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# A Study on Performance of Adjuster Rod System and Banking Scheme in Operational Transient of CANDU-6 RUFIC Core

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## Abstract

The performance of adjuster rod system in four operational transients of CANDU-6 RUFIC (Recovered Uranium Fuel In CANDU) core was preliminarily assessed, where the operational transients include startup after a short shutdown, startup after a poison-out shutdown, shim mode operation, and a stepback to 60% full power. The results of the preliminary assessment indicated that the adjuster rod system as currently designed and installed in the CANDU-6 NU (Natural Uranium) core will adequately meet the functional requirements in the RUFIC core. Comparing to the performance of adjuster rod system in the NU core, the total worth of the adjuster system in the RUFIC core is reduced, leading to less xenon override capability and shimming capability. In spite of the reduction of total worth, however, the overall performance of adjuster rod system in the operation transient of the RUFIC core is expected to still be satisfied. An alternative adjuster-banking scheme is also included in the assessment. The alternative adjuster-banking scheme involves rods in Bank 1 and Bank 7 being re-distributed within the two banks. The overall results from the transients studied indicated that the alternative banking scheme does show some better performance characteristics and merits.

## 1. Introduction

The use of recovered uranium (RU) in CANDU reactors is an exciting new fuel development for the reactors' operators seeking significantly improved fuel cycle economics since the CANDU reactor design has the flexibility to use alternative fuel cycles other than natural uranium (NU). Atomic Energy of Canada Limited(AECL), British Nuclear Fuels plc (BNFL) and Korea Atomic Energy Research Institute (KAERI) have recognized jointly that the CANFLEX (CANdu FLEXible fuelling) fuel bundle incorporating RU provides "improved fuel performance" and "reduced fuel cycle costs", since the RU from irradiated reactor fuel can be directly used in CANDU reactors without re-enrichment. The RU fuel is called as RUFIC (Recovered Uranium Fuel in CANDU). The RUFIC program has been initiated to assess the use of recovered uranium with 0.92 w/o U-235, in the CANFLEX bundle carrier, to be implemented in Wolsong CANDU reactor cores. The program is a co-operative effort between KAERI, BNFL and AECL, and covers technology development of all aspects of design and operation with the RUFIC bundles and minimal modifications to the basic core design.

This study covers the assessments of performance of adjuster rod system and banking schemes in operational transients of a CANDU-6 RUFIC core, where operational transients include restart after a short shutdown, restart after a poison-out shutdown, shim mode operation, and power stepback. An alternative banking scheme has also been investigated.

The computer codes used in this study are WIMS-AECL version 2-5d[1] with the nuclear libraries ENDF/B-VI for the lattice cell calculation, RFSP version IST-REL_3-00-05HP[2] for the fuelling simulation and the core flux/power calculation, and RFSP version IST-DEV_3-00-06HP for the snapshot calculation.

## 2. Overview of Current and Alternative Adjuster Rod System

In a CANDU-6 reactor such as Wolsong Units, twenty-one stainless steel adjusters are provided for xenon override capability needed to restart after a short shutdown or in power manoeuvres for reactivity shim when fuelling is temporarily interrupted, and for shaping the thermal flux distribution in the core. The adjuster rod configuration is shown in Figure 1. They are arranged in three rows of seven rod each. In general, the design target for the worth of the adjusters in a CANDU-6 37-element NU core is 15 *mk* with a nominal 30-minute xenon override capability. In a comparison of the 37-element NU core, one of the characteristics of the RUFIC core is that the adjuster worths are less than those of the 37-element NU core due to the flux shape differences in the two cores. Therefore, original banking scheme has to be re-confirmed and the bank worths have to be established for the RUFIC core.

One of the basic premises of the RUFIC program is that the existing control and shutdown systems designed for 37-element NU fuel would provide adequate performance in the CANDU-6 RUFIC core without major hardware modifications. This implies that the major reactivity devices such as the light water zone controllers, the adjusters, the MCA, and the SDS1 and SDS2 shutdown devices, as currently installed in the CANDU-6 NU core, are expected to fully meet their respective functional requirements. The flux shapes in the CANDU-6 RUFIC core are somewhat different from those expected when the control and shutdown systems were originally designed because of the high U-235 enrichment of 0.92 w/o and the different fuelling strategy to be used. The functions of these devices in operational manoeuvres and in shutdown and restart have to be demonstrated, or changes in the range of capability of these devices have to be assessed when a new fuel is introduced in the core.

In this work, therefore, the performance of current adjuster rod system and banking scheme in a CANDU-6 reactor fuelled with RUFIC fuel has been assessed for the four operational transients such as reactor startup after short shutdown, reactor startup after poison-out shutdown, shim operation, and power stepback to 60 % full power.

The past operation experiences in CANDU-6 reactors have indicated that the current adjuster banking scheme is somewhat deficient. The worth and reactivity change rate for Banks 6 and 7 are such that they are not compatible with the range and rate of the zone controller system. In a restart transient when these banks are to be re-inserted, adjuster bank cycling in and out of the core had been observed. Bank 7 consists of two rods (#10 and #12), and is the heaviest one among all the banks. These operational difficulties have contributed to a decision at Point Lepreau Generating Station in Canada to lock-in Banks 6 and 7 (i.e., they have been taken out of RRS (Reactor Regulation System) automatic control), and also at Gentilly-2 Generating Station in Canada to have Bank 7 split into two banks, with one rod in each of Bank 7 and Bank 8. Based on many years of operating experienced, D. Brissette at Gentilly-2 Generating Station has suggested an alternative banking scheme involving the re-grouping of the rods in Bank 1 and Bank 7 as shown in Figure 2. Bank 7 is to consist of the central rod only, and rods #10 and 12 are to be included in Bank 1 that now consists of six rods. In this work, this alternative banking scheme was also assessed in RUFIC core.

In Table 1, the adjuster bank worths in RUFIC core are compared with those in the current Wolsong 2, 3, and 4 cores. In these calculations of the adjuster worths, the zone controllers were modelled as fixed at 50 % full, as was done in the calculation for the NU core presented in Wolsong 2, 3, and 4 Physics Design Manual[3]. The total worth of the same adjuster rods is 12.52 *mk*, as opposed to 16.65 *mk* in the Wolsong cores. Bank 7 in the Wolsong cores is worth 3.46 *mk*, which is to be compared to the zone worth ranging from 20% to 70% of about 3.50 *mk*. The high worth of Bank 7, together with the relative speed of adjuster movement and the rate of change of the zone water level, could lead to adjuster bank cycling problems.

The adjuster bank worths with the alternative banking scheme are presented in Table 2. It can be seen that, with the revised banking scheme, Bank 7 worth has changed from 2.42 *mk* to 0.96 *mk*, and Bank 1 worth has changed from 1.14 *mk* to 2.13 *mk*. The worths of Banks 1 to 6 are fairly uniform, all within the range of 1.72 *mk* to 2.13 *mk*. Bank 1 is the heaviest one among all the banks, and the first bank to be withdrawn.

The incremental cross sections of adjuster rods and zone controller units used in the bank worths calculations are presented in Table 3.

## 3. Assessment of Adjuster Rod System Performance

### 3.1 Startup After a Short Shutdown

In order to confirm that the current adjuster rod system and banking scheme are adequate for a 30-minute xenon override in the CANDU-6 RUFIC core, a detailed simulation was carried out using TIME-AVER module[2] of RFSP code, and the results are summarized in Table 4.

In a restart transient, the reactor power levels as the banks are re-inserted are constrained by many considerations, including channel and bundle over powers, in-core ROP (Regional Over Power) detector margin to trip, and fission product inventory limits. The same power levels as stated in Wolsong 2, 3, and 4 Physics Design Manual were employed in this simulation for purposes of comparison between the 37-element NU core and the RUFIC core.

The results show that the current adjuster rod system and banking scheme can compensate for a 41-minute xenon reactivity following a shutdown from 100 % power, and reactor power can be returned to full power. In the simulations, adjuster banks were re-inserted when the average zone level fell close to 20%. The maximum channel and bundle powers throughout the transient are given Table 4, which are normalized to the 100% full power. It is found that the maximum channel powers after reaching 100 % full power exceed the licensing limit of 7300 kW. Some further delay in achieving full power would be anticipated. In addition, the simulations show that the time to reach 100 % full power from short shutdown, 5.8 hours, was fairly long, comparing to the results of the

37-element NU core, 4.0 hours given in the Physics Design Manual[3].

Table 5 shows that the simulation results of the restart transient with the alternative adjuster banking scheme. Again compensating a 41-minute xenon reactivity spike, the reactor can be returned to full power without exceeding the nominal maximum channel and bundle powers. It was also found that the time to reach 100 % full power, 4.5 hours, is significantly shorter than that for the current banking scheme case. The restart time difference can be attribute to the worth of the first bank that was re-inserted (Bank 7). The heavy Bank 7 in the current scheme depressed the flux more strongly, leading to a slower burnout of the xenon.

### 3.2 Startup After a Poison-out Shutdown

When restart of reactor is failed within 30 minutes after shutdown, the reactor should be kept as shutdown state until poison (xenon) decays out so that reactor core approaches to criticality. After a poison-out, startup transient was simulated with RFSP in order that the reactor power can be reached to full power.

The time required to restart the reactor core was calculated to be 35.7 hours. The reactor should be, therefore, kept as shutdown state for 35.7 hours if the reactor is not restarted within 30 minutes. In Table 6 and 7, the simulation results on the current and alternative adjuster banking schemes are summarized, respectively. Compared to the simulation of startup after a short shutdown, the periods between insertions of adjuster bank are very short since xenon decays out rapidly. The time to return to full power is 32.0-minutes for the case of the current adjuster banking scheme, on the other hand, the time is 28.1-minutes for the case of the alternative scheme. It is noted that the time required to restart the reactor core with the use of the alternative adjuster banking scheme is slightly shorter than the time for the case of the current scheme.

### 3.3 Shim Operation

In the event of a loss of refuelling capability, one or more adjusters can be withdrawn to provide the reactivity needed and maintain the reactor power. As the banks are pulled out, the flux shapes are more and more centrally peaked, and the reactor power has to be derated to restrict the peak power. After the withdrawal of each bank, a 4-hour step is, in general, taken at which time the xenon transient was expected to peak, and then again steady state xenon is simulated. In these simulations, fuel irradiation advancement is not accounted for while operating with adjusters pulled out.

The RUFIC core was simulated for the case of the current adjuster banking scheme and as well as for the case of the alternative banking scheme, and the results are presented in

Tables 8 and 9, respectively. The same power levels as used for the adjuster shim operation simulation in Wolsong 2, 3, and 4 Physics Design Manual were also followed. Based on a reactivity decay rate of 0.53 *mk* per full power day for the RUFIC core, it is estimated that the reactor can be operated with Bank 1 out for about 2.3 full power days without refuelling with the current adjuster banking scheme, and for about 4.2 full power days with the alternative adjuster banking scheme. If successive withdrawals of all adjusters were taken, reactor operation would be permitted for about 26 full power days without refuelling in the RUFIC core, which is shorter than over 30 days of 37-element NU core. The reduction in reactivity shim capability is due to both the higher reactivity decay rate and the lower reactivity worth of the adjusters in the RUFIC core.

### 3.4 Stepback to 60 % Full Power

When reactor power is reduced, there is initially a net increase in xenon reactivity load due to the decrease in xenon burnout rate. The effect of a stepback to 60 % full power from 100 % power was investigated using TIME-AVER module of RFSP code with the time average model, and with the spatial control option. The transient was initiated by a reduction in reactor power to 60 % full power, and the excess reactivity required to override the xenon transient was provided through successive withdrawals of adjuster banks. As the xenon re-equilibrates at the new flux level, the adjuster banks would be then re-inserted.

The simulations were done with the current and the alternative banking schemes. The simulation results including the peak channel and bundle powers are summarized in Tables 10 and 11, respectively. As xenon builds up, up to five banks of adjusters were successively pulled out over the first 2 hours of the transient with the current adjuster banking scheme, and peak xenon level was reached at about 2.7 hours after the stepback. With the alternative banking scheme, only four banks were pulled over the first 1.6 hours, and xenon peaked at about 3.1 hours after the stepback. The heaviest Bank 1 in the alternative banking scheme has resulted in less number of banks withdrawn, and lower peak powers in the overall transient.

## 4. Summary and Conclusions

The results of the preliminary performance assessment of the adjuster rod system in the RUFIC core indicated that, for the most common situations where adjusters are involved namely in a startup transient, in shim operation and in power stepback manoeuvres, the adjuster rod system as currently designed and installed in the NU core will adequately meet the functional requirements. Comparing to the performance of adjuster rod system in the NU core, the total worth of the adjuster in the RUFIC core is reduced, leading to less xenon override capability and shimming capability. However, the overall performance is expected to be still satisfied.

An alternative adjuster banking scheme, originally proposed by D. Brissette of Hydro Quebec for the CANDU-6 NU core, was also investigated for the RUFIC core. Noting that the hardware is not modified, only the adjuster rods in Bank 1 and Bank 7 are re-distributed within the two banks. As a result of the re-grouping of the rods, Bank 1 will become the heaviest one (2.13 *mk* in the RUFIC core) instead of Bank 7 in the current banking scheme (2.81 *mk* in the NU core). The overall results from the transient studied indicated that the alternative banking scheme does show some better performance characteristics.

It should be noted that the assessments on the adjuster performance presented in this work are preliminary. Further studies are necessary to demonstrate that the adjuster functions within the overall RRS context are not compromised, despite the reduced total worth. Also, the alternative banking scheme appears to be attractive, but further studies are required to confirm that the heavy Bank 1 would not lead to operational problems, as has occurred with Bank 7 in the current NU core. For these further assessments, the zone system and other subsystems in RRS are to be considered in conjunction with the adjusters.

## Acknowledgement

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## References

[1] J. Griffiths, “WIMS-AECL User's Manual,” RC-1176/COG-94-52 Rev. 3, February 1999.

[2] B. Arsenault, D. A. Jenkins and A. U. Rehman, “RFSP-IST User's Manual,” COG-98-272 Rev. 0, June 1999.

[3] Design Manual, “CANDU 6 Generating Station Physics Design Manual: Wolsong NPP 2 3 4,” 86-03310-DM-000 Rev. 1, August 1995.

Table 1. Current Adjuster Bank Worths in RUFIC Core and 37-Element NU Core

| Adjuster Bank Position | RUFIC Core | | 37-element NU Core | |
|---|---|---|---|---|
| | k-eff | Worths (*mk*) | k-eff | Worths (*mk*) |
| All Adjuster Rods Out | 1.012680 | 12.52 | 1.018150 | 16.65 |
| BK 7 In | 1.010209 | 2.42 | 1.014572 | 3.46 |
| BK 7+6 In | 1.008162 | 2.01 | 1.012022 | 2.48 |
| BK 7+6+5 In | 1.006158 | 1.98 | 1.009507 | 2.46 |
| BK 7+6+5+4 In | 1.004509 | 1.63 | 1.007065 | 2.40 |
| BK 7+6+5+4+3 In | 1.002819 | 1.68 | 1.004921 | 2.12 |
| BK 7+6+5+4+3+2 In | 1.001147 | 1.67 | 1.002783 | 2.12 |
| BK 7+6+5+4+3+2+1 In | 1.000005 | 1.14 | 1.000004 | 1.59 |

Table 2. Alternative Adjuster Bank Worths in RUFIC Core

| Bank Status | RUFIC Core | |
|---|---|---|
| | k-eff | Worths (*mk*) |
| All Adjuster Rods Out | 1.012680 | 12.52 |
| BK 7 In | 1.011694 | 0.96 |
| BK 7+6 In | 1.009535 | 2.11 |
| BK 7+6+5 In | 1.007405 | 2.09 |
| BK 7+6+5+4 In | 1.005622 | 1.76 |
| BK 7+6+5+4+3 In | 1.003873 | 1.73 |
| BK 7+6+5+4+3+2 In | 1.002139 | 1.72 |
| BK 7+6+5+4+3+2+1 In | 1.000005 | 2.13 |

Table 3. Incremental Cross Sections of Adjuster Rod System and Zone Controller Units

| | A-Inner | A-Outer | B-Type | C-Inner | C-Outer |
|---|---|---|---|---|---|
| 2GTR1 | 5.6931067E-04 | 4.9800114E-04 | 9.4437134E-04 | 8.1922297E-04 | 3.1990967E-04 |
| 2GTR2 | 1.2984873E-04 | 1.1308899E-04 | 2.1786207E-04 | 1.8851969E-04 | 7.1196194E-05 |
| 2GSA1 | 3.3287000E-05 | 2.8714000E-05 | 5.3223000E-05 | 4.6779000E-05 | 1.8903000E-05 |
| 2GSA2 | 6.1936000E-04 | 5.3464000E-04 | 9.1966000E-04 | 8.3732000E-04 | 3.7129000E-04 |
| 2GS12 | 5.4915274E-05 | 4.7684118E-05 | 7.3588755E-05 | 7.0401341E-05 | 3.5401101E-05 |
| 2GS21 | 4.7939873E-06 | 4.1348786E-06 | 7.2856264E-06 | 6.5648246E-06 | 2.8269586E-06 |
| 2GNF1 | -4.9737000E-06 | -4.3027000E-06 | -7.4359000E-06 | -6.7371000E-06 | -2.9748000E-06 |
| 2GNF2 | 9.9978000E-05 | 8.6887000E-05 | 1.5059000E-04 | 1.3561000E-04 | 5.9500000E-05 |
| 2GH1 | -2.3245355E-04 | -2.0109460E-04 | -3.4769579E-04 | -3.1495072E-04 | -1.3898456E-04 |
| 2GH2 | 4.9928029E-03 | 4.3393933E-03 | 7.5209253E-03 | 6.7722627E-03 | 2.9712043E-03 |

| | D-Type | ADJ_GT | ZCU21 | ZCU21_Empty | ZCU10 |
|---|---|---|---|---|---|
| 2GTR1 | 4.6236201E-04 | 1.7748120E-05 | 7.0694485E-03 | -6.6961933E-03 | 8.1600308E-03 |
| 2GTR2 | 1.0889928E-04 | -6.7007432E-05 | 7.2278277E-02 | -9.4446855E-03 | 7.9933121E-02 |
| 2GSA1 | 2.7453000E-05 | 1.6127000E-06 | 1.1261000E-04 | -8.7533000E-06 | 1.2872000E-04 |
| 2GSA2 | 5.1630000E-04 | 6.0773000E-06 | 1.2156000E-03 | 1.8039000E-04 | 1.3433000E-03 |
| 2GS12 | 4.6530364E-05 | -5.4938234E-06 | 2.3382040E-03 | -4.4988997E-04 | 2.6701321E-03 |
| 2GS21 | 3.9806579E-06 | 7.2290929E-08 | -1.4010946E-06 | -8.7320805E-07 | -1.7314556E-06 |
| 2GNF1 | -4.1489000E-06 | -2.7416000E-07 | 8.4822000E-05 | -2.1159000E-05 | 9.7227000E-05 |
| 2GNF2 | 8.3600000E-05 | 1.3602000E-06 | 8.9798000E-06 | 6.4153000E-05 | 6.2748000E-06 |
| 2GH1 | -1.9389459E-04 | -1.3095228E-05 | 4.0808850E-03 | -1.0202501E-03 | 4.6764756E-03 |
| 2GH2 | 4.1750739E-03 | 6.7766466E-05 | 4.9964256E-04 | 3.1994872E-03 | 3.5919132E-04 |

| | ZCU10_Empty | ZCU32 | ZCU32_Empty |
|---|---|---|---|
| 2GTR1 | -7.7155494E-03 | 6.1016901E-03 | -5.7811722E-03 |
| 2GTR2 | -1.4100815E-02 | 6.3396260E-02 | -4.6212098E-03 |
| 2GSA1 | -2.3604000E-05 | 9.7296000E-05 | 5.4182000E-06 |
| 2GSA2 | 1.0125000E-04 | 1.0725000E-03 | 2.5827000E-04 |
| 2GS12 | -7.4511613E-04 | 2.0412009E-03 | -1.8942075E-04 |
| 2GS21 | -4.2788166E-07 | -9.3451878E-07 | -1.1677826E-06 |
| 2GNF1 | -3.2707000E-05 | 7.3165000E-05 | -1.1067000E-05 |
| 2GNF2 | 7.1326000E-05 | 1.8678000E-05 | 5.3660000E-05 |
| 2GH1 | -1.5741789E-03 | 3.5210055E-03 | -5.3609949E-04 |
| 2GH2 | 3.5425366E-03 | 1.0214355E-03 | 2.6877415E-03 |

Table 4. Simulation Results for Startup After Short Shutdown Using Current Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) (Normalized to full power) |
|---|---|---|---|---|---|---|
| 0 | None In | 1.000002 | 40.56 | 20.00 | 8163.4 (L12) | 1027.6 (L11/8) |
| 56 | 1-7 Out | 1.000005 | 63 | 69.14 | 9052.2 (M10) | 1210.4 (M11/5) |
| 65 | BK 7 In | 1.000003 | 0 | 23.08 | 7988.8 (M09) | 1038.4 (M13/5) |
| 65 | 1-6 Out | 1.000003 | 42 | 69.18 | 8462.0 (M14) | 1120.6 (M13/5) |
| 68 | 6, 7 In | 0.999998 | 0 | 30.92 | 7894.3 (M08) | 1053.2 (M09/5) |
| 68 | 1-5 Out | 1.000005 | 54 | 68.99 | 8084.5 (L15) | 1095.4 (M09/5) |
| 76 | 5, 6, 7 In | 0.999999 | 0 | 34.72 | 7734.1 (M16) | 971.5 (M07/5) |
| 76 | 1 to 4 Out | 1.000008 | 46.2 | 69.34 | 7614.2 (M08) | 959.1 (M07/5) |
| 87 | 4 to 7 In | 1.000003 | 0 | 43.79 | 7340.9 (M16) | 909.3 (M07/5) |
| 87 | 1 to 3 Out | 0.999997 | 26.4 | 68.98 | 7293.1 (M15) | 901.2 (M07/5) |
| 91 | 3 to 7 In | 0.999997 | 0 | 44.37 | 7011.5 (M07) | 885.6 (M17/5) |
| 91 | 1 and 2 Out | 1.000003 | 31.2 | 68.02 | 6867.3 (M07) | 863.4 (M07/5) |
| 95 | 2 to 7 In | 1.000003 | 0 | 44.37 | 6874.4 (M18) | 837.4 (M05/5) |
| 95 | Bk 1 Out | 1.000003 | 43.2 | 68.59 | 6719.3 (L18) | 823.8 (L18/5) |
| 100 | All In | 1.000004 | 0 | 52.84 | 6581.4 (M18) | 777.6 (M19/5) |
| 100 | | 0.999995 | 90 | 84.30 | 6814.4 (S14) | 816.5 (T10/5) |
| 100 | | 1.000009 | 90 | 84.70 | 7371.8 (S13) | 891.8 (T10/5) |
| 100 | | 0.999996 | 90 | 78.10 | 7493.5 (T13) | 907.6 (T10/5) |
| 100 | | 1.000003 | 90 | 76.09 | 7022.4 (S13) | 841.9 (T10/5) |
| 100 | | 1.000000 | 90 | 75.76 | 6498.7 (E10) | 764.0 (T10/5) |
| 100 | | 1.000002 | 90 | 73.95 | 6502.3 (M18) | 760.6 (M19/5) |
| 100 | | 1.000000 | 90 | 69.07 | 6531.5 (M18) | 762.6 (M19/5) |

Table 5. Simulation Results for Startup After Short Shutdown Using Alternative Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) (Normalized to full power) |
|---|---|---|---|---|---|---|
| 0 | None In | 1.000002 | 40.56 | 20.00 | 8163.4 (L12) | 1027.6 (L11/8) |
| 56 | 1-7 Out | 1.000005 | 63 | 69.14 | 9052.2 (M10) | 1210.4 (M11/5) |
| 65 | BK 7 In | 1.000018 | 0 | 52.06 | 8498.7 (M09) | 1115.4 (M13/5) |
| 65 | 1-6 Out | 1.000005 | 12 | 69.14 | 8737.3 (M14) | 1160.3 (M13/5) |
| 68 | 6, 7 In | 0.999992 | 0 | 28.09 | 8017.2 (M14) | 1085.8 (M09/5) |
| 68 | 1-5 Out | 1.000008 | 34.2 | 71.03 | 8394.5 (M14) | 1155.0 (M09/5) |
| 76 | 5, 6, 7 In | 0.999990 | 0 | 30.23 | 7835.6 (M15) | 985.1 (M07/5) |
| 76 | 1 to 4 Out | 1.000000 | 34.2 | 69.01 | 7969.7 (M15) | 1005.4 (M07/5) |
| 87 | 4 to 7 In | 1.000001 | 0 | 38.95 | 7532.4 (M15) | 935.8 (M07/5) |
| 87 | 1 to 3 Out | 1.000004 | 24 | 69.52 | 7606.3 (M15) | 944.8 (M07/5) |
| 91 | 3 to 7 In | 0.999993 | 0 | 41.91 | 7173.6 (M15) | 920.7 (M07/5) |
| 91 | 1 and 2 Out | 1.000000 | 26.4 | 68.58 | 7147.5 (M15) | 908.4 (M07/5) |
| 95 | 2 to 7 In | 0.999997 | 0 | 42.46 | 6858.1 (M17) | 842.0 (M05/5) |
| 95 | Bk 1 Out | 1.000000 | 35.4 | 69.16 | 6762.3 (M18) | 838.2 (M05/5) |
| 100 | All In | 1.000003 | 0 | 38.24 | 6593.2 (N18) | 773.6 (O05/5) |
| 100 | | 1.000002 | 90 | 77.07 | 6477.5 (S14) | 768.5 (T10/5) |
| 100 | | 0.999999 | 90 | 81.54 | 6641.1 (S14) | 791.7 (T10/5) |
| 100 | | 1.000003 | 90 | 79.29 | 6630.1 (S14) | 788.7 (T10/5) |

Table 6. Simulation Results for Startup After a Poison-Out Shutdown Using Current Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) (Normalized to full power) |
|---|---|---|---|---|---|---|
| 0.0001 | All Bk In | 0.925781 | 600 | 50.00 | 6255.8 (E14) | 690.5 (S14/10) |
| 0.0001 | | 0.945682 | 600 | 50.00 | 6282.0 (E14) | 679.4 (E14/3) |
| 0.0001 | | 0.975099 | 600 | 50.00 | 6322.9 (E14) | 696.4 (F15/4) |
| 0.0001 | All Bk Out | 1.000110 | 342 | 50.00 | 8008.6 (L10) | 1005.3 (L13/8) |
| 56 | | 1.000111 | 3.24 | 69.98 | 7933.0 (M13) | 1004.7 (L13/8) |
| 65 | BK 7 In 1-6 Out | 1.000118 | 0 | 35.37 | 7335.1 (M15) | 891.5 (M09/5) |
| 65 | | 1.000112 | 5.55 | 70.16 | 7575.0 (M15) | 935.3 (M09/5) |
| 68 | 6, 7 In 1-5 Out | 1.000119 | 0 | 39.56 | 7167.6 (M16) | 885.7 (M14/8) |
| 68 | | 1.000111 | 5.55 | 69.80 | 7337.5 (L15) | 921.6 (M09/5) |
| 76 | 5, 6, 7 In 1 to 4 Out | 1.000116 | 0 | 42.37 | 7093.4 (M16) | 835.6 (M07/5) |
| 76 | | 1.000113 | 5.1 | 69.09 | 7071.1 (L16) | 844.8 (M07/5) |
| 87 | 4 to 7 In 1 to 3 Out | 1.000104 | 0 | 48.58 | 6857.6 (M16) | 799.3 (M07/5) |
| 87 | | 1.000115 | 4.02 | 69.84 | 6867.0 (M16) | 808.2 (M07/5) |
| 91 | 3 to 7 In 1 and 2 Out | 1.000111 | 0 | 48.57 | 6675.8 (M17) | 800.4 (M17/5) |
| 91 | | 1.000103 | 4.26 | 69.64 | 6586.1 (M07) | 789.6 (L06/5) |
| 95 | 2 to 7 In Bk 1 Out | 1.000110 | 0 | 48.77 | 6658.8 (M18) | 771.3 (M18/8) |
| 95 | | 1.000113 | 4.26 | 69.33 | 6580.9 (L18) | 773.2 (L18/5) |
| 100 | All In | 1.000110 | 0 | 55.13 | 6444.6 (M18) | 731.2 (M07/4) |
| 100 | | 1.000119 | 2.88 | 70.18 | 6415.2 (S14) | 732.9 (M19/5) |
| 100 | | 1.000111 | 1.62 | 80.00 | 6490.6 (S14) | 744.6 (T10/5) |

Table 7. Simulation Results for Startup After a Poison-Out Shutdown Using Alternative Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) (Normalized to full power) |
|---|---|---|---|---|---|---|
| 0.0001 | All Bk In | 0.925781 | 600 | 50.00 | 6255.8 (E14) | 690.5 (S14/10) |
| 0.0001 | | 0.945682 | 600 | 50.00 | 6282.0 (E14) | 679.4 (E14/3) |
| 0.0001 | | 0.975099 | 600 | 50.00 | 6322.9 (E14) | 696.4 (F15/4) |
| 0.0001 | All Bk Out | 1.000110 | 342 | 50.00 | 8008.6 (L10) | 1005.3 (L13/8) |
| 56 | | 1.000111 | 3.24 | 69.98 | 7933.0 (M13) | 1004.7 (L13/8) |
| 65 | BK 7 In 1-6 Out | 1.000117 | 0 | 57.44 | 7740.0 (M14) | 957.4 (M09/5) |
| 65 | | 1.000119 | 1.95 | 70.46 | 7820.8 (M14) | 972.1 (M09/5) |
| 68 | 6, 7 In 1-5 Out | 1.000102 | 0 | 37.97 | 7295.9 (M08) | 920.5 (M09/5) |
| 68 | | 1.000113 | 5.19 | 69.61 | 7512.9 (L08) | 962.5 (M09/5) |
| 76 | 5, 6, 7 In 1 to 4 Out | 1.000103 | 0 | 39.45 | 7137.3 (M16) | 848.8 (M07/5) |
| 76 | | 1.000109 | 5.22 | 69.73 | 7250.9 (M15) | 868.8 (M07/5) |
| 87 | 4 to 7 In 1 to 3 Out | 1.000110 | 0 | 46.39 | 6907.6 (M15) | 813.0 (M07/5) |
| 87 | | 1.000108 | 4.02 | 69.86 | 7007.7 (M15) | 827.7 (M07/5) |
| 91 | 3 to 7 In 1 and 2 Out | 1.000108 | 0 | 46.91 | 6684.9 (M07) | 807.7 (M07/5) |
| 91 | | 1.000110 | 4.26 | 70.51 | 6703.8 (M15) | 810.8 (L16/5) |
| 95 | 2 to 7 In Bk 1 Out | 1.000099 | 0 | 48.17 | 6627.9 (M18) | 770.9 (M18/8) |
| 95 | | 1.000110 | 4.26 | 70.27 | 6589.0 (M18) | 776.9 (M05/5) |
| 100 | All In | 1.000127 | 0 | 42.53 | 6447.3 (S10) | 737.9 (P08/4) |
| 100 | | 1.000115 | 5.34 | 69.86 | 6412.3 (S09) | 732.5 (M19/5) |
| 100 | | 1.000116 | 1.62 | 79.66 | 6482.5 (S14) | 743.9 (T10/5) |

Table 8. Simulation Results for Shim Operation Using Current Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step | Average Zone Level (%) | MCP(kW) MBP(kW) (Normalized to full power) | |
|---|---|---|---|---|---|---|
| 100 | All In | 1.002362 | Steady State | 20.00 | 6601.8 (S12) | 767.1 (P08/4) |
| 94 | Bk 1 Out | 1.002360 | 0 | 34.00 | 6722.5 (M18) | 796.8 (M05/5) |
| 94 | | 1.002364 | 4.0 hr | 22.51 | 6697.0 (M18) | 795.2 (M18/8) |
| 94 | | 1.003600 | SS | 19.86 | 6654.5 (M18) | 786.2 (M18/8) |
| 87 | Bk 1-2 Out | 1.003600 | 0 | 40.62 | 6758.5 (M05) | 830.8 (M05/5) |
| 87 | | 1.003597 | 4.0 hr | 27.27 | 6821.3 (M18) | 839.4 (M17/5) |
| 87 | | 1.005504 | SS | 19.55 | 6756.6 (M18) | 826.8 (M05/5) |
| 82 | Bk 1-3 Out | 1.005491 | 0 | 40.01 | 6926.5 (N16) | 830.0 (M06/8) |
| 82 | | 1.005494 | 4.0 hr | 30.11 | 6935.4 (N16) | 833.7 (M06/8) |
| 82 | | 1.007301 | SS | 20.02 | 6918.4 (N07) | 829.8 (M06/8) |
| 79 | Bk 1-4 Out | 1.007303 | 0 | 38.67 | 7211.2 (M16) | 873.6 (M17/5) |
| 79 | | 1.007300 | 4.0 hr | 33.79 | 7252.3 (M16) | 885.7 (M17/5) |
| 79 | | 1.008993 | SS | 19.48 | 7233.5 (M07) | 877.5 (M06/8) |
| 68 | Bk 1-5 Out | 1.009004 | 0 | 43.67 | 7350.6 (M07) | 923.6 (N08/5) |
| 68 | | 1.008995 | 4.0 hr | 14.59 | 7283.6 (M07) | 930.5 (N08/5) |
| 68 | | 1.011209 | SS | 19.90 | 7287.6 (M07) | 915.4 (M07/5) |
| 61 | Bk 1-6 Out | 1.011191 | 0 | 46.69 | 7583.6 (M08) | 937.8 (M08/8) |
| 61 | | 1.013417 | SS | 19.98 | 7401.0 (M08) | 909.5 (M08/8) |
| 52 | All Bks Out | 1.013445 | 0 | 54.36 | 7881.5 (M09) | 997.8 (M13/5) |
| 52 | | 1.016019 | SS | 20.07 | 7680.5 (N09) | 968.3 (N10/5) |

Table 9. Simulation Results for Shim Operation Using Alternative Adjuster Banking Scheme

| Power Level for Xenon (% FP) | Adjuster Banks | k-eff | Xenon Time Step | Average Zone Level (%) | MCP(kW) MBP(kW) (Normalized to full power) | |
|---|---|---|---|---|---|---|
| 100 | All In | 1.002362 | Steady State | 20.00 | 6601.8 (S12) | 767.1 (P08/4) |
| 94 | Bk 1 Out | 1.002363 | 0 | 46.80 | 6739.2 (M18) | 806.1 (M05/5) |
| 94 | | 1.002357 | 4.0 hr | 36.56 | 6718.4 (M18) | 808.4 (M05/5) |
| 94 | | 1.004585 | SS | 20.22 | 6654.0 (M18) | 790.4 (M18/8) |
| 87 | Bk 1-2 Out | 1.004591 | 0 | 41.25 | 6767.9 (M17) | 837.2 (M17/5) |
| 87 | | 1.004606 | 4.0 hr | 27.23 | 6818.9 (M17) | 846.4 (M17/5) |
| 87 | | 1.006506 | SS | 19.81 | 6768.8 (M17) | 841.1 (M17/5) |
| 82 | Bk 1-3 Out | 1.006505 | 0 | 41.32 | 6996.3 (N07) | 839.9 (M06/8) |
| 82 | | 1.006491 | 4.0 hr | 31.38 | 6996.0 (N07) | 847.4 (M16/8) |
| 82 | | 1.008404 | SS | 19.09 | 6963.0 (N07) | 834.6 (N06/5) |
| 79 | Bk 1-4 Out | 1.008404 | 0 | 40.63 | 7293.1 (M16) | 888.1 (M07/5) |
| 79 | | 1.008402 | 4.0 hr | 35.95 | 7327.6 (M16) | 898.5 (M07/5) |
| 79 | | 1.010108 | SS | 20.38 | 7281.9 (M07) | 882.0 (M06/8) |
| 68 | Bk 1-5 Out | 1.010097 | 0 | 47.33 | 7509.1 (M08) | 960.8 (M09/5) |
| 68 | | 1.010105 | 4.0 hr | 16.94 | 7462.3 (N08) | 967.6 (N08/5) |
| 68 | | 1.012498 | SS | 19.84 | 7361.7 (N08) | 939.4 (N08/5) |
| 61 | Bk 1-6 Out | 1.012508 | 0 | 50.06 | 7807.3 (M09) | 978.0 (M09/5) |
| 61 | | 1.014795 | SS | 20.13 | 7588.1 (N09) | 944.0 (M09/5) |
| 52 | All Bks Out | 1.014800 | 0 | 30.89 | 7771.5 (M09) | 979.0 (M10/8) |
| 52 | | 1.016014 | SS | 20.51 | 7680.6 (N09) | 968.3 (N10/5) |

Table 10. Simulation Results for Stepback to 60 % FP Using Current Adjuster Banking Scheme

| Adjuster Bank Position | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) |
|---|---|---|---|---|---|
| All In | 1.000063 | 17.1 | 20.00 | 6602.2 (S12) | 764.6 (P08/4) |
| Bk 1 Out | 1.000057 | 0 | 33.90 | 6703.3 (M18) | 791.1 (M18/8) |
| | 1.000068 | 10.2 | 19.52 | 6644.9 (M18) | 781.2 (M18/8) |
| Bk 1-2 Out | 1.000051 | 0 | 40.25 | 6755.5 (M17) | 825.0 (M17/5) |
| | 1.000058 | 18 | 20.17 | 6755.7 (M18) | 823.4 (M17/5) |
| Bk 1-3 Out | 1.000053 | 0 | 40.25 | 6914.6 (M07) | 827.1 (M17/5) |
| | 1.000067 | 26.4 | 19.79 | 6973.5 (N07) | 834.9 (M17/5) |
| Bk 1-4 Out | 1.000047 | 0 | 38.53 | 7265.5 (M16) | 879.9 (M17/5) |
| | 1.000064 | 48 | 20.02 | 7437.8 (M07) | 909.3 (M17/5) |
| Bk 1-5 Out | 1.000078 | 0 | 44.33 | 7520.0 (M16) | 959.9 (L15/8) |
| | 1.000059 | 276 | 68.98 | 7850.7 (L08) | 1047.8 (M09/5) |
| Bk 1-4 Out | 1.000050 | 0 | 36.93 | 7586.1 (M16) | 945.4 (M07/5) |
| | 1.000056 | 228 | 68.48 | 7289.3 (L16) | 906.6 (M16/8) |

Table 11. Simulation Results for Stepback to 60 % FP Using Alternative Adjuster Banking Scheme

| Adjuster Bank Position | k-eff | Xenon Time Step (min) | Average Zone Level (%) | MCP(kW) (Normalized to full power) | MBP(kW) |
|---|---|---|---|---|---|
| All In | 1.000063 | 17.1 | 20.00 | 6602.2 (S-12) | 764.6 (P-08/4) |
| Bk 1 Out | 1.000061 | 0 | 46.77 | 6738.0 (M-18) | 802.4 (M-18/8) |
| | 1.000069 | 21 | 19.08 | 6638.8 (M-18) | 784.7 (M-18/8) |
| Bk 1-2 Out | 1.000054 | 0 | 40.38 | 6752.0 (M-17) | 832.7 (M-17/5) |
| | 1.000059 | 22.2 | 19.81 | 6781.7 (M-17) | 844.8 (M-17/5) |
| Bk 1-3 Out | 1.000050 | 0 | 41.17 | 6996.0 (M-07) | 842.2 (M-07/5) |
| | 1.000059 | 37.8 | 20.14 | 7068.6 (N-07) | 852.4 (M-07/5) |
| Bk 1-4 Out | 1.000051 | 0 | 42.09 | 7409.1 (M-07) | 912.3 (M-07/5) |
| | 1.000056 | 375 | 68.93 | 7636.4 (M-15) | 958.6 (M-07/5) |
| Bk 1-3 Out | 1.000066 | 0 | 41.01 | 7242.5 (M-15) | 894.1 (M-16/8) |
| | 1.000059 | 210 | 68.84 | 7219.2 (M-15) | 878.9 (M-16/8) |

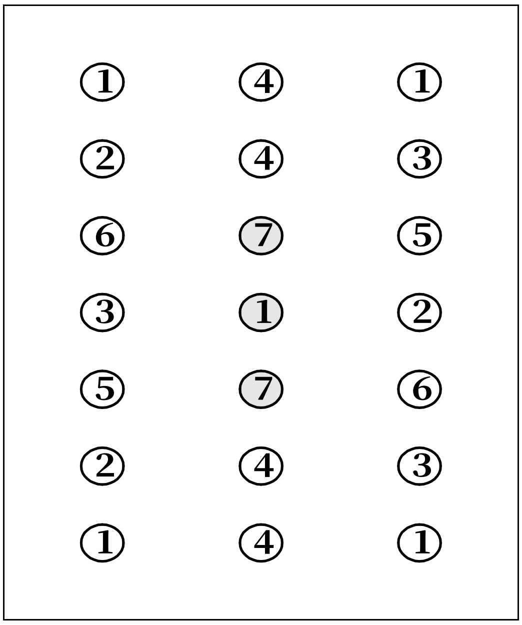


Figure 1.  Current Adjuster Bank System in CANDU-6 Reactor

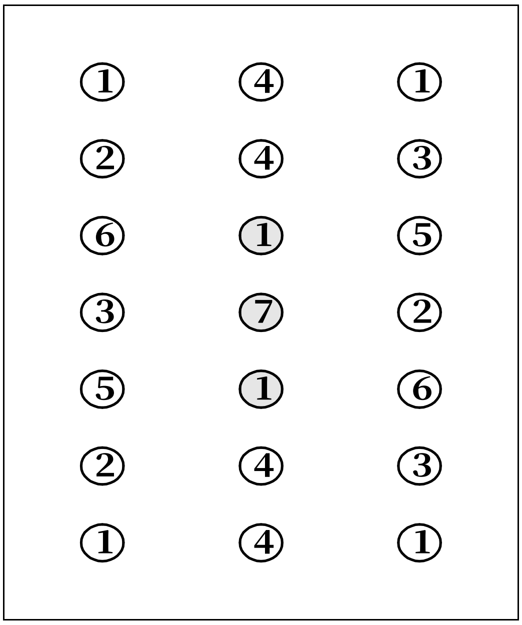


Figure 2.  Alternative Adjuster Bank System in CANDU-6 Reactor