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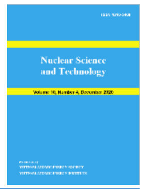

Application of Evolutionary Simulated Annealing Method to Design a Small 200 MWt Reactor Core

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Abstract: This paper presents the application of an evolutionary simulated annealing (ESA) method to design a small 200 MWt reactor core. The core design is based on a reference ACPR50 reactor deployed in a floating nuclear power plant. The core consists of 37 typical 17x17 PWR fuel assemblies with three different U-235 enrichments of 4.45, 3.40 and 2.35 wt%. Core loading pattern (LP) has been optimized for obtaining the cycle length of 900 effective full power days, while minimizing the average U-235 enrichment and the radial power peaking factor. The optimization process was performed by coupling the ESA method with the COREBN module of the SRAC2006 system code.

Keywords: *Small reactor, core design optimization, ESA method.*

I. INTRODUCTION

In recent years, interest in small module reactors (SMR) has been increasing due to their flexibility in power generation for wider ranger users, locations and applications. They also show an enhanced safety performance through passive safety systems and updated technologies [1]. Currently there are more than 50 designs of SMR under development in the world [2]. Because of flexibility and safety features of SMRs, researches in this technology are very necessary to energy development strategy in Viet Nam. One of the first tasks of the research in SMRs is reactor core design and its loading pattern.

Fuel loading optimization is one of the important tasks in designing a nuclear reactor core, which is performed after every cycle of a nuclear reactor. The problem of fuel loading pattern (LP) optimization has received attention from the beginning of nuclear reactor technology with the application of various optimization methods. Most of the methods are based on the simulation of natural systems such as simulated annealing (SA) 0-0, generic algorithms (GA) 0, 0, 0, 0, evolution method 0, particle swarm optimization method (PSO) 0, 0, 0, differential evolution 0 and so on. Although many attempts have been done, it is still a complicated multi-objective task 0.

In the present work, an evolutionary simulated annealing (ESA) method has been applied to design a small 200 MWt reactor core. The ESA method is developed to improve the original SA by using crossover and mutation operators to generate new trial solutions, instead of binary or ternary exchanges in the original SA 0. The crossover

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and mutation operators are similar to that used in GA. The reactor core is designed based on a reference ACPR50S reactor deployed in a floating nuclear power plant (FNPP) using typical PWR fuel assemblies [2], 0, 0. The core design is targeted to attain a cycle length of about 900 effective full power days (EFPDs) similar to the reference ACPR50S, while minimizing the U-235 enrichment and radial power peaking factor. Core physics calculations were performed using the COREBN module of the SRAC2006 code system. The ESA method has been coupled with the COREBN module to perform the optimization process.

II. METHODOLOGY

A. ESA method

Simulated annealing (SA) method has been soon applied to the problem of fuel LP optimization 0. The SA method has ability to escape local optima due to an acceptance probability of a worse solution. However, due to a slow convergence, the number of calculated LPs is usually large. In a previous work, the ESA method was developed to improve the original SA by using crossover and mutation to generate trial solutions. The advantages of ESA over SA and ASA have been examined 0. The procedure of ESA is described as follows:

(1) Starting with an initial trial LP.

(2) Core physics calculation of the trial LP is performed, and the fitness function is evaluated.

(3) Comparison of the fitness function with that of the current base LPs is performed. The base LPs are updated if:

- The fitness value of the trial LP is greater than or equal to that of the base LP.
- The fitness value of the trial LP is less than that of the base LP, the base LP is updated by an acceptance probability: $\rho = \exp\left(-\frac{\delta C}{T^{(n)}}\right)$. Where, δC is the difference of the fitness between the base LP and the trial LP; T is the temperature of the search.

(4) A new trial LP is generated from two base LPs using crossover and mutation operators.

(5) The temperature $T^{(n)}$ is decreased as $T^{(n+1)} = \alpha T^{(n)}$, $\alpha < 1$, after a number of calculated trial LPs with constant T, known as Malkov length.

(6) The convergence criteria is checked, and the search is stopped if the convergence criteria are met. Otherwise, step (2) is repeated.

In the ESA method, the two base LPs are referred to as parents, and the new trial LP is an offspring. The crossover is executed by exchanging two assemblies between the parents as displayed in Fig. **1**. Then, a new trial LP is generated from the offspring by applying the mutation with a probability of 0.5. The crossover is performed as follows:

i) In the father LP, two locations L1 and L2 are randomly selected, and the corresponding assemblies at the locations L1 and L2 are identified as F1 and F2.

ii) A temporary offspring is generated by copying the mother.

iii) The assemblies F1 and F2 are located at the locations L1 and L2 of the offspring. At the same time, the assemblies at the locations L1 and L2 of the offspring are moved to the locations L3 and L4, where the assemblies F1 and F2 are formerly located.

The mutation is performed in two steps. First, two or three assemblies of the offspring are selected and exchanged randomly to generate a new trial LP. Second, an assembly of the offspring is selected randomly and replaced by a random assembly with different U-235 enrichment by a probability of 0.5.

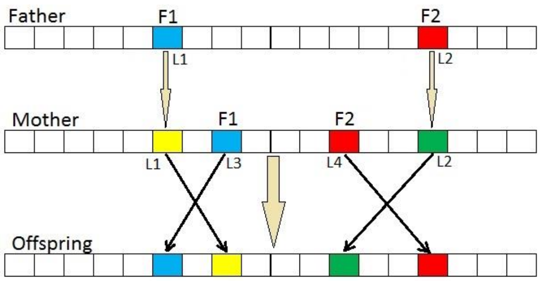


Fig. 1. Crossover operator used in the ESA method

The two base LPs are updated by replacing the worse base LP by a better trial. Therefore, the best current LP is always selected as one of the two base LPs. Since the offspring contains more characteristics of the mother than that of the father, the selection of the mother from the two base LPs would have a significant effect on the performance of the crossover. Thus, to increase the diversity of the search process, the worse base LP is chosen as the mother. The convergence criteria were set to stop the calculation loop if the current base LP is remained unchanged after 100 trial solutions or the current best LP is remained unchanged after 1000 trial solutions.

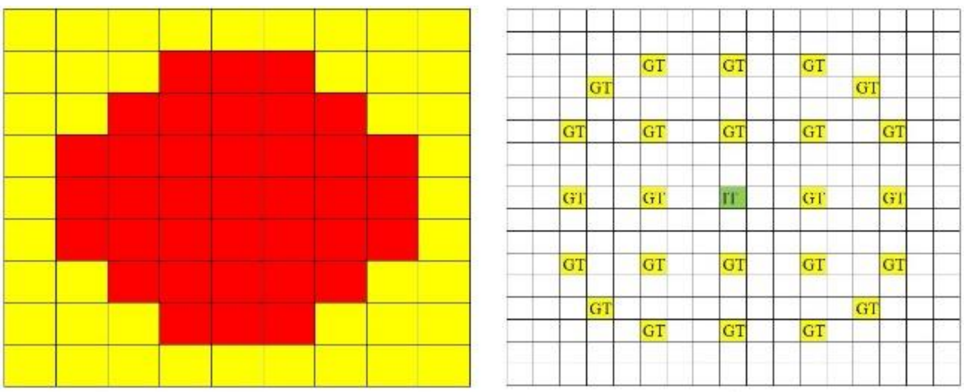
B. Objective function

A fitness function has been used to design the core for achieving a cycle length of about 900 EFPDs, which is similar to the cycle length of the reference ACPR50 reactor. The average U-235 enrichment and radial power peaking factor are minimized. Therefore, the fitness function is written as:

$$Fitness = -w_c \times |C - C_0| - w_e \times E - w_p \times max\,(0, PPF - P_0) \quad (1)$$

$$E = \frac{\sum E_i n_i}{\sum n_i} \quad (2)$$

Where, C is cycle length; E is the average enrichment of loaded assemblies, E_i is enrichment of fuel assembly type i and n_i is the number of loaded fuel assembly type i; and PPF is the radial power peaking factor. C_0 = 900 effective full power days (EFPDs), P_0 = 1.5 are chosen as constants. w_c = 0.00333, w_e = 0.1 and w_p = 10 are weighting factors. The cycle length is determined when the k_{eff} decreases to unity. A better LP corresponds to a larger value of Fitness.



(a) (b)

Fig. 2. Core configuration (a) and a typical 17x17 PWR fuel assembly (b)

C. Description of the core

The core is designed based on typical PWR assembles similar to the reference ACPR50 core as shown in Fig. **2**. The core consists of 37 fuel assemblies with 1/4th symmetrical geometry. The assemblies are typical types of PWR, with 17x17 lattice, containing 264 rods, 24 guide tubes and a instrumentation tube. Three types of fuel assemblies corresponding to the U-235 enrichments of 4.45, 3.40 and 2.35 wt%, respectively, are considered for loading into the core. The main design parameters of the core are given in Table 0, 0, 0.

Core physics and burnup calculations have been performed based on a 2D full-core model using the COREBN module of the SRAC2006 code system and the JENDL-3.3 data library. The core is reflected by water as shown in Fig. **2**. The eight-group macroscopic cross-section set of reflector and fuel lattices were generated using the PIJ module of the SRAC2006 code. The COREBN calculations were performed for obtaining the effective multiplication factor (k_{eff}) and power distribution during the burnup. Then the cycle length (C) and the maximum PPF are determined.

Table I. Main parameters of the small modular reactor core based on the reference ACPR50 reactor [2], 0

Parameters	Values
Reactor thermal power [MW]	200
Cycle length [day]	900
Number of assembly [-]	37
Assembly pitch [cm]	21.4173
Assembly height [cm]	220
Fuel rod pitch	1.2598
Fuel pellet radius [cm]	0.4096
Fuel inner cladding radius [cm]	0.4178
Fuel outer cladding radius [cm]	0.475
Fuel enrichment [%wt U235]	4.45, 3.40, 2.35
Operation pressure [MPa]	15.5
Inlet coolant temperature [K]	572.6
Outlet coolant temperature [K]	595.1
Fuel temperature [K]	1145

III. RESULTS AND DISCUSSION

A. Core design and optimization

In the optimization process using the ESA method, the control parameters have to be chosen firstly. A survey has been conducted to determine the values of α and Malkov length. In this survey, the values of α and Malkov length were varied in the ranges of [0.85, 0.95] and [20, 50] with steps of 0.5 and 5, respectively. The values of α = 0.9 and Malkov length = 25 have been selected to maximize the fitness function whereas the number of searching LP in each run is lower than 2000.

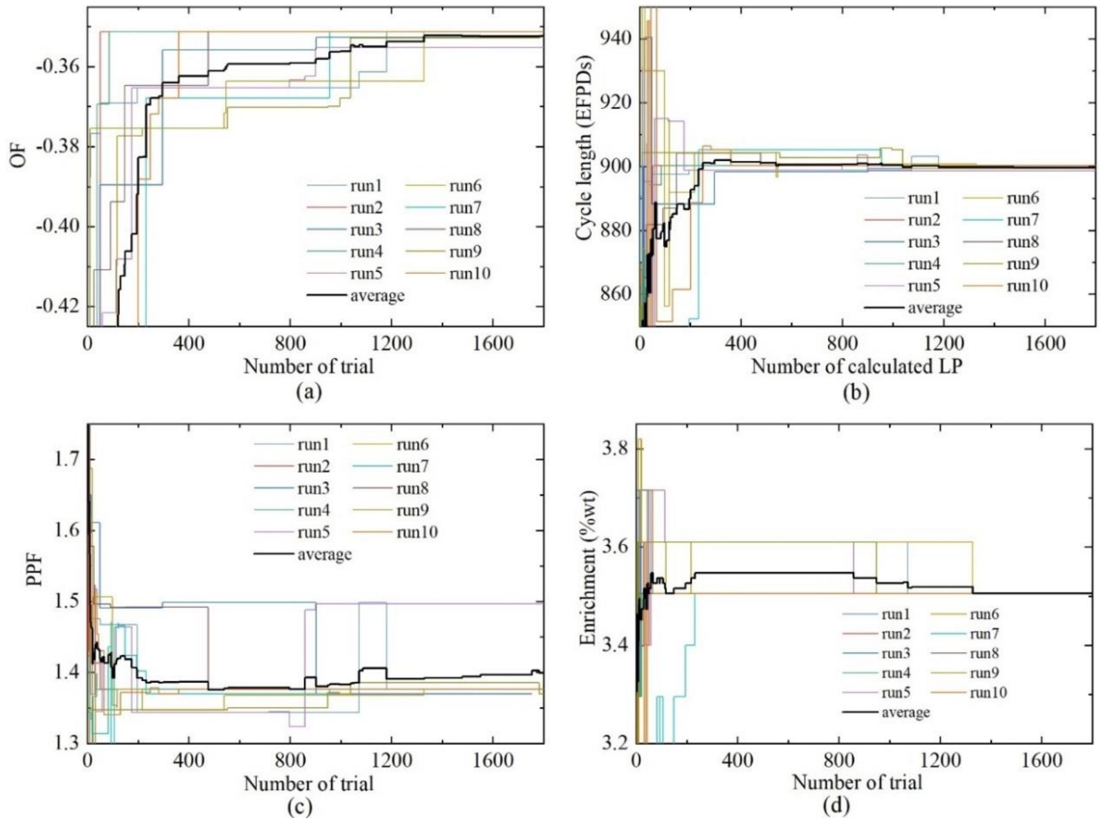


Fig. 3. Evolution of the fitness (a), cycle length (b), PPF (c) and average enrichment with the number of calculated LPs in ten independent runs

Table II. Optimal objective parameters obtained by ESA method in ten independent runs

run	Fitness	Cycle length (EFPDs)	PPF	Enrich-ment (wt%)
1	-0.35127	900.2	1.377	3.505
2	-0.35127	900.2	1.377	3.505
3	-0.35268	899.3	1.370	3.505
4	-0.35127	900.2	1.377	3.505
5	-0.35515	898.6	1.497	3.505
6	-0.35127	900.2	1.377	3.505
7	-0.35128	900.2	1.377	3.505
8	-0.35128	900.2	1.377	3.505
9	-0.35268	899.3	1.370	3.505
10	-0.35127	900.2	1.377	3.505
Average	-0.35194	899.9	1.387	3.505

The initial temperature T were selected as 15.0 to ensure the initial acceptance probability approximate unity. Due to the 1/4 symmetry of the core, the calculation model consists of 10 fuel assemblies with three types of U-235 enrichments of 4.45 %wt (F445), 3.40 %wt (F340) and 2.35 %wt (F235), respectively, loaded in the 1/4th core geometry. The search processes were performed with ten independent runs 0, 0, 0, 0.

Fig. 3 shows the change of the fitness function and other objective parameters in ten independent runs. Once can see the improvement of the Fitness occurs throughout the search process. The objective parameters such as cycle length, PPF and average enrichment are also converged to stable values together with the convergence of Fitness function. Table summaries the optimal objective parameters obtained in ten independent runs. The PPFs are converged to the values of about 1.387, while the average enrichment is 3.505 wt%, and the cycle length is approximate 900 EFPDs.

B. Optimal core LP

Fig. **4** shows the optimal core LP of the small 200 MWt reactor selected from the ten independent runs of the optimization process. The relative radial power distribution at the beginning of cycle shows that the PPF of 1.377 appear near the core central at the assembly with the enrichment of 3.40 wt%. Fig. **5** shows the change of k_{eff} and PPF during the burnup. The PPF is decreased during the EFPDs, and the k_{eff} is unity at about 900 days.

Several main parameters of the optimal LP have been calculated and summarized in Table . One can see that two parameters of the core included PPF and EFPDs satisfy the requirements of the ACPR50S reactor those are PPF < 1.377 and EFPDs = 900 days. The temperature coefficients of moderator and fuel are negative also. Furthermore, the average enrichment of the ACPR50S core is estimated at 3.505 wt%. The number of loaded fuel types are nine assemblies of F235, 12 assemblies of F340 and 16 assemblies of F445.

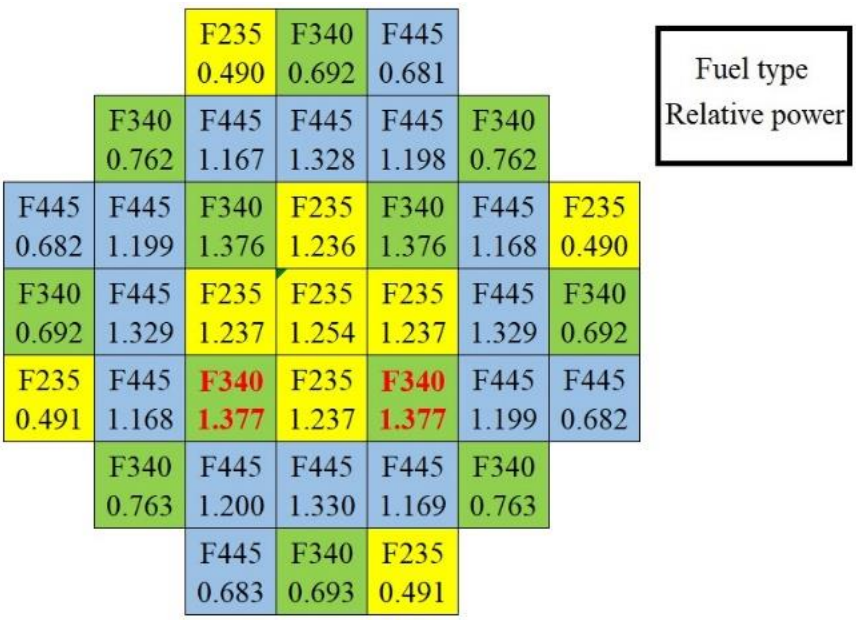


Fig. 4. Optimal loading pattern and relative power distribution of the small reactor core

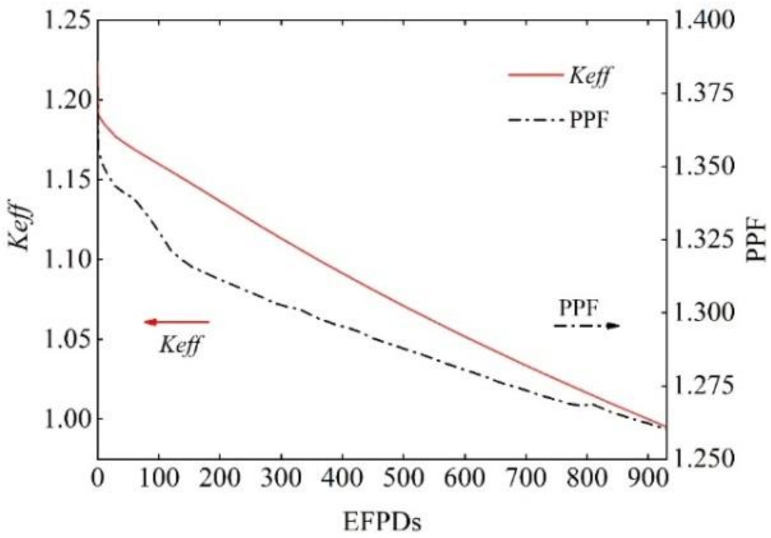


Fig. 5. Evolution of the k_{eff} and PPF of the optimal core as functions of burnup

Table III. Parameters of the optimal core

Parameters	Values
Cycle length (days)	900
Average enrichment [wt% U-235]	3.505
Maximum PPF [-]	1.377
Maximum keff	1.22417
Fuel temperature coefficient [pcm/K]	-2.564
Moderator temperature coefficient [pcm/K]	-104.3
Number of fuel assembly F235	9
Number of fuel assembly F340	12
Number of fuel assembly F445	16

IV. CONCLUSIONS

The ESA method was applied to design a small 200 MWt modular reactor core based on the reference ACPR50S reactor. The COREBN module of the SRAC2006 code system was for core physics and burnup calculations, which was coupled with the ESA method for performing the design process. The core consists of 37 typical PWR fuel assemblies with the enrichments of 4.45, 3.40 and 2.35 wt%. The target designs are to obtain the core cycle length of about 900 EFPDs, while minimizing the PPF and the average U-235 enrichment. The optimal core is obtained with the number of F445, F340 and F235 assemblies of 16, 12 and 9, respectively. The cycle length of the optimal core is 900 EFPDs, while the PPF is 1.377 and the average enrichment is 3.505 wt%. Negative fuel temperature and coolant temperature coefficients have been confirmed.

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