Developing a Long-term Fuel Management Strategy for APR1400

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1. Introduction

In-core fuel management is an important aspect of the operation of nuclear reactor. Designing of reload pattern for each cycle is significant due to the economics and safety. Many researches have been performed for optimization of loading pattern of large pressurized water reactors (PWRs), and the most of results are feasible for initial cycle [1, 2]. Since the reactor operation life covers multicycle fuel loading, the long-term fuel management is essential. Multicycle fuel management strategy (FMS) involves defining of the fuel batch size and its enrichment, fuel assembly (FA) design and loading pattern (LP) search and operation guidelines of whole life of reactor [3].

Advanced Power Reactor 1400 (APR1400) was selected as a target reactor for this research. Several units of APR1400 are under construction in South Korea and the United Arab Emirates. Shin-Kori 3 is the first APR1400 reactor that was commissioned in 2016, and more are expected in upcoming years. The purpose of this research is to develop a systematic method for optimal FMS strategy of APR1400 reactors.

2. Methodology

Cycle length of each cycle is fixed to 18 month based on the current reactor operation experience. To define the core average enrichment for each cycle the fuel management graph was developed [4]. A new nonlinear optimization method will be proposed to determine a number of fuel assemblies in each batch and batch average enrichment under multi-constraints of reactor core and regulation limits.

2.1 Fuel management graph

A number of fuel assemblies with different enrichment and burnable poison rods, gadolinia (8 w/o) were designed, and CASMO code was used to complete calculation [5]. Then a graph can be plotted using the depletion results as shown in Fig. 1. Critical boron concentration (CBC) at beginning of cycle (BOC) was kept below 1500 ppm for all cycles to keep the moderator temperature coefficient (MTC) negative or below the limit. However, specific CBC values were used for the initial cycle 900 ± 100 ppm and the second cycle 1100 ± 100 ppm. The core average enrichment and boron concentration were determined to satisfy the given energy requirements. Table I shows target cycle burnup and corresponding core average enrichment from the fuel management graph.

2.2 Optimization method

A number of research focused on how to minimize the fuel cost while keeping the energy output and satisfy constraints that applied [6]. Nuclear fuel cost includes a several cost factors involved from mining to disposal [7]. Nature of objective function (OF) is complex and nonlinear due to the uncertainties in nuclear fuel cycle. Nonlinear programming algorithms were used to solve optimization problems in in-core fuel management [8, 9].

A generalized reduced gradient (GRG) algorithm is suitable when optimization problem is large-scale with many constraints and complex objective function. The idea of GRG algorithm linearize the nonlinear OF and constraints using Taylor series [10]. Then decision variables divided into two sets, basic and non-basic. The optimal solution can be found at point where the gradient is equal or close to zero [10].

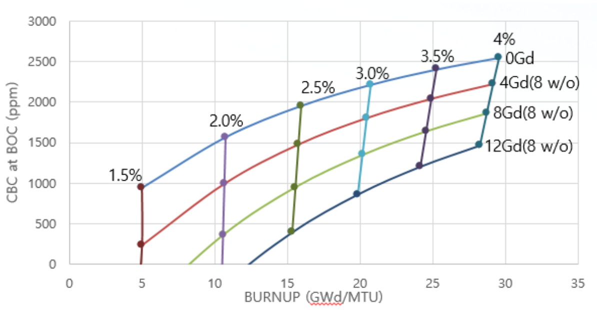

Fig. 1. Fuel management graph

Fuel performance is common in in-core fuel optimization and widely investigated by researchers [1, 2, 6]. However, batch size approach can minimize the nuclear fuel cost due to reduced and uranium loading of batches. The objective function is the minimization of the uranium loading and defined as

$$\min Z(x,e) = \sum_{i=1}^{n} (x_i \cdot e_i) \qquad (1)$$

where,

x_i – number of FAs in batch *I*,

e_i – enrichment of batch *i*.

Constraints were checked and corrected until it converges. To avoid high pin peaking factor (PPF), enrichment of reload fuel batch was kept below limit 5 w/o. Use of Gd and low enriched fuel rods in FAs reduced the batch average enrichment, which do not violate the industry limit. In addition, reduce of batch enrichment and number of fuel assemblies in the batch have economic benefits. Taking in account above, following constraints were applied for this optimization problem.

Cycle and batch enrichment

$$e_{cyc} \geq e_{core.avg}$$
$$1.5 \leq e_1 \leq 2.0$$
$$2.0 \leq e_2, e_3 \leq 3.5$$
$$3.0 \leq e_4, e_5, e_6, e_7, e_8, e_9, e_{10} \leq 4.25$$

APR1400 reactor core consists of 241 FAs

$$x_i + x_{i+1} + x_{i+2} = 241$$

Reload batch size

$$76 \leq x_i r \leq 100$$

where,

$x_i r$ – reload batch size

This optimization problem results are represented in Table II. It shows that same amount of FAs from cycle 4 and same enrichment from batch D.

Table I: Burnup and corresponding cycle enrichment

Cycle ID	Target cycle length (GWd/MTU)	Core avg. ^{235}U enrichment (w/o)
1	17.5	2.67
2	17.5	2.67
3	18.5	2.80
4	19.5	2.92
5	19.5	2.92
6	19.5	2.92
7	19.5	2.92
8	19.5	2.92

Table II: Batch specification from GRG

Cycle ID	Batch ID	Load FAs	Batch ave. ^{235}U enrichment (w/o)
1	A	88	1.65
1	B	77	3.08
1	C	76	3.50
2	D	89	4.25
3	E	92	4.24
4	F	97	4.25
5	G	97	4.25
6	H	97	4.25
7	I	97	4.25
8	J	97	4.25
Total		**907**	**3.83**

3. Result and Discussion

In this section, using the batch specifications in Table II, the loading pattern from the initial cycle up to equilibrium cycle determination was performed in order to confirm the GRG method. Several types of fuel assemblies were designed as shown in Fig. 2. CASMO and MASTER codes were used for the cross-section generations and the nodal calculation [5, 11].

3.1 Loading pattern

Based on the methodology results, the initial cycle loaded fresh 241 FAs with average core enrichment of 2.69 w/o ^{235}U. A sub-batch information was determined to satisfy the energy requirement and to make safety related parameters under control. Fig. 3 shows the loading pattern of initial cycle. To define LP for the initial cycle out-in strategy was used. This approach has strength to control the peaking factors. High enriched fuels were located outside and low enriched fuels were located inside of core. Simulation results did not violate safety aspects, the maximum pin peaking factor (PPF) was 1.44, under the target limit ($F_{xy} \leq 1.55$) and target cycle length was achieved.

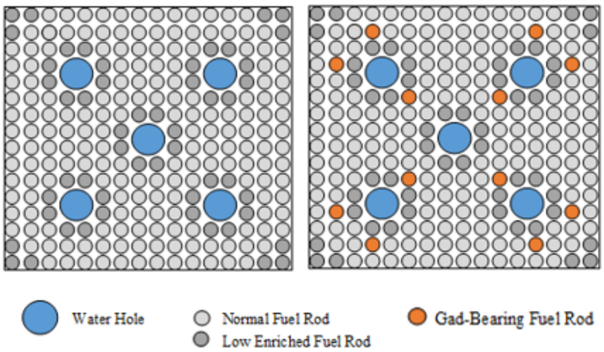

Fig. 2. FA design

In case of reload core design, the low-leakage loading pattern strategy was used. This strategy has strength in neutron economy, but it is hard to control the peaking factor and the CBC at the beginning of cycle (BOC).

The LPs from cycle 2 to the equilibrium cycle were determined by the following rules; place the twice burned fuels on periphery of core, keep PPF under the limit and reduce the CBC at BOC. Fig. 4 represents the equilibrium cycle LP. The cycle length deviation between consecutive cycles is less than 1 effective full power day (EFPD) and other parameters are similar from cycle 8.

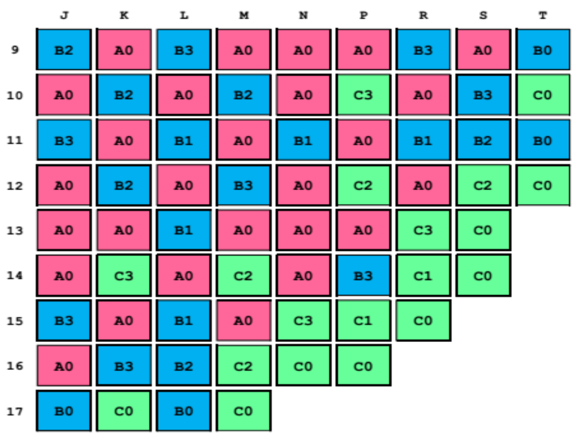

Fig. 3. Loading pattern for initial cycle

3.2 Assessment of safety related parameters

To investigate the defined LPs satisfying the safety factors, simple safety related parameters such moderator temperature coefficient (MTC) and F_{xy} were calculated for the transient cycles. The MTCs in hot full power (HFP) and hot zero power (HZP) condition at BOC and EOC satisfied the design criteria (below than 0 pcm/ºC for HFP and 5 pcm/ºC for HZP). All safety parameters for transient cycles are shown in Table III.

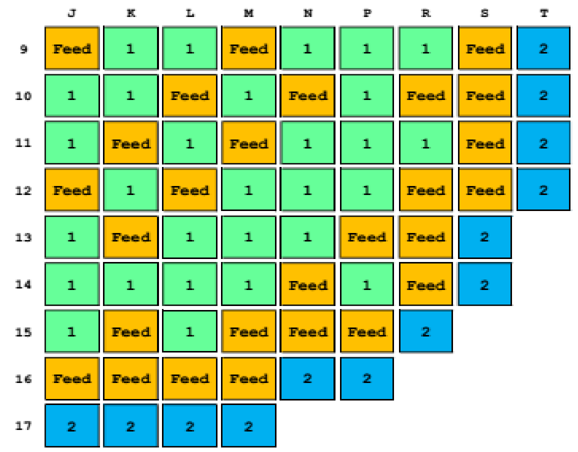

Fig. 4. Loading pattern for equilibrium cycle (green box once burnt, blue box twice burnt fuel)

Table III: Safety parameters for cycles 1, 2 and 3

	Cycle 1	Cycle 2	Cycle 3
Max. F_{xy}	1.45	1.53	1.53
CBC at BOC (ppm)	835	1,089	1,221
HFP MTC (pcm/ºC)	-10.75	-17.59	-17.60
HZP MTC (pcm/ºC)	-2.25	2.34	3.29

3.3 Feasibility checks

The cycle length for the initial cycle was satisfied the energy requirement, but following cycles could not meet the targeted burnup. This is mainly because of the GRG used the equal power sharing for each batch. In fact, actual power sharing factors were not exactly 1.0. And more gadolinia rods were used to suppress excess reactivity and to control peaking factor in reload cycles, and this made the actual core average enrichment slightly lower.

Fig. 5 and Fig. 6 represent the critical boron concentration and maximum pin peaking factor from the initial cycle to equilibrium cycle, respectively. It is shown that the fuel management strategy based on the GRG showed accurate result. In Fig. 6 red dashed line is design limit for F_{xy}, and all points are under the limit.

Table IV summarizes the core parameter results such as cycle length, EPFD, maximum pin power, discharge burnup and amount of burnable absorber rods from the nodal calculation using MASTER code. Power sharing of each batch from initial to equilibrium cycle was plotted in Fig. 7. It can be seen that deviation between the following cycle's parameters is less than 1%. It can be declared that it reaches to equilibrium from cycle 8.

Some constraints were determined through the feasibility check to reach target burnup. To increase several tips were applied, however, it is recommended to improve power sharing factor in order to increase cycle length [12]. Total fuel loading of the initial cycle is 103.8 t, similar UO_2 weight and cycle length with reference design [13]. In case of equilibrium cycle, calculated mass of UO_2 loaded in batch is 41.642 t, which is lower than fuel loading (42.98 t) of reference design [13].

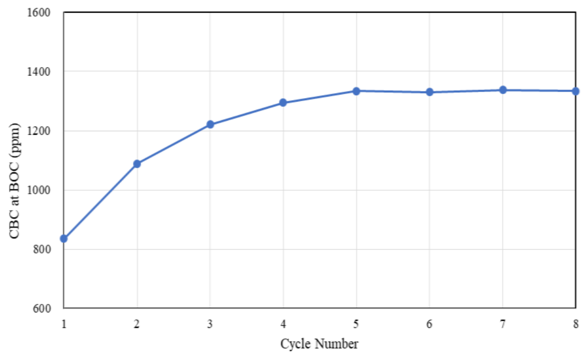

Fig. 5. Critical boron concentration at BOC

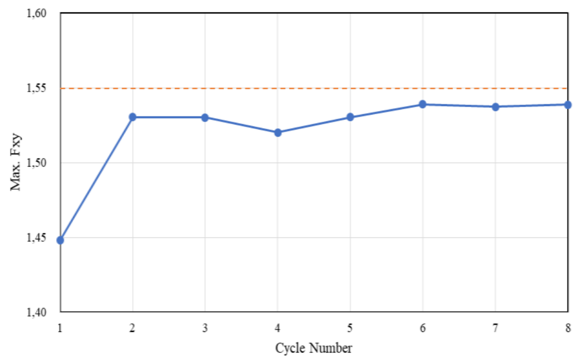

Fig. 6. The maximum F_{xy} for 8 cycles

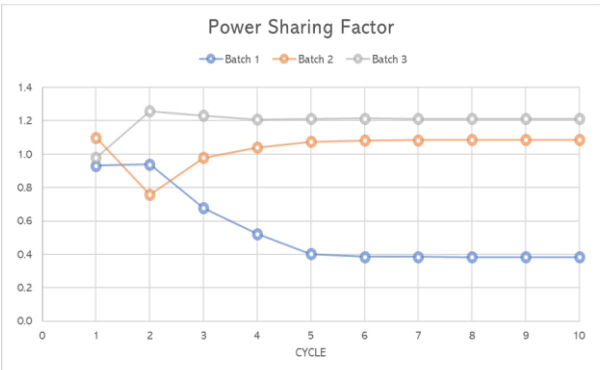

Fig. 7. Power sharing factor for 8 cycles

Table IV: Summary of calculation results

Cycle	1	2	3	4	5	6	7	8
Cycle Length (GWd/MTU)	17.594	17.369	18.454	19.249	19.226	19.109	19.166	19.130
EFPD	459.6	452.7	480.7	501.1	500.5	497.6	499.1	498.2
Target Cycle Length (GWd/MTU)	17.500	17.500	18.500	19.500	19.500	19.500	19.500	19.500
CBC at BOC (ppm)	835	1089	1221	1294	1335	1331	1337	1334
Max. Fxy	1.448	1.530	1.530	1.520	1.530	1.539	1.537	1.539
Batch Discharge BU (GWd/MTU)	16.41	35.13	42.56	43.40	46.50	47.49	47.52	47.46
Burnable Poison Fuel Rods	1548	1344	1440	1504	1440	1440	1440	1440

4. Conclusion

Batch specifications to meet energy requirements were searched using the generalized reduced gradient method. Based on applied objective function and constraints, nonlinear programming determined the batch specifications, which are the number of FAs in the batch and batch average enrichment for all cycles, since initial to equilibrium cycle. Observing the achieved results using the data from GRG method, it is clear that they meet the safety aspects, once that pin peaking factors were kept under control, from initial to equilibrium core, and boron concentration remained in an acceptable level during all cycles.

Regarding to performance, the proposed energy requirements and obtained cycle lengths were similar. Amount of burnable absorber rods and total weight of UO_2 are below than reference core design. In case of core average discharge burnup, proposed method shows higher than the reference core design. It proves that FMS can reduce uranium requirement up to 3-4%.

Despite the good results, we are aware that there are some aspects, which should be improved, such as power sharing and leakage factors. In this research, we were able to explore and better understand the core behavior regarding of these aspects, however, further research is necessary.

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