A Study on the Application of Rule-based Refueling Optimization for an Existing CANDU Reactor

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1. Introduction

The fuel reloading problem has been a goal for fuel management in terms of both safety and economic aspects since the birth of all kinds of nuclear reactors. To determine the fuel reloading strategy and mechanism for each reactor that minimizes unit energy cost under the constraints imposed on various core parameters has been the most significant task in core management.

CANDU reactor has a specific refueling mechanism so called *on-power refueling*, which is to refuel during operation. CANDU reactor refuels on average about 20 fuel bundles (8 fuel bundles per channel) daily to maintain the criticality of reactor during normal operation.

Therefore in CANDU reactor, to determine refueling candidates is more important and difficult process. And that is why the system-wise optimal refueling process should be developed for more efficient core management.

The objective of the study is to apply a technique, which can be used to determine refueling candidates in an optimum manner, for an existing CANDU reactor.

In the study we used combination method, permutation method, and genetic algorithm for the purpose of optimizing refueling candidates, which are based on “Floppy Rules” announced by Dennis Brissette [1].

2. Evaluation Rules for Channel Selection

Evaluation rules for channel selection are based on many different core properties: some are related to individual channels (exit burnup, reactivity increase, etc.), others are related to the environment of channels (max. channel overpower, min. channel power margin, predicted burnup spacing, etc.) and core status (average exit burnup, ratio of actual power to reference power).
To determine refueling candidates, the following requirements should be satisfied simultaneously:

- Providing sufficient positive reactivity to enable the operation of the reactor at high.
- Maintaining Liquid Zone Controllers (LZCs) levels within their normal operation range.
- Maintaining LZC levels as close as possible to the Average Zone Level (AZL) at the end of a refueling sequence.
- Maintaining the reactor power distribution (regionally, axially and locally) as close as possible to the reference power distribution.
- Maximizing the operation margin on the ROPT system, by maintaining channel overpowers and Channel Power Peaking Factor (CPPF) at a low value.
- Maximizing the operation margin on max. channel and bundle power.
- Maximizing the burnup of discharged bundles by refueling channels with an exit burnup close to 100% TA (i.e. closed to the time-average calculation).
- Removing and preventing channel clustering that may result in localized power peaking.
- Ensuring the availability of a sufficient number of refueling candidates and adequate distribution of these channels in the reactor core to balance LZC levels.

2.1 Combination of individual ratings

To determine refueling candidates, above requirements are converted into rating functions whose main purposes are to maintain desirable operating conditions during refueling and after.

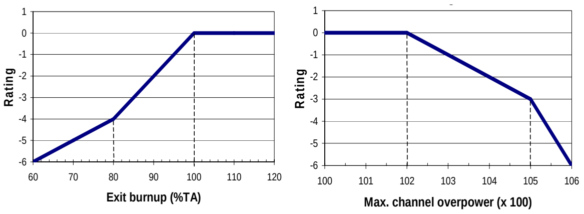

Figure 1. Examples of rating function with regard to exit burnup and max. channel overpower separately.

Finding individual refueling candidates is performed by applying estimation rule to each channel and calculates combining rating value (global rating) as follows:

$$\text{Global rating value} = -\sqrt{\sum_{i=1}^{n} f_i^{2}(x_i)} \text{ ...... (2.1)}$$

Where, i is # of rule, x_i is core property, and f_i is piecewise linear interpolation function of each rule.

Table 1. Calculation results of individual rating functions for each channel.

CHANNEL	ZONE #	BURNUP (%TA)	RULE # 0 (x10)	RULE # 1 (x10)	RULE # 2 (x10)	RULE # 3 (x10)	RULE # 4 (x10)	RULE # 5 (x10)	RULE # 6 (x10)	RULE # 7 (x10)	RULE # 8 (x10)	GLOBAL (x10)
B06	1	82	6	-36	0	-15	-28	0	0	0	0	-48
F06	1	110	0	0	-20	-69	-18	0	0	-10	-20	-72
H04	1	93	0	-14	0	-20	-35	0	0	-10	0	-44
J05	1	86	0	-28	0	-18	-35	0	0	-10	0	-49
J07	1	95	0	-10	-5	-20	-18	-11	0	-10	0	-32

2.2 Search of best refueling sequences

Since the refueling is performed for 2-3 channels daily in CANDU, the effects due to the refueling in the point of channel set as well as individual channel should be considered. In the process of optimization of refueling sequences, LZC level fluctuation and average LZC response to the refueling (from the historical database) are also reviewed for the purpose. Besides LZC level prediction, average reactivity increase, average exit burnup, and recent refueling history should be considered [2].

2.3 DB Construction of Wolsong LZC levels' variations due to refuelings

Prediction of LZC levels in CANDU reactor is very important in the process of selection of refueling candidates. For the prediction, DB for level variations of LZCs due to refueling of Wolsong NPP unit 1 in operation should be needed. It is very useful in the determination of refueling set and individual candidates and increase the optimization level of refueling as a result.

In order to develop localized refueling support system, LZC level prediction model was investigated and Wolsong's LZC response database was constructed using historical LZC level data of Wolsong #1 [3].

3. Refueling Support System

This refueling optimization is researched as a part of development CANDU monitoring and operation support system and integrated with CANDU Core On-line Monitoring System (COMOS) as Figure 2.

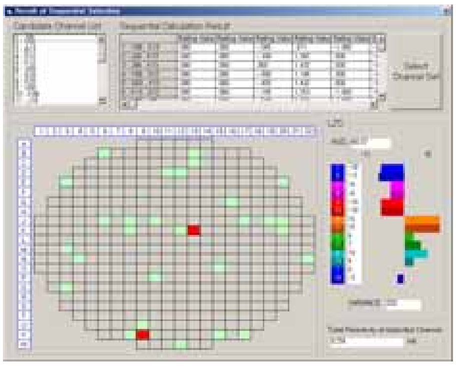

Figure 2. Refueling candidates calculated by COMOS using rule-based optimization.

Once refueling channels are selected, COMOS runs RFSP to get reactor core status after refueling by pre-simulation module, which can be a verification for determined refueling.

4. Conclusion

CANDU refueling evaluation rules are tested and verified by number of comparison with real refueling history. As we expected the results are not same but it shows its trends as Table 2.

Table 2. Results of rule-based refueling calculation vs. real refueling data. * G-2 data, ** Wolsong data

Start date (FPD)	End date (FPD)	Real refueling channel	Estimation by old LZC*	Estimation by new LZC**
6170	6172	J09 J21 P07	A09 J09 L21	A09 J09 L21
		G07 O20 D14 U08	D14 F04 P07 W13	G21 P07 V16 W13
6172	6177	M14 P15 J04 E10	A09 F04 P15 W13	A09 N05 P15 V16
		O10 G17 N05 T14 F04 H14	E10 J18 O01 V16 N05 T12	E10 F03 J18 W13 O01 T12

Moreover, this approach shows quantitative evaluation of refueling selection could be used instead of experience-based decision and highly adaptive to changing real-time constraints. Finally the optimization for the automatic determination of refueling suggested in the study was expected to reduce the time and human error in channel selection process.

REFERENCES

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