USE OF FISSION CHAMBERS FOR MONITORING NEUTRON FLUX FOR THE FIRST START-UPS OF THE REFURBISHED BRUCE A REACTORS

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Abstract

As BF_3 and ^3He counters are inoperable in the high gamma fields inside the calandria of a refurbished reactor, a design using in-core fission chambers to monitor neutron flux over the range 10^{-14} to 10^{-6} full power was adopted for the first start-ups of the refurbished Bruce A Units 1&2 in 2012.

Three 1 inch diameter fission chambers were installed in a temporary tube in the view port to monitor neutron flux during manual fuel loading and the first approach to critical of each unit.

Although there were issues related to low fission chamber sensitivity and noise pickup during fuel loading, the system performance satisfied neutron monitoring requirements for fuel loading and responded in accordance with theoretical predictions during the first approach to critical of both units.

1.0 Introduction

In their 2007 paper [1], Mohindra, Vartolumei and McDonald had recognized that fission chambers were required for the start-up of refurbished reactors because of the high gamma radiation fields inside the calandria.

A detailed fission chamber based design for start-up instrumentation (SUI) was prepared for the first start-ups of Bruce A Units 1&2 following refurbishment. The design involved three 1 inch diameter fission chambers installed in a temporary tube in the inspection port to monitor neutron flux during manual fuel loading and the first approach to critical of each unit.

In-core fission chambers had previously been used to monitor neutron flux for the first start-ups of the Nuclear Power Demonstration (NPD) reactor, Douglas Point and the first two Pickering A reactors. More sensitive and cheaper BF_3 and ^3He proportional counters were then used for the first start-ups of the Bruce A, Bruce B and Darlington reactors.

This paper summarizes the experience with the use of fission chambers for Bruce 1&2 start-ups in 2012.

2.0 Design

The design involved Amec Foster Wheeler and Bruce Power staff from instrumentation and control and mechanical engineering groups, reactor physics, and human factors analysis. In addition, the design incorporated input from Bruce A licensed staff during work-shops on fuel loading and the 1st Approach to Critical (ATC).

Fig. 1 shows the fission chamber chosen for the system. The neutron sensitive material is 75 mg of ^{235}U deposited as a thin layer on the inner surface of each fission chamber. The fill gas is Argon/Nitrogen and each fission chamber is encased in a film of kapton for electrical isolation from the reactor.

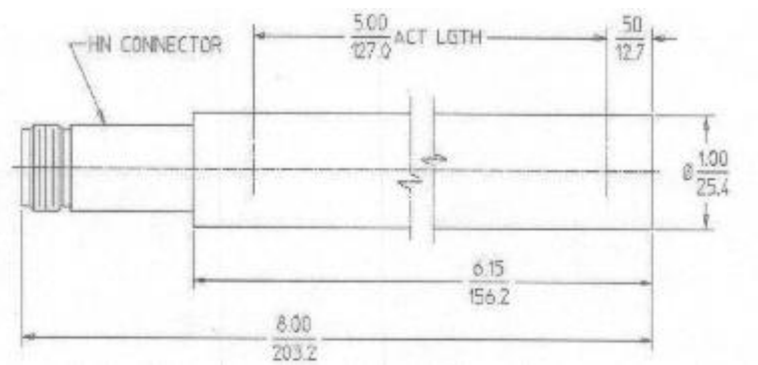

Figure 1 Fission Chamber LND Model 30773

Fig. 2 shows the location of the fission chambers in the reactor for fuel loading and the start of 1st Approach to Critical (ATC). The fission chambers were housed in separate tubes in an aluminum start-up unit (SUU) installed in the viewport port and extending to fuel channel row “E".

A design requirement for the SUU was to accommodate a shut-off rod drive shaft which traversed the view port and is shown as a horizontal tube in the diagram.

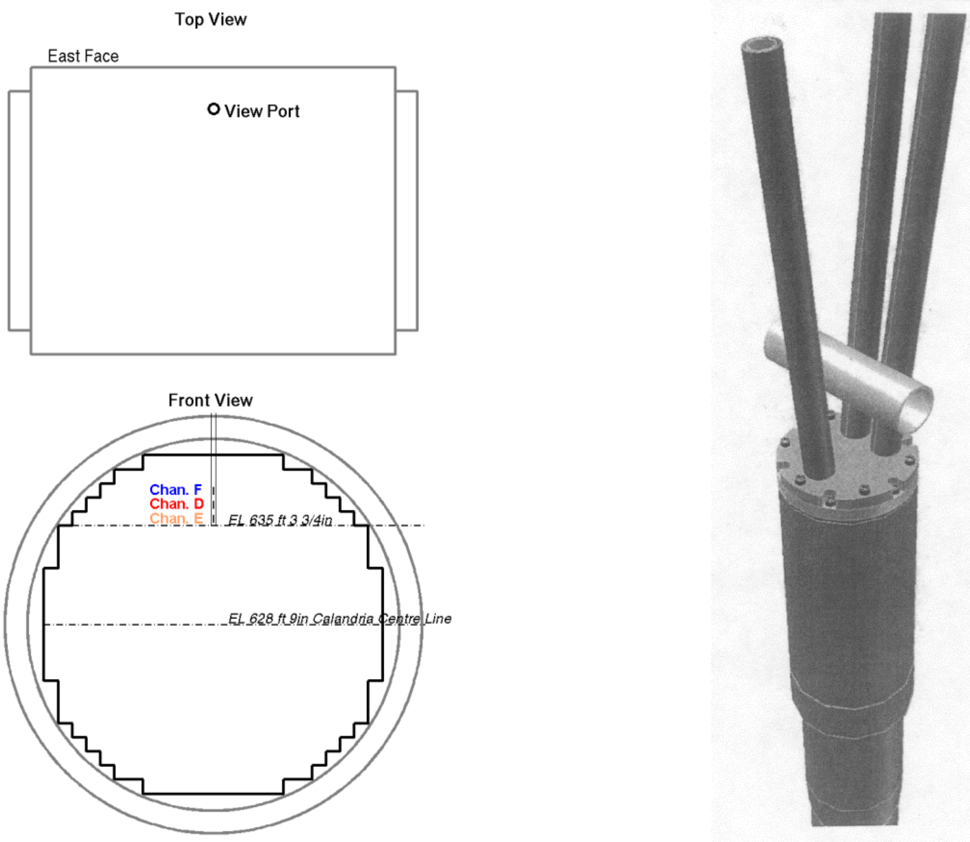

Figure 2 Fission Chamber Locations and Upper Portion of Start-Up Unit

Fig. 3a shows the instrumentation for Channel "E" located on the reactivity mechanisms deck consisting of a pre-amp, main amp and high voltage power supply.

Figure 3a Channel "E" SUI Instrumentation on Reactivity Mechanisms Deck

Fig. 3b shows the instrumentation for Channel "E" located in a movable cabinet in the main control room. The instrumentation from left to right consists of a single channel analyzer (SCA), ratemeter, counter timer, interface module and alarm unit.

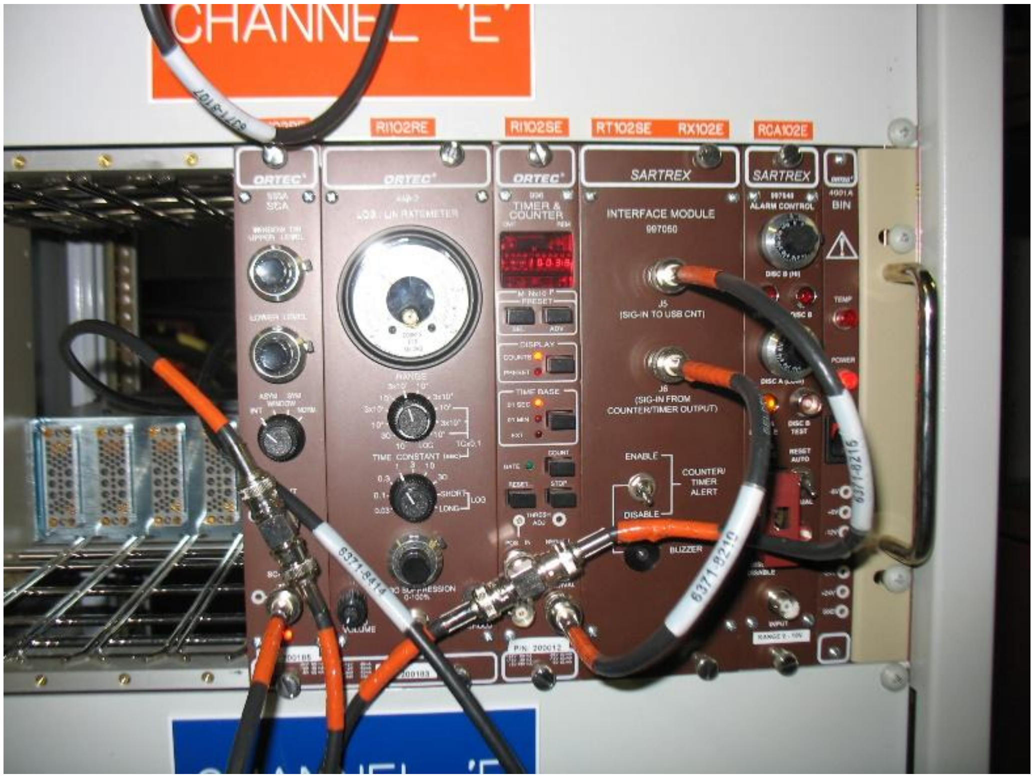

Figure 3b Channel “E” SUI Instrumentation in the Main Control Room

Each fission chamber was operated in the ionization range with a bias voltage of 500 volts. Pulses caused by fission events within each chamber were processed by a pre-amplifier and amplifier located on the reactivity mechanisms deck, and the SCA located in the main control room. The SCA discriminates against non-fission events and noise. In particular, the SCA screens out 4 MeV α-particles from the decay of ^{235}U within the fission chamber. Standardized pulses from the SCA are passed in parallel to a counter/timer and ratemeter also located in the main control room. The ratemeter provides an analog signal to an alarm unit with trip contacts wired into the SDS1 trip logic.

The control room instrumentation included an interface module with electrical isolators which allowed an oscilloscope, chart recorder, and multichannel analyzer (MCA) to be connected to the SUI loops without requiring the trip channels to be failed safe. The chart recorders, oscilloscope, and PC were located in a small, custom built cabinet behind the Authorized Nuclear Operator’s (ANO) desk as shown in Fig. 4.

Figure 4 Scope and Chart Recorder Located Behind the ANO's Desk

Count rate profiles during fuel loading were predicted by simulation of the fuel loading sequence and normalized to the expected count rates for the fully loaded core. The normalization was based in part on experience from Bruce B Unit 6 fuel loading in 1983. After manual fuel loading with 22 ppm of gadolinium in the moderator, the count rates from two BF_3 counters installed in the viewport were 40.5 and 45 counts / minute. Taking the sensitivity of the 1983 BF_3 detector for Unit 6 at 0.3 cps/nv and the sensitivity of the fission chambers selected for Bruce 1&2 as 0.14 counts /nv, the expected count rate for the fully loaded Bruce 1 &2 reactors was (0.14/0.3 x 43) = 20 counts / min.

Acceptance tests for the fission chambers and instrumentation performed by SARTREX Power Control Systems Inc. included sensitivity measurements. For the six installed fission chambers (3 on each unit), the sensitivities were in the range 75% to 121% of the mean fission chamber sensitivity.

3.0 SUI Commissioning and Field Checks Using a Neutron Source

Commissioning of the start-up instrumentation included cable checks and tests and calibration of the instrumentation and fission chambers in the control maintenance shop prior to installation in the field.

Final checks using an Am-Be source on the reactivity mechanisms (RM) deck with the fission chambers removed from the core were made to finalize the instrumentation settings prior to fuel loading. Pulses from the fission chambers on the RM deck were monitored using the oscilloscope and the counter/timers in the main control room.

These final tests were intended to confirm functionality of the system in the operating environment and to assess the reactor for neutron sources prior to loading fuel. While count rates from in-core locations were too low to obtain meaningful spectra from the MCA, observation of the pulses using the oscilloscope satisfied the objectives of these final checks.

The objectives of the final checks were:

i. Perform fission chamber pull-back checks to ensure that there would be no problems with repositioning the fission chambers during the 1st ATC.

ii. Establish the optimum settings for the amplifier shaping time constants for the operating environment. This involved a trade-off between minimizing the width of the output pulses while obtaining an acceptable signal-to-noise ratio.

iii. Establish the α-particle cut-off setting for the Low Level Discriminator on each channel.

iv. Perform a rough check on the detector relative sensitivities.

v. Scan the instrumentation tube with one of the fission chambers to determine whether there were significant neutron sources or photo-neutron precursors present from irradiated material in the core structures which had not been replaced as part of refurbishment.

These objectives were satisfied. Count rates during the scans of the instrumentation tube with no poison present in the moderator were approximately 1 count / min. Count rates just prior to fuel loading with the moderator overpoisoned were less than 0.5 counts / min. We concluded that there were no significant photo-neutron precursors present in the reactor and that the neutron source would be only from spontaneous fission of ^{238}U in the new fuel.

3.0 Fuel Loading

3.1 Fuel Loading Strategy

Fuel loading was performed from maintenance platforms at both ends of the reactor and monitored from the control room which included CCTV. Safeguards and fuel accounting measures were in place to accommodate manual fuel loading procedures. Each reactor was in the overpoisoned guaranteed shutdown state (OPGSS) with the moderator being circulated using an auxiliary pump and sampled regularly for gadolinium concentration and other chemistry parameters. Core reactivity was monitored using the fission chamber based SUI system with count rates from the three fission chambers recorded regularly by control room staff.

The fuel loading sequence shown in Fig. 5 was divided into 4 stages. In Stage A, the first 6 channels were fuelled adjacent to the fission chambers. A hold point was specified after Stage A to confirm the capability of the system to count neutrons from the fuel and to "calibrate" predicted count rates for the remainder of fuel loading against the Stage A measurements. In

Stage B, row C was completed then rows B and A were loaded. The critical core configuration in the absence of moderator poison had been predicted to occur during this stage after the 42nd channel was loaded. In Stage C, rows D, E, F and G were completed after which the pre-simulations had predicted that the fission chamber count rates would be close to their final values. In Stage D, channels were progressively loaded row by row starting with row H and finishing with row Y.

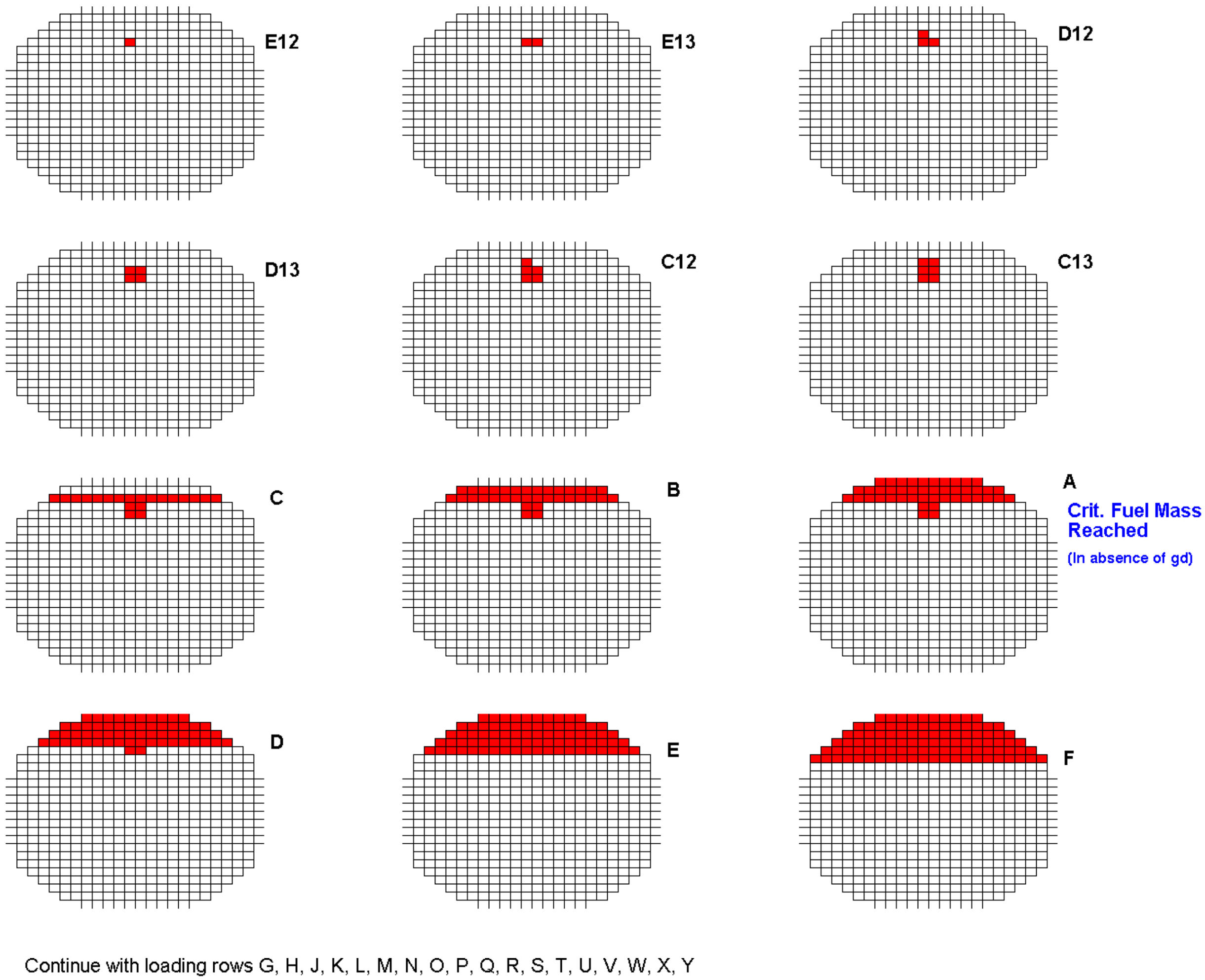

Figure 5 Fuel Loading Sequence

3.2 Unit 2 Fuel Loading

Unit 2 fuel loading commenced with Channel E12 on 28-Jun-2011. A single-channel oscilloscope was connected to each SUI channel in turn to monitor the output pulses from each amplifier. This was later replaced with a four channel scope to facilitate the monitoring. Also, three of the channels of a 4 pen chart recorder were connected to the output signals from the three ratemeters. This diagnostic equipment was connected using the electrical isolators in the interface modules so that the SUI trip logic did not have to be failed safe.

The oscilloscope was crucial to confirm that the system was counting neutrons. The chart recorder captured the noise bursts caused from external sources and was helpful for troubleshooting this interference.

Trip setpoints of 2 cps had been implemented on each channel and the ratemeter time constants were set to 30 seconds to reduce the probability of spurious trips. Routine trip testing of each SUI channel was performed by reducing the Low Level Discriminator (LLD) on the single channel analyzer such that some α-particle pulses would pass through to the ratemeter and counter. Channels D and F were tested on the night shift. Channel E was tested during the day shift. There was an apparent random failure of the channel D alarm unit on June 29 and it was substituted with the spare alarm unit.

An expectation established from the pre-simulations and previous experience was that a response from fission chamber E would be observed as soon as the first channel (E12) was fuelled. This expectation was not satisfied. Physics support staff recommended completion of Stage A fuelling based on the following rationale:

- Fuelling of 6 channels could not represent a critical mass.
- SUI detectors were measuring neutron interactions
- A purpose of Stage A was to "calibrate" predictions based on observations.

The engineering decision making process (EDM) was triggered by certified staff at the end of Stage A fuel loading. The EDM memo prepared by Fuel and Physics staff recommended proceeding with Stage B fuelling up to the completion of Row B. At that time, a hold point was imposed to verify the position of fission chamber "E". This recommendation was accepted by Bruce Power management and fuel loading was allowed to continue. Fission chamber "E" was subsequently found to be some 30 cm out of position.

Predicted and measured count rates during fuel loading of Unit 2 are shown in Fig. 6.

The measured count rates for fission chamber "D" for Unit 2 suffered from excessive noise during Stage A and B fuel loading. On June 29, in late afternoon, the detector cable and pre-amplifier were switched with a cable and pre-amplifier from Unit 1 and communication cables which had been left on the channel D instrumentation bin on the RM deck were removed. However these actions appeared to have had a negligible effect on the noise, although the problem was less evident after the start of Stage C fuelling.

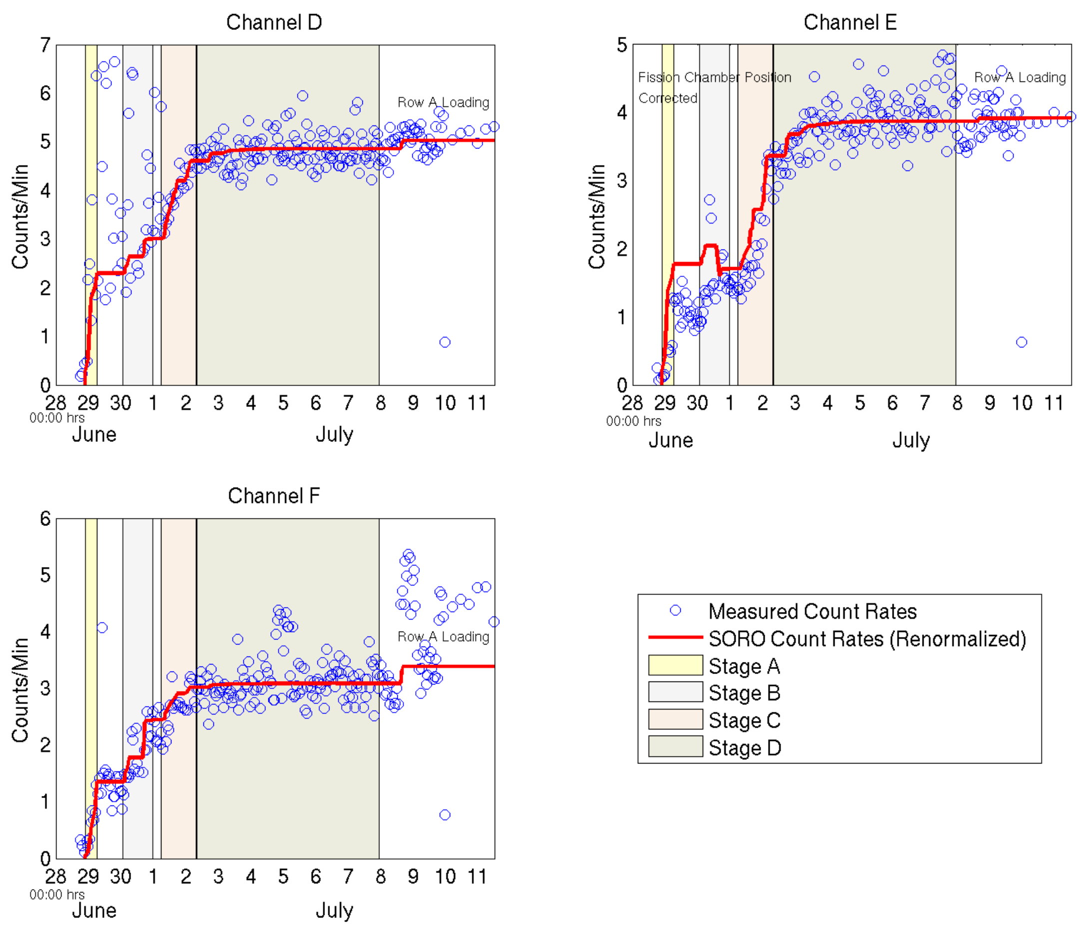

Figure 6 Unit 2 Count Rates During Manual Fuel Loading- Prediction vs. Measurement

3.3 Unit 1 Fuel Loading

The same general strategy that was used for Unit 2 was also applied to Unit 1 fuel loading which commenced 20-Nov-2011. Unit 1 benefited from the experience on Unit 2. For example, the time span from the end of Stage A fuelling (C13) and the start of Stage B fuelling (C05) was 19 hours for Unit 2 and less than 3 hours for Unit 1. The Fuel and Physics hold to confirm that SUI was counting neutrons and to "calibrate" the count rate predictions for the remainder of fuel loading was much shorter for Unit 1.

Predicted and measured count rates during fuel loading on Unit 1 are shown in Fig. 7.

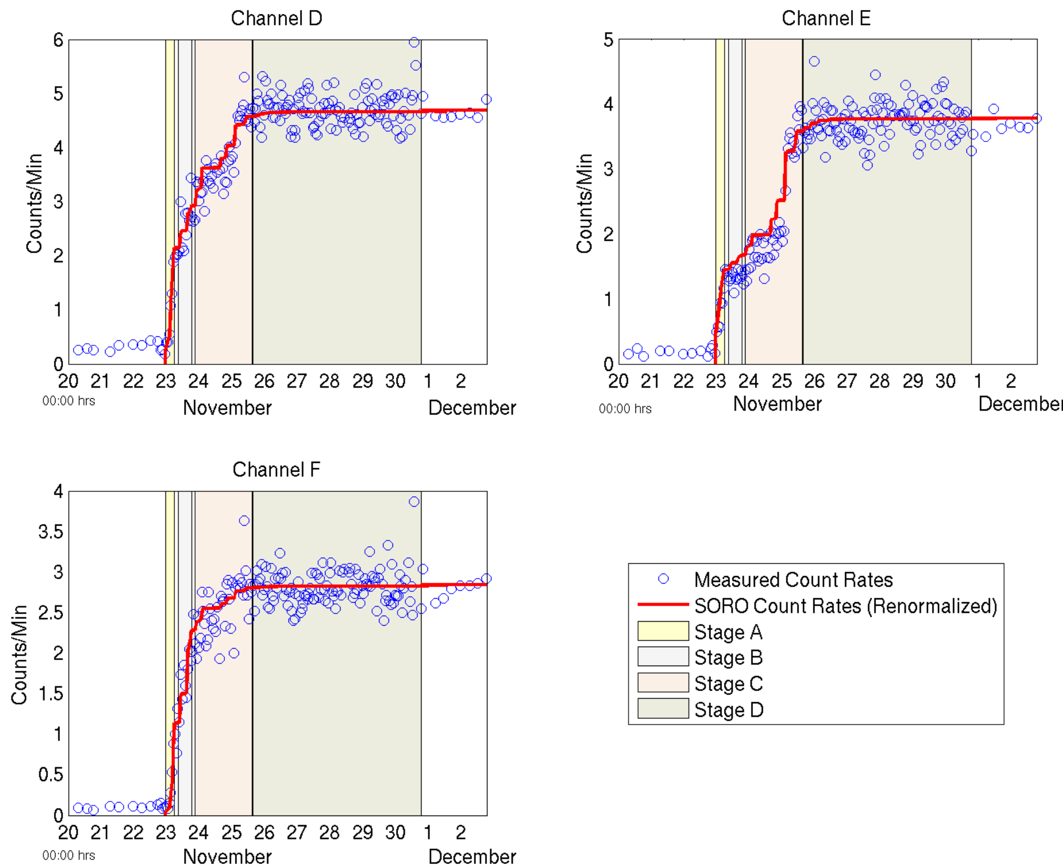

Figure 7 Unit 1 Count Rates During Manual Fuel Loading- Prediction vs. Measurement

4.1 Sensitivity Issue

A discrepancy between predicted and measured count rates for both units consisted of:

a) The average measured count rate of 4 cpm was a factor of 5 lower than the averaged predicted count rate of 20.4 cpm.

b) Count rates for the fully loaded reactors were expected to be about the same at the three fission chamber sites. However the highest measured count rate of 5.3 cpm (Unit 2, fission chamber "D") was nearly a factor of 2 greater than the lowest measured count rate of 2.8 cpm (Unit 1 fission chamber "F").

The theoretical sensitivity in cps/nv is equal to the product of the macroscopic thermal fission cross-section and the volume of the ^{235}U within the fission chamber. The sensitivity calculated after fuel loading and consistent with reactor conditions during fuel loading was 0.0897 cps/nv.

For the six installed fission chambers (3 on both units) the sensitivities were in the range 75% to 121% of the mean fission chamber sensitivity.

Conclusions were:

i. The discrepancy between measured and predicted count rates was attributed to a lower than expected sensitivity of the fission chambers, and lost fission events due to lower level discriminator settings which ensured that all α-particles from the decay of ^{235}U in the fission chambers would be excluded. The calculated sensitivity of 0.0897 cps/nv is considered to be an upper bound, but is less than the sensitivity of 0.14 cps/nv assumed in the original count rate predictions and given in the vendor's product information sheet.

ii. The cause of the variation in fission chamber readings at the three sites was consistent with the variation in fission chamber sensitivities observed in the acceptance tests.

iii. However, changes in count rates tracked core loading predictions on all three channels confirmed that the fission chamber based SUI would adequately track reactivity changes during the 1st ATC of both units.

4.2 Noise Issue

The presence of noise is evident in the count rate data plotted in Figs. 6 and 7. External disturbances which caused noise pick-up in the fission chamber loops included:

i. Welding involving large currents and release of substantial quantities of energy.

ii. Radio transmissions close to the SUI equipment on the RM Deck.

iii. Use of the drill attached to rod drive shafts to raise a rod in the absence of the regulating system. The proximity of the fission chamber cable and pre-amp to the drill is a factor.

iv. Rod clutches de-energizing, which releases considerable electro-magnetic energy which can cause interference pick-up in the fission cables.

v. Use of the crane over the reactivity mechanisms deck.

vi. Commissioning and start-up of heat transport pumps.

Following Unit 2 fuel loading, a team was convened at Bruce Power to investigate the sensitivity and noise issues.

Tests were performed in the control maintenance shop to measure the neutron sensitivity of the fission chamber. The fission chamber count rate was compared with the count rates of two BF_3 detectors of different manufacture that were placed in the same neutron source bucket. The tests indicated that the fission chamber sensitivity was lower by about a factor of 4 compared to the value that had been used to establish count rate expectations.

The idea of shielding the preamplifier input cable from radiated electromagnetic interference (EMI) noise was tested, but the test did not eliminate EMI pickup. SUI modifications included shortening the detector cables and improving the shielding by installing ferrites on the detector cables.

The fission chamber based SUI subsequently responded in accordance with theoretical predictions as gadolinium was removed from the moderator during the 1st ATCs for both Units. The response of the fission chambers during the 1st ATC for Unit 1 is shown in Fig. 8 and further details are given in Reference [2].

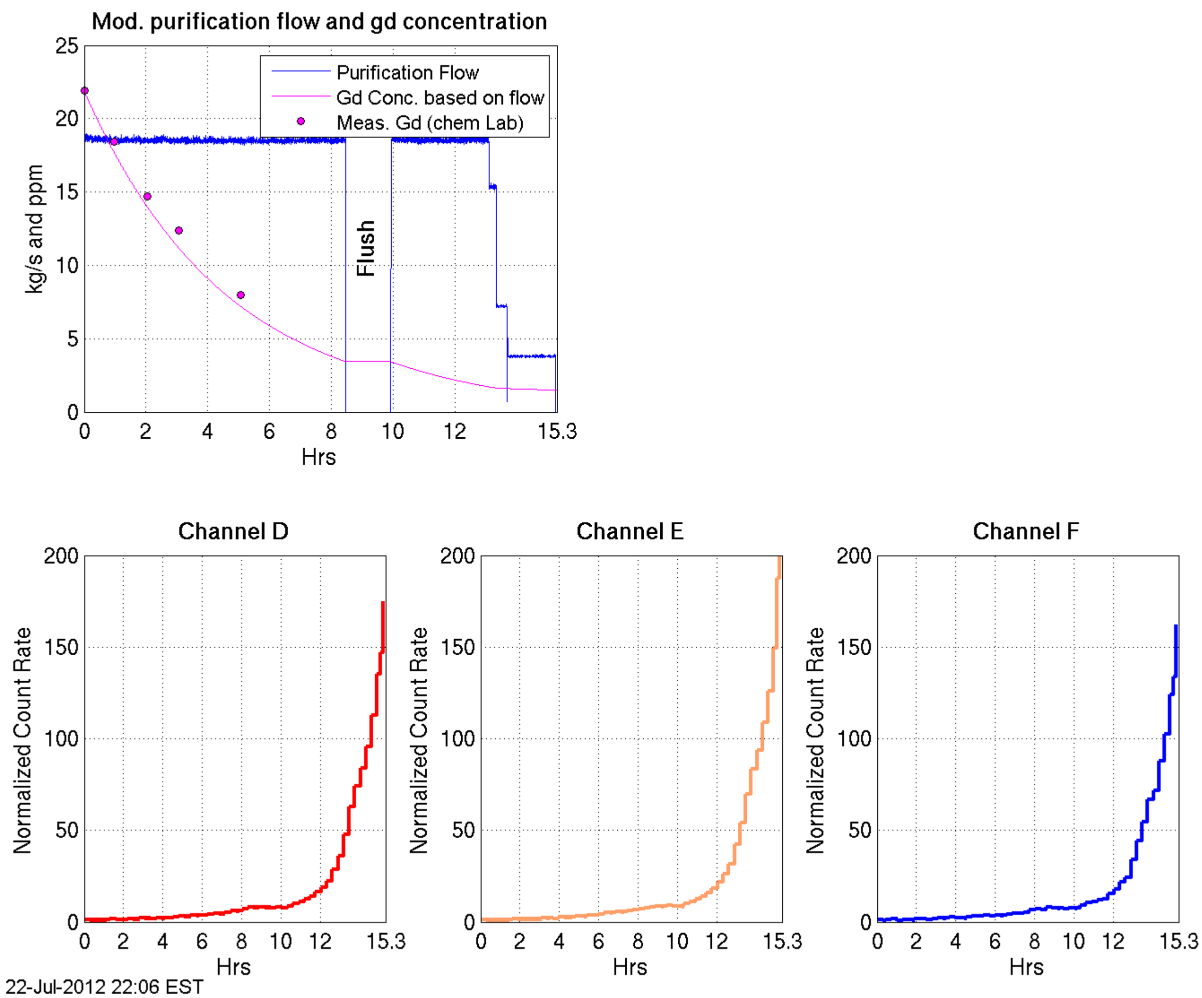

Figure 8 First ATC – Unit 1 Continuous Poison Removal Stage

Following low power testing, the fission chambers and start-up unit were removed. The build-up of photo-neutron sources during high power operation permits ATCs to be performed using ^{3}He and BF_3 counters installed in the spare SDS2 ion chamber slots in the vault.

5.0 Conclusions

The experience with the use of a fission chamber based SUI system for Bruce 1&2 has been summarized in this paper. Although there were issues related to low fission chamber sensitivity and noise pick-up in the SUI loops during fuel loading, the system performance satisfied neutron monitoring requirements for fuel loading and then responded in accordance with theoretical predictions as gadolinium was removed from the moderator during the 1st ATCs for both Units.

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Collaboration and information exchange between NB Power and Bruce Power for the restart of the Pt. Lepreau and Bruce 1&2 reactors was encouraged by the senior management of both utilities. Benchmarking sessions were hosted by Pt. Lepreau technical staff which included staff from Hydro Quebec and Amec Foster Wheeler as well as Bruce Power to discuss plans and calculations for commissioning of the start-up instrumentation, first approach to critical and physics testing and these sessions contributed to the successful restart of the Bruce 1&2 reactors. In particular, thanks are due to Dean Taylor and Rick Sancton of NB Power for sharing their expertise and experience in the physics and start-up instrumentation areas.

References

1. Virender (V.K.) Mohindra, Marius Andrei Vartolumei and Alex McDonald, "Fission Chambers for CANDU SDS neutronic trip application", presented at the 28th Annual Conference of Canadian Nuclear Society, Saint John, New Brunswick, Canada, 03-06 June, 2007.
2. C. Olive, D. Luth, P. Paquette, T. Stroud, "First Approach to Critical (ATC) for Bruce Units 1&2 Following Refurbishment", to be presented at the 36th Annual Conference of the Canadian Nuclear Society, Toronto Downtown Eaton Centre, ON, Canada, June 19-22, 2016.