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An Optimal Fuel Management Method Based on CANDU In-Core Detector Readings

Chang Joon Jeong, Hangbok Choi
Korea Atomic Energy Research Institute
P.O. Box 105, Yusong, Taejon, Korea 305-600

Nam Zin Cho
Korea Advanced Institute of Science and Technology
373-1, Kusong-dong, Yusong-gu, Taejon, Korea 305-701

Abstract

An optimal refueling simulation method, considering the actual core state of a Canada deuterium uranium 600 MWe (CANDU 6) reactor, has been developed. The channel powers are provided by power mapping using in-core detector reading. The objective of the optimization is to maintain the reference core performance during refueling simulation, while satisfying the operation limits of channel and bundle powers. The optimization process consists of two stages: i) elimination of candidate refueling channels by several constraints and ii) selection of refueling channels by a direct search method. The developed fuel management method has been applied for refueling simulation for CANDU-6 reactor, and the results are compared with the plant operation data. It is found that the developed method could be used as a fuel management tool for CANDU-6 reactors.

I. Introduction

In-core fuel management plays an important role in the design and operation of nuclear power reactors. The in-core fuel management is regarded as the collection of principles and practices required for the planning, scheduling, refueling, and safe operation of nuclear power plants [1]. In general, the fuel management strategy aims to minimize total plant and system energy costs through the timely procurement of nuclear fuel and related services. However, there is a basic difference between the fuel management strategies of a Canada deuterium uranium (CANDU) reactor [2] and a light water reactor (LWR). 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 differences in fuel management between CXANDU and LWR are summarized in Table I.

For an economic and efficient in-core fuel management, it is very important that state point information available from the diagnostic tools be processed to give the most accurate representation of the operating state of the reactor. Generally, the point information is obtained by power or flux mapping method.

In this study, an optimal fuel management method is developed, which considering the actual core state using power mapping. The optimization is performed such that the reference zone power distribution is maintained during the refueling simulations. In Sec. II, a power mapping method is derived. The optimal fuel management method is described in Sec. III. In Sec. IV, the performance of new fuel management method is demonstrated by comparing the results of a refueling simulation against actual plant operation data. Finally, summary is given in Sec. V.

II. Power Mapping by In-Core Detector Reading

In this section, a new power mapping method by diffusion equation with Kalman filtering (DIKAL) technique is described. The in-core detector reading is used as internal boundary conditions in the diffusion equation.

II.1. Governing Equation

Flux and power distributions are obtained by solving a multigroup three-dimensional diffusion equation. Standard numerical techniques give the following equation in vector form

$$\boldsymbol{M}f = \frac{1}{k}\boldsymbol{F}f \qquad (1)$$

which express the neutron balance, and where **M** and **F** are removal and multiplication matrices, respectively; f is the flux vector and k is the eigenvalue.

For an iterative solution, the above equation becomes:

$$\boldsymbol{M}\boldsymbol{F}^{(n+1)} = \frac{1}{k^{(n)}}\boldsymbol{M}\boldsymbol{F}^{(n)} \qquad (2)$$

where n is the iteration number.

In order to use detector readings as internal boundary conditions through the flux iteration, optimally estimated fluxes with detector readings and Kalman filter are incorporated into the diffusion equation.

Then, the above iteration equation can be written as:

$$\boldsymbol{M}\boldsymbol{F}^{(n+1)} = \frac{1}{k^{(n)}}\boldsymbol{M}\boldsymbol{F}^{(n)'} \qquad (3)$$

where $\boldsymbol{F}^{(n)'}$ is the optimally estimated mesh flux near the detector locations. For the optimal estimation of measured mesh flux, it is necessary that the detector reading should be transformed into the mesh flux and Kalman filtering for a calculated and measured reading.

II.2 Transform of Measured Reading

Flux detectors are placed interstitially between fuel channels in CANDU reactor (see Fig. 1). The physical locations of the detectors do not coincide with the coordinates of the mesh points in the DIKAL model. In order to use the measured detector readings as internal boundary conditions in the DIKAL calculations, it is firstly necessary to transform the detector readings into the appropriate DIKAL measured mesh fluxes.

The measured detector flux is transformed into the measured mesh flux by the following equation:

$$j_{j,m} = T_{dj} j_m \tag{4}$$

where, $j_{j,m}$ is the measured mesh flux, and j_m is the measured detector flux. The conversion factor T_{dj} is the ratio of calculated mesh flux to the theoretical detector flux, which is calculated by interpolation of mesh flux:

$$T_{dj} = \frac{j_j}{j_d}, \quad \text{j=1 to 8.} \tag{5}$$

Here, each detector reading gives 8 measured DIKAL mesh fluxes which surround the detector, j_m.

II.3 Kalman Filtering

In this section, an optimal estimate of the mesh flux from actual detector readings is performed by use of a similar Kalman filtering technique. In the CANDU reactor, the detector measurements are performed for thermal neutron only. From Sec. II.2, the measured mesh flux is expressed in Eq. (4), and relation between the mesh average thermal flux in mesh j, j_j and the measurement signal, **A** is

$$A = H j_{\mathrm{j}} + \mathrm{v}, \qquad E(\mathrm{v}^2) = s_m^2 \tag{6}$$

where v is the measurement noise and **H** is the measurement matrix with

$$\mathbf{H} = (H) = \frac{1}{T_{dj}} \tag{7}$$

The factor 1/T_{dj} is taken from the precalculation performed prior to the adaptation. Now, the optimal estimate of the thermal mesh flux can be written as:

$$\hat{j}_j = j_j + K(j_m - Hj_j), \quad \text{j = 1 to 8} \tag{8}$$

where, k is Kalman gain factor.

III. Optimal Refueling Channel Selection

The optimal fuel management (OPTIMA) method developed in this study consists of two processes: elimination and direct search process.

The elimination is a multi-stage process that sorts out the channels qualified for refueling based on general characteristics of the fuel channel. In the elimination process, an appropriate number of constraints are imposed, which reflect actual operation experience. Specifically, the elimination constraints used in this study are the maximum channel power (MCP), maximum bundle power (MBP), channel power peaking factor (CPPF), fuel burnup, and the last refueling date. Typically, about 20 to 40 channels can be selected as candidates for a natural uranium CANDU core.

The refueling channels are selected from the candidate channels chosen through the elimination process. The channels are selected such that reference zone power distribution is maintained. The objective can be written as follows:

$$J = \text{Min} \sum_{i=1}^{14} \left| P_i - P_{ref,i} \right| \tag{9}$$

subject to

$$CP_j \le CP^{\lim}, \quad j = 1, 380 \tag{10}$$

and

$$CPPF_j = \frac{CP_j}{CP_{ref,j}} \le CPPF^{\lim} \tag{11}$$

where

J = objective function

P_i = zone i power after refueling

$P_{ref,i}$ = zone i reference power

CP_j = channel j power after refueling

$CP^{\lim}$ = limiting channel power

$CP_{ref,j}$ = channel j reference power

$CPPF^{\lim}$ = limiting channel power peajing factor.

IV. Application to CANDU 6 Refueling Simulation

The DIKAL-OPTIMA method has been applied to the analysis of the operation data of Wolsong-3 reactor. For this study, the operation data from 502-FPD to 699-FPD (Jan. 8, 2000 - July 5, 2000) are used. The analysis procedure is as follows:

(1) Perform power mapping every week using DIKAL method,

(2) Perform refueling channel selection by OPTIMA method based on the channel power generated by DIKAL method, and

(3) Perform refueling simulation for the selected time points.

The DIKAL-OPTIMA simulation results are summarized in Table II and compared with the operation data. After 198-FPD refueling simulation, the MCP of the DIKAL-OPTIMA method is 6967 kW, which is much lower than the license limit of 7300 kW. Also, the MCP of the DIKAL-OPTIMA method is lower than the operation data of 7109 kW. For the MBP, the result of the DIKAL-OPTIMA is slightly lower than that of the operation data. Figures 2 and 3 compare the time-dependent behavior of the MCP and MBP, respectively.

Figure 4 shows that the CPPF is maintained below the typical value of 1.10, which is better than the plant operation data. In Figs. 5 and 6, the DIKAL-OPTIMA simulation shows the similar performance to the plant operation data in maintaining the ZCU water levels between 20 and 80%. For the economic view point, the average discharge burnup and fueling rate of the DIKAL-OPTIMA are comparable to those of the plant operation data, which are also shown in Table II.

V. Summary

A new optimal fuel management method using in-core detector reading has been developed. In this study, optimum refueling channel selection was performed to minimize zone power difference from the reference value.

The validity of the method has been demonstrated by refueling simulations of a CANDU-6 reactor, which have shown that the optimum channel selection can be performed with enough margins of the channel and bundle power limits. It was also found that the DIKAL-OPTIMA method gives the better performance for the MCP and MBP and similar performance of the ZCU water level control compared with the plant operation data.

Consequently, DIKAL-OPTIMA has the potential to be used for the fuel management study of a CANDU-6 reactor, and the DIKAL-OPTIMA method could be used as a fuel management tool for an operating CANDU-6 reactor.

References

1. M. L. BROWN, N.D. ECKHOFF and J. O. MINGLE, “Key constraints for simulation of nuclear fuel management”, *Proc. ANS Top. Mtg.*, Ann Arbor, Michigan (1973).
2. “Design Manual: CANDU 6 Generating Station Physics Design Manual, Wolsong NPP 2 3 4”, 86-03310-DM-000, Rev. 1, KAERI/AECL (1995)

Acknowledgement

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Table I Comparison of CANDU and PWR Fuel Management

	CANDU	PWR
Refueling		
Reactor state	On-power	Off-line
Fueling interval	One day	12 to 18 months
Reload fraction	~0.0017	1/3 or 1/4
Fuel material	Natural uranium	Enriched uranium
Fuel shuffling	Axial	Radial
Power shaping		
Axial	Adjuster + axial shuffling	Axial rods & blankets
Radial	Adjuster + fueling zone	Burnable poison + core reload
Excess reactivity control	Boron (initial core) ZCU (operating core)	Burnable poison, soluble boron
Equilibrium cycle	Reached rapidly (~6 months) Defined over the refueling interval in each channel	Take many years (> 5 yr) Defined over whole core
Fuel management design	Three-dimensional	Two-dimensional

Table II Comparison of 198-FPD simulation for Wolsong-3 reactor

		DIKAL-OPTIMA	Wolsong*
Maximum channel power (kW)	Highest	6967	7109
	Average	6816	6958
	Lowest	6716	6846
Maximum bundle power (kW)	Highest	834	840
	Average	815	825
	Lowest	799	810
Channel power peaking factor	Highest	1.12	1.13
	Average	1.07	1.09
	Lowest	1.04	1.07
Average ZCU level (%)	Highest	80	80
	Average	45	44
	Lowest	22	19
Average discharge burnup (MWh/kgU)		165.6	164.7
Average refueling rate (channels/FPD)		1.94	1.92

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

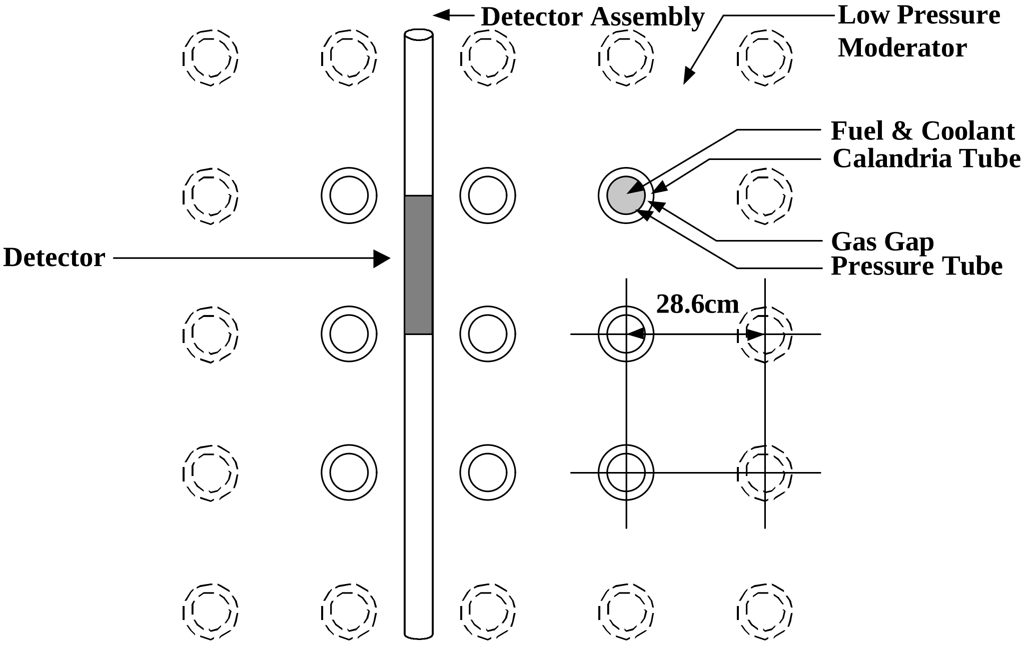

Fig. 1 Schematic of a CANDU fuel lattice

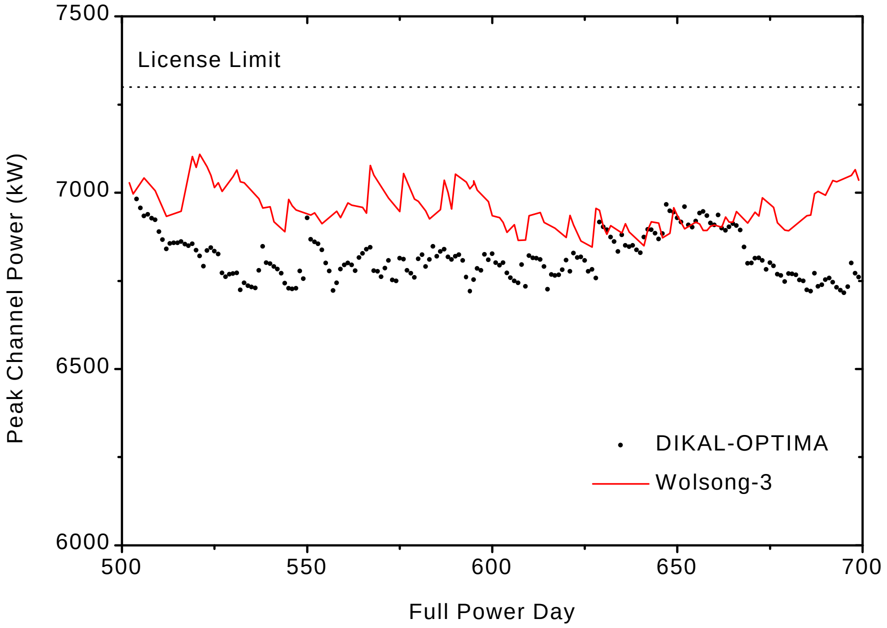

Fig. 2 Comparison of maximum channel power (Wolsong-3)

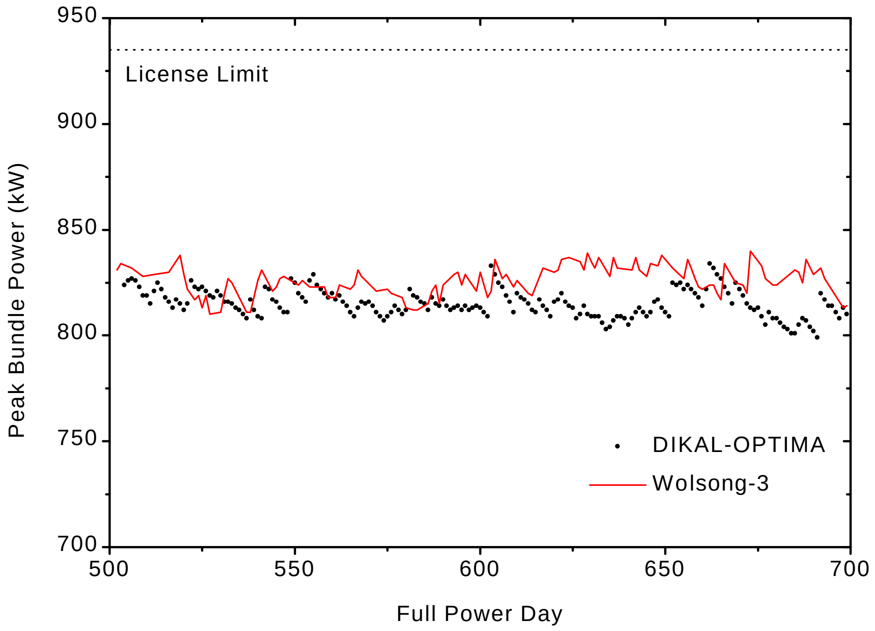

Fig. 3 Comparison of maximum bundle power (Wolsong-3)

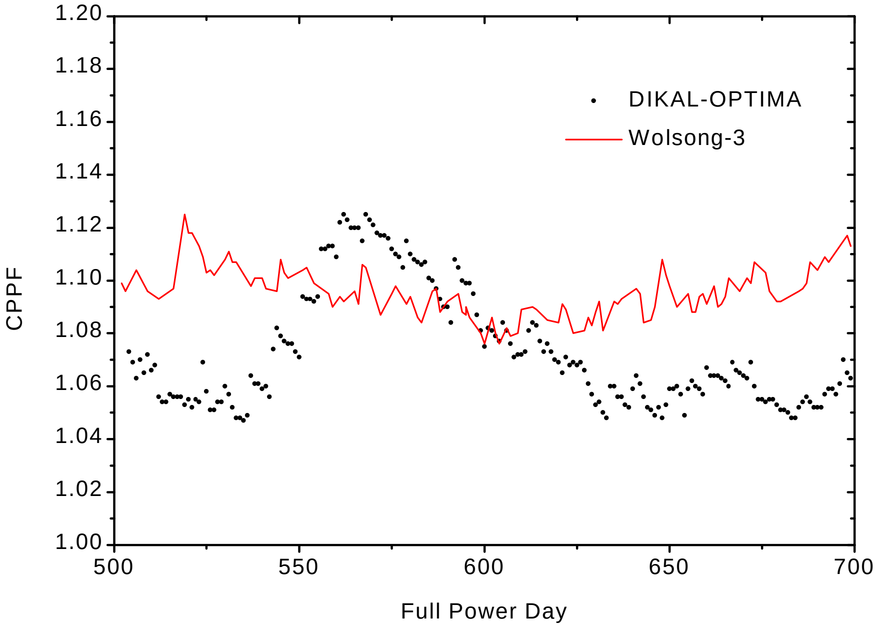

Fig. 4 Comparison of channel power peaking factor (Wolsong-3)

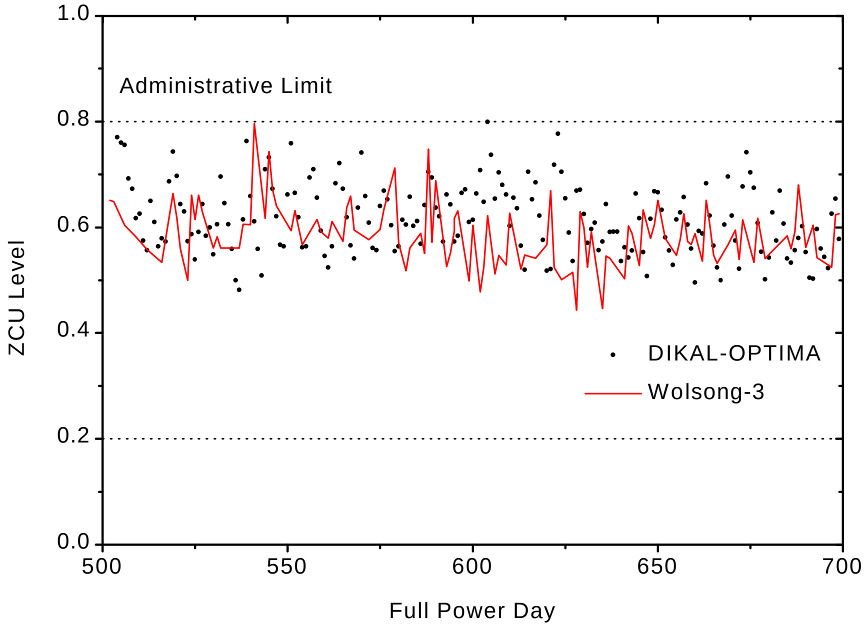

Fig. 5 Comparison of ZCU level (Upper values)

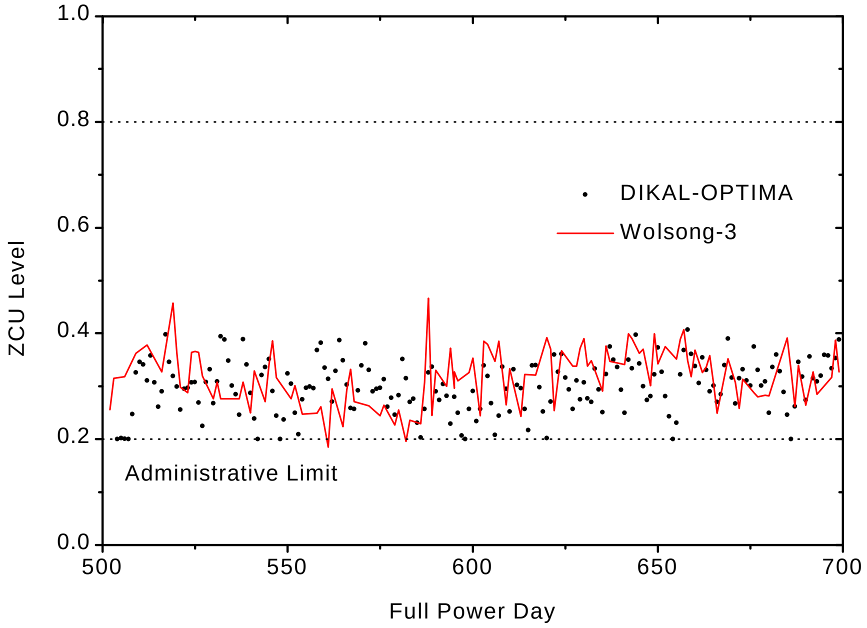

Fig. 6 Comparison of ZCU level (Lower values)