Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 1995

Fuel Management Study on DUPIC Core

Hangbok Choi, Bo W. Rhee, Hyunsoo Park

Korea Atomic Energy Research Institute

Abstract

A parametric study has been performed for the various refueling schemes of CANDU 6 reactor loaded with reference DUPIC fuel. The optimum discharge burnup was determined such that the peak bundle power is minimized for the equilibrium core. Based on the results of instantaneous core calculation using patterned random age distributions, it was decided to perform the refueling simulations only for 2-bundle and 4-bundle shift refueling schemes. The 600 FPD simulation has shown that the operational margins of the channel and bundle power to the license limits are 7.9% and 17.1%, respectively, for 2-bundle shift refueling scheme. The 4-bundle shift refueling scheme also satisfies the license limits and the operational margins of the channel and bundle power are 7.1% and 9.8%, respectively. The results of refueling simulation indicate the possibility of using reference DUPIC fuel in current CANDU 6 reactor.

I. Introduction

A fuel management study for the direct use of spent PWR fuel in CANDU (DUPIC)[1] was performed to establish a refueling scheme for a CANDU core loaded with the reference DUPIC fuel. The reference DUPIC fuel is made of the spent PWR fuel of which the initial enrichment and discharge burnup are 3.5 w/o and 35000 MWD/T, respectively. The DUPIC fuel bundle utilizes CANFLEX[2] geometry which has 43 fuel pins. The fissile content of the reference DUPIC fuel is 1.56 w/o, which is more than twice that of natural uranium fuel. For a reactor which is operated with the fuel of higher fissile content, the power ripple upon refueling is expected to be much higher than that of natural uranium core because the reactivity insertion is more localized if the refueling schemes are the same in both DUPIC and natural uranium cores. In order to ensure the operational safety and controllerability, it is necessary to find a refueling scheme and fuel management strategy appropriate for the DUPIC core.

In this study, the lattice parameters of the reference DUPIC fuel are generated by a transport code WIMS-AECL[3] using ENDF/B-V cross-section library. The incremental cross-sections, which are the properties of the reactivity devices and the structural materials in the reactor, are calculated by a 3-dimensional transport code SHETAN[4] using a model[5] developed previously. And the refueling scheme was studied by a finite difference diffusion code RFSP[6].

II. Equilibrium Core

Because of the daily refueling feature of CANDU reactor, the reactor condition is not the same all the time. In RFSP, an equilibrium core is obtained by the time-average model which uses the lattice parameters averaged over a irradiation time. To determine the discharge burnup of the equilibrium core, the core is divided into 2 regions in radial direction and the critical core is searched by adjusting the average discharge burnups of inner and outer core with a fixed zone controller level of 50% for the calculational simplicity.

II.1 Discharge Burnup

There are many combinations of inner and outer core discharge burnups which make the core critical. The critical core was searched for a given burnup ratio, defined as the discharge burnup of the inner core over that of the outer core, and the optimum burnup ratio was searched by changing the burnup ratio from 0.9 to 1.5 for the possible refueling schemes. The optimum burnup ratio was determined such that the peak bundle power reaches the minimum. The peak bundle power becomes the minimum when the burnup ratio is between 1.00 and 1.15. Based on this, the optimum burnup ratios were determined as 1.15, 1.10, 1.00, and 1.00 for 2-, 4-, 6-, and 8-bundle shift refueling schemes, respectively.

II.2 Refueling Region

The 2-region core model has shown that the power distribution is tilted in the top and bottom regions because the distribution of zone controller water is not exactly symmetric in the vertical direction. The channel power produced in the bottom half of the core is about 2.5% higher than a half of the total reactor power. In order to maintain a symmetric power profile, the core was subdivided into top and bottom region, resulting in total of 4 refueling regions.

The discharge burnup of top region was slightly reduced while that of bottom region was increased by the same increment until the power shape is symmetric. Therefore the average discharge burnups of inner and outer core are the same as those of 2-region core model. The major advantage of the 4-region core model is the reduction of peak channel and bundle power because of the radial power flattening. It was possible to achieve about 2.5% reduction in the peak channel and bundle power compared to the 2-region core model.

The properties of the equilibrium core are summarized in Table 1 and compared to those of natural uranium core. For the 6-bundle shift refueling scheme, a half of the fuel bundles in a channel are refueled at a time, which results in the lowest axial form factor. Compared to the natural uranium core, the peak channel and bundle powers are reduced appreciably for the 2-bundle and 4-bundle refueling schemes because of the improved axial power flattening.

III. Instantaneous Core

During the refueling operation, the channel and bundle power should be kept below the operating limits. Because the instantaneous power distribution is not available from the time- average model of RFSP, an instantaneous core calculation is performed by RFSP using a patterned random number (age) distribution, shown in Figure 2, which was artificially generated based on engineering judgement and experience. Using the age distribution, the instantaneous core model assumes the fuel burnup as below:

$$\omega(i,j,k) = \omega_1(k) + f(i,j) \times (\omega_2(k) - \omega_1(k))$$

where $\omega_1(k)$ and $\omega_2(k)$ are the burnups immediately after and before refueling, respectively, and are obtained from the time-average calculation. f(i,j) is the fraction of time that channel (i,j) is through its cycle. In this way, the instantaneous core model represents a snapshot of the fuel burnup upon refueling.

The reference age distribution is composed of 24 blocks where each block contains 25 channels. In order to simulate a core which has the fresh fuel at different locations, 30 different age patterns were produced, which approximates 30 different refueling operations. The instantaneous calculation was performed for 30 age patterns and the results are summarized in Table 2. The reactivity insertion of each refueling operation for the 6-bundle and 8-bundle shift refueling schemes are so large that the channel and bundle power exceed the current operating limits of 7300 kW and 935 kW, respectively. Though this is not an actual refueling simulation, it is quite probable that the operating limits of channel and bundle power could be violated for certain refueling operations when 6-bundle or 8-bundle shift refueling scheme is applied for the DUPIC core. Therefore it was decided to perform the refueling simulations only for 2-bundle and 4-bundle shift refueling schemes.

IV. Refueling Simulation

The refueling simulation has been performed for the 2-bundle and 4-bundle shift refueling schemes using an auto-refueling method[7] which applies several constraints for the selection of refueling channels. The neutronics properties of 2-bundle and 4-bundle shifted core are different from the typical 8-bundle shifted core such that the axial power shape is channel-front-peaked. If the fuel channel is near the adjusters, the neutron flux in the middle of the channel is depressed and the axial decoupling is pronounced.

In order to maintain the reference (equilibrium) power distribution, the refueling channel should be selected uniformly over the entire channels. It is also desirable to select the same number of channels from two bi-directional channels in order not to deteriorate the dished axial power shape. Therefore the channels are selected in the following sequence:

- channel in the zone-pair of the highest reactivity requirement,
- channel of the highest discharge burnup ratio in a zone-pair,
- channel in the side of the lower zone level.

Therefore a channel which belongs to a zone-pair (the front and back zones which share the same channels) of the highest reactivity requirement will be selected if the discharge burnup ratio, defined as the current discharge burnup over the reference one, is the highest in that zone-pair. If a channel of high burnup is refueled in one direction, a channel to be refueled from the other side will likely be refueled next time if its discharge burnup becomes the highest. If the zone power is relatively high in a particular region, the fuel bundles in that zone will be irradiated more and the probability of being selected as a refueling channel increases accordingly.

IV.1 2-Bundle Shift Refueling

The 2-bundle shift refueling simulation was performed for 600 FPD and the results are summarized in Table 3. Because the refueling perturbation is relatively small, the channel and bundle powers are well below the operating limits. The averages of peak channel and bundle power are 6722 kW and 775 kW, which correspond to 7.9% and 17.1% margins to the license limits for operation, respectively. The channel power peaking factor (CPPF) increases up to 1.11 while the average CPPF over 600 FPD is 1.07, which is close to that of the natural uranium core. The zone controller level varies sensitively to compensate for the local power peaking caused mainly by the highly reactive DUPIC fuel and the axially decoupled power shape.

IV.2 4-Bundle Shift Refueling

The 4-bundle shift refueling simulation was also performed for 600 FPD and the results are summarized in Table 3.. In this case, the refueling ripple is higher than 2-bundle shift refueling scheme and the peak channel and bundle powers are very close to the operating limits. As given in Table 4, the operating margins of the channel and bundle power are 7.1% and 9.8%, respectively. The CPPF is about twice as big as that of 2-bundle shift refueling simulation. The CPPF is exacerbated in the 4-bundle shift refueling scheme because the refueling reactivity of a channel is doubled while the reference channel power distribution is similar to that of 2-bundle shift refueling scheme. The time-dependent behaviour of peak channel and bundle powers are compared in Figures 1 and 2, respectively.

V. Conclusion

The results of 2-bundle shift refueling simulation indicate that the reference DUPIC fuel can be used in the current CANDU 6 reactor. Compared to the natural uranium core, the operational margins of the channel and bundle power increase in 2-bundle shift DUPIC core because of more power flattening. For 4-bundle shift refueling scheme, the operational limits of the channel and bundle power are still satisfied but the CPPF is deteriorated compared to 2-bundle shift refueling scheme. In conclusion, it is feasible to utilize the reference DUPIC fuel in current CANDU 6 reactor without design changes.

In order to improve the core performance and the quality of the simulation results, it is necessary to develope an analytic method for the refueling simulation and to study on the following items in the future:

- an improved method for the refueling channel selection in order to minimize the channel power, bundle power, CPPF, and zone controller level change,
- analysis on the performance of reactivity devices including reactor shutdown margin and xenon over-ride capability,
- analysis on the regional over power (ROP) trip system performance.

References

1. J.S. Lee et al., "Reaserch and Development Program of KAERI for DUPIC (Direct Use of Spent PWR Fuel in CANDU Reactors)", Proc. International Conference and Technology Exhibition on Future Nuclear Syetem: Emerging Fuel Cycles and Waste Disposal Options, GLOBAL'93, Seattle, USA, 1993.
2. A.D. Lane et al., "CANFLEX: A CANDU Fuel Bundle Design with Expanded Operating Capabilities" Tran. ENS/ANS Conf. ENC'90, Vol.6, pp.205, Lyon, France, Sept.23-28, 1990.
3. J.V. Donnelly, "WIMS-CRNL: A User's Manual for the Chalk River Version of WIMS", AECL-8955, Chalk River, Canada, 1986.
4. H. Chow and M.H.M. Roshd, "SHETAN - A Three-Dimensional Integral Transport Code for Reactor Analysis", AECL-6787, AECL-CANDU, Canada, 1980.
5. H.B. Choi, "Evaluation of WIMS/SHETAN for CANDU Reactivity Device Analysis", *Trans. Am. Nucl. Soc.*, Vol.72, June 25-29, 1995.
6. B. Rouben, "Overview of Current RFSP - Code Capabilities for CANDU Core Analysis", *Trans. Am. Nucl. Soc.*, Vol.72, June 25-29, 1995.
7. H.B. Choi and A.S. Gray, "The Application of an Auto-Refueling Method for CANDU 6", Proc. International Conference on Mathematics and Computations, Reactor Physics, and Environmental Analysis, Portland, USA, 1995.

Table 1. Fuel Management Characteristics for 4-Region Core Model

		2-Bundle Shift	4-Bundle Shift	6-Bundle Shift	8-Bundle Shift	8-Bundle (Nat. U)
Discharge Burnup (MWD/T)	Inner Top	16088.8	15711.3	14963.3	14810.9	7741.0
	Inner Bottom	16204.4	15829.1	15077.9	14918.0	7741.0
	Outer Top	14452.1	14591.9	14911.6	14764.7	6854.3
	Outer Bottom	14572.7	14711.3	15023.7	14867.5	6854.3
	Whole	15050.9	15042.4	14988.1	14834.9	7167.2
Refueling Rate (Channels/Day)	Inner Top	0.68	0.36	0.27	0.20	0.69
	Inner Bottom	0.67	0.35	0.27	0.20	0.69
	Outer Top	1.39	0.67	0.42	0.31	1.27
	Outer Bottom	1.33	0.65	0.41	0.31	1.27
	Whole	4.06	2.03	1.36	1.03	1.97
Form Factor (Average/Maximum)	Radial	0.84	0.84	0.81	0.81	0.81
	Axial	0.78	0.76	0.64	0.67	0.67
	Whole	0.61	0.59	0.52	0.56	0.55
Peak Channel Power (kW)	Inner	6223.3	6335.9	6687.1	6716.0	6701.4
	Outer	6490.8	6444.2	6382.2	6397.6	6732.0
Peak Bundle Power (kW)	Inner	709.1	760.95	866.7	813.2	819.1
	Outer	738.8	768.56	853.1	795.6	827.5

Table 2. Summary of 30 Instantaneous Calculations

		2-Bundle Shift	4-Bundle Shift	6-Bundle Shift	8-Bundle Shift	8-Bundle (Nat. U)
Peak Channel Power (kW)	Maximum	6699.0	7232.0	8157.0	9054.0	7135.0
	Average	6629.3	7043.8	7765.5	8373.5	6875.1
	Minimum	6580.0	6911.0	7447.0	7769.0	6704.0
Peak Bundle Power (kW)	Maximum	783.0	906.0	1147.0	1200.0	894.0
	Average	771.1	874.8	1077.8	1106.8	871.9
	Minimum	763.0	858.0	1029.0	1024.0	840.0
Channel Power Peaking Factor	Maximum	1.129	1.1480	1.277	1.425	1.127
	Average	1.110	1.1219	1.207	1.303	1.093
	Minimum	1.088	1.1040	1.169	1.234	1.080
Zone Controller Level	Maximum	0.797	0.8000	0.800	0.800	0.800
	Average	0.538	0.5781	0.692	0.754	0.538
	Minimum	0.200	0.2650	0.227	0.237	0.200
Radial Form Factor	Maximum	0.824	0.7850	0.728	0.698	0.809
	Average	0.818	0.7703	0.699	0.649	0.789
	Minimum	0.810	0.7500	0.665	0.599	0.760

Table 3. Comparison of 2-Bundle and 4-Bundle Shift Refueling Simulation

		2-Bundle Shift	4-Bundle Shift
Inner Core Discharge Burnup (MWD/T)	Maximum	16416.7	18250.0
	Average	16133.3	15779.2
	Minimum	15562.5	13666.7
Outer Core Discharge Burnup (MWD/T)	Maximum	14958.3	19875.0
	Average	14516.7	14579.2
	Minimum	13000.0	13083.3
Peak Channel Power (kW)	Maximum	7150.0	7066.0
	Average	6722.2	6781.4
	Minimum	6530.0	6620.0
Peak Bundle Power (kW)	Maximum	825.0	886.0
	Average	775.2	843.1
	Minimum	750.0	820.0
Channel Power Peaking Factor	Maximum	1.1470	1.1930
	Average	1.0716	1.1363
	Minimum	1.0480	1.1000
Zone Controller Level	Maximum	0.8000	0.8000
	Average	0.5088	0.5022
	Minimum	0.2000	0.2000
Refueling Rate(Channels/FPD)	Inner	1.3328	0.6922
	Outer	2.7171	1.3461
	Whole	4.0499	2.0383

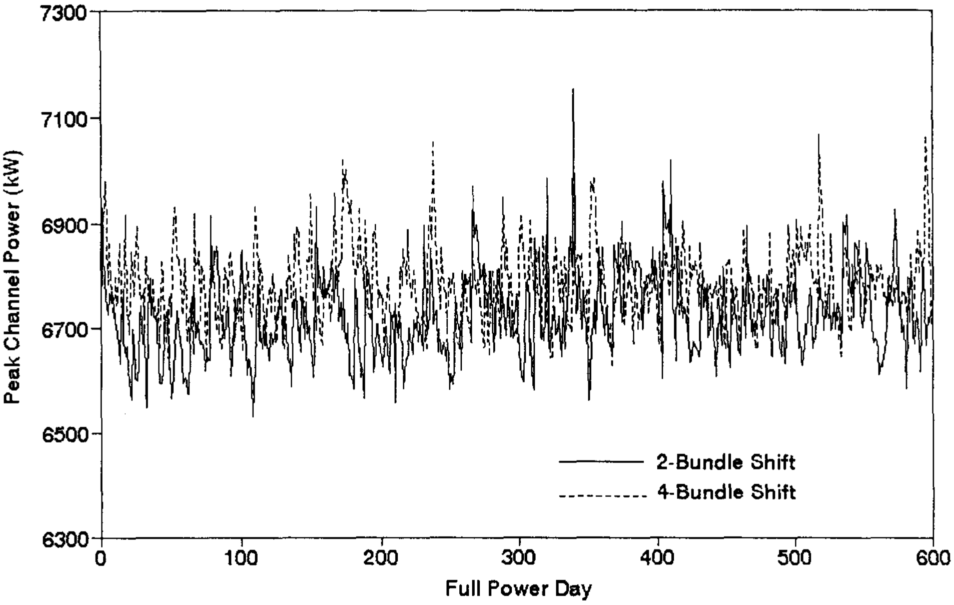

Figure 1. Comparison of Peak Channel Power(kW)

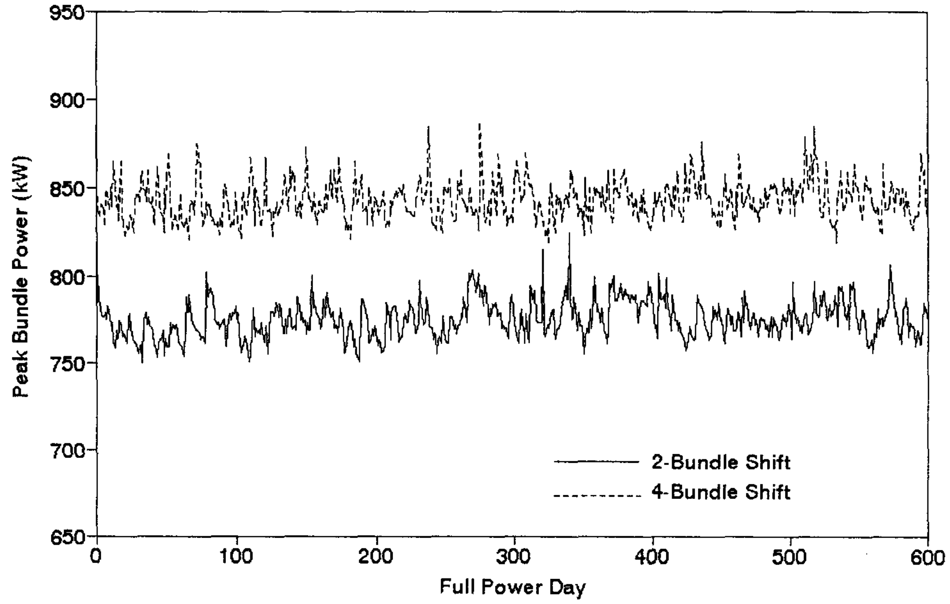

Figure 2. Comparison of Peak Bundle Power(kW)