

# **In-CORE NUCLEAR FUEL MANAGEMENT OPTIMIZATION OF VVER1000 USING PERTURBATION THEORY**

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## **ABSTRACT**

In-core nuclear fuel management is one of the most important concerns in the design of nuclear reactors. The two main goals in core fuel loading pattern design optimization are maximizing the core effective multiplication factor in order to extract the maximum energy, and keeping the local power peaking factor lower than a predetermined value to maintain fuel integrity. Because of the numerous possible patterns of the fuel assemblies in the reactor core, finding the best configuration is so important and complex. Different methods for optimization of fuel loading pattern in the core have been introduced so far. In this study, a software is programmed in C# language to find an order of the fuel loading pattern of the VVER-1000 reactor core using the perturbation theory. Our optimization method is based on minimizing the radial power peaking factor. The optimization process lunches by considering the initial loading pattern and the specifications of the fuel assemblies which are given as the input of the software. It shall be noticed that the designed algorithm is performed by just shuffling the fuel assemblies. The obtained results by employing the mentioned method on a typical reactor reveal that this method has a high precision in achieving a pattern with an allowable radial power peaking factor.

*Key Words:* Fuel management, optimization, perturbation theory, power peaking factor.

## **1. INTRODUCTION**

In-core fuel management is one of the most challenging areas in nuclear engineering. It involves the optimal loading pattern of hundreds fuel assemblies in the core. The optimization of this arrangement is very important in either economics or safety. In this regard various methods, as shown in Table I, have already been elaborated.

Each method has its own merits and shortcomings. In fact, the numerous possible loading patterns of the fuel assemblies and the nonlinearity nature of the optimization problem, make the use of conventional methods complex. One of the most important objective functions in the fuel loading pattern optimization problems is reduction the radial power peaking factor which is a measure of the plainness of neutron flux distribution. The optimum fuel loading pattern is the one that produces the flattest shape of the neutron flux distribution [13].

Moore and Turinsky introduced an implementation of adjoint methods to BWR for accurate prediction of core characteristic during loading pattern optimization [3]. Maldonado proposed a model for determination of power distribution in PWR reactors by combining the generalized perturbation and diffusion theories to evaluate different fuel loading pattern [5].

In this paper, a programmed software in C# language is elaborated to find an order of the fuel loading of a typical VVER-1000 reactor core using the perturbation theory. The optimization method is based on minimizing the radial power peaking factor. Considering the initial loading pattern of the fuel assemblies and their specifications as the input of the software, the optimization process is started. It should be noticed that the employed algorithm is performed by just shuffling the fuel assemblies and no changes are imposed in the specifications of fuel assemblies.

**Table I. The various methods used in fuel management optimization**

<b>Method</b>	<b>Objective</b>	<b>Presenter</b>
<b>Linear programming + Direct search algorithm</b>	Maximize discharge burn up	Kim, Downar, Sesonske [15]
<b>Linear programming</b>	Maximize core reactivity	Stillman, Chao, Downar [7]
<b>Dynamic programming</b>	Minimize power peaking factor	Wall, Fenech [6]
<b>Optimal control theory</b>	Minimize power peaking factor	Chang, Levine [4]
<b>Perturbation Theory + Monte Carlo Integer Programming</b>	Minimize cost of fuel and Maximize core reactivity	Turinsky, Hobson [13]
<b>Perturbation Theory</b>	Maximize core reactivity	White [10]
<b>Direct Search Algorithm</b>	Minimize power peaking factor	Naft, Sesonske [2]
<b>Genetic Algorithm</b>	Minimize power peaking factor	Loon, Parks [14]
<b>Linear Programming + Haling Method</b>	Maximize core reactivity	Suh, Levine [9]
<b>Neural network + Simulated annealing</b>	Maximize core reactivity and Minimize power peaking factor	Sadighi, Setayeshi [11]

WIMS and CITATION computer codes have been used for neutronic calculation of VVER-1000 core. The WIMS code generates the group constants, infinite and finite multiplication factors in the steady state and calculates the atomic densities of desired isotopes as fuel burnup [12]. Using these data, CITATION code solves the multigroup diffusion equation by finite difference method in two or three dimensions and wanted in desired number of energy groups to calculate neutron flux or power distribution and effective multiplication factor of core as well [15].

## 2. TECHNICAL SPECIFICATIONS OF THE VVER-1000

The reactor core of VVER-1000 contains 163 hexagonal fuel assemblies with equal dimensions. These fuel assemblies can be sorted in to 6 groups based on the enrichment and the type of the burnable absorbers [17]. Table II and Fig. 1 show fuel assemblies' specifications and their typical arrangement in first fuel cycle, respectively.

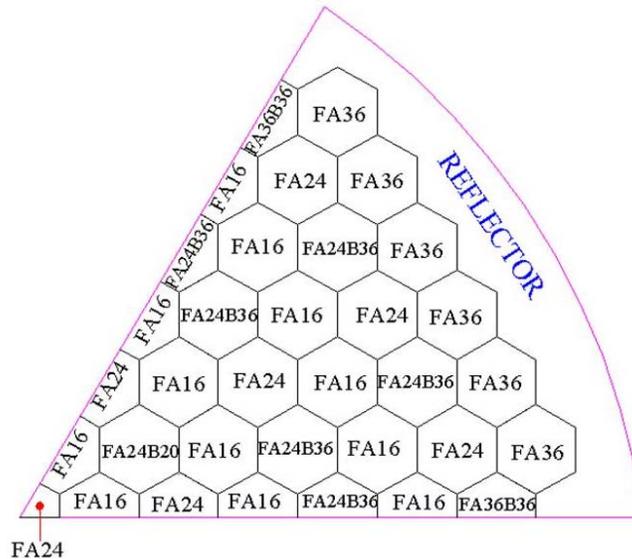
**Table II. Description of fuel assembly type [16]**

FA <sup>a</sup> type	Average enrichment	Number of fuel rods (enrichment)	BP <sup>b</sup> ?	Number of BP rods	BC <sup>c</sup> in BP (gr/cm <sup>3</sup> )
16	1.6 %	311 (1.6)	No	0	0
24	2.4 %	311 (2.4)	No	0	0
36	3.62 %	245 (3.7) + 66 (3.3)	No	0	0
24B20	2.4 %	311 (2.4)	Yes	18	0.020
24B36	2.4 %	311 (2.4)	Yes	18	0.036
36B36	3.62 %	245 (3.7) + 66 (3.3)	Yes	18	0.036

<sup>a</sup> FA = Fuel Assembly

<sup>b</sup> BP = Burnable Poison

<sup>c</sup> BC = Boron Concentration



**Figure 1. Typical Fuel Assembly Arrangement of VVER-1000 in first cycle (1/6<sup>th</sup> symmetry) [14]**

The core has  $1/6^{\text{th}}$  symmetry and it can be used in simulation for simplification of the optimization process.

### 3. PERTURBATION THEORY

It is frequently of interest to evaluate the effect of a small perturbation. If the perturbation occurs uniformly in the whole core or in a portion of it, the problem can be solved using direct methods. For example the effect of a uniform change in the reactor core can be calculated by recalculating the group constants and solving the multigroup equations for the new core. However this method is not appropriate for small perturbations because it is possible for the effect of the perturbation to be eliminated in the rounding process of the calculations. The problems of uniform and small perturbations can be solved by differential methods; but these methods are only applicable for simple reactors [8]. The equations governing the system are as follows:

$$-\nabla \cdot D_g(r) \nabla \Phi_g(r) + \Sigma_{ag}(r) \Phi_g(r) = \sum_{g'=1}^G \Sigma_{sg' \rightarrow g}(r) \Phi_{g'}(r) + \frac{1}{k} \chi_g \sum_{g'=1}^G \nu \Sigma_{fg'}(r) \Phi_{g'}(r) \quad (1)$$

$g', g = 1, \dots, G$

$$\nabla \cdot D_g(r) \nabla \Phi_g^+(r) + \Sigma_{ag}(r) \Phi_g^+(r) = \sum_{g'=1}^G \Sigma_{sg \rightarrow g'}(r) \Phi_{g'}^+(r) + \frac{1}{k} \nu \Sigma_{fg}(r) \sum_{g'=1}^G \chi_{g'} \Phi_{g'}^+(r) \quad (2)$$

$g', g = 1, \dots, G$

Where

$D_g(r)$  = diffusion coefficient for group  $g$  at position  $\mathbf{r}$

$\Phi_g(r)$  = neutron flux for group  $g$  at position  $\mathbf{r}$

$\Phi_g^+(r)$  = adjoint neutron flux for group  $g$  at position  $\mathbf{r}$

$\Sigma_{ag}(r)$  = macroscopic absorption cross section for group  $g$  at position  $\mathbf{r}$

$\Sigma_{sg' \rightarrow g}(r)$  = macroscopic scattering cross section of neutron scattering from group  $g'$  to  $g$  at position  $\mathbf{r}$

$k$  = criticality eigenvalue (effective multiplication factor)

$\chi_g$  = fission neutrons both with energy in the  $g^{\text{th}}$  group

$\Sigma_{fg}(r)$  = macroscopic fission cross section for group  $g$  at position  $\mathbf{r}$

To solve eqs. 1 and 2, in the whole core gives the spatial flux distribution and its adjoint correspondingly in different energy groups.

If there is a small perturbation in  $D$  parameter (diffusion coefficient) to change it to  $D + \delta D$ ; the neutron flux  $\Phi$  changes to  $\Phi + \delta \Phi$  and the effective multiplication factor  $k$  change from  $k$  to  $k + \delta k$ , respectively. The equation of the perturbed system may be expressed as:

$$-\nabla \cdot (D_g + \delta D_g) \nabla (\Phi_g + \delta \Phi_g) + \Sigma_{ag} (\Phi_g + \delta \Phi_g) = \sum_{g'=1}^G \Sigma_{sg' \rightarrow g} (\Phi_{g'} + \delta \Phi_{g'}) + \frac{1}{k + \delta k} \chi_g \sum_{g'=1}^G \nu \Sigma_{fg'} (\Phi_{g'} + \delta \Phi_{g'}) \quad (3)$$

$g', g = 1, \dots, G$

Equation 3 may be solved by direct method to get  $\delta k$ ; however this would be too times consuming. Here, the perturbation theory may be used to reduce the calculation time by preventing of solving the equations again. The change in neutron flux distribution and effective multiplication factor may be evaluated in this manner.

Multiplying (3) by the adjoint flux  $\Phi^+(r)$  and integrating over the reactor volume yields to:

$$\begin{aligned} & \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ [-\nabla \cdot (D_g \nabla (\delta \Phi_g))] \right) + \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ [\Sigma_{ag} (\delta \Phi_g)] \right) - \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ \left[ \sum_{g'=1}^G (\Sigma_{sg' \rightarrow g} (\delta \Phi_{g'})) \right] \right) \\ & - \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ \left[ \frac{1}{k + \delta k} \sum_{g'=1}^G (\nu \Sigma_{fg'} (\delta \Phi_{g'})) \right] \right) + \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ [-\nabla \cdot (\delta D_g \nabla (\Phi_g))] \right) \\ & + \left( \int_{core} dV \sum_{g=1}^G \Phi_g^+ [-\nabla \cdot (\delta D_g \nabla (\delta \Phi_g))] \right) = \left( \frac{1}{k + \delta k} - \frac{1}{k} \right) \int_{core} dV \sum_{g=1}^G \Phi_g^+ \chi_g \sum_{g'=1}^G \nu \Sigma_{fg'} \Phi_{g'} \end{aligned} \quad (4)$$

The first four terms in the brackets on the left hand side of Eq. 4 are vanished, because  $\Phi^+(r)$  satisfies Eq. 2 with the boundary conditions that  $\Phi^+(r) = 0$  for  $\vec{r}$  on the external surface of the reactor. The sixth term in the brackets on the left hand side of Eq. 4 is neglected as well since it is the result of multiplication of two small quantities.

Finally the reactivity change result of a change in the diffusion coefficient  $D$  would be evaluated by Eq. 5:

$$\Delta \rho_{pert} \equiv \frac{\delta k}{k} = \frac{\int_{core} dV \sum_{g=1}^G \Phi_g^+ [\nabla \cdot (\delta D_g) \nabla \Phi_g]}{\int_{core} dV \sum_{g=1}^G \Phi_g^+ \chi_g \sum_{g'=1}^G \nu \Sigma_{fg'} \Phi_{g'}} \quad (5)$$

The same discussed methodology may be used for reactivity evaluation produced as the result of other group constants like absorption and/or fission cross sections.

It is evident from eq. 5 that spatial flux distribution and its adjoint should be calculated to evaluate the reactivity change. CITATION computer code is employed in current study to solve the neutron diffusion equation and its adjoint in the desired number of energy groups. Neutron flux distribution and its adjoint are evaluated in two energy groups.

Equation 6 shows the general correlation used for the evaluation of reactivity variation results of change in group constants (in two energy groups).

$$\Delta\rho_{pert} = \left( \left[ \int_{core} dV\Phi_1^+(\nabla\cdot(\delta\mathcal{D}_1)\nabla\Phi_1) + \int_{core} dV\Phi_2^+(\nabla\cdot(\delta\mathcal{D}_2)\nabla\Phi_2) \right] + \left[ \int_{core} dV\Phi_1^+(\delta\Sigma_{a1})\Phi_1 \right] + \left[ \int_{core} dV\Phi_2^+(\nabla\cdot(\delta\Sigma_{a2})\nabla\Phi_2) \right] \right) - \left( \int_{core} dV\Phi_1^+(0) + \int_{core} dV\Phi_2^+(\delta\Sigma_{s1\rightarrow 2})\Phi_1 \right) + \left[ \int_{core} dV\Phi_1^+\left(\frac{1}{k}\right)\left([\delta(v\Sigma_{f1})]\Phi_1 + [\delta(v\Sigma_{f2})]\Phi_2\right) \right] \div \left( \int_{core} dV\Phi_1^+(v\Sigma_{f1}\Phi_1 + v\Sigma_{f2}\Phi_2) \right) \quad (6)$$

#### 4. OPTIMIZATION ALGORITHM USING PERTURBATION THEORY

The optimization process in current study is based on the substitution of the fuel assemblies which is known as shuffling. It is conventional to fix the central and peripheral fuel assemblies in their initial place in the optimization process. Therefore one may calculate that just 20 fuel assemblies take part in the optimization process ignoring the position change of central and peripheral assemblies.

First of all, the fuel assemblies which take part in the optimization process are sorted by a special specification which may be the K-infinite or any other neutronic parameters.

The optimization process is done in 1/6<sup>th</sup> of the core assuming an initial fuel loading pattern.

The optimization algorithm is summarized as follows:

1. Flux, adjoint flux and power distribution are calculated for initial pattern.
2. According to the infinite multiplication factor (were calculated by WIMS code), fuel assemblies are sorted in following order:
  - Number 1 is assigned to the fuel assembly with the maximum infinite multiplication factor.
  - Number 20 is assigned to the fuel assembly with the minimum infinite multiplication factor.
  - The numbers between 1 to 20 are assigned for other fuel assemblies according to their multiplication factor.
3. Two fuel assemblies with higher multiplication factor (fuel assemblies No.1 and 2) are chosen and substituted to each other. The method of assembly selection in order to substituting is led to the resultant change of reactivity has been small and its value has been computed using perturbation theory

4. After above substitution; group constants are calculated base on Tables III. The position of fuel assemblies 1 and 2 are pointed out by letters A and B respectively.

5. The change in reactivity due to the variation of group constants is separately calculated for each assembly by Eq. 6 which is derived based on the perturbation theory.

$\Delta\rho_{pert}^{B\rightarrow A}$  = The reactivity change in location A caused by moving fuel assembly positioned in location B to location A.

$\Delta\rho_{pert}^{A\rightarrow B}$  = The reactivity change in location B caused by moving fuel assembly positioned in location A to location B.

6. Summing two calculated reactivity changes to get the total core reactivity change ( $\Delta\rho$ ) due to fuel assembly shuffling.

**Table III. Change of group constants due to shuffling**

Group Constants	Fuel Assembly A	Fuel Assembly B
Diffusion coefficient for group 1	$\delta(D_{1A}) = D_{1B} - D_{1A}$	$\delta(D_{1B}) = D_{1A} - D_{1B}$
Macroscopic Absorption XS <sup>a</sup> for group 1	$\delta(\Sigma_{a1A}) = \Sigma_{a1B} - \Sigma_{a1A}$	$\delta(\Sigma_{a1B}) = \Sigma_{a1A} - \Sigma_{a1B}$
Macroscopic Nu-fission XS for group 1	$\delta(v\Sigma_{f1A}) = v\Sigma_{f1B} - v\Sigma_{f1A}$	$\delta(v\Sigma_{f1B}) = v\Sigma_{f1A} - v\Sigma_{f1B}$
Macroscopic Scattering XS from group 1 to 2	$\delta(\Sigma_{s1\rightarrow 2A}) = \Sigma_{s1\rightarrow 2B} - \Sigma_{s1\rightarrow 2A}$	$\delta(\Sigma_{s1\rightarrow 2B}) = \Sigma_{s1\rightarrow 2A} - \Sigma_{s1\rightarrow 2B}$
Diffusion coefficient for group 2	$\delta(D_{2A}) = D_{2B} - D_{2A}$	$\delta(D_{2B}) = D_{2A} - D_{2B}$
Macroscopic Absorption XS for group 2	$\delta(\Sigma_{a2A}) = \Sigma_{a2B} - \Sigma_{a2A}$	$\delta(\Sigma_{a2B}) = \Sigma_{a2A} - \Sigma_{a2B}$
Macroscopic Nu-fission XS for group 2	$\delta(v\Sigma_{f2A}) = v\Sigma_{f2B} - v\Sigma_{f2A}$	$\delta(v\Sigma_{f2B}) = v\Sigma_{f2A} - v\Sigma_{f2B}$

<sup>a</sup> XS = Cross Section

7. The shuffling is accepted if two following condition are satisfied:

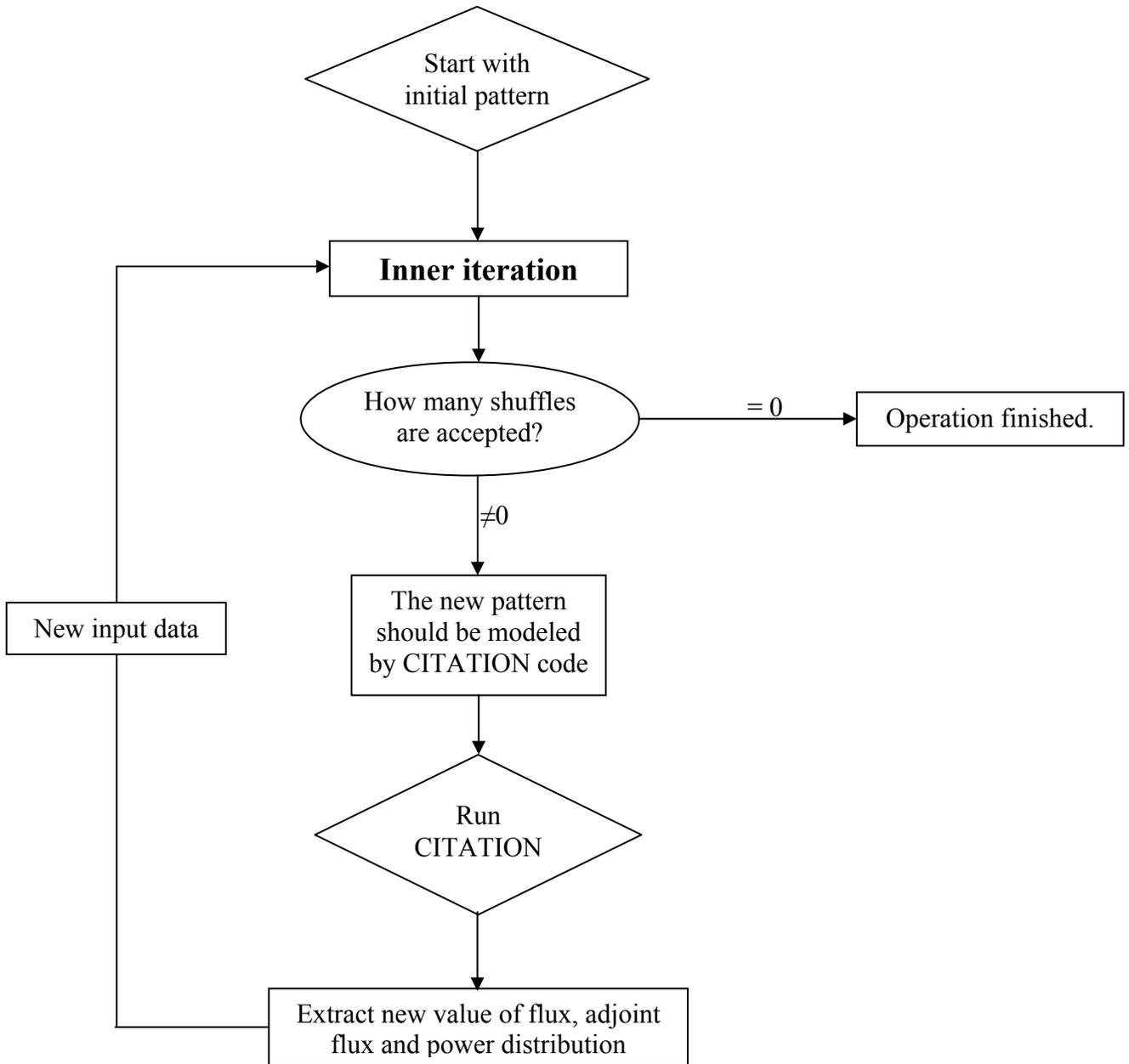
- I. the reactivity change is negative ( $\Delta\rho < 0$ )
- II. Power fraction of fuel assembly A is less than B

Then steps 4 through 6 would be repeated for fuel assemblies 3 and 4. Otherwise, the substitution is rejected and steps 4 through 4 are repeated for fuel assemblies 2 and 3.

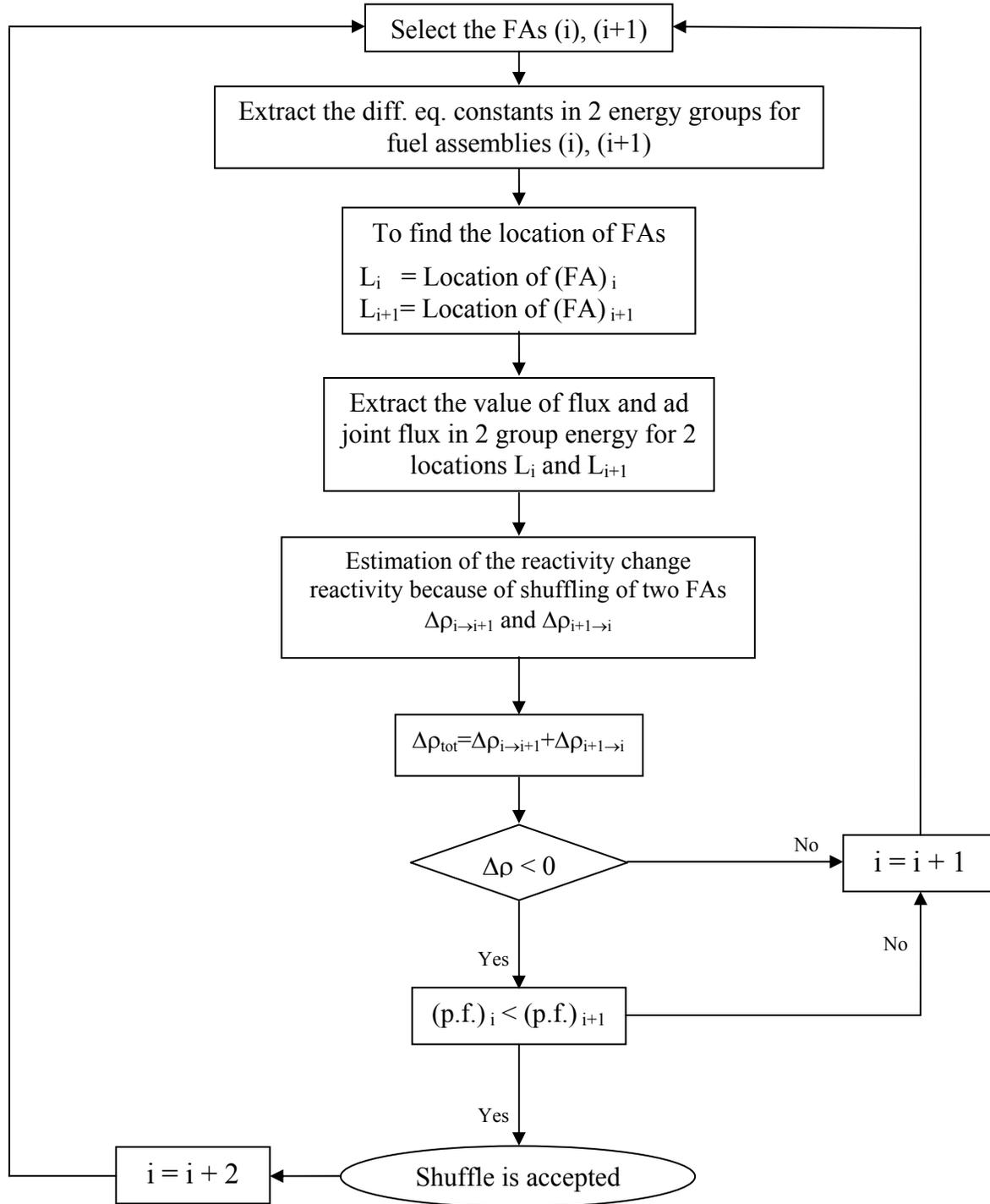
8. Steps 3 through 7 are repeated until all the possible substitutions are considered. Then the accepted substitutions are prepared as the new fuel loading pattern of the core (end of this step, flux, adjoint flux and power distribution for obtained pattern are calculated by CITATION code).

9. Steps 2 through 8 are repeated after doing core calculations for any new loading pattern. The optimization program will be finished, when no possible substitution is left.

The general approach of optimization algorithm and the process of shuffling in each iteration are shown in Figs. 2 and 3, respectively.



**Figure 2. General approach of optimization algorithm**

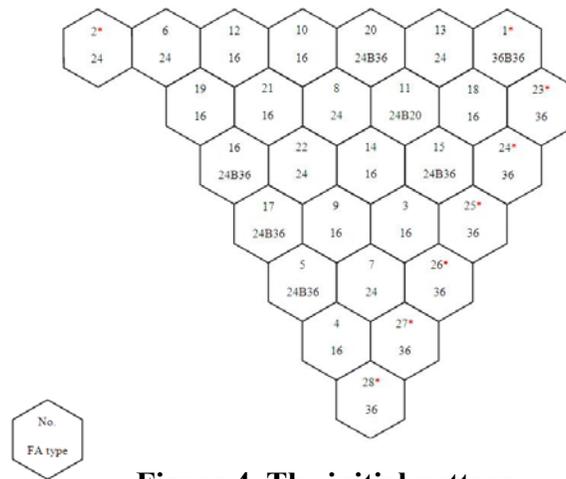


**Figure 3. The process of shuffling in each iteration (inner iteration)**

**5. Results and Discussion**

The first fuel cycle of a typical VVER-1000 reactor core is assumed as a case study. Fig. 4 shows the initial loading pattern of the reactor core. The maximum power peaking factors in the initial patterns is calculated as 1.5072.

The proposed optimization process is applied for the initial pattern, Fig. 4.



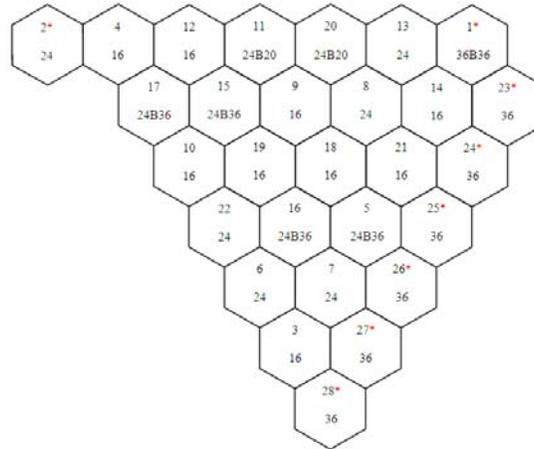
**Figure 4. The initial pattern**

The final core is reported after 7 iterations (Table IV), Fig. 5. The maximum power peaking factor is calculated as 1.2150 in optimized core.

**Table IV. Number of shuffling in each iteration**

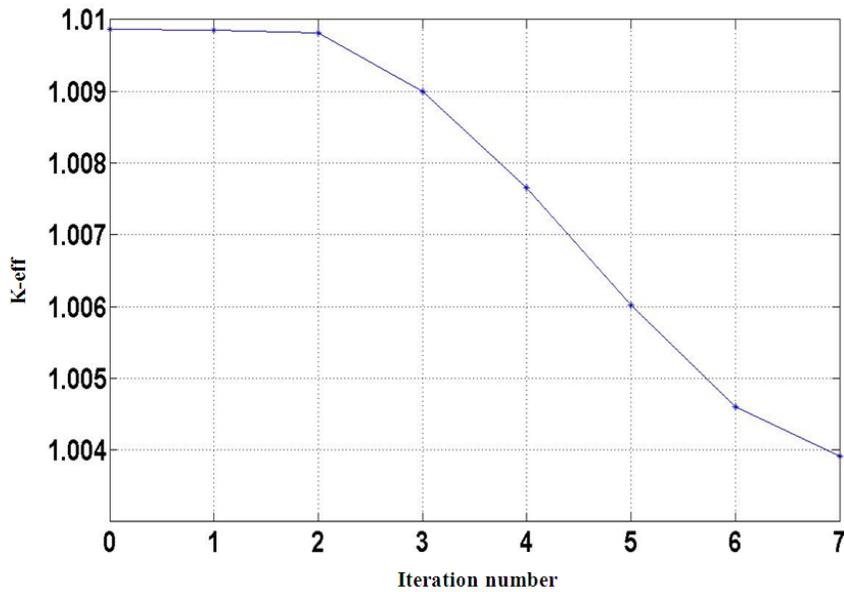
Iteration number	Number of shuffling	$\Delta\rho$
1	6	-5.76983e-05
2	6	-1.41491e-05
3	6	-5.18995e-06
4	6	-2.11791e-05
5	6	-6.96170e-06
6	5	-5.76481e-05
7	2	-2.97297e-06

*Number of total shuffling = 37*

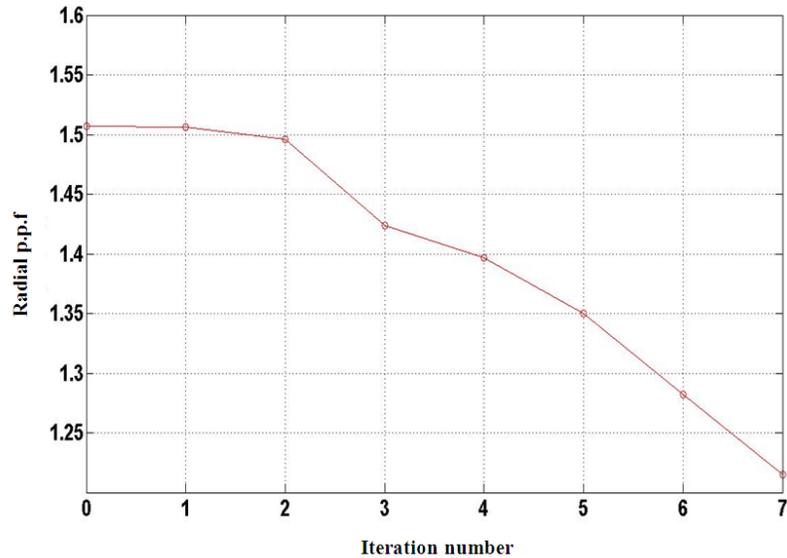


**Figure 5. The final pattern**

Figs. 6 and 7 show the variation of multiplication factor and radial power peaking factor during the optimization process, respectively.



**Figure 6. The variation of multiplication factor**



**Figure 7. The variation of radial power peaking factor**

Comparison of obtained results for power peaking factor and effective multiplication factor from between the initial pattern and final pattern (after applying algorithm) for more samples are shown in Table V.

**Table V. Comparison of results**

No.	Number of iteration	Total shuffling	Initial p.p.f *	Initial K-eff **	Final p.p.f	Final K-eff
1	6	37	1.3693	1.0082	1.2334	1.0045
2	11	62	1.4995	1.0088	1.2753	1.0058
3	8	56	2.3390	1.0100	1.2780	1.0041
4	8	30	1.4034	1.0073	1.3041	1.0060
5	5	34	1.3237	1.0042	1.1764	1.0038
6	6	42	2.8840	1.0224	1.3270	1.0050
7	6	38	2.6249	1.0124	1.2104	1.0039
8	7	43	1.8405	1.0075	1.2284	1.0048
9	5	30	1.3253	1.0066	1.2048	1.0047
10	3	20	1.2898	1.0041	1.2339	1.0034

\* p.p.f = power peaking factor

\*\*K-eff = multiplication factor

With regard to the theoretical basis of the perturbation theory and the obtained results in the preceding section, it can be concluded (deduced) that the resultant final pattern by employing the mentioned method is extremely dependant on the initial pattern. In other words, there is a limitation in the shuffle of the fuel assemblies. Consequently the outcome of this algorithm (final pattern) will be close to the initial pattern. Thus, this method can be used for the improvement of other optimization methods such as neural network, Particle swarm optimization, genetic algorithm, etc.

## 6. CONCLUSIONS

A fuel management optimization program based on perturbation theory is developed in this research. The optimization purpose is to reduce the power peaking factor. The developed program is employed for the first operating cycle of a typical VVER-1000 reactor. It's shown that the developed algorithm is capable to generate a pattern with reduced power peaking factor very fast but the effective multiplication factor of the final pattern is reduced as well. Several initial guess patterns are generated to overcome the above mentioned shortcoming since the final pattern strictly depends on the initial guess. The optimization program is used for the all initial guesses. In due course a pattern with maximum multiplication factor and an acceptable power peaking factor can be chosen amongst many final patterns.

Considering the fast convergence of results, the algorithm is functional for a huge number of initial patterns. As a result the single objective optimization process could be transformed into a partly multiobjective algorithm.

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