UDC 621.039.548

THEORY OF VVER-1000 FUEL REARRANGEMENT OPTIMIZATION TAKING INTO ACCOUNT BOTH FUEL CLADDING DURABILITY AND BURNUP

S.N. Pelykh, M.V. Maksimov
Odessa National Polytechnic University, Odessa, Ukraine
E-mail: 1@pelykh.net; tel. +38(066)187-21-45

Using the VVER-1000 fuel element (FE) cladding failure estimation method based on creep energy theory (CET-method), it is shown that practically FE cladding rupture life at normal operation conditions can be controlled by an optimal assignment of fuel assembly (FA) rearrangement algorithm. The probabilistic FA rearrangement efficiency criterion based on Monte Carlo Sampling takes into account robust operation conditions and gives results corresponding to the deterministic ones in principle, though the robust efficiency estimation is more conservative. It is proved that CET-method allows us to create an automated complex controlling FE cladding durability in VVER-1000.

INTRODUCTION

Recently the problem of fuel cladding life control at nuclear power plants (NPP) with VVER-1000 reactors has become actual in Ukraine [1]. This problem consists of several subproblems: creating a physically based method of VVER-1000 fuel cladding failure estimation; determination of main factors influencing VVER-1000 fuel cladding life; working out methods to optimize main factors influencing VVER-1000 fuel cladding life.

To predict likelihood of VVER-1000 fuel cladding failure accurately, it is necessary to use a relevant physical model of the fuel cladding failure process during cyclic pressurization. When loading frequency is below 1 Hz, creep governs the entire deformation process in zircaloy-4 cladding [2]. According to creep energy theory (CET), energy spent for FE cladding material destruction is called as specific dispersion energy (SDE) [3].

For the first time, a method of analysis of VVER-1000 FE cladding running time at variable loading based on CET (CET-method) was proposed in [4]. The main features of CET-method are: creep is the main mechanism of cladding deformation when VVER-1000 is operated at variable loading; creep and destruction processes proceed in common and influence against each other; at any moment intensity of failure is estimated by SDE accumulated during creep process by this moment; cladding failure criterion components do not depend on VVER-1000 loading conditions, power maneuvering methods, dispositions of regulating units, FA rearrangement algorithms, etc. The VVER-1000 cladding corrosion rate is determined by design constraints for cladding and coolant, and depends slightly on a regime of variable loading. At the same time, practically FE maximum LHR is determined not only by current reactor capacity level, which is a value given to a NPP by the integrated power system, but also by FA rearrangement algorithm. Therefore, the FE cladding rupture life at normal variable loading operation conditions can be controlled by an optimal assignment of FA rearrangement algorithm [5].

THE APPROACH TO OPTIMIZE REARRANGEMENTS IN VVER-1000

Optimization of FA rearrangements is undertaken for a core segment containing 1/6 of all the FAs, as well as 1/6 of all the regulating units used for power maneuvering. Disposition of the 10th regulating group in case of A-algorithm [1] and the analysed core segment are shown in Fig. 1.

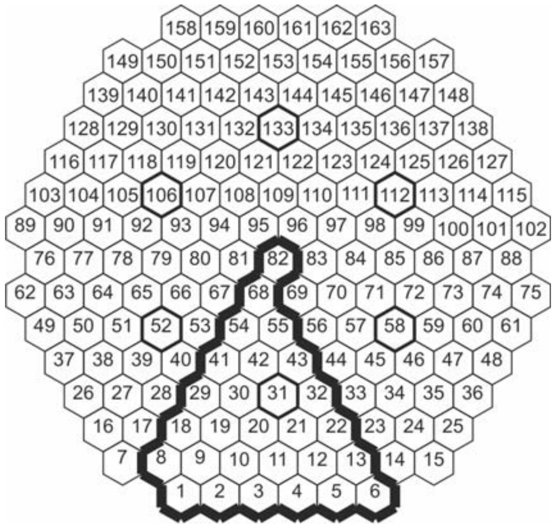

Fig. 1. Disposition of the 10th group: (figure) FA cell number (360 symmetry). The 10-th group cells and the analysed core segment (1/6) borders are in bold

The amplitude of relative linear heat rate (LHR) jumps at FE axial segments (ASs) occurring when the reactor thermal capacity N increases at power maneuvering, was estimated using the "Reactor Simulator" (RS) code [6]. According to the distribution of long-lived and stable fission products specified for the start of the 5th four-year campaign of KhNPP Unit 2, distribution of FAs in the core segment by campaign year is given in the input data file for the RS code. Having used RS, to establish conditions at the start of the 5th campaign, it was found that there are 7 FAs of each campaign year in the specified core segment. Hence, it can be assumed that at the beginning of each campaign year FAs are placed according to the distribution shown in Fig. 2.

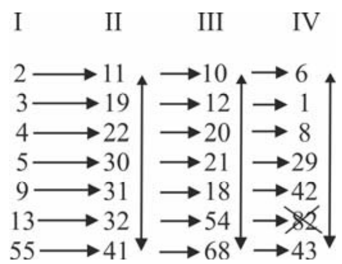

Fig. 2. Transpositions of FAs: (number) FA cell number; (roman numerals I, II, III and IV) 1st, 2nd, 3rd and 4th campaign year, respectively (6 cells for the 4th year FAs)

Nowadays two main approaches are used at NPP with VVER-1000 [7]: 1) a 4th year FA is placed in the central core cell 82, and 7 core cells are appointed for FAs of each year; 2) a 1st or a 2nd year FA is placed in cell 82, and 7 core cells are appointed for FAs of each year, with the exception of 4th year FAs which can be placed in 6 core cells only. In this case cell 82 is not considered when making optimization of FA rearrangements. The last approach is used in practice mainly, because it gives an optimal fuel utilization to ensure the necessary campaign duration, so this approach with 6 cells appointed for 4th year FAs will be considered when making optimization of rearrangements (see Fig. 2).

CALCULATION OF DAMAGE IN THE FE CLADDING

The light water reactor (LWR) fuel analysis finite element code FEMAXI [8] was used for determination of the evolution of VVER-1000 cladding creep stresses and strains under variable loading in a given power history and coolant conditions. Sintered uranium dioxide was assumed to be the pellet material, while stress-relieved zircaloy-4 was assumed to be the cladding material.

Cladding durability is estimated for the most strained AS (№6), 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 axial offset at daily power maneuvering with T_{in} = const [5]. Changes in SDE during the 4-year campaign (1460 calendar days) were calculated using the MATPRO-A [9] corrosion model by the following procedure: 1) Using RS, for the cells shown in Fig. 2, calculation of relative power coefficients $k_{6,j}$ in AS 6 at N=80 and 100 %; 2) Using FEMAXI, calculation of stress-strain development in FE cladding and fuel burnup; 3) Using CET-method and A_0 = 30 MJ/m^3 (SDE at the moment of cladding material failure beginning), calculation of $\omega(1460\,\text{d}) = A(1460\,\text{d})/A_0$ and burnup B(1460 d) for selected rearrangement algorithms.

Because of a great number of possible variants, when considering a new FA rearrangement algorithm, a random choice of core cells using the MATLAB function "rand" was adopted. To illustrate the method, it was adopted that $N_{alg} = 18$, that is 18 rearrangement algorithms containing 126 different rearrangements were analyzed, where 16 algorithms containing 112 rearrangements were randomly chosen, while two algorithms were practically used at Zaporizhzhya NPP, Unit 5 [7]. These two practical algorithms which were used during campaigns 22 and 23 (algorithms 17 and 18, respectively) are shown in Table 1.

Table 1

Cladding failure parameters and burnups for algorithms 17 and 18

j	Rearrangement	A, MJ/m^3	$\omega(\tau)$, %	B, MW·d/kg
17	2-22-12-6	1.463	4.877	54.35
	3-41-29	1.184	3.947	48.8
	4-11-68-43	1.078	3.593	60.63
	5-19-10-8	1.498	4.993	57.18
	9-30-20-1	2.058	6.86	59.39
	13-32-21-42	2.667	8.89	68.23
	55-31-54-18	2.437	8.123	67.45
18	2-22-21-6	1.55	5.167	54.86
	3-41-68	1.18	3.933	48.83
	4-11-29-18	1.159	3.863	60.84
	5-19-20-1	1.449	4.83	54.55
	9-32-12-42	2.586	8.62	67.86
	13-30-10-43	2.551	8.503	67.73
	55-31-54-8	1.982	6.607	61.37

THE CRITERION OF REARRANGEMENT EFFICIENCY

Considering all the FAs used in rearrangement algorithm j, let's suppose that $\omega_j^{\max}$ is the maximum value of cladding failure parameter, $<\omega>_j$ is the average value of cladding failure parameter; $B_j^{\min}$ is the minimum value of fuel burnup. Let's introduce

$$\omega^{opt} = \min\{\omega_j^{\max}\}; \quad <\omega>^{opt} = \min\{<\omega>_j\};$$
$$B^{opt} = \max\{B_j^{\min}\}. \qquad (1)$$

Let's accept that ω^{lim}, $<\omega>^{lim}$ and B^{lim} are specified permissible limits for $\omega_j^{\max}$, $<\omega>_j$ and $B_j^{\min}$, respectively. Hence, the permissible values of $\omega_j^{\max}$, $<\omega>_j$ and $B_j^{\min}$ lie in the following ranges:

$$\omega^{opt} \le \omega_j^{\max} \le \omega^{lim};$$
$$<\omega>^{opt} \le <\omega>_j \le <\omega>^{lim}; \qquad (2)$$
$$B^{lim} \le B_j^{\min} \le B^{opt}.$$

Then we obtain

$$\omega^{lim,*} \le \omega_j^{\max,*} \le 1; \quad <\omega>^{lim,*} \le <\omega>_j^{*} \le 1;$$
$$B^{lim,*} \le B_j^{\min,*} \le 1, \qquad (3)$$

where

$$\omega^{lim,*} \equiv (1-\omega^{lim})/(1-\omega^{opt});$$
$$\omega_j^{\max,*} \equiv (1-\omega_j^{\max})/(1-\omega^{opt});$$
$$<\omega>^{lim,*} \equiv (1-<\omega>^{lim})/(1-<\omega>^{opt});$$
$$<\omega>_j^{*} \equiv (1-<\omega>_j)/(1-<\omega>^{opt}); \qquad (4)$$

$B^{\lim,*} \equiv B^{\lim} / B^{\text{opt}}$; $B_j^{\min,*} \equiv B_j^{\min} / B^{\text{opt}}$.

As $\left|B^{\lim,*};\ 1\right|$ can be >> $\left|\omega^{\lim,*};1\right|$, from the condition of equal importance of nuclear safety and economy requirements:

$$\omega^{\lim,*} = <\omega>^{\lim,*} = B^{\lim,*}. \quad (5)$$

Hence having some value of $\omega^{\lim}$, the corresponding values of $<\omega>^{\lim}$ and $B^{\lim}$ are defined from the following equations

$$<\omega>^{\lim} = 1 - (1 - \omega^{\lim})(1 - <\omega>^{\text{opt}})/(1 - \omega^{\text{opt}});$$

$$B^{\lim} = (1 - \omega^{\lim})B^{\text{opt}}/(1 - \omega^{\text{opt}}). \quad (6)$$

To compare efficiency *Eff* of different FA rearrangement algorithms, the FA rearrangement algorithm efficiency criterion is proposed:

$$Eff_j = 1 - L_j / L^{\lim}, \quad (7)$$

where

$$L_j = \sqrt{\left(1 - \omega_j^{\max,*}\right)^2 + \left(1 - <\omega>_j^*\right)^2 + \left(1 - B_j^{\min,*}\right)^2}, \quad (8)$$

$$L^{\lim} = \sqrt{\left(1 - \omega^{\lim,*}\right)^2 + \left(1 - <\omega>^{\lim,*}\right)^2 + \left(1 - B^{\lim,*}\right)^2}. \quad (9)$$

Using Eqs. (4), (5) and (9)

$$L^{\lim} = \sqrt{3}\left|1 - \omega^{\lim,*}\right| = \sqrt{3}\left|\omega^{\lim} - \omega^{\text{opt}}\right|/(1 - \omega^{\text{opt}}). \quad (10)$$

The physical meaning of criterion (7) is: 1) if any of the dimensionless components ($\omega_j^{\max,*}$, $<\omega>_j^*$ or $B_j^{\min,*}$) lies out of the permissible range $[\omega^{\lim,*};1]$, then this component gives a negative contribution to the total efficiency defined by Eq. (7); 2) advantage of some algorithm over another is determined on the basis of summation of advantages given by the dimensionless components; 3) weight factors can be used in Eq. (5) to give priority to some component.

Using criterion (7) and setting $\omega^{\lim} = 13\%$, *Eff* was calculated for 18 algorithms. Algorithm 2 having the worst *Eff*, the first five algorithms (3, 4, 6, 8, 14) having the greatest values of *Eff*, as well as the practical algorithms (17 and 18) are shown in Table 2.

Table 2

Algorithm efficiency

j	$\omega_j^{\max}$, %	$<\omega>_j$, %	$B_j^{\min}$, MWd/kg	Eff_j
2	8.84	5.861	47.61	-0.1442
3	7.51	5.865	54.67	0.9372
4	6.87	5.796	54.05	0.9008
6	6.847	5.787	53.05	0.741
8	7.017	5.771	54.27	0.9341
14	8.247	5.864	54.07	0.8371
17	8.89	5.898	48.8	0.0420
18	8.62	5.932	48.83	0.0515

It can be seen: 1) algorithms 3 and 8 are characterizied by both high cladding durability and high burnup, hence all the corresponding dimensionless criterion components are high, so Eff_3 and Eff_8 are highest; 2) algorithms 17 and 18 have both cladding durability and burnup worse than the ones of algorithms 3 and 8, so Eff_{17} and Eff_{18} are close to 0; 3) algorithm 2 is characterizied by cladding durability close to the same for algorithms 17 and 18, but burnup is considerably lower than the same for these algorithms, and as a result $Eff_2 < 0$.

THE ROBUST MODEL

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

$$q_{l,j,\max} \equiv < q_{l,j,\max}^{\text{rand}} >. \quad (11)$$

To take into account VVER-1000 robust operating conditions when making the probabilistic analysis, cladding damage parameter and burnup in the most strained AS are calculated for rearrangements of the best algorithms 3, 4, 6, 8 and 14 at $< q_{l,cn,\max}^{\text{rand}} > -10\%$ and $< q_{l,cn,\max}^{\text{rand}} > +10\%$, where cn is core cell number for the corresponding campaign year, e.g., for algorithm 3 and rearrangement 9-19-21-8: $cn = 9$, 19, 21 and 8 for 1st, 2nd, 3rd and 4th year, respectively. Hence, use of deterministic criterion (7) allows us to reduce N_{alg} from $N_{alg} = 18$ to $N_{alg} = 5$. The efficiency of rearrangement algorithm j is calculated using Eq (7) and there are 2 random variables ($\omega_{j,k}^{\text{rand}}$ and $B_{j,k}^{\text{rand}}$) for each pair of algorithm j and rearrangement k; $\omega_j^{\max} = \max\{\omega_{j,k}^{\text{rand}}\}$, $<\omega>_j = <\{\omega_{j,k}^{\text{rand}}\}>$, $B_j^{\min} = \min\{B_{j,k}^{\text{rand}}\}$, where $j = 1,...,N_{alg}$; $k = 1,...,7$. Hence, we have the total number of input random variables $2 \cdot N_{alg} \cdot 7 = 70$, that is 35 rearrangements are described by 70 random variables.

For $k = 1,...,7$ and $j = 3$, 4, 6, 8, 14, using three sigma rule (assuming normal distribution), the corresponding means $<\omega_{j,k}^{\text{rand}}>$, $<B_{j,k}^{\text{rand}}>$ and standard deviations $\sigma(\omega_{j,k}^{\text{rand}})$, $\sigma(B_{j,k}^{\text{rand}})$ of random variables $\omega_{j,k}^{\text{rand}}$, $B_{j,k}^{\text{rand}}$ are calculated. For instance, algorithm 3 − (9-19-21-8 + 5-41-68-43 + 55-22-10 + 13-11-20-6 + 3-30-54-1+ 4-32-18-42 + 2-31-12-29) − is described by the following random values $\tau_{j,p,k}$, where p=1 denotes $\omega_{j,k}^{\text{rand}}$ and p=2 denotes $B_{j,k}^{\text{rand}}$:

$$\tau_{3,1,1} \equiv \omega_{9\text{-}19\text{-}21\text{-}8}^{\text{rand}}; \ldots \tau_{3,1,7} \equiv \omega_{2\text{-}31\text{-}12\text{-}29}^{\text{rand}};$$

$$\tau_{3,2,1} \equiv B_{9\text{-}19\text{-}21\text{-}8}^{\text{rand}}; \ldots \tau_{3,2,7} \equiv B_{2\text{-}31\text{-}12\text{-}29}^{\text{rand}}.$$

Hence, for rearrangement 9-19-21-8 of algorithm 3, $\tau_{3,1,1}$ and $\tau_{3,2,1}$ are random values described by $\{<\omega_{3,1}^{\text{rand}}>,\ \sigma(\omega_{3,1}^{\text{rand}})\}$ and $\{<B_{3,1}^{\text{rand}}>,\ \sigma(B_{3,1}^{\text{rand}})\}$, respectively.

As we have 70 random variables, non-intrusive polynomial chaos (NIPC) methods [10] are not computationally attractive in comparison with Monte Carlo Sampling (MCS) methods. To use the MCS method, a set of normally distributed random variables $\tau_{j,p,k}$ is obtained substituting the means and standard deviations of $\omega^{\text{rand}}_{j,k}$ and $B^{\text{rand}}_{j,k}$ into the MATLAB function "normrnd", and the efficiency of algorithm j is found using Eq. (7) in the form:

$$Eff_j = f\left(\theta_{j,1,1}, \theta_{j,1,2}, \theta_{j,2,1}\right), \qquad (12)$$

where $j = 1,...,N_{alg}$; $\theta_{j,1,1} = \max\{\tau_{j,1,1},...,\tau_{j,1,7}\}$; $\theta_{j,1,2} = <\{\tau_{j,1,1},...,\tau_{j,1,7}\}>$; $\theta_{j,2,1} = \min\{\tau_{j,2,1},...,\tau_{j,2,7}\}$.

OPTIMIZATION OF REARRANGEMENTS

Thus, the efficiency of algorithm j is calculated using Eq. (12). For the case of uncertain conditions, $\omega^{\text{opt}}, <\omega>^{\text{opt}}, B^{\text{opt}}$ and L^{lim} can not be set as for the deterministic case (Table 3).

It should be noted that if N_{alg} increases, then ω^{opt} decreases. On the contrary, when the number of core cells used for optimization increases, ω^{opt} increases also. The trade-off between the mean value of Eff_j and its standard deviation, as estimated using MCS, for the best five FA transposition algorithms, as well as for the simplest robust optimization of FA rearrangements taking into account only two core cells appointed for each year, is shown in Fig. 3.

Table 3

Difference between the deterministic and robust cases

Deterministic case	Robust case
$\omega^{\text{lim}} = 13\%$	
$\omega^{\text{opt}} = 6.847$;	MCS ω^{opt} $<\omega>^{\text{opt}}$ B^{opt}
$<\omega>^{\text{opt}} = 5.771$;	1 8.121 6.793 55.23
$B^{\text{opt}} = 54.67$;	10 10.67 7.934 55.69
$<\omega>^{\text{lim}} = 0.12$;	100 9.950 7.449 53.83
$B^{\text{lim}} = 51.06$;	$<\omega>^{\text{lim}}, B^{\text{lim}}, L^{\text{lim}}, \omega^{\text{lim},*}$
$L^{\text{lim}} = 0.1144$;	are variable on MCS
$\omega^{\text{lim},*} = 0.9339$	

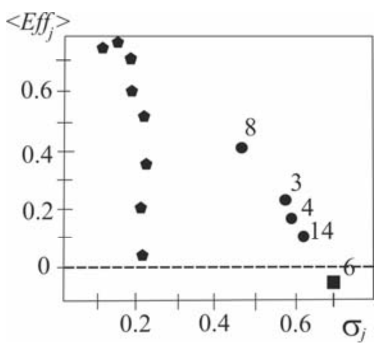

Fig. 3. Mean efficiency and standard deviation for ω^{lim}=13 % in the robust case: (number) algorithm number for optimization with 7 cells per year (excluding year 4), A_0=30 MJ/m^3; (pentagon) random algorithm for optimization with 2 cells per year, A_0=40 MJ/m^3

Algorithm 3 had the largest efficiency in the deterministic case, while in the robust case algorithm 8 is most efficient (see Fig. 3). This can be explained by the fact that $\omega_3^{\max} \approx 7.5\%$, while $\omega_8^{\max} \approx 7\%$. As dependence of SDE on LHR is nonlinear and SDE depends greatly on FA rearrangement history, in the robust case this difference $\omega_3^{\max} - \omega_8^{\max} = 0.5\%$ turned to be sufficient to obtain a greater mean efficiency for algorithm 8 in comparison with algorithm 3. In addition, algorithm 3 has a greater standard deviation than algorithm 8, and thus there is no trade-off between these two options. Both algorithms dominate all the other options, having both higher mean efficiencies and smaller standard deviations.

CONCLUSIONS

1. The deterministic FA rearrangement efficiency criterion taking into account both safety (cladding durability) and economic (burnup) factors allows us to improve existing methods of fuel rearrangement optimization which take into account only economic efficiency estimated in terms of fuel burnup, power form factor, etc., as well as pin failure probability for a hypothetical severe depressurization accident [11].

2. The probabilistic FA rearrangement efficiency criterion based on Monte Carlo Sampling takes into account robust operation conditions and gives results corresponding to the determinisic ones in principle, though the robust efficiency estimation is more conservative. Hence deterministic FA rearrangement optimization can be used as a preliminary procedure to decrease the number of analysed rearrangement algorithms.

3. CET-method allows us to improve existing control and protection equipment by creating an automated program-technical complex making control of FE cladding durability and optimization of fuel rearrangements in VVER-1000.

REFERENCES

1. S.N. Pelykh, M.V. Maksimov. Cladding rupture life control methods for a power-cycling WWER-1000 nuclear unit // *Nuclear Engineering and Design (241)*. 2011, №8, p. 2956-2963.

2. J.H. Kim, M.H. Lee, B.K. Choi, Y.H. Jeong. Deformation behavior of Zircaloy-4 cladding under cyclic pressurization // *Journal of Nuclear Science and Technology*. 2007, №44, p. 1275-1280.

3. О.В. Соснин, Б.В. Горев, А.Ф. Никитенко. *Энергетический вариант теории ползучести*. Новосибирск: «СО Академии наук СССР», 1986, 94 с.

4. S.N. Pelykh, M.V. Maksimov, V.E. Baskakov. Model of cladding failure estimation under multiple cyclic reactor power changes // *Proc. of the 2nd International Conference on Current Problems of Nuclear Physics and Atomic Energy*. Kyiv: KINR, 2008, p. 638-641.

5. S.N. Pelykh, M.V. Maksimov. *Nuclear reactors*. Rijeka: "InTech", 2012, p. 197-230.

6. П.Е. Филимонов, В.В. Мамичев, С.П. Аверьянова. Программа «Имитатор реактора» для

моделирования маневренных режимов работы ВВЭР-1000 // *Атомная энергия.* 1998, №6, в. 84, с. 560-563.

7. Р.Ю. Воробьев. *Альбомы нейтронно-физических характеристик активной зоны реактора энергоблока №5 ЗАЭС, кампании 20-23*. Энергодар: «Запорожская АЭС», 2008-2011, 323 с.

8. M. Suzuki. *Light water reactor fuel analysis code FEMAXI-V (Ver.1)*. Tokai: “Japan atomic energy research institute”, 2000, 285 p.

9. М. Сузуки. *Моделирование поведения твэла легководного реактора в различных режимах нагружения*. Одесса: «Астропринт», 2010, 248 с.

10. T. Ghisu, G.T. Parks, J.P. Jarrett, P.J. Clarkson. Adaptive polynomial chaos for gas turbine compression systems performance analysis // *AIAA Journal*. 2010, №6, p. 1156-1170.

11. G.T. Parks. An intelligent stochastic optimization routine for nuclear fuel cycle design // *Nuclear Technology*. 1990, №2, p. 233-246.

Статья поступила в редакцию 07.09.2012 г.

ТЕОРИЯ ОПТИМИЗАЦИИ ПЕРЕСТАНОВОК ТВС ВВЭР-1000 С УЧЕТОМ ДОЛГОВЕЧНОСТИ ОБОЛОЧЕК ТВЭЛОВ И ГЛУБИНЫ ВЫГОРАНИЯ ТОПЛИВА

С.Н. Пелых, М.В. Максимов

Используя метод расчета поврежденности оболочки твэла ВВЭР-1000, основанный на энергетическом варианте теории ползучести (ЭВТП-метод), показано, что путем оптимального выбора алгоритма перестановок ТВС возможно управлять долговечностью оболочек твэлов в нормальных условиях эксплуатации. Вероятностный критерий эффективности перестановок ТВС, основанный на методе выборок Монте-Карло, учитывает робастные условия эксплуатации оболочек твэлов и дает результаты, соответствующие в основном результатам детерминистического анализа, хотя робастная оценка эффективности более консервативна. Показано, что ЭВТП-метод позволяет создать автоматизированный комплекс управления долговечностью оболочек твэлов ВВЭР-1000.

ТЕОРІЯ ОПТИМІЗАЦІЇ ПЕРЕСТАВЛЕНЬ ТВЗ ВВЕР-1000 ВРАХОВУЮЧИ НА ДОВГОВІЧНІСТЬ ОБОЛОНОК ТВЕЛІВ ТА ГЛИБИНУ ВИГОРАННЯ ПАЛИВА

С.М. Пелих, М.В. Максимов

Використовуючи метод розрахунку пошкодження оболонки твела ВВЕР-1000, заснований на енергетичному варіанті теорії повзучості, викладено, що шляхом оптимального вибору алгоритму переставлень ТВЗ можливо управляти довговічністю оболонок твелів за нормальних умов експлуатації. Імовірнісний критерій ефективності переставлень ТВЗ, заснований за методом вибірок Монте-Карло, враховує робастні умови експлуатації оболонок твелів і дає результати, які відповідають у цілому результатам детерміністичного аналізу, хоча робастна оцінка ефективності є більш консервативною. Доведено, що ЕВТП-метод дозволяє створити автоматизований комплекс управління довговічністю оболонок твелів ВВЕР-1000.