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THE MODIFICATION OF FUELLING FREQUENCY AND THE USE OF BURNABLE ABSORBERS IN CANDU REACTORS

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ABSTRACT – As CANDU reactors age, operational margins have narrowed. Power ripples that result from the insertion of fresh fuel constantly challenge the limit of these boundaries. To address the situation, this study has altered the conventional fuelling scheme in an iterative fashion, with the addition of 8 bundle shift rings to reduce the fuelling frequency, and thus the demand on fuelling machines. Both NU and NU laced with BNAs were considered. Results indicated that both the absolute maximum channel power and LZC fill fractions were reduced when 150 mg of Gd_2O_3 was added to NU fuel; these findings were unanimous for the various fuelling schemes considered.

1. State of the Art

1.1 Mechanical and Safety Hazards Associated with Fuelling Machines

Though fuelling machines fulfill a critical role in the safe and efficient operation of a CANDU reactor, they also create ongoing disruptions and safety hazards. Premature wear and/or failure of key components and support equipment can result in the need for unscheduled or excessively frequent overhauls and repairs[7]. In extreme cases, power reactors were forced to shut down for weeks at a time because the fuelling machines were not available to maintain the core reactivity when LZC levels were already below 20%. This often results in financial penalties to both the nuclear power plant and the province[10]. Furthermore, during every refuelling cycle, approximately 1 L of D_2O is spilled. Resultantly, the ambient air in both the fuelling machine vaults and the boiler room can be contaminated with levels of tritiated water vapour up to 50 μSv/h under normal conditions. Though design improvements to minimize the spills have been made, there is still an inherent radiation exposure risk to nuclear workers[6].

Refuelling is the primary method of maintaining both core criticality and an even power distribution in the reactor. Since the CANDU industry favours the use of NU fuel, the refuelling process must occur daily for nuclear utilities to satisfy the conditions of their energy output agreements. However, as fuelling machines age and experience frequent breakdowns, plant authorities must either hasten the repair of the machine or de-rate power output. Both options prove to be economically unfavourable for the station, and thus the fuel management plan for the reactor should be reviewed and adjusted to suit the current disposition of the aging CANDU reactors that are currently employed in the nuclear industry.

1.4 Liquid Zone Controllers

Thoughtful consideration must be given to the location of refuelling because the insertion of fresh fuel creates power ripples (the ratio of the peak transient channel power to the steady state channel power) and can often bring the reactor very close to safe operating limits. As a result, reactivity control devices, such as liquid zone controllers must often be engaged to keep channel power within the safe operating envelope.

Liquid Zone Controllers provide immediate response to a power ripple, and they deliver excellent bulk and spatial reactivity control. However, a dependency on LZCs is not favoured as they impart a significant detriment to the economy of neutrons within the core.

2. Key Message

Fuel safety and performance management are of primary interest to the nuclear industry. This unique study of reducing the fuelling machine usage through the employment of a different fuelling scheme in combination with natural uranium (NU) doped with BNAs in the conventional CANDU fuel bundle, offers the benefit of improving safety margins, fuel consumption, and operational flexibility to compensate for fuelling machine outages.

3. Background

3.1 Adding BNAs to CANDU Fuel

In the study conducted by Chan *et al*[1], BNAs were introduced to the CANDU fuel bundle to diminish both the fuelling transient and the plutonium peak. This was a brave approach as neutron conservation in a NU-fuelled CANDU reactor is of primary concern. It was proven that when a mixture of Gd_2O_3 and Eu_2O_3 is added to the 24 kg CANDU fuel bundle, that both the fuelling transient and the subsequent plutonium peak can be lowered to improve the reactor's operating margins.

3.2 Steady State Operation of a CANDU with BNA Fuel

A subsequent study conducted by Song *et al*[2], examined the impact on steady state operation when a CANDU reactor is fuelled with the Burnable Neutron Absorber Fuel (BNAF) created by Chan *et al*[1]. Through the employment of a fuel management program called Refuelling Simulation Program (RFSP-IST) it was proven that the use of a BNAF with the reference fuelling scheme in a CANDU reactor reduces reactor power without penalizing fuel burnup.

A significant reduction in the average LZC fill fraction was also observed. This desirable effect proved the sophistication of the BNAF fuel design, as the gadolinium served to suppress the initial fuelling transient, and the longer-lived europium stifled the plutonium peak. Essentially, CANDU on-power fuelling became more influential than the use of reactivity suppression devices, and the approximate 6 mk of reactivity worth provided by the 14 LZCs was essentially 'banked'.

3.6 The Replacement of Europium Oxide

In subsequent studies conducted by Paquette *et al* (work to be formally published[3]), it was determined that boron oxide is favourable over europium oxide for long-term reactivity control.

On average, an approximate 2.25 – 4.5 kW gain in operating margin was observed through the use of B_2O_3. Its use has therefore become more favourable over that of Eu_2O_3.

4. Objectives

4.1 Intent

The objectives of this study are to observe the behaviour of a CANDU core when modest, and cumulative augmentations to the conventional fuelling scheme are made with 8-bundle-shifts. The CANDU core will be studied with natural uranium and NU with 150 mg Gd_2O_3. It is speculated that BNAs can increase the dwell time of a fuel bundle in the reactor. Therefore, fuelling rates could be reduced without penalty to bundle power, channel power and average discharge burnup when BNAF fuel is used in the CANDU reactor.

4.2 Overview of Study

The behaviour of the entire CANDU core will be observed with the fuel management program, RFSP-IST with LZCs allowed to fluctuate. Comparisons will be made against the predictions created with the WIMS-AECL tool. The performance of the core over an extended period of time will be studied to determine if gains in both fuel burnup and operating margins can be realized and if a reduction in fuelling machine usage can be achieved, when different fuelling schemes were considered.

5. Methodology

5.1 WIMS Calculations

The lattice cell is modeled using the Winfrith Improved Multigroup Scheme-Atomic Energy of Canada Limited (WIMS-AECL) lattice-depletion code. WIMS-AECL, Version 3.1 is a two-dimensional multi-group neutron transport code capable of applying leakage corrections and performing fuel burn-up routines for multi-cell lattices. This deterministic code is well suited for flux distribution calculations and establishes the reactivity of a nuclear reactor by solving the integral form of the neutron transport equation[4].

For Case One of this study, natural uranium will be examined, so the CANLUB is not doped with BNAs. WIMS calculations will be performed to confirm the results obtained in previous studies.

In Case Two, the CANLUB layer will be supplemented with 150 mg of Gd_2O_3. The intent is to study the impact on bundle power, channel power and average discharge burnup when the CANDU reactor is refuelled with BNA fuel using various refuelling schemes.

5.2 Refuelling Simulation Program

RFSP-IST is a fuel management program designed to perform physics calculations for CANDU reactors. Its main function is to calculate neutron flux and power distributions using a two-group, three-dimensional neutron diffusion theory. RFSP-IST can calculate both instantaneous and time-averaged flux and power distributions [5].

The core-following study for both cases of this examination will be conducted using a generic set of refuelling history. This dataset was created based the regular 37-element NU fuel. Every 0.25 FPD, the instantaneous core state is logged and its data is analyzed using a refuelling algorithm (written in MATLAB by J. Song *et al*[2]) to decide if refuelling is necessary. A list of potential channels is created, and scores are assigned to each channel based on parameters such as accumulated burnup and power readings. Based on the results of the score, the algorithm decides when refuelling is required, and which channel should be refuelled. The MATLAB/RFSP program also ensures that the desired (reference target) core state for normal operation is maintained at all times. Additionally, the refuelling history is generated with LZCs at fixed positions, such that the refuelling algorithm will attempt to flatten the flux profile of the core without the assistance from the LZCs[2].

Both cases will be trialed with the reference fuelling scheme that is currently used in a CANDU reactor (Figure 1). Bundle power, channel power and average discharge burnup results for this fuelling scheme will be collected using the MATLAB/RFSP program and compared with data obtained in previous studies.

The conventional fuelling scheme will then be carefully altered with the modest and balanced addition of eight bundle shifts to the periphery of the CANDU core. Examples of these changes are reflected in Figures 8 and 9. All cases will be subjected to the new fuelling scheme using the MATLAB/RFSP program, and the impact on bundle power, channel power, average discharge burnup and rate of fuelling will be studied.

0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0
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Figure 1: Reference CANDU Fuelling Scheme conventionally used

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Figure 2: Reference Fuelling Scheme augmented with 8-bundle shifts in the periphery

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0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0

Figure 3: Trial #2: Further modifications to the CANDU Reference Fuelling Scheme

6. Results and Discussion

6.1 WIMS Calculations

150 mg of Gd_2O_3 was added to the CANLUB coating, and using WIMS-AECL, the criticality of the CANDU core was studied over a period of 180 days. As depicted in Figure 4, the classic fuelling transient that is experienced with NU fuel has been removed. This is not a novel observation; it just merely confirms the results obtained in previous studies.

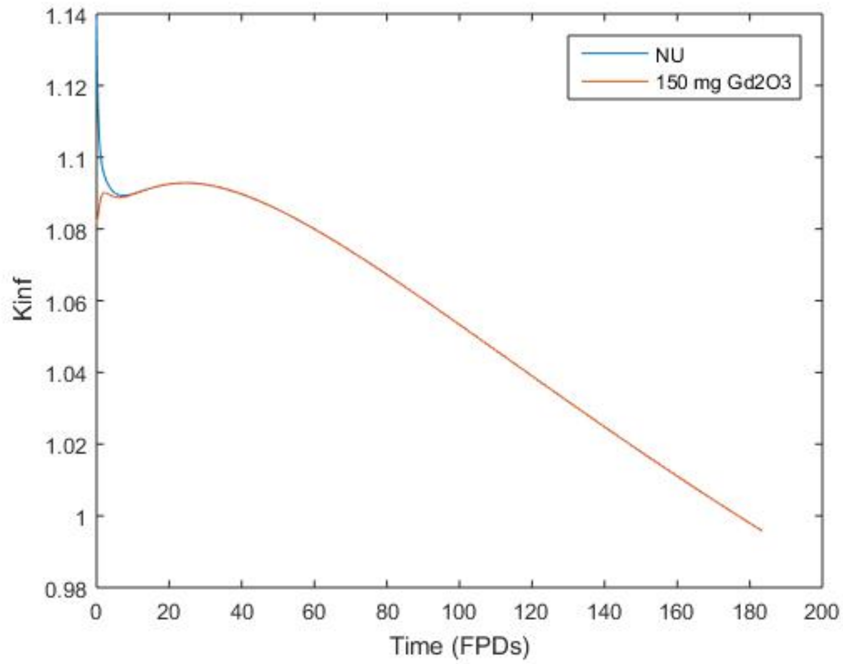

Figure 4: K_{inf} vs. Time for NU with 150 mg Gd_2O_3

The lattice calculations indicate the behavior that is likely to be observed in the core under normal operating conditions. Now, thoughtful changes must be made to the conventional fuelling scheme if the flux shape of the core is to be flattened. It will be important that the integrity of the new flux shape is preserved so that power does not peak above operational limitations. The alterations to the fuelling scheme will also help to reduce the use of the very finicky fuelling machine.

6.2 Refuelling Simulations

The initial core at t=0 FPD is an equilibrium core containing only NU fuel bundles. Three 500 FPD core following studies were conducted using the MATLAB-RFSP program created by Song *et al*[2] using natural uranium in the first case, and NU with 150 mg of Gd_2O_3 in the second case. The conventional fuelling scheme was used in all instances, the fuelling frequency remained constant at four times per day, and the LZCs were allowed to respond without restriction. The results have been tabulated in Table 1 below. Though little change in the average discharge burnup was noted, it can be seen that the absolute maximum channel power was reduced by 81 kW when natural uranium fuel was doped with 150 mg of gadolinium oxide, and LZC fill fractions were reduced slightly.

Reference Fuelling Scheme			
	NU	Gd_2O_3	Difference
Mean Exit Burnup [MW-h/KgU]	194.7	194.8	+0.1
Average Max Bundle Power [kW]	820	805.3	-14.7
Max Bundle Power [kW]	859	853	-6
Average Max Channel Power [kW]	6589.8	6571.7	-18.1
Max Channel Power [kW]	6914	6833	-81
CPPF	1.161	1.157	-0.004
Average LZC Fill [%]	42.0	33.7	-8.3

Table 1: Core following for 500 FPD with Reference Fuelling scheme

Keeping the fuelling frequency steady at four times per day, and allowing the LZCs to react without restriction, both natural uranium and NU with 150 mg of gadolinium oxide were subjected to a 500 FPD core following study using the Trial #1 fuelling scheme, as depicted in Figure 2 above. The absolute maximum channel power was reduced by 68 kW when natural uranium was augmented with 150 mg of Gd_2O_3.

Trial #1 Fuelling Scheme (see Figure 8)			
	NU	Gd_2O_3	Difference
Mean Exit Burnup [MW-h/KgU]	194.0	194.0	0
Average Max Bundle Power [kW]	809.1	807.3	-1.8
Max Bundle Power [kW]	865	863	-2
Average Max Channel Power [kW]	6600.4	6589.5	-10.9
Max Channel Power [kW]	6929	6861	-68
CPPF	1.169	1.162	-0.007
Average LZC Fill [%]	42.4	36.1	-6.3

Table 2: Core following for 500 FPD with Trial #1 fuelling scheme

Table 4 depicts the results collected from a 500 FPD core following study conducted with both natural uranium and NU with 150 mg of gadolinium oxide using the Trial #2 fuelling scheme displayed in Figure 3 above. Like previous trials, the fuelling frequency remained unchanged at four times per day, and the LZCs were unrestricted.

With the exception of the absolute maximum channel power, there were no outstanding differences noted with this trial. The maximum channel power was reduced by 82 kW when the CANDU reactor was fuelled with a mixture of natural uranium and gadolinium oxide. However, the absolute channel power continues to increase for both the natural uranium and gadolinium cases as more 8-bundle shifts are added to the fuelling scheme. Though this is undesirable, the results remain consistent with known nuclear theories and phenomenon.

Trial #2 Fuelling Scheme (see Figure 9)			
	NU	Gd_2O_3	Difference
Mean Exit Burnup [MW-h/KgU]	192.9	194.8	+1.9
Average Max Bundle Power [kW]	812	807.1	-4.9
Max Bundle Power [kW]	871	861	-10
Average Max Channel Power [kW]	6619.7	6604.9	-14.8
Max Channel Power [kW]	6979	6897	-82
CPPF	1.179	1.164	-0.015
Average LZC Fill [%]	47.4	40.0	-7.4

Table 3: Core following for 500 FPD with Trial #2 Fuelling Scheme

In each NU trial, the absolute maximum channel power increases dangerously close to the channel power limit of 7000 kW, which is not in line with the objectives of this study. Trials #1 and #2 clearly demonstrate that there are no operational advantages to be gained for the employment of these fuelling schemes, using NU fuel, with a fuelling frequency of four times per day.

For the NU fuel containing gadolinium oxide case, the absolute maximum channel power has increased from Trial #1 to Trial #2 by 28 kW. This observed rise could be attributable to the increase in mass of fissile U^{235}. When this 8-bundle shift is inserted into the center of the core, for example, it will reside in regions of higher axial power and flux. Though the neutron absorbers in both the resident and fresh fuel serve to supress the initial fuelling transient, their lifespan does not extend to subdue the subsequent plutonium peak, which will naturally be larger due to the influx of fresh fuel to an area rich in thermal neutrons.

Overall, the channel power and use of the LZCs is reduced when natural uranium is doped with 150 mg of gadolinium oxide. Furthermore, a slight gain in the average discharge burnup is also observed. Aside from these slightly interesting conclusions, no other arguments can be made in favour of the employment of either Trial #1 or Trial #2's fuelling scheme. Perhaps the flux in the periphery of the core is too low for the 8-bundle shift augmentation to significantly influence the global core physics parameters.

It was also realized that the start-state of the MATLAB/RFSP program is with an equilibrium, natural uranium core. Thus, during the 500 FPD of this study, the CANDU reactor is gradually transitioned from a NU core to one that is fuelled with natural uranium and burnable absorbers. Furthermore, it was recalled that it could take up to 3 years, or 1095 FPDs for some selected bundles in the reactor to be replaced. As mentioned above, the flux in the periphery of the core is somewhat lower than in the center. Thus, it could take longer for fuel bundles in the periphery of the core to accumulate the burnup required to warrant replacement. Therefore, it is very unlikely that all fuel bundles in the periphery were replaced during the 500 FPD of study, meaning that the effects of augmenting the reference fuelling scheme with more 8-bundle shifts in the periphery might not have been observed. This could account for the results achieved so far in this study.

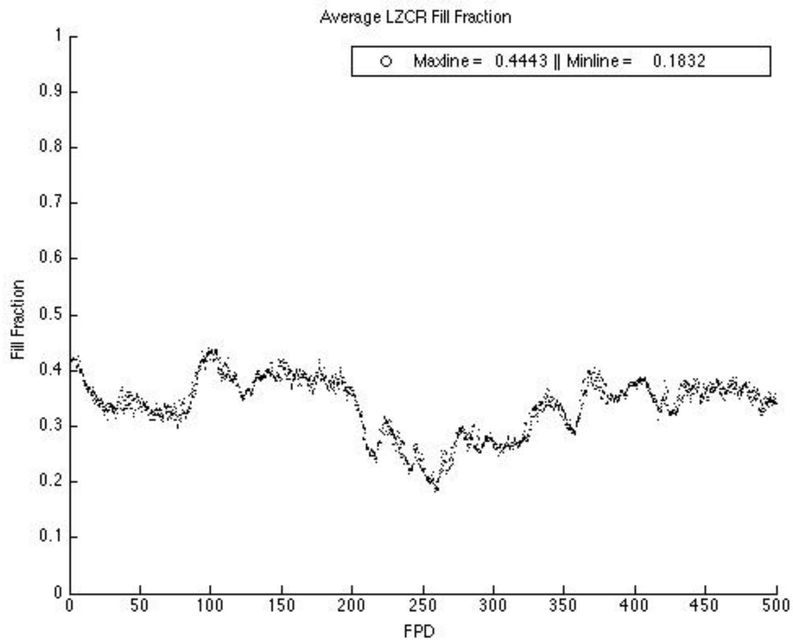

Figure 4: Average LZC Fill for 150 mg Gd_2O_3

Figure 4 depicts the reaction of the LZCs during the transition of the CANDU core from one fuelled only with natural uranium, to one fuelled with NU and BNAs. Utilizing the reference fuelling scheme, it can be seen that the transitional period lasts for approximately 360 FPDs, and afterwards a new equilibrium is established. It was asserted that it could take approximately 1100 FPDs to observe any perturbation from the insertion of more 8-bundle shifts to the periphery. Therefore, the results reported above could differ if the study were carried out for an additional 600 FPD, as the effects of the 8-bundle shift increase would be captured.

A fuelling frequency map was also created from the log of Trial #1 executed with 150 mg of Gd_2O_3.

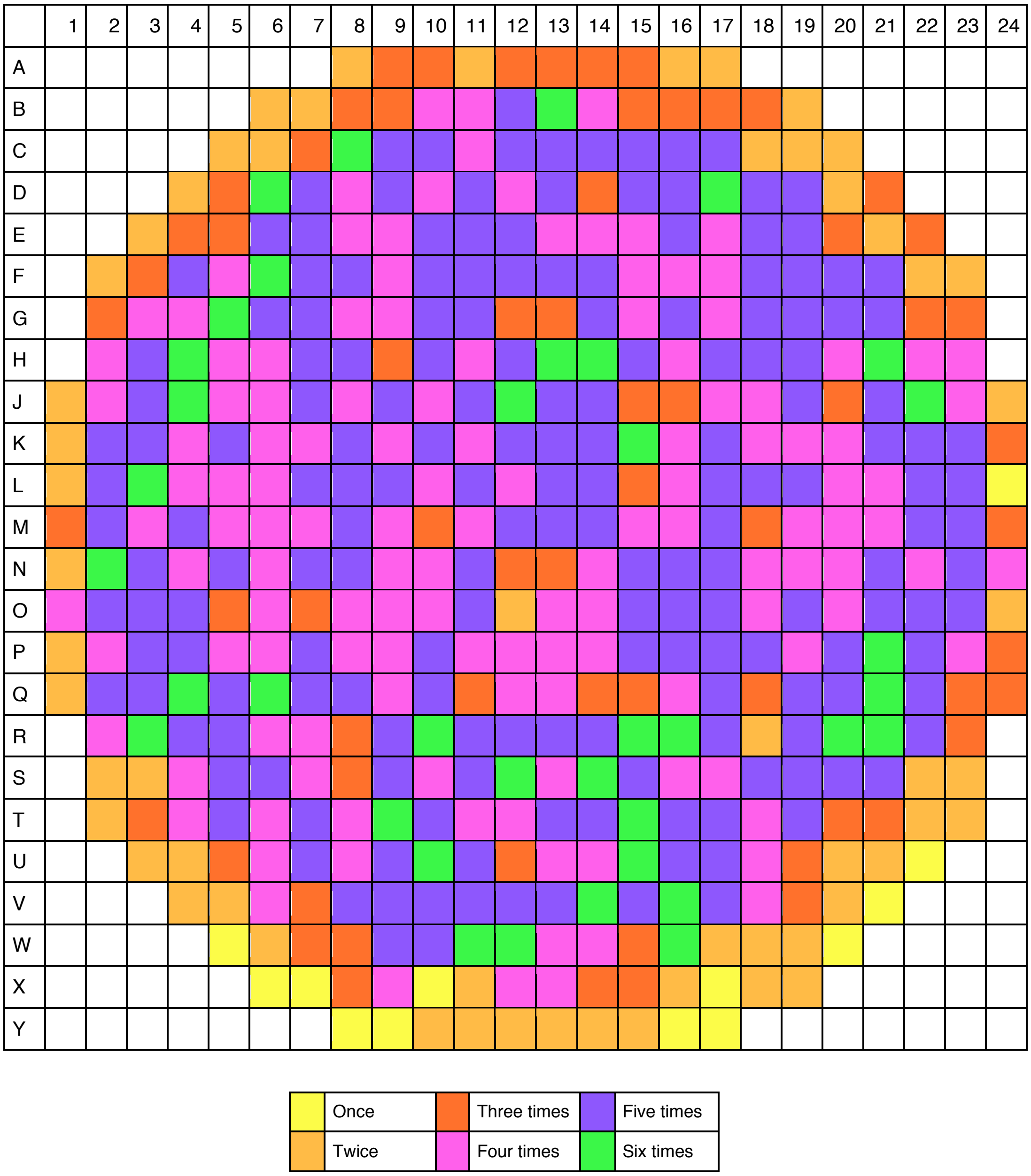

Figure 5: Refuelling Map for Trial #1 with 150 mg of Gd_2O_3 after 500 FPD

Figure 5 depicts the number of times a particular channel was refuelled during the 500 FPD study. It is clear that all of the peripheral channels modified with 8-bundle shifts (channels L-1, M-1, N-1, O-1, L-24, M-24, N-24 and O-24) were fuelled between one and four times. Thus, extending ensuing trials by 600 FPDs is unnecessary as all channels of interest are fuelled at least once, and a new equilibrium is established during the period of observation.

So far, 8-bundle shifts have been added to the periphery of the core, in an area of low flux. When these channels are refuelled, perhaps the perturbation is so minor that noteworthy changes to global reactivity, power and burnup are very minute. Therefore, subsequent trials will have to be executed with significantly more 8-bundle shifts in the periphery to observe changes to both the channel power and fuelling frequency. Conversely, it could be advantageous to consider adding 8-bundle shifts to the center of the reactor. Both power and flux is higher in this area of the core. Therefore, even conservative modifications to the fuelling scheme will have a significant impact on the physics parameters of the reactor. It is assumed that altering the fuelling mode in the center of the core will only work if BNAs are added to NU fuel. Adding more 8 bundle shifts of natural uranium fuel to the center of the core will rapidly accelerate reactivity and channel power values beyond compliance limits and will invariably initiate a reactor trip. This postulation will be tested in consequent simulations.

6.2.1 Refuelling From the Inside-Out

0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0
0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0
0	0	0	0	8	8	8	8	8	8	4	4	4	4	8	8	8	8	8	8	0	0	0	0
0	0	0	8	8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	8	8	0	0	0
0	0	8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8	0	0
0	8	8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8	8	0
0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
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8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	4	8	8	4	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	4	8	8	4	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	4	8	8	4	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	4	8	8	4	4	4	4	4	4	4	4	4	4	8
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0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
0	8	8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8	8	0
0	0	8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8	0	0
0	0	0	8	8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	8	8	0	0	0
0	0	0	0	8	8	8	8	8	8	4	4	4	4	8	8	8	8	8	8	0	0	0	0
0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0
0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0

Figure 6: Trial #3 Fuelling scheme; fuelling from inside-out

Figure 6 depicts the new fuelling scheme used to study any perturbations that the addition of 8-bundle shifts will impose on the core. The fuelling scheme was first employed with NU fuel with a fuelling frequency of four times per day and LZCs allowed to fluctuate at will. As expected, the average maximum channel power increased by 33.5 kW, in comparison to the reference case. The increase in power results from the large amount of reactivity inserted in both the periphery and center of the core via 8-bundle shifts. To compensate for this increase in reactivity, control devices responded to keep the reactor within regulation. Trial #3 proved to be successful as the reactor remained within safe limitations without a significant dependency on the LZCs. The average discharge burnup also remained quite high at a value of 194.8 MW-h/KgU. No alarming results were obtained for the NU case; therefore, this fuelling scheme could be considered for employment in the CANDU industry.

Trial #3			
	NU	Gd_2O_3	Difference
Mean Exit Burnup [MW-h/KgU]	194.8	194.8	0
Average Maximum Bundle Power [kW]	807.1	805.3	-1.8
Maximum Bundle Power [kW]	861	853	-8
Average Maximum Channel Power [kW]	6604.9	6589.8	-15.1
Maximum Channel Power [kW]	6897	6833	-64
CPPF	1.164	1.157	-0.007
Average LZC Fill [%]	40.0	33.7	-6.3

Table 4: Core following study for 500 FPD with Trial #3 fuelling scheme

Trial #3 was repeated with NU fuel doped with 150 mg of Gd_2O_3. The average discharge burnup was identical in comparison to the NU case; however, the average maximum channel power was approximately 15 kW less, the absolute maximum channel power was reduced by 64 kW, and the average LZC fill was only 33.7% when the reactor is fuelled with Gd_2O_3. This proves that gadolinium oxide has successfully suppressed the fuelling transient and lowered the channel power by keeping the LZCs within a reasonable limit.

Overall, the results of Trial #3 have proven that a CANDU core responds in a kinder fashion to more 8-bundle shifts in both the periphery and the center of the core with 150 mg of Gd_2O_3 than its NU counterpart. Both the absolute maximum channel power and LZC fill fractions are lower. Since the core reacted in a reasonable manner to the NU case, Trial #4 was concocted to test the response of the CANDU core with more 8-bundle shifts in the center.

0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0
0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0
0	0	0	0	8	8	8	8	8	8	4	4	4	4	8	8	8	8	8	8	0	0	0	0
0	0	0	8	8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	8	8	0	0	0
0	0	8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8	0	0
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0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
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8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	4	4	4	4	4	4	4	4	4	8	8	8	8	4	4	4	4	4	4	4	4	4	8
8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8
0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
0	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	0
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0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0
0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	0	0	0	0	0	0	0

Figure 7: Trial #4 fuelling scheme

Table 5 depicts the dismal results obtained for the NU case. Discharge burnup has declined as fuel is likely being replaced before the optimal burnup can be obtained. The average maximum channel power and the absolute maximum channel power both exceed the limit of 7000 kW by 154.5 kW and 879 kW respectively. This fuelling scheme clearly directs too much reactivity towards the center of the core. Furthermore, for the last 170 FPDs of this study, LZCs were employed at full capacity. Though each of the 14 devices adds 6 mK worth of reactivity suppression, it was not enough to quell the power below regulation values. This is completely unacceptable, and it is obvious that this fuelling scheme is not suited for natural uranium fuel, and further 8-bundle augmentations beyond that of Trial #3 would be futile.

Trial #4			
	NU	Gd_2O_3	Difference
Mean Exit Burnup [MW-h/KgU]	185.0	185.1	+0.1
Average Maximum Bundle Power [kW]	840.6	836.2	-4.4
Maximum Bundle Power [kW]	991	953	-38
Average Maximum Channel Power [kW]	7154.5	7126.6	-27.9
Maximum Channel Power [kW]	7879	7753	-126
CPPF	1.23	1.22	-0.01
Average LZC Fill [%]	87.6	82.1	-5.5

Table 5: Core following study for 500 FPD with Trial #4 fuelling scheme

Trial #4 was executed once again with NU fuel laced with 150 mg of Gd_2O_3. As with previous trials, it was observed that gadolinium oxide reduced the absolute maximum channel power, in this case, by 126 kW.

A trend has emerged from Trials #1 to #4, whereby gadolinium oxide suppresses the channel power and relaxes the use of liquid zone controllers. This has been confirmed in previous studies; however, only with the use of the reference fuelling scheme that is currently employed in the CANDU industry. Trials #1 to #4 have proven that gadolinium continues to perform in a similar fashion independently of its fuelling application. It was also shown that the average discharge burnup marginally improved in all trials. However, as with the NU case, as more 8-bundle shifts were added to the fuelling scheme, the reactor heated up and edged closer to the operational limitations that this study is attempting to broaden. This is due to the fact that the reactor is fuelled four times per day, with increasingly more 8-bundle shifts. Perhaps any of the proposed fuelling schemes would work if the fuelling frequency were reduced below the current norm of four times per day. Trial#4 and with more 8-bundle shifts should be repeated with a reduced fuelling frequency to observe the core behaviour. The use of BNA in NU fuel offers an opportunity in keeping the channel and bundle power limits below the compliance values. It is hoped that channel power can be significantly reduced, and the average LZC fill fraction can be lowered to flow within the accepted range with a decreased use of the fuelling machines.

8. Conclusion

This study furthered the work of both Chan *et al*[1] and Song *et al*[2] by using BNAF with unconventional fuelling schemes to observe the impact on reactor power, LZC fill fraction, burnup and fuelling machine usage.

Results indicated that both the absolute maximum channel power and LZC fill fractions were reduced when 150 mg of Gd_2O_3 was added to NU fuel; these findings were unanimous for the various fuelling schemes considered, with a fixed fuelling frequency of four times per day. The mean discharge burnup of irradiated fuel containing the BNA also increased slightly for all core following studies. This is reassurance that gadolinium oxide reduces both channel power and

LZC levels regardless of the chosen fuelling scheme. Further studies will re-examine the fuelling schemes proposed in this study with a fuelling rate of two times per day with the expectation that gadolinium oxide will successfully broaden the operational envelope of the CANDU reactor, and reduce fuelling machine usage without imposing a penalty to either burnup or LZC usage.

References

[1] P.K. Chan, S. Paquette, and H.W. Bonin, "Variation of Burnable Neutron Absorbers in Heavy Water-Moderated Fuel Lattice: A Potential to Improve CANDU Reactor Operating Margins", Nuclear Technology, 1, 191 (2015)..

[2] J.J. Song, P.K. Chan, H.W. Bonin and S. Paquette, "Fuelling Study of a CANDU Reactor Using Fuels Containing Burnable Neutron", Accepted, Nuclear Technology, MS# NT16-1 (2016).

[3] P.K. Chan, J. Song, S. Paquette and H. Bonin, "Refuelling Simulation Study that Demonstrates Operating Margins for a Fuel Design Containing Burnable Neutron Absorbers", Draft, CANDU Owners Group Report, 2016.

[4] Jonkmans, "WIMS-AECL User's Manual, Version 3.1", Reactor and Radiation Physics Branch, Chalk River Laboratories, August 2006.

[5] P. Schwanke, "RFSP-IST Version REL_3-04: User's Manual", Reactor Core Physics Branch, Atomic Energy of Canada Ltd., December 2006.

[6] A. Harms, "An Introduction to the CANDU Nuclear Energy Conversion System", McMaster University, May 1972

[7] Wm. J. Garland, "The Essential CANDU: A Textbook on the CANDU Nuclear Power Plant Technology", McMaster University, 2014

[8] "Failure Analysis of CANDU Fuelling Machines and Supporting Equipment", Kinetrics: Life Cycle Management Solutions for the Electricity Industry, 2011

[9] S. Zhang and B. Rouben, "CANDU Fuel Management", Xi'an Jiaotong University, Atomic Energy Canada Ltd., 1999

[10] Robert Jones, "Point Lepreau reactor hit by unexpected shutdown", CBC News, 18 March, 2015