FIRST APPROACH TO CRITICAL (ATC) FOR BRUCE UNITS 1&2 FOLLOWING REFURBISHMENT

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Abstract

Following refurbishment, Bruce Units 1 and 2 achieved first criticality in March (Unit 2) and July (Unit 1) 2012.

During fuel loading, three in-core fission chambers confirmed that the neutron source was from spontaneous fission of ^{238}U only. Therefore, first criticality would occur on manual control of power well before the permanent ion chambers became rational at $10^{-7.2}$ full power.

For Unit 2, after the moderator gadolinium had been reduced to slightly above the critical concentration, incremental control absorber withdrawals achieved administrative criticality at -0.2 mk. Decreases in fission chamber count rates were then observed and attributed to ingress of poisoned heavy water from the expansion tank into the calandria. The reactivity fell below administrative criticality.

Modifications to the procedures were approved by the duty manager to continue the ATC using intermittent poison removal rather than incremental control absorber withdrawals. These modified procedures were also used for the first ATC for Unit 1 four months later.

1.0 Introduction

After being shutdown in the late 1990's, Bruce Units 1 and 2 were refurbished and achieved first criticality in March (Unit 2) and July (Unit 1) 2012.

Prior to the first approach to critical (ATC), both units were manually loaded with natural uranium and depleted uranium fuel bundles with their moderators over-poisoned with 22 ppm of gadolinium. Three fission chambers installed in a temporary start-up instrumentation tube had confirmed that the neutron source was from spontaneous fission of uranium only with no photo-neutron sources present [1]. Therefore, criticality would occur on manual control of power at about -10.3 decades (zero decades is full power), well before -7.2 decades when the permanent ion chamber systems become rational.

For Unit 2, and starting at about -1 mk, reactivity was increased to -0.2 mk using control absorber withdrawals in 2 to 5% increments. This method of incremental cadmium rod withdrawal was first used to obtain a diverging chain reaction by Fermi and his team in 1942 [2], and was used for the first start-up of Bruce Unit 4 in 1978 and the Bruce B Units in the 1980's.

However, decreases in fission chamber count rates were then observed and attributed to ingress of poisoned heavy water from the expansion tank into the calandria. The reactivity fell below administrative criticality.

Modifications to the procedures were approved by the duty manager to continue the ATC using intermittent poison removal rather than incremental control absorber withdrawals. The modified procedures were incorporated into the procedures for the first ATC for Unit 1 four months later.

The purpose of this paper is to summarize the first ATCs of the refurbished Bruce A reactors in 2012 with highlights from the Unit 1 ATC. The procedures for this unit incorporated lessons learned from the Unit 2 ATC earlier that year.

2.0 Neutron source

Fig. 1 illustrates a start-up of an operating reactor with photo-neutron precursors present following an extended outage and a first ATC with the neutron source from spontaneous fission of uranium only.

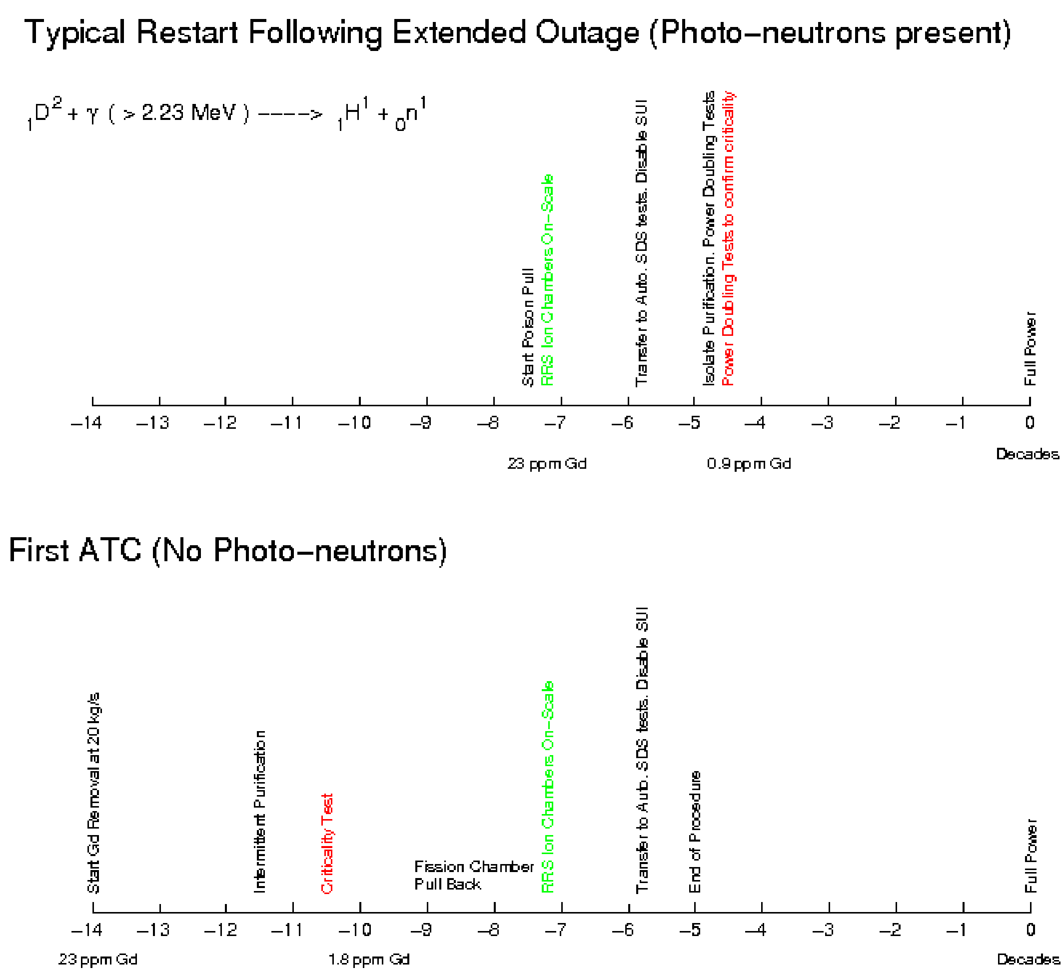


Figure 1 ATC Milestones vs. Log Power – Restart After an Extended Outage & First Start-Up

The upper part of the figure shows ATC milestones superimposed on the power range in decades which is traversed with photo-neutrons present following a 30 day outage. Photo-neutron precursors which build-in during operation at high power decay during the outage such that the neutron power in the core after 30 days is about -7.5 decades in the overpoisoned guaranteed shutdown state (OPGSS). Start-up Instrumentation is installed after about 20 days with BF_3 counters in out-of-core locations. For longer outages, the initial power is lower as the photo-neutron precursors decay further. The ATC is performed by reducing the gadolinium in the moderator using the moderator purification system. The regulating system ion chambers become rational at -7.2 decades and there is an overlap of a decade between the SUI and the permanent ion chambers before RRS takes control at -6 decades. Following a 30 day outage, criticality occurs at about -4.0 decades and 1 ppm gd, after traversing about 3.5 decades.

The lower part of the figure shows that when the neutron source is from spontaneous fission of uranium only, then neutron power must be increased over a much larger power range - almost seven decades, before the RRS ion chambers become rational. Criticality occurs at about -10.3 decades and fission chamber pull-backs are performed to out-of-core locations to maintain margin to pulse pile-up in the start-up instrumentation.

3.0 Start-up Configuration

Fig. 2 shows a simplified schematic of the reactor and systems associated with the first ATCs for Bruce 1&2 reactors.

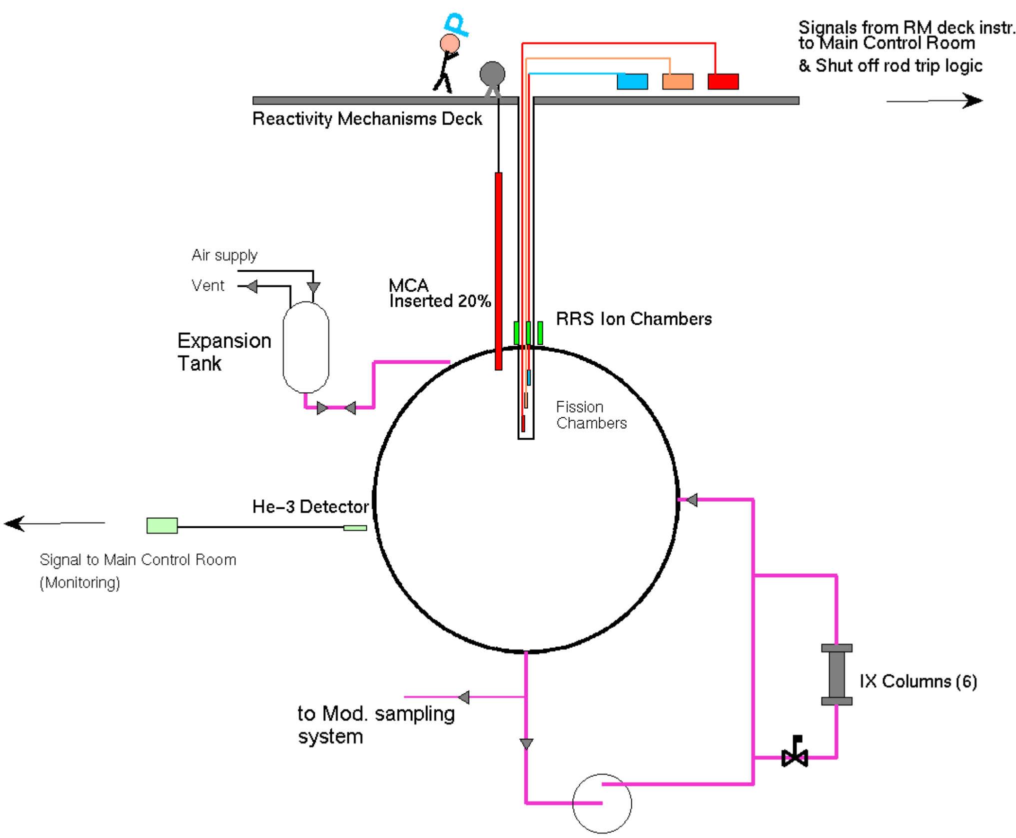


Figure 2 First Approach to Critical – Unit 1 (July 2012)

The fission chambers were housed in separate tubes in an aluminum start-up unit installed in the inspection port and extending to fuel channel row "E". The fission chambers and start-up unit were required from the start of manual fuel loading [1] until the end of low power testing, after which they were removed. The fission chambers were connected to instrumentation on the Reactivity Mechanisms deck consisting of a high voltage power supply, preamplifier and amplifier for each fission chamber. The amplifiers were connected to instrumentation in the Main Control Room (MCR) shown in Fig. 3. Each SUI channel was wired to an SDS1 logic channel so that there would be a reactor trip if count rates exceeded the trip setpoint.

The instrumentation in the MCR for each SUI channel consisted of a single channel analyzer, counter / scaler and ratemeter. The instrumentation included an interface module with electrical isolators which allow an oscilloscope, chart recorders, and multichannel analyzer to be connected to the SUI loops without requiring the trip channels to be failed safe.

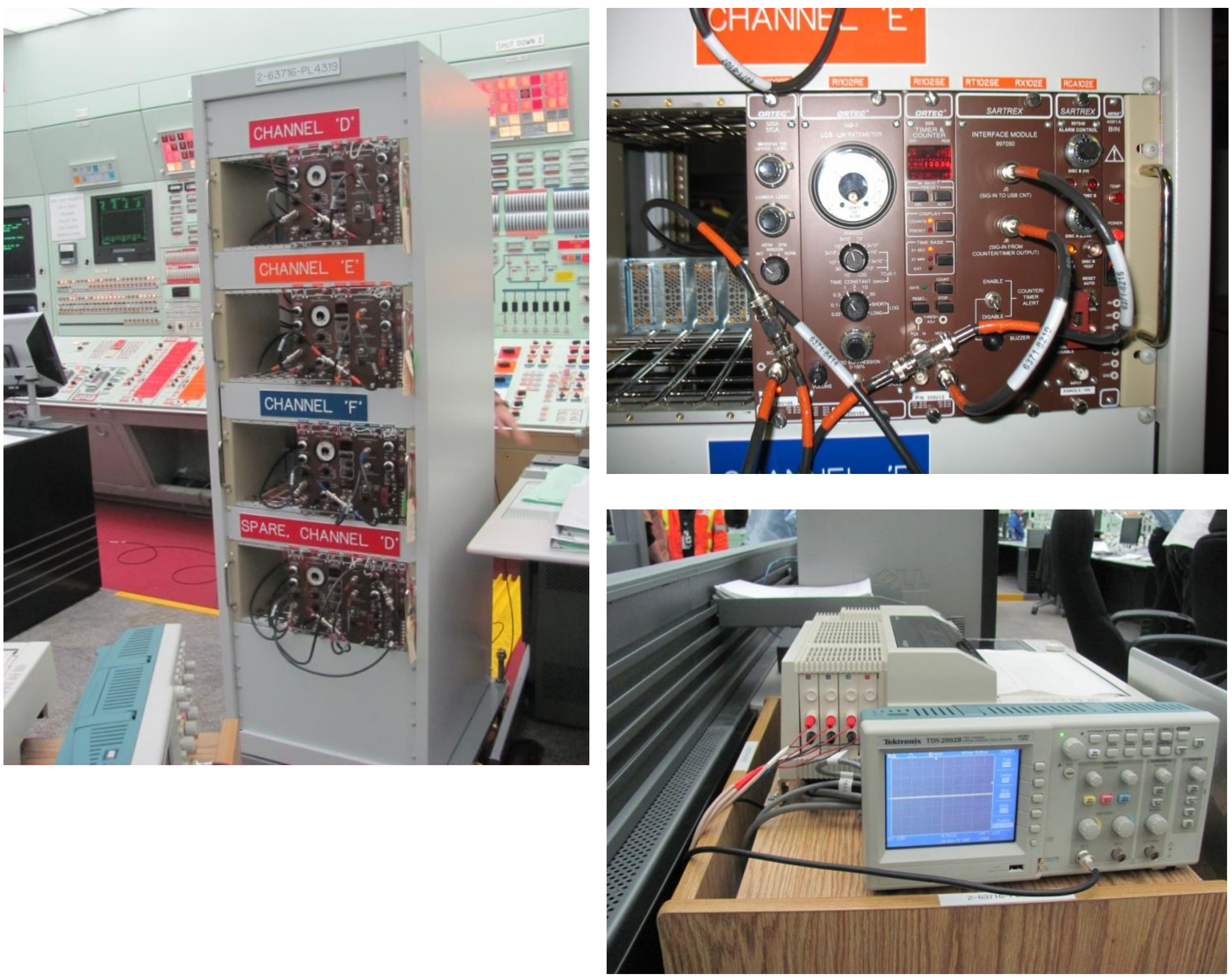


Figure 3 Start-Up Instrumentation in Main Control Room

4.0 First Approach to Critical

4.1 Overview

For Unit 2, two control absorbers (CA1 and CA2) were initially inserted to 60%. Following the poison removal period and when close to critical, withdrawals of CA2 then CA1 in 3% (0.06 mk) increments, were used to increase reactivity. After administrative criticality had been achieved at -0.2 mk, unexpected decreases in fission chamber count rates were observed which were attributed to ingress of poisoned heavy water from the expansion tank (see Fig. 2) into the calandria. Since the heavy water in the expansion tank contained the initial concentration of gadolinium, the ingress caused the reactivity to decrease to below -0.2 mk.

Modifications to the procedures were approved by the duty manager to re-establish administrative criticality and continue the power raise with incremental poison removal, while leaving both control absorbers at 20% inserted.

Four months later, the ATC for Unit 1 was performed following procedures which incorporated lessons learned from Unit 2:

- One control absorber only was inserted to 20% initially, available for a 2% insertion to stabilize power for fission chamber pull backs after administrative criticality;

- The final stage of the power raise to administrative criticality was performed using intermittent gadolinium removal in 5 minute increments at 4 kg/s. Each increment was equivalent to a 0.2 mk increase in reactivity. Administrative criticality was declared when the count rates doubled after one such incremental poison-pull.

- One minute poison pull increments at 4 kg/s were used for the ascent to -5.88 decades where a transfer of control to the reactor regulating system took place at 32.5 hours after initiating poison removal.

Fig. 4 gives an overview of the ATC evolution for Unit 1. The ATC with initiated by starting Main Moderator Pump 1 at 21:15 EST on July 22 2012 and the automatic transfer of control from manual to RRS took place 32.5 hours later. The evolution can be considered as divided into three stages: (i) continuous poison removal; (ii) intermittent poison removal in 0.2 mk increments until administrative criticality is observed; (iii) intermittent poison removal in 0.04 mk increments or less until transfer of control to RRS. These stages are highlighted with different colours in Fig. 4.

The continuous poison removal stage included a flush of the moderator main circuit and auxiliary circuit piping by running the auxiliary pumps to ensure that the poison concentration is uniform throughout. The purification flow is throttled towards the end of this stage when count rate doubling times dropped below 30 minutes. After about 15 hours and 7 power doubles, the core excess reactivity was -2.5 mk and intermittent poison removal was initiated in 0.2 mk increments. Each increment involved valving-in one ion exchange (IX) column for 5 minutes with a purification flow of 4 kg/s.

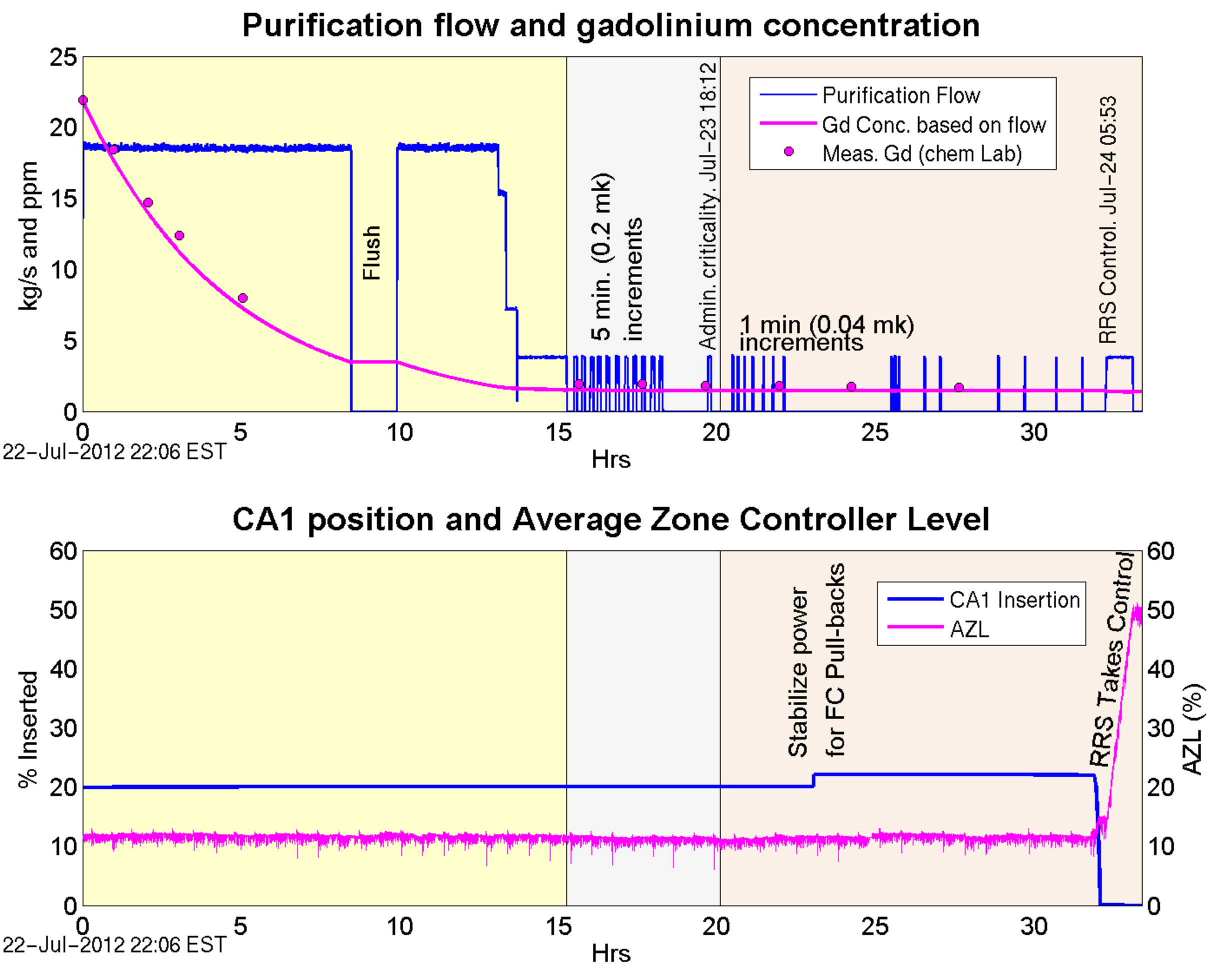


Figure 4 Unit 1 First ATC - Overview

After administrative criticality, reactivity was increased in the third stage of the ATC using smaller poison removal increments of 1 minute or 30 seconds at 4 kg/s, equivalent to 0.04 mk and 0.02 mk gains respectively. Procedures during this stage ensured that count rate doubling times were maintained at about 30 minutes until the transfer of control to RRS. Pull-backs of the fission chambers to lower flux, out-of-core locations were performed when the count rates were approximately 7000 cps.

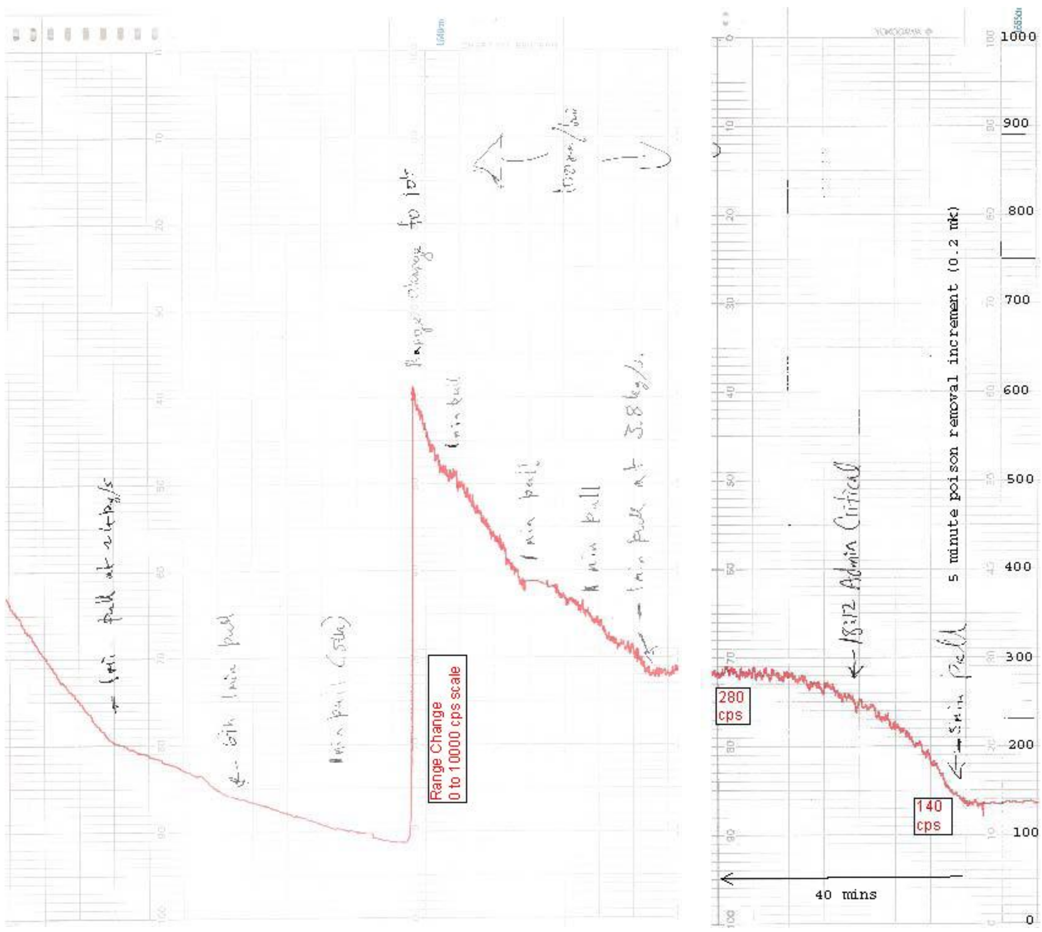
4.2 Administrative Criticality

Fig. 5 shows a segment from the chart recorder trend for channel “D” during which administrative criticality was achieved on Unit 1.

The trend shows the following:

- The count rate at the start of the trend segment was 140 counts/s (cps) (The selected scale on the ratemeter was 0 to 1000 cps)
- As a result of an increase in reactivity of 0.2 mk, the count rate stabilized at 280 cps after about 50 minutes.

- After administrative criticality, poison removal increments were reduced from 5 minutes at a purification flow of 4 kg/s to 1 minute at the same flow.
- After the count rate had increased to 600 cps, the chart recorder trend shows that the ratemeter was up-ranged from the 0 to 1000 scale to the 0 to 10000 cps scale.

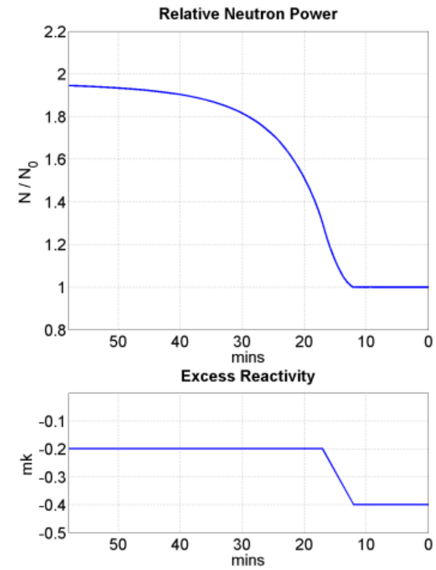


← Time

Figure 5 Unit 1 First Approach to Critical - Chart recorder segment showing Admin. Criticality and Beyond

For comparison with theory, a point kinetics simulation of the reactivity increase of 0.2 mk to administrative criticality is given in Fig. 6.

Figure 6 Point Kinetics Simulation – Administrative Criticality



4.3 Fission Chamber Pull-backs

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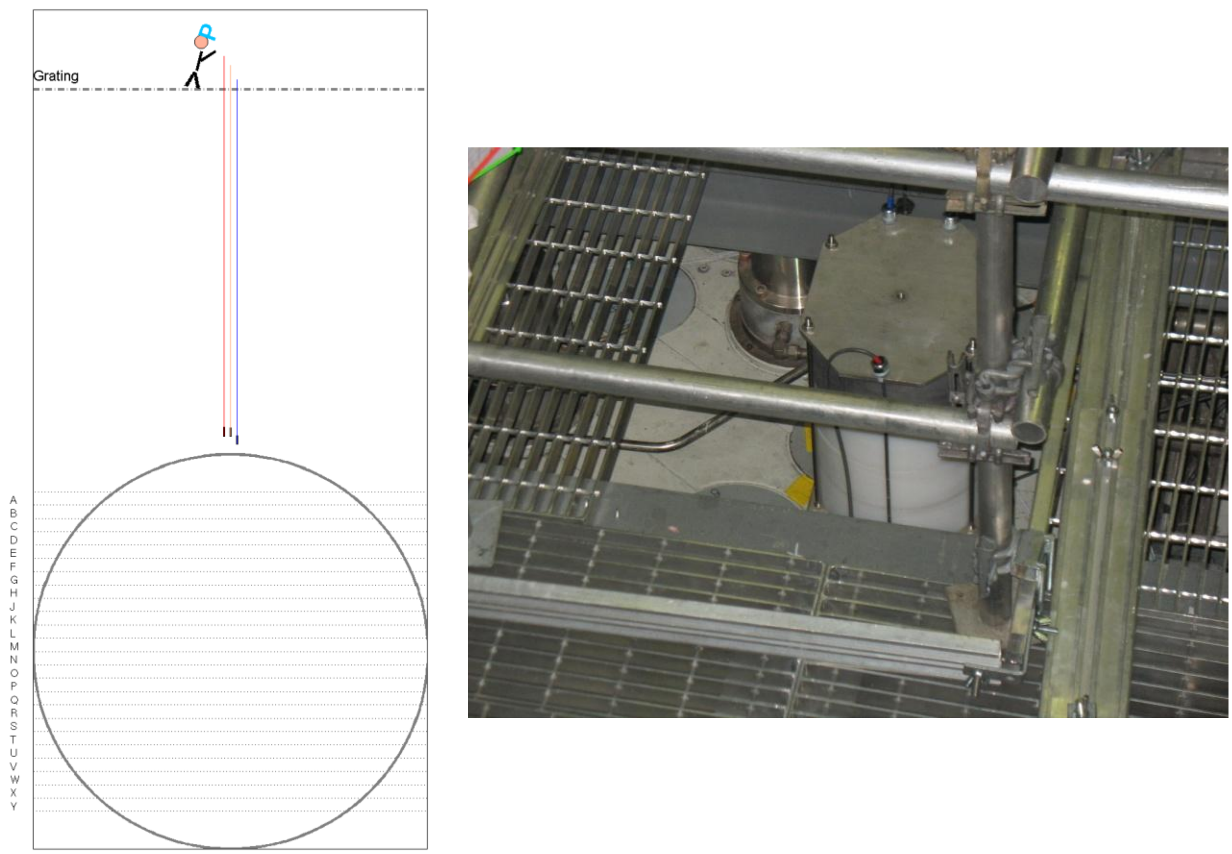
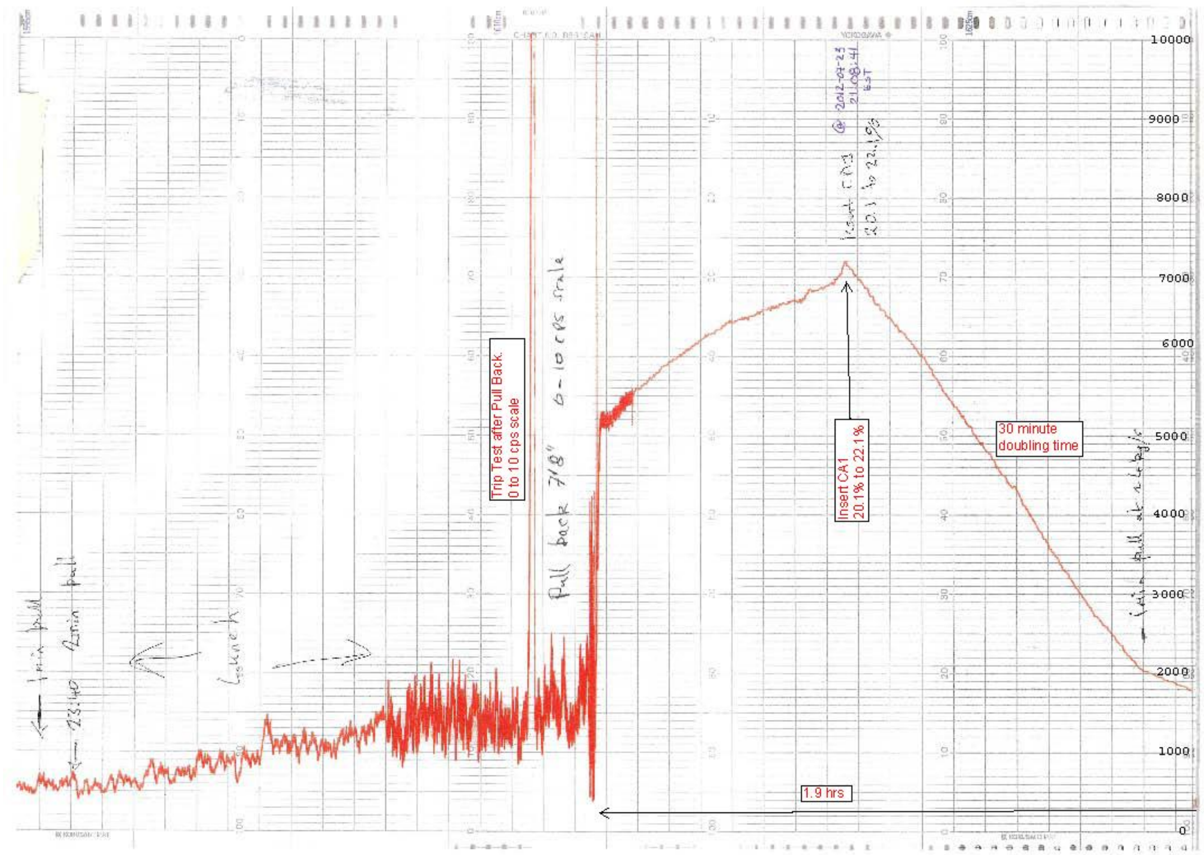


Figure 7 Schematic showing fission chambers in pulled-back locations and photo of the top of the start-up unit

Unit 1 required only one pull-back to the approximate out-of-core locations shown in Fig. 7 to limit the count rates to less than 7000 cps to provide adequate margin to the risk of pulse pile-up.

As shown in Fig. 8, at 21:10 EST on July 23, the count rate was approximately 7000 cps on Channel "D". CA1 was inserted from 20.1% to 22.1%. This stopped the power increase and count rates drifted slowly down. At 21:45 EST, with headset communication established between the Authorized Nuclear Operator (ANO) in the control room panels and Control Maintainers on the reactivity mechanisms deck, Channel "D" SUI was rejected and the fission chamber was pulled-up until the count rates were between 1 and 2 counts/s. The ratemeter scale was down-ranged to 0 to 10 cps and the counting interval was increased from 10s to 100s. At 22:11 EST, Channel "D" was returned to service after a trip test.



← Time

Figure 8 Unit 1 First Approach to Critical – Chart recorder segment showing pull-back of fission chamber “D”

The procedure was repeated for Channels "E" and "F". The Unit 1 pull-backs were completed at 22:41 EST after an elapsed time (from rejection of Channel "D") of 56 minutes.

4.3 Ascent to -5.88 decades

Fig. 9 illustrates the final power ramp for Unit 1 under manual control from -7.0 decades to -5.88 decades when transfer to automatic control by the regulating system. Several 30s to 60s poison removal increments (each of approximately 0.03 mk) were required to sustain the doubling time at about 28 minutes. The transfer of control is marked by a small increase in the Average Zone level (AZL) as RRS responds to a positive power error and takes action to hold power to the setpoint.

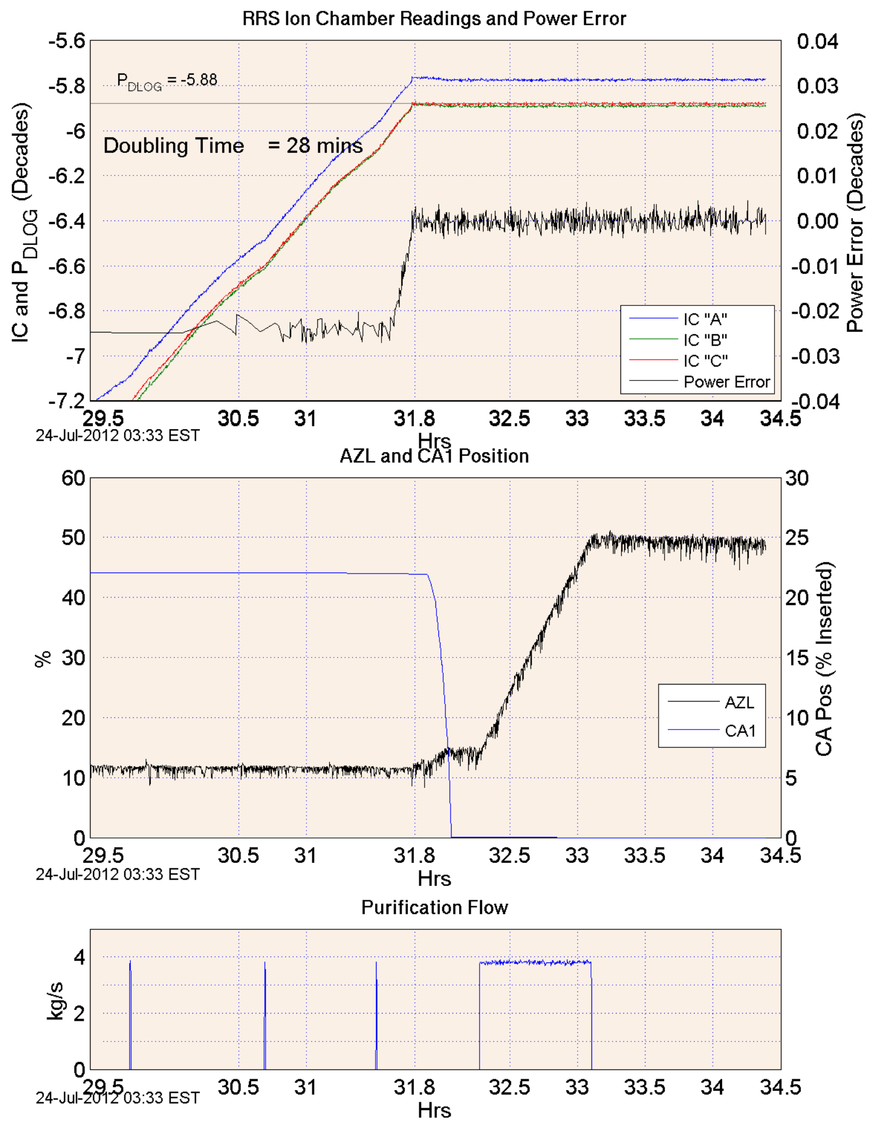


Figure 9 Unit 1 First ATC – Transfer to RRS Control

The responses of the RRS, SDS1 and SDS2 ion chamber systems were checked over the range -7 to -6 decades. After RRS had taken control at -5.88 decades, safety systems tests were performed for the neutronic trips, then the start-up instrumentation trip was disabled. Moderator samples were taken to measure the critical gadolinium concentration, which were in good agreement with predicted concentrations as shown in Table 1.

Table 1 Critical Gadolinium Concentrations

	Unit 2 (25-Mar-2012)	Unit 1 (24-Jul-2012)
Predicted Value (RFSP-IST with actual conditions	1 .78	1.678
Chem Lab Measurement	1.8	1.69

5.0 Conclusions

In-core fission chambers used also for the first start-ups on NPD, Douglas Point and Pickering A Units 1 and 2 were effective for monitoring neutron flux changes for the first start-ups of Bruce Units 1and 2 and for increasing excess reactivity while on manual control of reactor power.

Reactivity increases of 0.2 mk using poison removal were found to be more effective in establishing administrative criticality than the 0.06 mk increments using a control absorber originally planned. While a control absorber had been effectively used for the final stages of the first ATC in Bruce B reactors, a complication in the Bruce 1&2 start-ups was ingress of overpoisoned heavy water from the expansion tank.

Both ATC evolutions were completed successfully by control room staff, field operators, chem tech, control techs and mechanical maintainers with oversight by control room shift supervisors and shift managers and senior managers at Bruce Power. The evolutions were deemed to be IPTE (infrequently performed evolutions) and involved extensive planning, physics simulations, workshops and training sessions and the preparation of procedures, spreadsheets, and reactivity plans. Briefs were conducted in the control room at different stages during each ATC and the evolutions were witnessed by staff from the CNSC. After each ATC evolution, there was period of low power physics testing (range -6 to -3.3 decades) including shutdown system effectiveness tests after which each unit was placed in the OPGSS to remove the start-up unit and fission chambers.

References

1. C. Olive, D. Luth, P. Paquette, T. Stroud, "Use of Fission Chambers for Monitoring Neutron Flux for the First Start-ups of the Refurbished Bruce A Reactors", to be presented at the 36th Annual Canadian Nuclear Society (CNS) Conference, Toronto Marriott Downtown Eaton Centre Hotel, ON, CANADA, June 19-22, 2016.

2. Fermi, Enrico et al, Experimental Production of a Divergent Chain Reaction, Am. J. of Phy, 536-558, 1952.