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S.N. Pelykh, Ph. D., Senior Research Fellow, Odessa National Polytechnic Univ.

A MODEL OF FUEL REARRANGEMENT OPTIMIZATION FOR A VVER-1000 CYCLING UNIT CONSIDERING REACTOR POWER GROWTH UP TO 110 %

С.М. Пелих. **Модель оптимізації переставлень палива маневрувального блока з ВВЕР-1000 із врахуванням підвищення потужності реактора до 110 %.** Розглядаючи довговічність оболонок твелів і вигорання палива, а також підвищення потужності реактора до 110 %, розроблено модель оптимізації перестановок палива маневрувального блока з ВВЕР-1000, яка придатна для будь-якого режиму нормальної експлуатації. Розглянуто основні етапи оптимізації перестановок на основі робастного моделювання. Шляхом застосування запропонованого критерію ефективності перестановок проблему оптимізації перестановок палива розв'язано на простому тестовому прикладі.

Ключові слова: оболонка, оптимізація перестановок палива, ВВЕР-1000.

С.Н. Пелых. **Модель оптимизации перестановок топлива маневренного блока с ВВЭР-1000 с учетом повышения мощности реактора до 110 %.** Рассматривая долговечность оболочек твэлов и выгорание топлива, а также повышение мощности реактора до 110 %, разработана модель оптимизации перестановок топлива маневренного блока с ВВЭР-1000, пригодная для любого режима нормальной эксплуатации. Рассматриваются основные этапы оптимизации перестановок на основе робастного моделирования. Путем использования предложенного критерия эффективности перестановок проблему оптимизации перестановок топлива решено на простом тестовом примере.

Ключевые слова: оболочка, оптимизация перестановок топлива, ВВЭР-1000.

S.N. Pelykh. **A model of fuel rearrangement optimization for a VVER-1000 cycling unit considering reactor power growth up to 110 %.** Considering both fuel cladding durability and fuel burn-up, as well as reactor power growth up to 110 %, a model of fuel rearrangement optimization for a VVER-1000 cycling unit, fit for any regime of normal reactor operation, has been worked out. The main stages of fuel rearrangement optimization on the basis of robust modeling have been considered. Using the proposed fuel rearrangement efficiency criterion, the fuel rearrangement optimization problem has been solved for a simple test example of rearrangements.

Key words: cladding, fuel rearrangement optimization, VVER-1000.

Introduction

Analyzing the 110 % capacity VVER-1000 fuel optimization problem, it should be noticed that existing fuel designs do not have adequate safety margins to operate reliably and it would be valuable to develop advanced fuel designs which have more robust operating margins, as well as universal fuel resource control methods.

Usually the problem of LWR fuel rearrangement optimization is considered taking into account only economic efficiency, as well as pin failure probability for a hypothetical severe depressurization accident [1], though it is obvious that when optimizing fuel rearrangements for the case of LWR normal operation, accumulated cladding failure parameter must be taken into account.

When loading frequency is below 1 Hz, creep governs the entire deformation process in the Zircaloy-4 cladding [2]. Having used a new theory of fuel life control methods at nuclear power plants with WWER(VVER)-reactors based on creep energy theory (CET), a method of VVER-1000 fuel assembly (FA) rearrangement optimization taking into account both fuel cladding durability and fuel burnup, which is suitable for any regime of normal reactor operation including increased capacity, can be proposed [3].

Let us suppose that the Advanced power control algorithm (A-algorithm) is used. Optimization of rearrangements of FAs is made for the core segment containing one sixth of all the FAs, as well as one sixth of all the regulating units used at power maneuvering. Distribution of long-lived and stable fission products causing reactor slagging is specified for the Khmelnitskiy NPP Unit 2 fifth four-year campaign start. Having used the Reactor Simulator (RS) code, for the fifth campaign start moment, it was found that there are 7 FAs of each campaign year in the specified core segment. Hence, for the specified core segment, it can be supposed that at the beginning of each campaign year the FAs are placed in the core cells according to the determined distribution.

Sintered uranium dioxide was assumed to be the material of pellets while stress relieved Zircaloy-4 was assumed to be the material of cladding. Considering 8 axial segments of a fuel element, cladding durability is estimated for the most strained (6-th) axial segment (AS), taking into account the disposition of regulating units in the A-algorithm case, as well as considering the amplitude of regulating unit movement necessary to stabilize the axial offset at power maneuvering. Inlet coolant temperature at power maneuvering is kept constant. When reactor power N changes from 100 % to 80 %, the lowest control rod axial coordinate measured from the core bottom changes from 90 % to 86 %. The amplitude of the relative linear heat rate (LHR) jumps was calculated for the distingushed FA rearrangement algorithms and for the daily power maneuvering method [3].

As a simple example, FA rearrangement optimization can be done for the case when two core cells are appointed to each campaign year within the core segment containing a 1/6 part of all FA cells. It is supposed that two FAs could remain in the core cells 2, 55, 11, 44, 10, 69, 6 and 43 for a 4-year campaign, and have 8 unique variants of rearrangement history within the borders of the analysed core segment (Fig. 1).

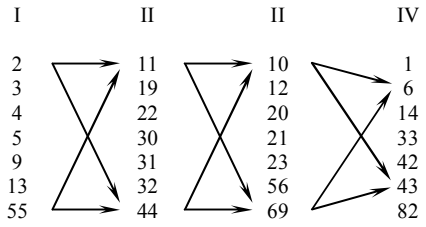

Fig. 1. Transpositions of FAs during rearrangements: (figure) the FA cell number; (roman numeral I, II, III and IV) 1-st, 2-nd, 3-d and 4-th campaign year, respectively

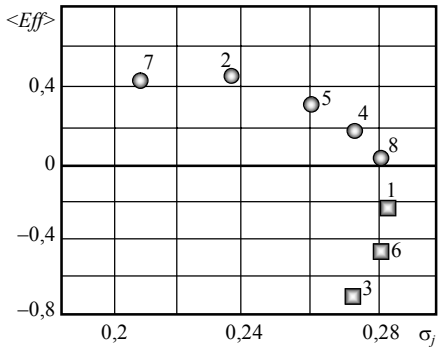

Fig. 2. Rearrangement mean efficiency and standard deviation for the robust case with reactor power growth up to 110 %: (1) algorithm 2–11–10–6+55–44–69–43; (2) 2–44–69–43+55–11–10–6; (3) 2–11–69–6+55–44–10–43; (4) 2–44–10–43+55–11–69–6; (5) 2–11–10–43+55–44–69–6; (6) 2–44–69–6+55–11–10–43; (7) 2–11–69–43+55–44–10–6; (8) 2–44–10–6+55–11–69–43

Evolution of cladding creep stresses and strains was determined using the FEMAXI code, while LHR values were calculated using the RS code. Change of specific dispersion energy (SDE) during the 4-year campaign (1460 calendar days) has been calculated for the most strained 6-th cladding AS and MATPRO corrosion model. The cladding failure criterion at reactor variable loading was used in the form given in [3].

FA rearrangement efficiency criterion

The FA rearrangement efficiency criterion should allow us to consider simultaneously requirements for reactor key elements integrity as well as reactor operation efficiency. To compare efficiency of different FA rearrangement algorithms, the FA rearrangement algorithm efficiency criterion is proposed

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$$Eff_j = 1 - \frac{L_j}{L^{\lim}}, \tag{1}$$

where:

$$L_j = \sqrt{\left(1-\omega_j^{\max,*}\right)^2 + \left(1-<\omega>_j^*\right)^2 + \left(1-B_j^{\min,*}\right)^2}, \tag{2}$$

$$L^{\lim} = \sqrt{\left(1-\omega^{\lim,*}\right)^2 + \left(1-<\omega>^{\lim,*}\right)^2 + \left(1-B^{\lim,*}\right)^2}, \tag{3}$$

$$\omega_j^{\max,*} = \frac{1-\omega_j^{\max}}{1-\omega^{\text{opt}}}, \tag{4}$$

$\omega_j^{\max}$ is maximum (among all the FAs) cladding failure parameter for *j*-rearrangement algorithm;

$$\omega^{\text{opt}} = \min\left\{\omega_j^{\max}\right\};$$

$$<\omega>_j^* = \frac{1-<\omega>_j}{1-<\omega>^{\text{opt}}}, \tag{5}$$

$<\omega>_j$ is all the FAs average cladding failure parameter for the *j*-th rearrangement algorithm;

$$<\omega>^{\text{opt}} = \min\left\{<\omega>_j\right\};$$

$$B_j^{\min,*} = \frac{B_j^{\min}}{B^{\text{opt}}}, \tag{6}$$

$B_j^{\min}$ is all the FAs minimum fuel burnup for the *j*-th rearrangement algorithm;

$$B^{\text{opt}} = \max\left\{B_j^{\min}\right\};$$

$$\omega^{\lim,*} = \frac{1-\omega^{\lim}}{1-\omega^{\text{opt}}}, \tag{7}$$

where $\omega^{\lim}$ is a specified permissible limit for $\omega_j^{\max}$.

$$<\omega>^{\lim,*} = \frac{1-<\omega>^{\lim}}{1-<\omega>^{\text{opt}}}, \tag{8}$$

where $<\omega>^{\lim}$ is a specified permissible limit for $<\omega>_j$;

$$B^{\lim,*} = \frac{B^{\lim}}{B^{\text{opt}}}, \tag{9}$$

where $B^{\lim}$ is a specified permissible limit for $B_j^{\min}$;

When using the FA rearrangement efficiency complex criterion $\left\{\omega_j^{\max}, <\omega>_j, B_j^{\min}\right\}$, the point $\left(\omega^{\text{opt}}, <\omega>^{\text{opt}}, B^{\text{opt}}\right)$ corresponds to the best rearrangement algorithm, while the point $\left(\omega^{\lim}, <\omega>^{\lim}, B^{\lim}\right)$ corresponds to the worst permissible rearrangement algorithm.

Hence, at variable loading, the permissible values of the criterion components lie in the following ranges

$$\omega^{\text{opt}} \le \omega_j^{\max} \le \omega^{\lim};\ <\omega>^{\text{opt}} \le <\omega>_j \le <\omega>^{\lim};\ B^{\lim} \le B_j^{\min} \le B^{\text{opt}}. \quad (10)$$

Introducing $\omega_j^{\max,*}$, $<\omega>_j^*$, $B_j^{\min,*}$, as

$$\omega^{\text{opt},*} = \frac{1-\omega^{\text{opt}}}{1-\omega^{\text{opt}}} = 1;\ <\omega>^{\text{opt},*} = \frac{1-<\omega>^{\text{opt}}}{1-<\omega>^{\text{opt}}} = 1;\ B^{\text{opt},*} = \frac{B^{\text{opt}}}{B^{\text{opt}}} = 1, \quad (11)$$

hence when a rearrangement algorithm improves, the point $\left(\omega_j^{\max,*}, <\omega>_j^*, B_j^{\min,*}\right)$ tends to the limit point (1; 1; 1), while when a rearrangement algorithm retrogresses, it tends to the limit point $\left(\omega^{\lim,*}, <\omega>^{\lim,*}, B^{\lim,*}\right)$. It follows from (10)

$$\omega^{\lim,*} \le \omega_j^{\max,*} \le 1;\ <\omega>^{\lim,*} \le <\omega>_j^* \le 1,\ B^{\lim,*} \le B_j^{\min,*} \le 1. \quad (12)$$

So, having used (1), the rearrangement algorithm efficiency *Eff* for the possible variants of FA transpositions can be calculated to optimize FA transpositions.

For example, let us accept that

$$\omega^{\lim} = 5\,\%;\ <\omega>^{\lim} = 4\,\%;\ B^{\lim} = 55\ \text{MW}\cdot\text{d/kg}. \quad (13)$$

Assuming the four-year FA transposition algorithm, the $\omega(\tau)$ values have been calculated using the following procedure: calculating $\sigma_e(\tau)$, $\dot{p}_e(\tau)$ and $\sigma_0(\tau)$; calculating $A(\tau = 1460\,\text{days})$; calculating $\omega(1460\,\text{d}) = A(1460\,\text{d})/A_0$ using $A_0 = 40$ MJ/m^3.

Efficiency of the *j*-th rearrangement algorithm can be found substituting the calculated components of the FA rearrangement efficiency criterion in (2)…(4). It was found that

$$\omega^{\text{opt}} = 3,714\,\%;\ <\omega>^{\text{opt}} = 3,608\,\%;\ B^{\text{opt}} = 61,15\ \text{MW}\cdot\text{d/kg}. \quad (14)$$

Using (3), (7)...(9), (13), (14), $L^{\lim}$=0,1019 and the permissible values of the criterion $\left\{\omega_j^{\max,*}, <\omega>_j^*, B_j^{\min,*}\right\}$ components lie in the following ranges

$$0,987 \le \omega_j^{\max,*} \le 1;\ 0,996 \le <\omega>_j^* \le 1;\ 0,899 \le B_j^{\min,*} \le 1. \quad (15)$$

Hereby, efficiency of different FA rearrangement algorithms can be compared numerically, analyzing the fuel state at two levels: safety (fuel cladding failure parameter) and economy (fuel burnup). It was obtained for the deterministic case, that the algorithm (2–11–69–43 + 55–44–10–6) has the maximum efficiency *Eff*=0,8714, while the algorithm (2–11–10–6 + 55–44–69–43) has the minimum efficiency *Eff*=0,0265 (considering only permissible algorithms with *Eff* > 0).

Model of fuel rearrangement optimization considering reactor power growth up to 110 %

Let us suppose that the calculated maximum LHR in *j*–FA $q_{l,j,\max}$ is mean of some random variable $q_{l,j,\max}^{\text{rand}}$

$$q_{l,j,\max} \equiv \left\langle q_{l,j,\max}^{\text{rand}} \right\rangle. \quad (16)$$

To make FA rearrangements optimization considering possibility of reactor power growth up to 110 %, it is necessary to find influence of the LHR interval Δ_{LHR} on $\Delta\omega$ and ΔB considering the average $q_{l,\max}$ for the transposition algorithms. In terms of $q_{l,j,\max}$ and $q_{l,j,\max}^{\text{rand}}$, as well as accepting Δ_{LHR} = 10 %, $q_{l,j,\max}^{\text{rand}}$ lies in the range

$$q_{l,j,\max} - 10\%\ \text{ŸЬ} q_{l,j,\max}^{\text{rand}}\ \text{ŸЬ} q_{l,j,\max} + 10\%. \quad (17)$$

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Using the proposed CET method [3], fuel cladding life has been estimated for the transposition algorithms and Δ_{LHR} = 10 %. For the *j*-algorithm of FA rearrangements, the average fuel cladding failure parameter $<\omega_j>$, calculation error $\Delta\omega_j$, and the same for fuel burnup ($<B_j>$ and ΔB_j) have been found. Using $\Delta\omega_j$ and ΔB_j, as well as taking into account the three-sigma rule, standard deviation for the random variables ω_j^{rand} and B_j^{rand} is found. Hence considering the random variable ω_j^{rand} distributed according to the Gaussian distribution, the probability density function (PDF) for ω_j^{rand} is found (the same for B_j^{rand}).

For the case of uncertain conditions, $\omega^{\text{opt}}, <\omega>^{\text{opt}}, B^{\text{opt}}, \omega^{\text{lim}}, <\omega>^{\text{lim}}, B^{\text{lim}}$ can be set like the deterministic case. Efficiency of the *j*-th rearrangement algorithm is calculated using (1) where $\omega_j^{\max}$ is maximum of $\{\omega_j^{\text{rand}}\}$, $<\omega>_j$ is mean of $\{\omega_j^{\text{rand}}\}$, $B_j^{\min}$ is minimum of $\{B_j^{\text{rand}}\}$.

It was supposed that within the borders of the analysed core segment, two FAs could remain in the core cells 2, 55, 11, 44, 10, 69, 6 and 43 for a four-year campaign, and have 8 unique variants of rearrangement history and 32 corresponding input random variables τ (see Fig. 1). For instance:

(Algorithm № 1) 2-11-10-6 + 55-44-69-43:

$$\begin{gathered}\tau_{1,1,1} \equiv \omega^{\text{rand}}_{2-11-10-6};\quad \tau_{1,1,2} \equiv \omega^{\text{rand}}_{55-44-69-43}; \tau_{1,2,1} \equiv B^{\text{rand}}_{2-11-10-6}; \tau_{1,2,2} \equiv B^{\text{rand}}_{55-44-69-43};\\ \theta_{1,1,1} = \max\left\{\tau_{1,1,1}, \tau_{1,1,2}\right\}; \theta_{1,1,2} = \text{mean}\left\{\tau_{1,1,1}, \tau_{1,1,2}\right\}; \theta_{1,2,1} = \min\left\{\tau_{1,2,1}, \tau_{1,2,2}\right\}.\end{gathered} \tag{18}$$

That is, the random variables $\theta_{1,1,1}$, $\theta_{1,1,2}$ and $\theta_{1,2,1}$ are not independent. The other random variables are written like (18). So the PDFs for the 32 input random variables

$$\tau_{1,1,1}; \tau_{1,1,2}; \tau_{1,2,1}; \tau_{1,2,2}; .....\tau_{8,1,1}; \tau_{8,1,2}; \tau_{8,2,1}; \tau_{8,2,2}$$

have been calculated.

If non-intrusive polynomial chaos (NIPC) methods are used to determine the PDF of an observable, then $(p+1)^n$ deterministic solves of the system model are required, where *n* is the number of random variables and *p* is the polynomial chaos order. In the case under consideration $n = 32$, so even if quadratic polynomials $(p = 2)$ provided sufficient accuracy, $3^{32} \approx 2\times10^{15}$ deterministic solves would be required. NIPC methods are computationally attractive in comparison with Monte Carlo Sampling (MCS) methods when the number of noise factors (random variables) is small, but this is not the case here. Therefore MCS is used to estimate the PDF of the FA rearrangement efficiency measure [1].

To use the MCS method, a set of normally distributed random variable τ is obtained using the function "normrnd" (MATLAB) on the basis of mean M_τ and standard deviation σ_τ defined for random variables $\{\omega_j^{\text{rand}}\}$ and $\{B_j^{\text{rand}}\}$. Substituting M_τ and σ_τ into the function "normrnd", the FA *j*-th rearrangement algorithm efficiency for the probabilistic case is found using the criterion (1) in the form

$$Eff_j = f\left(\theta_{j,1,1}, \theta_{j,1,2}, \theta_{j,2,1}\right), \tag{19}$$

where: j =1…8;

$$\theta_{j,1,1} = \max\left\{\tau_{j,1,1}, \tau_{j,1,2}\right\}; \theta_{j,1,2} = \text{mean}\left\{\tau_{j,1,1}, \tau_{j,1,2}\right\}; \theta_{j,2,1} = \min\left\{\tau_{j,2,1}, \tau_{j,2,2}\right\}.$$

For the robust case of fuel rearrangement optimization considering possibility of reactor power growth up to 110 %, the results of FA rearrangement optimization obtained in the deterministic case are confirmed in principle (Fig. 2).

It was found that efficiency of FA rearrangements in the robust case is decreased greatly in comparison with the same for the deterministic case (e.g., for the deterministic case, the algorithm (2–11–

69–43+55–44–10–6) had the efficiency *Eff*=0,871, while the algorithm (2–11–10–6+55–44–69–43) had the efficiency *Eff*=0,0265).

As a result, for the case of increased reactor power, algorithm № 8 is near the critical line *Eff*=0 and can be considered not permissible. Algorithm № 1 was permissible in the deterministic case, while for the robust case it is not permissible. Algorithm № 7 had the largest efficiency in the deterministic case, while for the robust case the most efficient algorithm is № 2, though it has a greater standard deviation in comparison with № 7.

Conclusions

The proposed model of fuel rearrangement optimization for a VVER-1000 cycling unit considering both fuel burnup and cladding life allows us to develop a practical procedure for making optimization of FA rearrangements under real uncertain conditions of normal VVER-1000 operation taking into account possible reactor power growth up to 110 %.

When making robust optimization of rearrangements taking into account all the core cells as well as all possible variants of FA transpositions, the main stages of present analysis are not expected to be changed significantly in comparison with the discussed simple example of such an optimization.

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Reviewer Dr. techn. sciences, Prof. of Odessa nat. polytechnic univ. Maksimov M.V.

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