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ESTIMATION OF LOCAL LINEAR HEAT RATE JUMP VALUES IN THE VARIABLE LOADING MODE

A method of the WWER-1000 fuel element cladding durability analysis using the energy creep theory makes it possible to determinate the WWER-1000 reactor permissible operation time for the mode of varying loading. But the WWER-1000 axial segments and fuel assemblies differ greatly in their local linear heat rate jump value. It has been found that the value of linear heat rate is one of key parameters that influences on a fuel element cladding durability in the mode of variable loading. So, determination of the WWER-1000 reactor permissible operation time for the mode of varying loading requires estimation of the WWER-1000 local linear heat rate jumps.

Keywords: WWER, varying loading mode, fuel element cladding durability, linear heat rate jump.

Introduction

Analyzing the current Ukrainian energetic status it is necessary to state that on-peak regulating powers constitute 8 % of the total Consolidated Power System (CPS), while a stable CPS must have 15 % of on-peak regulating powers at least. More than 95 % of all thermal plants have passed their design life and the Ukrainian thermal power engineering averaged remaining life equals to about 5 years.

As known, the “Energy strategy of Ukraine for the period till 2030 y.” predicts the nuclear energetics part at approximately 50 %. So, operation of nuclear power units in Ukraine in the variable part of electric loading schedule (variable loading mode) has become actual recently, that means there are repeated cyclic nuclear reactor (NR) capacity changes during NR normal operation.

Fuel element (FE) cladding durability estimation under the multiple cyclic power changes has been widely known as a key issue in terms of rod design and reliability. Operation of a FE is characterized by long influence of high-level temperature-power stressing leading to uncontrollable cladding material creep processes causing, after a while, its destruction, and fission products enter the circuit in the quantities exceeding both operational limits and limits of safe operation. In this connection, estimation of cladding integrity time for a NR variable loading mode, taking into account some appointed criteria, becomes one of key problems of FE designing and active core operational reliability analysis [1].

There are following main characteristic cladding destruction mechanisms for the WWER-1000 varying loading mode: Pellet-Cladding Mechanical Interaction (PCMI), especially at low burnups and Stress Corrosion Cracking (SCC); corrosion at high burnups (> 50 MW·d/kg); cladding failure caused by multiple cyclic and long-term static loads (endurance failure) [2].

It is supposed that the low-burnup PCMI influence is eliminated by implementation of the WWER-1000 maximum linear heat rate regulation conditions. Non-admission of cladding mechanical damage caused by SCC is ensured by control of linear heat power permissible values and jumps also.

The high-burnup corrosion influence is eliminated by optimization of the alloy fabrication technique.

As all power history affects the cladding, it is incorrect to transfer experimental stationary and emergency operation cladding material creep data onto the FE cladding working at variable loading. Emergency NR operation leading to cladding material plastic deformation is not studied here, therefore the hot plasticity (stress softening) arising at the expense of yield stress decrease under emergency cladding temperature rise, is not considered.

To estimate FE cladding running time under multiple cyclic NR power changes, it is enough to calculate the energy accumulated during the creep process, by the moment of cladding failure and spent for cladding material destruction A_0. According to the Creep Energy Theory (CET), the energy spent for FE cladding material destruction is called as Specific Dispersion Energy (SDE) A (τ). The energy spent for cladding material destruction A_0 is calculated as the SDE value $A(\tau)$ at the cladding material stability loss moment τ_0, described by the equation $\sigma_e^{\max}(\tau_0) = \sigma_0^{\max}(\tau_0)$, that is when equivalent stress $\sigma_e^{\max}(\tau)$ becomes equal to yield stress $\sigma_0^{\max}(\tau)$, for a point situated on the inner surface of the FE central axial segment having the maximum temperature (according to the calculation model, the entire length of the fuel rod is divided into axial segments) [1].

The proposed method enables us to carry out quantitative assessment of the accumulated cladding failure parameter $\omega(\tau)$ for different NR loading modes, taking into account a real NR load history.

Method of the WWER-1000 FE cladding durability estimation at variable loading

The cladding material failure parameter $\omega(\tau)$ is entered into the analysis:

$$\omega(\tau) = A(\tau) / A_0 = 1;$$

$$A(\tau) = \int_0^\tau \sigma_e \cdot \dot{p}_e \cdot d\tau;\ A_0 = A(\tau_0),$$

$$\text{when } \sigma_e^{\max}(\tau_0) = \sigma_0^{\max}(\tau_0)\ , \qquad (1)$$

where A_0 – the SDE at the moment of cladding material failure beginning, J/m^3; $\omega = 0$ – for the intact material, $\omega = 1$ – for the damaged material; σ_e – equivalent stress, Pa; $\dot{p}_e$ – rate of equivalent creep strain, s^{-1}.

Equivalent stress σ_e is expressed as

$$\sigma_e = \sqrt{\frac{1}{2}\left[\left(\sigma_\theta - \sigma_z\right)^2 + \sigma_\theta{}^2 + \sigma_z{}^2\right]}, \qquad (2)$$

where σ_θ, σ_z – circumferential and axial stress, correspondingly.

Rate of equivalent creep strain $\dot{p}_e$ (s^{-1}) can be found using the known MATPRO-09 experimental equation [2]:

$$\dot{p}_e = \mathrm{K} \cdot \Phi\left(\sigma_\theta + \mathrm{B} \cdot \exp\left(\mathrm{C} \cdot \sigma_\theta\right)\right) \exp\left(-Q / \mathrm{R} \cdot T\right) \tau^{-0.5}\ , \qquad (3)$$

where $\dot{p}_e$ – biaxial creep strain rate, s^{-1} ; K, B, C – known constants characterizing the cladding material properties; Φ – fast neutron flux (E > > 1.0 MeV), 1/m^2·s; σ_θ – circumferential stress, Pa; Q = 10^4 J/mol; R = 1.987 cal/mol·K; T – cladding temperature, K; τ – time, s.

Cladding material failure parameter calculation tool

The FEMAXI code has been used to calculate the cladding stress/strain development for such its quality as simultaneous solution of the FE heat conduction and mechanical deformation equations using the Finite Element Method allowing consideration of variable loading [2].

Combined load cycle

For instance, let's consider the following NR loading mode: a NR works at 100 % capacity level within 16 hours, then the reactor is transferred to 75 % capacity level within 1 hour. Further the NR works at 75 % capacity level within 6 hours, then comes back to 100 % capacity level within 1 hour. But the NR capacity decreases to 50 % level within last hour of every fifth day of a week. Further the reactor works during 47 hours at 50 % capacity level and, at last, within last hour of every seventh day the NR capacity rises to the level of 100 %. Such NR operating mode will be designated as the combined load cycle.

Brief calculation results

Using the CET cladding durability estimation method, an analysis of the cladding (stress relieved zircaloy) durability estimation sensitivity to the WWER-1000 main regime and design initial data uncertainty, for a reactor working in a variable loading mode, has been done.

The WWER-1000 main regime and design parameters have been devided into two groups: the parameters that influence the cladding failure conditions slightly and the parameters that determine the cladding failure conditions. The second group includes such initial parameters that any one of them gives a change of τ_0 estimation near 2 % (or greater) if the initial parameter has been specified at the value assignment interval of 3 %. This group consists of outer cladding diameter, pellet diameter, pellet hole diameter, cladding thickness, pellet effective density, maximum FE linear heat rate, coolant inlet temperature, coolant inlet pressure, coolant velocity, initial He pressure, FE grid spacing, etc [3].

It has been found, that cladding running time, expressed in cycles, for the WWER-1000 combined load cycle decreases from 1925 to 1351 cycles, when maximum FE linear heat rate $q_{l,\max}$ increases from 248 W/cm to 298 W/cm [3].

Having done estimation of cladding material failure parameter ω after 1576 ef. days it was found that the WWER-1000 combined load cycle has an advantage in comparison with the stationary NR operation at 100 % power level when $q_{l,\max} \leq$ ≤ 273 W/cm [3].

For a WWER-1000 nuclear power unit, an integrated varying loading operation efficiency indicator taking into account the FE cladding integrity, active core neutron field stability, efficiency and controllability requirements has been proposed. Also the Compromise-combined WWER-1000 reactor power control method capable of maximum varying loading operation efficiency has been proposed and grounded.

Some possible directions of the CET cladding durability estimation method development

Consideration of the real fuel assembly rotation history could be an important advance of the method.

Also it is necessary to take into account the dependence of the cladding yield stress on the number and size of cladding material defects.

It would be useful to account the influence of cladding outer surface oxide layer on the WWER-1000 cladding durability.

A correct analysis must be probabilistic and consider that the WWER-1000 FE axial segments and Fuel Assemblies (FAs) differ greatly in their local linear heat rate jump value at variable loading. But it has been found using the FEMAXI code and the CET method of cladding failure estimation under multiple cyclic reactor power changes, that the value of linear heat rate is one of key parameters that influences on a FE cladding durability.

So, determination of the WWER-1000 permissible operation time for the mode of varying loading requires estimation of the reactor local linear heat rate jumps.

Estimation of the WWER-1000 local linear heat rate jumps

The estimation was made using the “Reactor Simulator” (RS) program, which is a verified tool of the WWER-1000 calculation modeling [4]. Using the RS code, the WWER-1000 core neutron-physical calculation numerical algorithms are based on consideration of simultaneous two-group diffusion equations, which are solved for a three-dimensional object (the reactor core), composed of a limited number of meshes.

It was supposed that only the tenth group control rods change their position when the NR power increases from 80 to 100 %. All other groups of control rods are located outside the active core when the NR power maneuver is carried out.

The location of the WWER-1000 tenth group control rods and coolant temperature for the power levels of 80 % and 100 % are listed in Table 1.

Table 1. **The WWER-1000 active core parameters for the power levels of 80 and 100 %**

NR Power, %	Position of the tenth group control rods, % from the core bottom	Inlet coolant temperature, ºC	Core coolant heating, ºC
80	84	285	24,6
100	90	287	30,3

It has been found that all the WWER-1000 FAs can be classified into three groups by the FA power growth amplitude being when the active core power increases from 80 % to 100 % (1.25 times) – see Table 2.

Table 2. **The WWER-1000 FA power growth amplitude being when the active core power increases from 80 to 100 %**

FA group	Total number of FAs	FA power growth , %	FA numbers (according to the core cartogram)
1	6	28	31, 52, 58, 106, 112, 133
2	37	26	20, 42, 43, 46, 51, 53…57, 66…71, 80…84, 93…98, 107…111, 113, 118, 121, 122, 144
3	120	≤ 25	all other FAs

The FE height was devided into 16 axial segments so that the first axial segment corresponds to the core bottom, while the 16-th one – to the core top. The comparative assessment of power jumps for different axial segments when the core power increases from 80 to 100 % has been made using the RS code for the 31-th (first group) and 43-th (second group) FAs. The 31-th FA has got control rods of the tenth group inside it while the 43-th FA is located next to the 31-th FA. The first and 16-th axial segment power jump assessment results for the mentioned FAs are listed in Table 3.

Table 3. **The first and 16-th axial segment power jumps for the 31-th and 43-th FAs when the active core power increases from 80 to 100 %**

FA number	The first axial segment power jump, %	The 16-th axial segment power jump, %
31	28	44
43	30	36

So, the following conclusions can be made:

1. The WWER-1000 fuel element cladding durability estimation method using the creep energy theory makes it possible to determine the influence of the main reactor regime and fuel assembly constructional parameters on the change of the cladding properties at different loading conditions of normal operation.
2. All the WWER-1000 fuel assemblies must be considered to have determined the reactor permissible varying loading operation time taking into account the history of their displacement inside

the core and the history of their linear heat rate levels.

3. A correct estimation of the WWER-1000 fuel element cladding durability must account the influence of oxide layer at the cladding outer surface on the cladding operation life as well as take into account the dependence of the cladding yield stress on the number and size of cladding material defects.

4. The active core top linear heat rate jumps can be equal up to 44 % when the reactor power increases only 1.25 times, from 80 to 100 % of nominal level. At the same time, the central axial segment has got the maximum stationary linear heat rate. So, an estimation of variable loading influence on all axial segments is required the cladding durability assessment accuracy to be increased.

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ОЦІНКА РОЗМІРУ ЛОКАЛЬНИХ СТРИБКІВ ЛІНІЙНОЇ ПОТУЖНОСТІ В ЗМІННОМУ РЕЖИМІ НАВАНТАЖЕННЯ

Метод аналізу довговічності оболонки твела, заснований на енергетичному варіанті теорії повзучості, дає змогу визначити припустиму тривалість експлуатації реактора ВВЕР-1000 в режимі змінного навантаження. Проте розмір локальних стрибків лінійної потужності в змінному режимі навантаження ВВЕР-1000 для різних аксіальних сегментів твела і тепловидільних збірок є істотно відмінним. Отримано, що розмір лінійної потужності є одним з ключових параметрів, що впливають на міцність оболонки твела в режимі змінного навантаження. Таким чином, для визначення припустимої тривалості експлуатації реактора ВВЕР-1000 в режимі змінного навантаження необхідно оцінювати розмір локальних стрибків лінійної потужності.

Ключові слова: ВВЕР, змінний режим навантаження, довговічність оболонки твела, стрибок лінійної потужності.

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ОЦЕНКА ВЕЛИЧИНЫ ЛОКАЛЬНЫХ СКАЧКОВ ЛИНЕЙНОЙ МОЩНОСТИ В ПЕРЕМЕННОМ РЕЖИМЕ НАГРУЖЕНИЯ

Метод анализа долговечности оболочки твэла на основе энергетического варианта теории ползучести дает возможность определить допустимое время эксплуатации реактора ВВЭР-1000 в режиме переменного нагружения. Однако величина локальных скачков линейной мощности в переменном режиме нагружения ВВЭР-1000 для различных аксиальных сегментов и топливных сборок существенно различается. Было получено, что величина линейной мощности является одним из ключевых параметров, влияющих на долговечность оболочки твэла в режиме переменного нагружения. Таким образом, для определения допустимого времени эксплуатации реактора ВВЭР-1000 в режиме переменного нагружения необходимо оценивать величину локальных скачков линейной мощности.

Ключевые слова: ВВЭР, переменный режим нагружения, долговечность оболочки твэла, скачок линейной мощности.

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