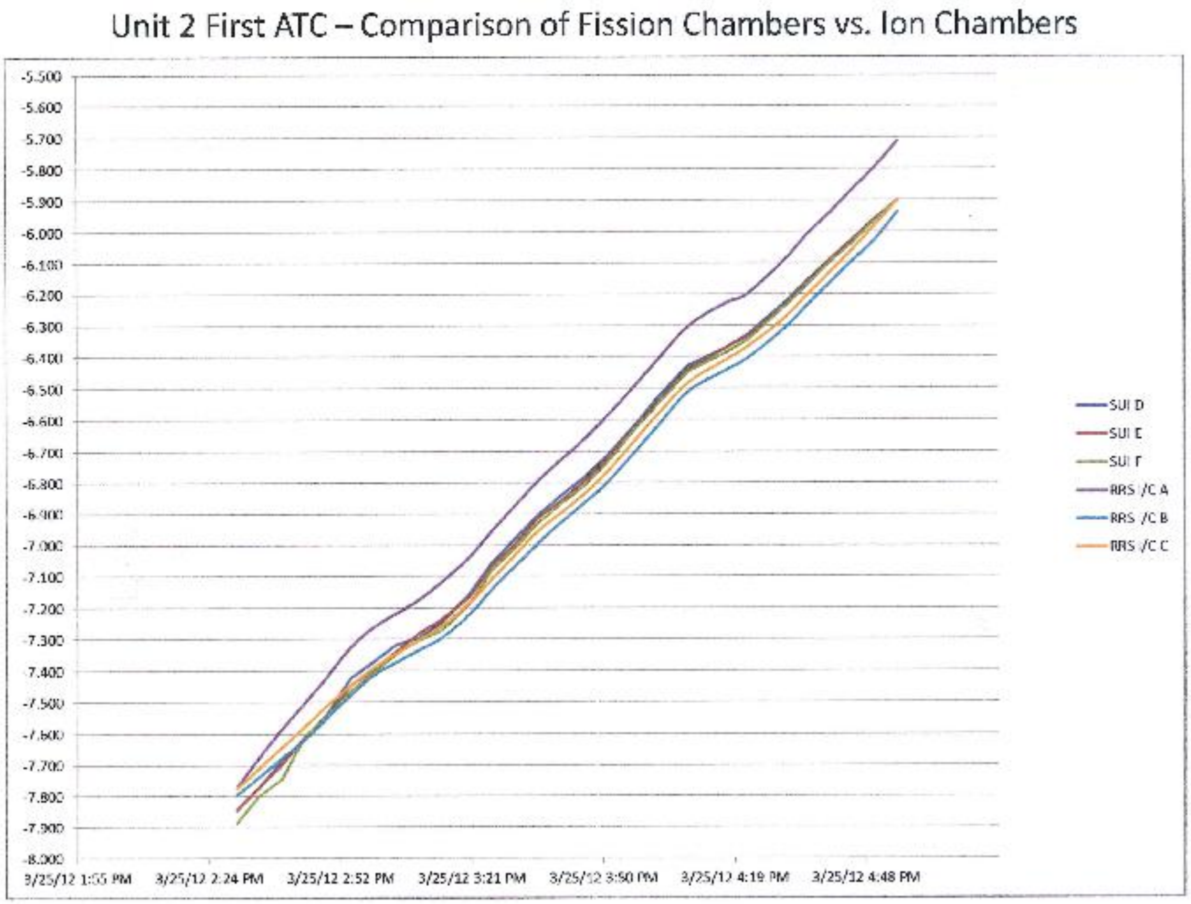

Figure 4 First ATC Data – Unit 2 March 2012

4.2 Shutter Tests

For the purposes of evaluation ion chamber neutron sensitivity during an extended outage, the withdrawn position of the shutter is taken as normal (or the initial position) and the check is based on how much the signal decreases when the shutter is inserted for several minutes. The size of the decrease depends upon the relative portions of the total ion chamber current from the local neutron and gamma fluxes.

Equation (5) is used to estimate κ from tests performed on Bruce B units which were shutdown for a vacuum building outage in the spring of 2015.

Data from Unit 8 RRS Ion Chamber “C' is presented in Figure 5. The Unit had been shutdown on 15-Apr-2015 and 8 days into the outage, the shutter in the housing containing Ion Chamber “C' was withdrawn. As shown in the top left graph of Fig. 5, the signal increased by 0.155 decades. The value of κ at this time is taken as 1.0 and the value of 0.155 decades was taken as reference for subsequent tests.

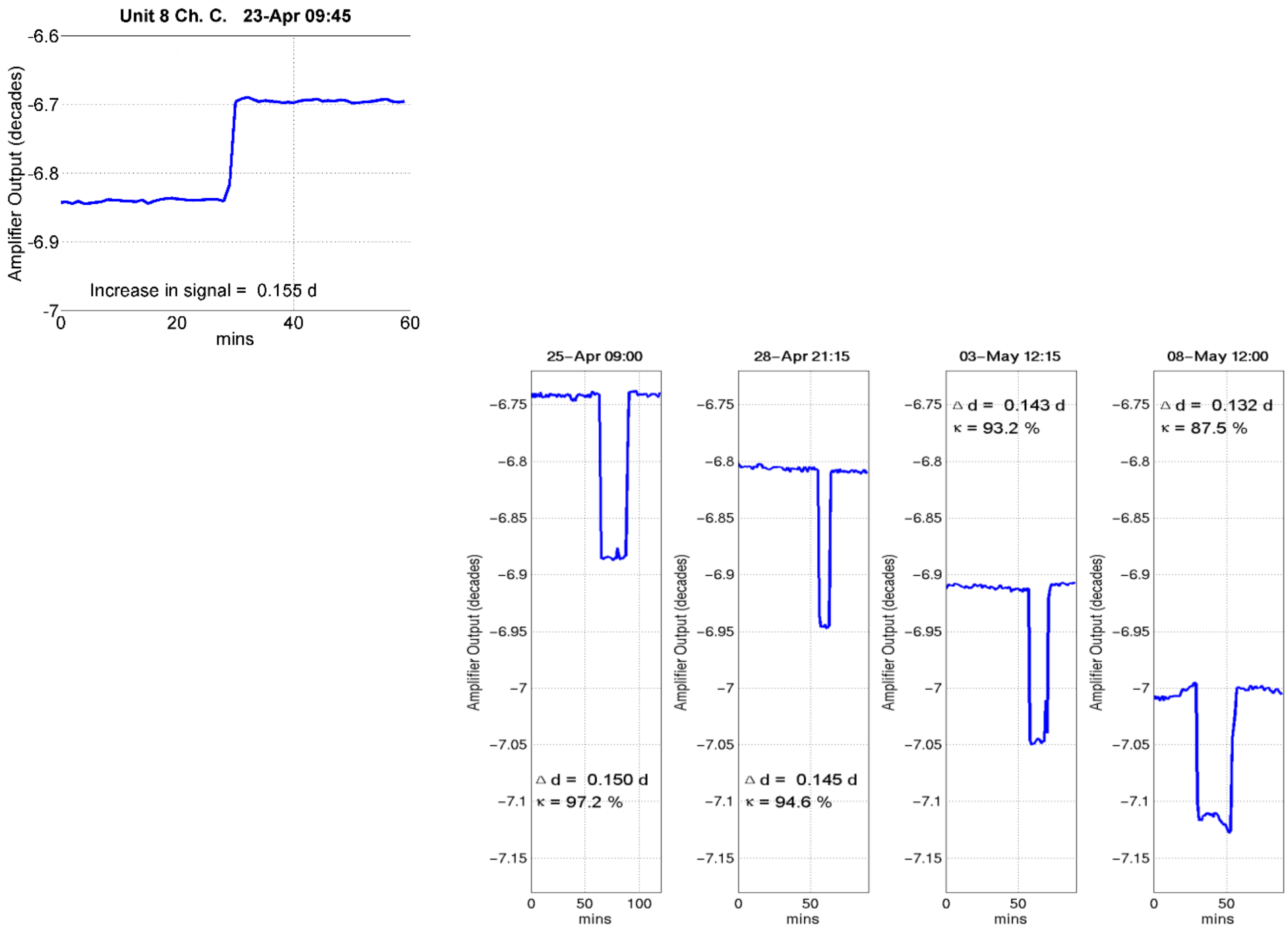

Figure 5 Sample Shutter Tests in 2015 – Bruce B Unit 8 Ion Chamber "C"

The subsequent tests were performed on 4 separate occasions for this ion chamber with the final test taking place on 08-May-2015. At this time inserting the shutter decreased the signal by 0.132 decades and the value κ calculated using Eq. (5) was 87.5%, which is well above the value of 50% when the neutronic component of the current has decreased such that it is equal to the residual current. Unit 8 was restarted on 09-May-2015.

4.3 Monte Carlo Simulations

During the outage on Unit 4 in 2015, the moderator containing 23 ppm of gadolinium was drained 40 days after the start of the outage. SUI count rates were observed to increase by 2.1 decades (i.e. factor of 125.9). A simulation of the moderator drain using MCNP was performed which predicted an increase in neutron flux at the ion chamber sites of 2.05 decades, closely agreeing with the observed increase. From the simulation output it was ascertained that the coolant within the channels represented a significant D_2O volume wherein photo-neutrons are produced (from hard gammas emitted by decay of precursors in the fuel). Without the presence of moderator for thermalization and capture (within the gadolinium), the photo-neutrons at the core periphery could pass unabated to the ion chamber. This phenomenon drove the increase in neutronic signal observed during the moderator drain.

For a sample ATC evolution, MCNP simulations were performed with varying concentrations of gadolinium within the moderator. These simulations were carried out to identify the period over which the relationship between in-core and ex-core fluxes returned to near linear; this period was found to be when the core gadolinium load transitioned between 4 and 1 ppm. These results indicate that core neutron multiplication does not increase substantially until about 1 ppm of gadolinium less than the critical poison concentration. The shading effect from the presence of gadolinium in the reflector does however, begin to decrease earlier.

5.0 Conclusions

Analysis of ATC data and the results of shutter tests performed with reactor in OPGSS have shown that the Bruce A and B RRS ion chambers are more sensitive to changes in flux at the low end of the operating range than was originally thought. Residual currents in these ion chambers from long-lived activation products in the ion chambers and nearby structures created during operation at high power are smaller than had been predicted in the design. A decrease in the lower operating range from -7.0 to -7.2 decades is justified. This conclusion is specific to the 1 inch RRS ion chambers installed in Bruce Power reactors.

The decision on when SUI should be installed during an outage can be based on the estimated value of κ from shutter tests rather than on a specific amplifier output. The shutter tests become a part of flux monitoring during outages and confirm the responsiveness of the ion chambers to changes in flux as the photo-neutron source decays.

Use of MCNP simulations have strengthened our understanding of the phenomena which characterize the ion chamber signal under shutdown and restart conditions.