Fuel Batch Optimization for Extra Longer Initial Core Design of APR-1400

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1. Introduction

Minimizing fuel cycle costs is an important factor in nuclear power plant management. The economics of the fuel cycle can strongly benefit from minimization of the amount of enriched uranium and burnable absorbers in a core, optimization of the reactor core loading pattern (LP), and increasing discharge burnup while maintaining nuclear power plant utility requirements as well as safety constraints.

This can be achieved by properly optimizing initial core parameters such as core and batch average enrichments, a number of burnable absorber rods (Gd_2O_3) in a core, and a proper loading pattern determination.

However, these steps are complex combinatorial and non-linear problem that requires a high level of engineering judgment, a set of heuristic rules, optimization methods, and a lot of time. In this research, a calculation procedure to minimize fuel cost for core design is proposed.

2. Methods and Results

In this work, we propose a methodology for the Initial Core Design of APR-1400 and produce a cost-efficient, high burnup (24 GWD/MTU) initial core model with the proposed methodology. The methodology consists of three main steps:

1. Evaluation of core average enrichment (w-t % of ^{235}U) and number of Gd_2O_3 rods in a core at beginning of company (BOC);
2. Optimization of batch average enrichment and number of fuel assemblies (FA) per batch;
3. Determination of FA configuration and core loading pattern.

2.1 Core Average Enrichment and Total Number of Gd_2O_3 Rods in a Core

Core average enrichment for the initial cycle should provide enough excess reactivity to produce energy during the planned cycle length which is one of the utility requirements. Moreover, a proper number of Gd_2O_3 rods should be placed to suppress the excess reactivity and decrease critical boron concentration (CBC) at BOC.

Based on a previous study [1] Fuel Management Net Graph (FMNG) is developed for approximate evaluation of initial core parameters as shown in Fig. 1. CASMO-3/MASTER-3 [2,3] code system used for APR-1400 full core model simulations and CBC evaluated using Inverse Boron Worth (IBW) values presented on Table I.

Table I: Inverse Boron Worth for APR-1400 [4]

Inverse boron worth, ppm/%Δρ (BOC/EOC)	
Hot, 308.9 °C (588 °F)	91/84
Cold, 20 °C (68 °F)	73/60

FMNG provides the approximate value of core average enrichment, maximum pin peaking factor (FXYP), CBC at BOC for various cycle lengths, and a total number of poison rods (8% Gd) for a desirable CBC at BOC.

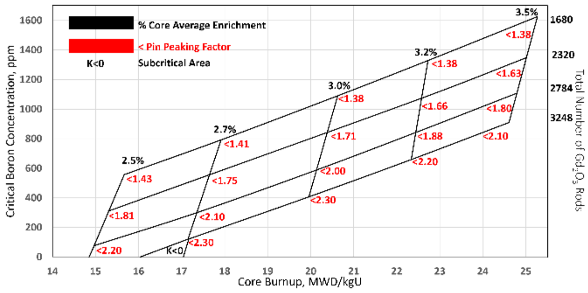


Fig. 1. Fuel Management Net Graph

Fig. 1 illustrates that for a given cycle length of 24 GWD/MTU the core average enrichment is determined at about 3.4 w-t % of ^{235}U while CBC and FXYP are 1200 and ≤1.6, respectively for a total number of poison rods equal to 2320.

2.2 Optimization of Batch Average Enrichment and Number of Assemblies Per Batch

The nuclear fuel cost accounts for approximately 20% of the total cost of operation [5]. Enrichment of loading fuel is the main factor determining the fuel cost. Consequently, choosing the right enrichment and number of FA per batch can considerably decrease fuel cost. Therefore, fuel cost is the objective function (OF) which should be minimized in this section. The OF is a nonlinear function of several variables expressed as

$$OF = \sum_{i=1}^{batch} N_i \times f_i(C_1, C_2, C_3, C_4) \qquad (1)$$

where:
C_1 : ore purchase cost;
C_2 : conversion cost;
C_3 : enrichment cost;
C_4 : fabrication cost;
N_i : Number of FA in a batch i.

There are several optimization algorithms adopted by engineers in nearly all types of problems, for example, simplex, simulated annealing, evolutionary, and others. However, according to NFL (no-free-lunch) [6] theorem, there cannot exist any algorithm for solving all types of optimization problems that is generally superior to any competitor and an optimization algorithm should be chosen depending on the problem features.

For this problem, the evolutionary algorithm (EA) [7] has been chosen because of its simplicity, quick implementation, and easy adaptability to nonlinear problems. The algorithm requires to set:

1. Objective Function: sum of every batch fuel cost;
2. Decision Variables: batch enrichments and number of FA per each batch;
3. Constraints: core average enrichment, each batch enrichment, number of FA per each batch.

The objective function calculation procedure is described in previous work [8]. The most economical combination of batch enrichment and the number of FA evaluated by EA are presented in Table II.

Table II: Results of 24-month initial cycle core parameters for APR1400

Batch enrichments, %			
1(AO)	2 (B1)	3 (C1)	4(D1)
2.3	3.1	4.1	4.95
Number of Assembly per batch			
65	64	56	56

2.3 Fuel Assembly Configuration and Core Loading Pattern Determination

In this step, after batch average enrichments and a total number of absorber rods are evaluated, FA zoning and absorber rod positioning are performed using Simulated Annealing (SA) [9]. After several hundred iterations, the code converges on very similar pin patterns (Fig. 4) found in APR1400 DESIGN CONTROL DOCUMENT TIER 2 (DCD) [4]. As shown in Fig. 2 and Fig. 3, the maximum pin peaking factor and probability converge below 1.1 and 0.05, respectively, achieved after 400 iterations.

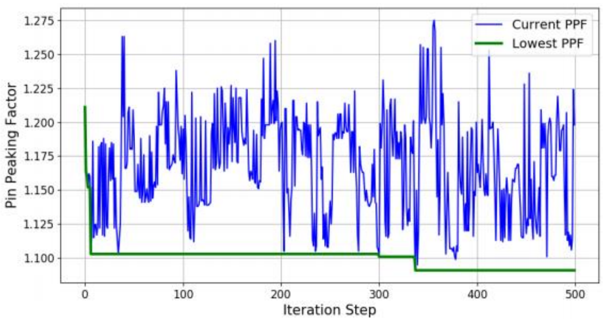


Fig. 2. Assembly pin peaking factor during SA iterations

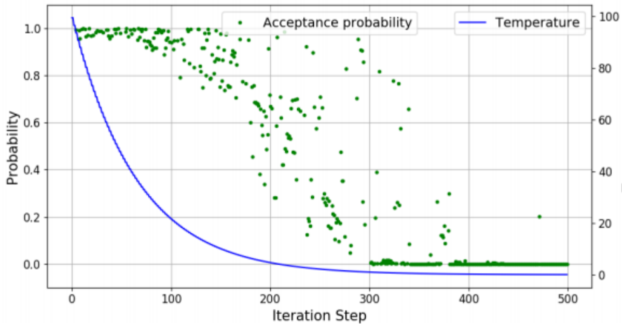


Fig. 3. Probability progression according to temperature during SA iterations

Fig. 4 shows fuel assembly configurations (enrichment zoning and poison rod locations for each batch) obtained from the SA simulation

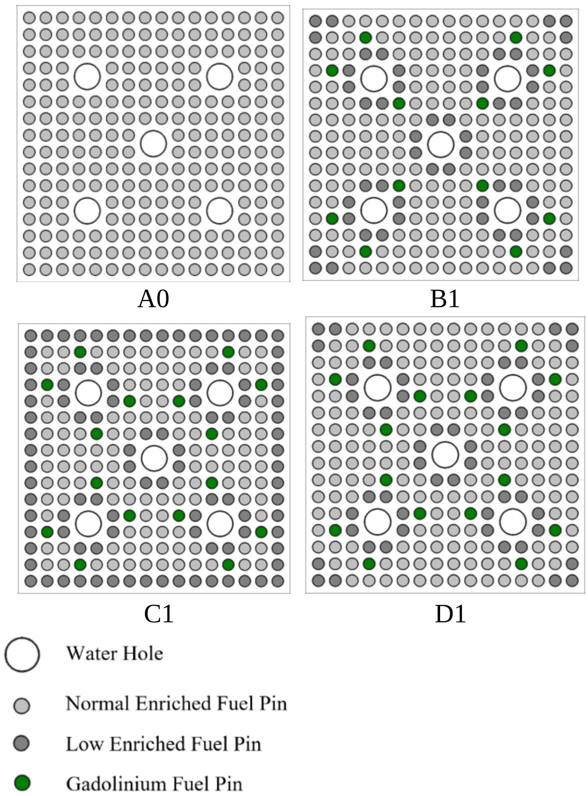


Fig. 4. Enrichment zoning and absorber rod positions for assemblies A0, B1, C1, and D1

During reactor operation, core characteristics regarding safety and economy are determined mainly by the fuel loading pattern in the core. LP is a combination of several fuel assemblies, with different nuclear properties, enrichments, and burnup. The LP is important to maximize the energy extracted from the core while maintaining the power distribution as flat as possible.

SA algorithm mentioned for FA configuration determination is applied for LP determination for given batches. The LP determined by SA simulation and its nuclear design parameters are presented in Fig. 5 and Table III, respectively. Fig. 6 compares the

FXYP distributions before and after optimization of a core LP by SA.

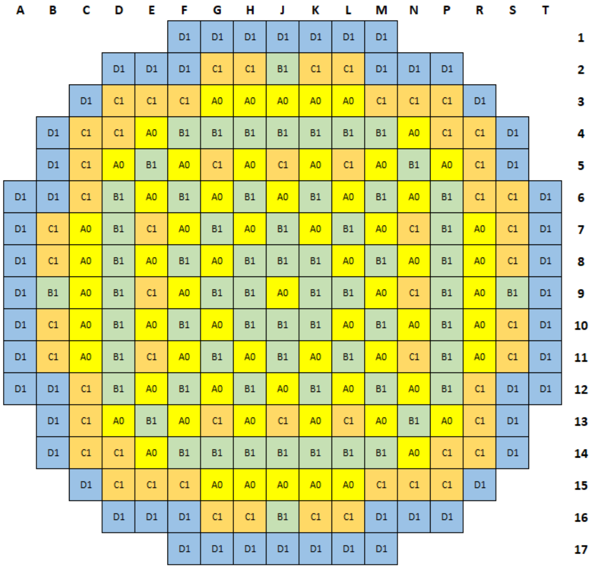
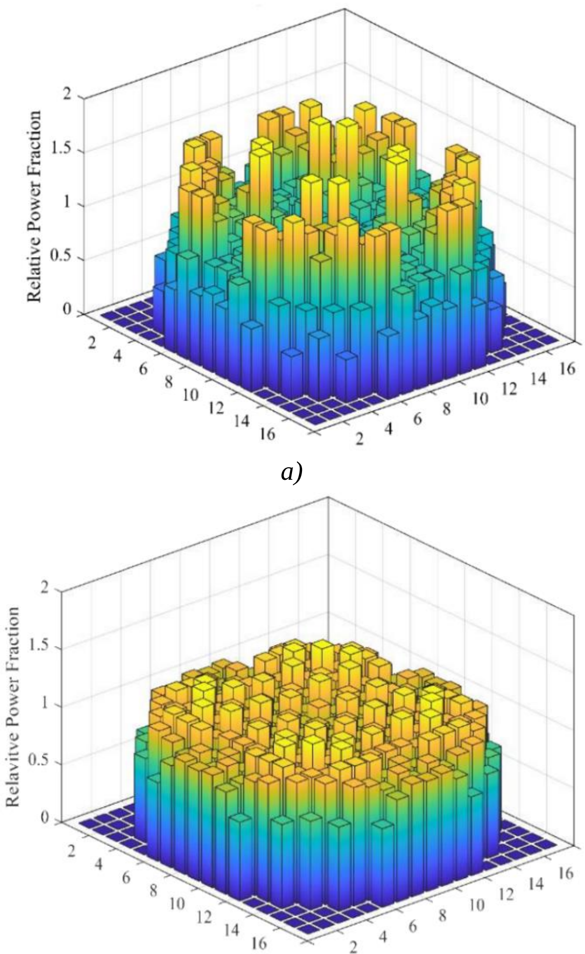


Fig. 5. Initial Cycle Loading Pattern for higher burnup



a)

b)

Fig. 6. Power distribution at the start a) and at the end b) of SA simulation

Table III: Evaluated initial Core Parameters

Model	MASTER	DCD[4]
Cycle Burnup, GWD/MTU	24.2	17.571
Max FXYP	1.52	1.59
CBC at BOC, ppm	1455	817
Core Average Enrichment	3.5	2.66
Number of Gd rods	2320	1680
Fuel Cost per unit BU, cent/ kWhe	0.97	1.02

3. Conclusions

In general, PWR in Korea uses a three-batch core LP and has a cycle length of about 18 GWD/MTU per cycle. In this research, a core design methodology is presented and evaluated by determining a 4-batch LP satisfying 24-month cycle length for the initial cycle.

The core design process consists of three stages: core average enrichment determination, batch-wise average enrichment determination, and loading pattern search.

In this process, FMNG is generated using a full core calculation to determine various core average enrichments depending on cycle length. The FMNG suggests possible candidates for a target core average enrichment and a number of poison rods satisfying a given cycle length.

And the batch-wise average enrichment is calculated using the evolutionary algorithm. In addition, the number of FA for each batch is determined in this process, and an optimum loading pattern is determined from Simulated Annealing simulations. As a result, it was validated that the core model using FMNG, and the evolutionary method satisfies the design requirements.

Finally, a fuel cost comparison was performed with the reference model of APR1400 DCD (0.97 cent/kWhe compared to 1.02 cent/kWhe [8]). Further research is to investigate a relationship between the number of feed FA and batch-wise average enrichment using the proposed method in this research for reload and equilibrium cycles.

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