APPLICATION OF DIRECT SEARCH TECHNIQUE TO OPTIMAL REFUELING CHANNEL SELECTION FOR CANDU REACTORS

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ABSTRACT

The direct search technique has been applied for the optimal refueling channel selection for CANDU 6 reactors. In the optimization problem, the refueling channels are determined so that the reference zone power distribution is maintained, while satisfying the operation limits of channel and bundle powers. The performance of the optimum refueling channel selection method has been demonstrated for CANDU 6 reactors, and the results are satisfactory. Also, for the advanced CANDU fuel core, the applicability of the method was demonstrated by refueling simulations.

1. INTRODUCTION

In a CANDU reactor, the refueling channels are selected daily to provide excess reactivity to the core and maintain reference core characteristics which were already optimized for the long-term operation of the power plant. The CANDU core fuel management has been developed by several investigators [1-4] that have established the optimal fuel management scheme of the equilibrium core by either minimizing cost or maximizing reactor safety performance. Recently, automated refueling channel selection methods have also been proposed to facilitate parametric analyses of various CANDU reactors. For example, Choi [5] has developed the AUTOREFUEL program, which selects refueling channels using various constraints on the channel and bundle powers. Though this method runs very fast, it does not consider the individual channel property quantitatively when it selects refueling channels. Therefore there is a chance that the reactor regulating system (RRS) may reach its limiting condition to satisfy the reference power distribution during refueling simulation, though this happens rarely.

In this study, an optimum fuel management method with a direct search technique is developed, which can improve on the drawbacks of the current automatic refueling simulation method. The optimization is performed such that the reference zone power distribution is maintained during the refueling simulations. In order to estimate the power distribution upon refueling quantitatively, sensitivity coefficients of channel power are used in this study, which were generated for the reference (time-average) core beforehand. These sensitivities enable searching for an optimum combination of refueling channels, which can keep the RRS in the operating range. The performance of the method is then assessed by comparing the results of a refueling simulation against actual plant operation data.

2. OPTIMAL REFUELING CHANNEL SELECTION

2.1 Channel Power Estimation

In order to estimate the zone power upon refueling, the channel power is calculated at first. The channel power can be calculated by the first-order approximation as follows:

$$CP_j = CP_{j,0} + \sum_{k=1}^{K} \Delta CP_{j,k}, \qquad (1)$$

where

$CP_{j,0}$ = power of channel j before refueling, and

$\Delta CP_{j,k}$ = power change of channel j after refueling channel k.

In this study, the channel power change upon refueling is obtained using sensitivity coefficients generated for the reference (time-average) core. Therefore, the channel power change after refueling can be expressed by following equation:

$$\Delta CP_{j,k} = S_{j,k} CP_{j,0} \qquad (2)$$

It is assumed that the channel power distribution of the equilibrium core is not much different from the reference distribution, which is what the optimum refueling simulation is aiming for. The sensitivity coefficients are obtained by directly perturbing 380 fuel channels of the reference core, which is written as follows:

$$S_{j,k} = \frac{\Delta CP_{j,k}}{CP_{ref,i}}, \tag{3}$$

$$= \frac{CP_{j,k} - CP_{ref,j}}{CP_{ref,j}}. \tag{4}$$

The sensitivity coefficient is a 380×380 matrix. It is important to confirm the adequacy of the sensitivity method because it influences the overall refueling simulation. The accuracy of the channel power calculation by the sensitivity coefficient was estimated for an instantaneous core which is regarded as a snapshot of the equilibrium core. In fact, the channel power variation is the largest for the refueling channel and the rest of the channels experience only minor changes. The small variation of channel power upon single refueling operation enables to use sensitivity coefficients for successive refueling simulations. From the 380 perturbation calculation results, it is known that the average and maximum channel power errors are 0.7 (rms error) and 8.7%, respectively.

2.2 Search of Refueling Channel

For the optimum refueling channel selection, the channel location is determined at first and the number of refueling channels is determined secondly. The perturbed channel powers are calculated for each candidate channel using sensitivity coefficients. Then its associated objective function, Eq. (5), is evaluated.

$$J = \mathrm{Min} \sum_{i=1}^{14} \left| P_i - P_{ref,i} \right| \tag{5}$$

subject to

$$CP_j \le CP^{\lim}, \quad j = 1, 380 \tag{6}$$

and

$$CPPF_j \leq CPPF^{\lim}, \quad j\text{=}1, 380 \tag{7}$$

If the candidate channel does not meet the constraints given in Eqs. (6) and (7), the channel is deleted from candidates. When a candidate channel that minimizes the zone power deviation satisfies constraints, it is selected for refueling. Once a channel is selected, the amount of reactivity insertion in each zone is compared with the zone reactivity requirement. The reactivity requirement of zone i is estimated such as

$$\Delta\rho_{i,0} = \Delta\rho_c + \Delta\rho_{zcu}(z_i - z_{i,ref}), \tag{8}$$

where

$\Delta\rho_c$ = core reactivity decay in one full power day (FPD) divided by the number of zones
$\Delta\rho_{zcu}$ = reactivity worth of ZCU
z_i = current ZCU level in zone i, and
$z_{i,ref}$ = reference ZCU level in zone i.

If the reactivity insertion by the refueling is greater or equal to the reactivity requirement, the channel selection is completed. If the inserted reactivity is not sufficient, more channels are selected in order to maintain the criticality of the core. For the selection of another refueling channel, the channel powers are recalculated, and the zone reactivity requirement is updated as Eq. (9). The selection process is continued until the reactivity requirement of the core is satisfied.

$$\Delta\rho_i = \Delta\rho_{i,0} + \Delta\rho_{i,k} \tag{9}$$

where $\Delta\rho_{i,k}$ = reactivity insertion to zone i due to refueling channel k.

3. APPLICATION TO CANDU 6 REFUELING SIMULATION

The OPTIMA method developed in this study has been applied to CANDU 6 reactor refueling simulation in order to verify its usefulness in performing practical optimized fuel management.

3.1 Natural Uranium Core

The results of 600-FPD simulation are summarized in Table 1 and compared with those of AUTOREFUEL simulation and Wolsong nuclear power plant operation data. The results of the new method are very close to those of the time-average core calculation except for the peak channel and bundle powers, which can be obtained only from refueling simulation. After 600-FPD refueling simulation, the MCP is 7025 kW, which is much lower than the license limit of 7300 kW. Furthermore, the MCP is lower than that of the AOTOREFUEL simulation and plant operation data. For the MBP, the result of the new method is almost the same as that of the AUTOREFUEL simulation, while it is slightly higher than that of the plant operation data. The CPPF is maintained below the typical value of 1.10, which is better than the plant operation data.

Figures 1 and 2 show the time-dependent behavior of the MCP, MBP, respectively. It can be seen that the constraints on the channel and bundle powers are properly imposed during the optimization process of the refueling channel selection.

3.2 Advanced CANDU Fuel Cores

The applicability of the new method to the fuel management of advanced CANDU fuels has also been demonstrated for CANDU flexible fueling (CANFLEX) fuel of recovered uranium (RU) [6] and Direct use of spent PWR fuel in CANDU reactors (DUPIC) [7]. The enrichment of CANFLEX-RU fuel is 0.9 wt% and a 4-bundle shift is used as refueling scheme. The results of refueling simulations are summarized in Table 2 and compared with those of the natural uranium core. For the CANFLEX-RU CANDU 6 core, the MCP and MBP are 7096 and 852 kW, respectively, which are also well below the license limits. The average and maximum CPPF are 1.12 and 1.18, respectively. The CPPFs are relatively high compared with those of the natural uranium core due to the characteristics of the 4-bundle-shift fueling scheme.

The fissile content of the DUPIC fuel is 1.45 wt% and a 2-bundle shift is used for refueling simulation. For the DUPIC fuel core, the MCP and MBP are 7004 and 828 kW, respectively. The average and maximum CPPF are 1.06 and 1.10, respectively, which are comparable to those of the natural uranium core. The results of CANFLEX-RU and DUPIC fuel core simulations show that the OPTIMA has the capability of simulating various CANDU cores while satisfying typical operating conditions of the CANDU 6 reactor.

4. SUMMARY AND CONCLUSION

A new fuel management method for CANDU reactors has been developed. In this study, the objective function was set up to minimize zone power difference from the reference value. The optimum refueling channels were searched directly using a simple sensitivity method that has reasonably good accuracy in estimating channel power variation.

The validity of this method has been demonstrated by refueling simulations of CANDU 6 reactors, which have shown that optimum channel selection can be performed with enough margin in the channel and bundle power limits. For the advanced CANDU fuel cores, the applicability of the new method was also demonstrated by refueling simulations.

In conclusion, the method developed in this study has the potential to be used for the fuel management study of various CANDU 6 reactors. In future, it is recommended that the new method be extended to have the capability of implementing plant operation data for refueling channel selection so that the code can actually be used for fuel management in CANDU reactors.

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Table 1 COMPARISON OF 600-FPD REFUELING SIMULATION FOR NATURAL URANIUM CORE

		Time-Average	AUTOREFUEL	New Method	Wolsong [1)]
Maximum channel power (kW)	Highest	6582	7095	7025	7109
	Average	–	6862	6844	6958
	Lowest	–	6712	6675	6846
Maximum bundle power (kW)	Highest	802	871	868	840
	Average	–	844	843	825
	Lowest	–	826	826	810
Channel power peaking factor	Highest	–	1.09	1.10	1.13
	Average	–	1.06	1.06	1.09
	Lowest	–	1.04	1.05	1.07
Average ZCU level (%)	Highest	–	82	80	80
	Average	50	50	50	44
	Lowest	–	28	22	19
Average discharge burnup (MWh/kgU)		175.1	172.2	174.6	164.7
Average refueling rate (channels/FPD)		1.93	1.95	1.92	1.92

1) Wolsong nuclear power plant unit 3 operation data during Jan. 8 2000 and July 5 2000

Table 2 COMPARISON OF 600-FPD REFUELING SIMULATION FOR DIFFERENT CANDU FUELS

		Natural Uranium	CANFLEX-RU	DUPIC
Fueling scheme (bundles/channel)		8	4	2
Maximum channel power (kW)	Highest	7025	7096	7004
	Average	6844	6890	6842
	Lowest	6675	6723	6693
Maximum bundle power (kW)	Highest	868	852	828
	Average	843	809	803
	Lowest	826	780	785
Channel power peaking factor	Highest	1.10	1.18	1.10
	Average	1.06	1.12	1.07
	Lowest	1.05	1.08	1.05
Average ZCU level (%)	Highest	80	80	80
	Average	50	50	51
	Lowest	22	20	29
Average discharge burnup (MWh/kgU)		175	313	355
Average refueling rate (channels/FPD)		1.92	2.24	4.07

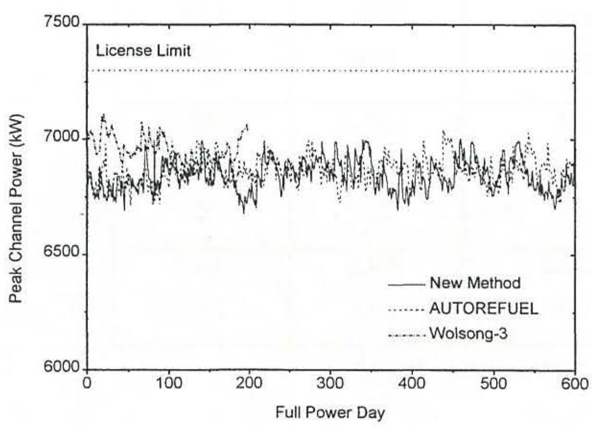

FIGURE 1 VARIATION OF MAXMUM CHANNEL POWER

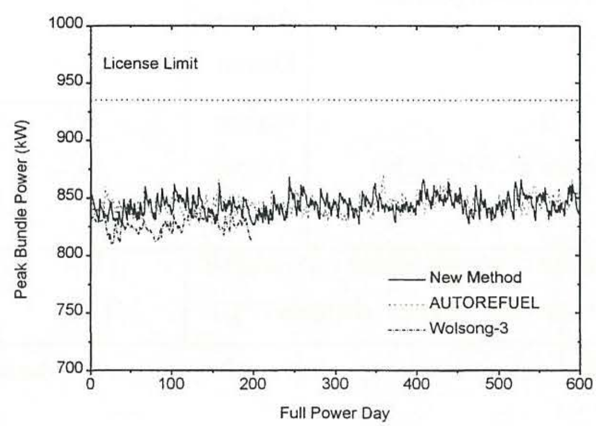

FIGURE 2 VARIATION OF MAXIMUM BUNDLE POWER