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AUTOMATED SYSTEM FOR CONTROL OF VVER-1000 FUEL PROPERTIES CONSIDERING FUEL CLADDING DAMAGE PARAMETER

С.М. Пелих, М.О. Фролов, А.В. Наливайко, Хуйюю Чжоу. **Автоматизована система керування властивостями ядерного палива ВВЕР-1000 з урахуванням параметра пошкодження оболонок твелів.** Запропоновано автоматизовану систему керування властивостями ядерного палива (ЯП) реактора ВВЕР-1000 з урахуванням параметра деформаційного пошкодження оболонок твелів, глибини ви-горання ЯП і аксіального офсету. Використовуючи синергетичний метод управління властивостями ялерного палива (ЕВТП-метод), показана можливість оптимізації режимів навантаження і перестановок ТВЗ реактора на основі цільової функції, що враховує водночас параметр пошкодження оболонок, глибину вигорання ЯП і аксіальний офсет. Запропоновані склад і структура автоматизованої системи керування властивостями палива реактора ВВЕР-1000, що забезпечує баланс між безпекою та економічністю експлуатації ЯП.
Ключові слова: автоматизована система керування, реактор ВВЕР-1000, програмний засіб, оболонка твела, параметр пошкодження

S. Pelykh, M. Frolov, A. Nalyvayko, Huiyu Zhou. **Automated system for control of VVER-1000 fuel properties considering fuel cladding damage parameter.** An automated system for control of VVER-1000 reactor fuel properties considering fuel element cladding damage parameter, fuel burnup and axial offset has been proposed. Using the synergic method for control of nuclear fuel properties (CET-method) optimization of reactor loading and fuel assembly rearrangement regimes, based on an objective function including fuel element cladding damage parameter, fuel burnup and axial offset, has been grounded. The composition and structure of an automated system for control of VVER-1000 reactor fuel properties ensuring the fuel operation safety-efficiency balance have been proposed.
Keywords: automated control system, VVER-1000 reactor, software tool, fuel cladding, damage parameter

Introduction. The current and predictable state of Ukrainian economy implies that strict demands for nuclear energy safety and efficiency will be constantly actual. This problem of nuclear energy safety and efficiency is tightly connected to the problem of safety and efficiency for nuclear fuel operation, first of all because a fuel cladding is the key safety barrier when operating nuclear reactors. Taking into account that, as a rule, the exact cause of a cladding failure in VVERs is still not reliably known, in order to guarantee the fuel operation safety and efficiency complex methods for control of the cladding failure probability must be developed, considering different physical mechanisms leading to cladding failure including damage accumulation [1].

Since for normal operating conditions including variable loading modes the synergic method for control of nuclear fuel properties (CET-method) allows us to minimize the radioactive leakage through fuel claddings into a VVER circuit simultaneously with optimization of fuel operation parameters, an

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automated system for control of VVER-1000 reactor fuel properties ensuring the fuel operation safety-efficiency balance can be developed based on the CET-method. Though some problems in implementing the CET-method still remain unsolved, e.g., the limit value of cladding damage parameter corresponding to any kind of cladding failure should be grounded, it has been clear that the radioactive leakage into the VVER-1000 circuit can be minimized, under normal operating conditions, by using an automated control system optimizing VVER-1000 loading modes and rearrangements of core fuel assemblies, applying an objective function including fuel cladding damage parameter, burnup and axial offset [2].

Thus, in order to plan and evaluate a research project devoted to improvement of the VVER safety-efficiency balance by means of improved controlling the fuel cladding fracture due to damage accumulation, the next issue is the composition and structure of such prospective automated system for fuel properties control, intending to implement it at a standard nuclear power unit with a VVER-1000 reactor presently used in Ukraine.

The aim of the research is working out grounds of an automated system for control of VVER-1000 reactor fuel properties, in order to ensure the fuel operation safety-efficiency balance. The synergic nature of the CET-method developed for control of nuclear fuel properties will be explained. Two main methods for ensuring the safety-efficiency balance when operating the VVER-1000 reactor fuel will be described and corresponding objective functions will be given. At last, the composition and structure of a prospective automated system for control of VVER-1000 fuel properties will be proposed.

Materials and Methods. The CET-method for control of nuclear fuel properties based on using the creep energy theory allows us to improve the safety-efficiency balance, when operating VVER reactors, by minimizing maximum and average values of damage parameter for fuel element (FE) claddings. This CET-method is synergic by nature as it takes into account the exact loading history for both a fuel assembly (FA) and a reactor. The processes of different nature (neutron-physical, heat generation and transfer, thermal-hydraulic, corrosion, creep, etc.) in a reactor core are considered simultaneously and, to say more, they are studied on different levels of the system hierarchy [2].

Some additional experimental program should be carried out for finding the exact dependence of the radioactive leakage through microcracks in fuel claddings on ω(t), as well as for verification of the known laboratory results [3, 4] under real VVER-1000 core conditions.

Nevertheless let us consider the procedure of VVER-1000 fuel performance optimization using an objective function *Eff* because the basic idea of improvement of the fuel operation safety-efficiency balance, by means of minimizing ω(t) for FE claddings using the CET-method, seems to be well grounded [2]. This is true taking into account both the fact that the CET-method was verified for non–irradiated thin tubes made of different alloys, under thermal and mechanical conditions close to real core conditions, as well as fundamental advantages of the CET-model compared to the calculation model for estimation of $\omega(t)$ using the normative SC4 criterion [5].

Step 1. The list of controlled parameters $\{c_i\}$ as well as the adjusted factors $\{d_j\}$ determining the controlled parameters should be defined.

As optimization of reactor loading and FA rearrangement regimes should be made taking into account safety and economic requirements simultaneously, it is reasonable that the objective function includes fuel cladding damage parameter (ω), fuel burnup (*B*) and axial offset (AO). So considering (1) reactor loading and (2) FA rearrangement optimization the set of controlled parameters included in the objective function is, respectively: (1) $\{c_1 = \omega,\ c_2 = B,\ c_3 = \mathrm{AO}\}$ and (2) $\{c_1 = \omega,\ c_2 = B\}$.

As FE maximum linear heat rate $q_l^{\max}$ is the chief factor determining the value of cladding damage parameter, the key variable factor to be adjusted for improvement of the fuel operation safety-efficiency balance and optimization of fuel performance is $q_l^{\max}$, that is $d \equiv q_l^{\max}$.

Step 2. Taking into account fuel safety and economic requirements the optimal c_i^{opt} and limiting c_i^{lim} values are specified for each c_i, so that the permissible values for c_i lie in the intervals:

$$c_i^{\mathrm{lim}} \le c_i \le c_i^{\mathrm{opt}} \quad \text{or} \quad c_i^{\mathrm{opt}} \le c_i \le c_i^{\mathrm{lim}} . \tag{1}$$

For instance, according to SC4 criterion for cladding damage parameter $c_1^{\mathrm{lim}} \equiv \omega^{\mathrm{lim}} = 0.1$ [5].

Having rewritten c_i, c_i^{lim} and c_i^{opt} in a dimensionless form:

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$$c_i^{\lim,*} \le c_i^* \le c_i^{\mathrm{opt},*} = 1. \quad .(2)$$

The objective function Eff for control of reactor fuel properties is written in the form [6]:

$$Eff = 1 - \frac{L}{L^{\lim}}, \quad (3)$$

where

$$L = \sqrt{\sum_{i=1}^{n_i} (1 - c_i^*)^2}; \quad L^{\lim} = \sqrt{\sum_{i=1}^{n_i} (1 - c_i^{\lim,*})^2}, \quad (4)$$

where n_i = 3 and 2 for reactor loading and FA rearrangement optimization, respectively.

The method of constructing equations for c_i^*, $c_i^{\lim,*}$ and $c_i^{\mathrm{opt},*}$ is based on such requirements [6]:

– if reactor and fuel design/operation parameters are such that the condition is satisfied:

$$\{c_i = c_i^{\mathrm{opt}} \text{ for any } i, \text{ that is } \omega = \omega^{\mathrm{opt}}, B = B^{\mathrm{opt}} \text{and } \mathrm{AO} = \mathrm{AO}^{\mathrm{opt}}\}, \quad (5)$$

then the condition for controlled parameters rewritten in a dimensionless form is satisfied also:

$$\begin{cases} \{c_i^* = c_i^{\mathrm{opt},*} = 1 \text{ for any } i, \text{ that is } \omega^* = \omega^{\mathrm{opt},*} = 1, B^* = B^{\mathrm{opt},*} = 1 \text{ and AO }^* = \mathrm{AO}^{\mathrm{opt},*} = 1\}, \\ Eff = Eff^{\max} = 1. \end{cases} \quad (6)$$

hence Eff is maximum, so the optimization task is solved;

– if for a controlled parameter c_i the condition $c_i^* < c_i^{\lim,*}$ is satisfied, then this controlled parameter gives a negative contribution to the total efficiency Eff;

– an advantage of one set of reactor and fuel design/operation parameters over another is determined by summarizing advantages given by controlled parameters c_i.

Step 3. Conducting fuel performance optimization using the accepted objective function Eff.

Results. Such VVER-1000 power control methods were considered hereinafter:

– coolant temperature averaged in the core is fixed: $<t_W>$ = const (method I);

– steam pressure at the second circuit inlet is fixed: p_2 = const (method II);

– coolant temperature at the core inlet is fixed: $t_{W,0}$ = const (method III).

Considering a 4-year fuel campaign core neutron flux stability was studied for the daily load cycle: {N=100 %; 80 %; 100 %}, where N is reactor thermal power. Accepting the limiting condition $\mathrm{AO}^{\lim}$ = 0.05, the permissible duration of core power maneuvering was studied for three power control methods using the “Reactor Simulator” program [7]. It was found that for methods I, II and III, AO remained stable during 7, 1 and 6 months, respectively. This means that for N =100 % and 80 % the AO alteration magnitude stayed in the permissible ranges [–5; 2.5] and [–5; 4], respectively.

Other components (B^* and ω*) of the objective function for methods I, II and III were found using the “Femaxi” program [8]. Then the task of reactor power control method optimization was completed for a 4-year fuel campaign by finding an extremum of the objective function (3) written in a simplified form described minutely in [2]. Considering the daily load cycle {N=100 %; 80 %; 100 %} such reactor load algorithms during a 4-year campaign were investigated:

Algorithm 1. N = var for 2 months, N = const for 10 months.

Algorithm 2. N = var for 3 months, N = const for 9 months.

Algorithm 3. N = var for 4 months, N = const for 8 months.

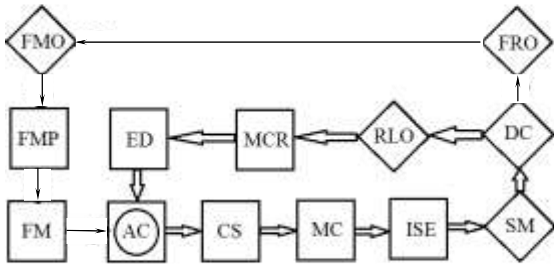
Algorithm 4. N = var for 5 months, N = const for 7 months.

Algorithm 5. N = var for 6 months, N = const for 6 months.

The optimal number of load switches between power control methods I and III was 38, 65, 69, 75 and 107 for loading algorithms 1, 2, 3, 4 and 5, respectively [2].

Examples of FA rearrangement optimization using the described technique were given in [6].

An automated system for control of reactor fuel properties will include both elements of the standard equipment of a VVER-1000 unit and some additional elements necessary for automated switches between reactor loading and FA rearrangement regimes – see Figure.



Block diagram of an automated system for control of VVER-1000 fuel properties: AC – active core; CS – core sensors; MC – marshalling cabinets; ISE – low-level and high-level equipment of the in-core instrumentation system; SM – simulation model for fuel performance optimization; DC – data comparator for analysis of cladding damage parameter values; RLO – block calculating the objective function for reactor loading optimization; MCR – main control room; ED – executive device for reactor power change; FRO – block calculating the objective function for fuel rearrangement optimization; FMO – block for fueling machine operation optimization; FMP – fueling machine control panel; FM – fueling machine

The prospective automated system for control of VVER-1000 fuel properties will have such elements and control objects:

– Active core (AC) of a VVER-1000 reactor, it contains 163 fuel assemblies, each FA includes 312 fuel elements. Hence the total number of FEs in a core is above 50.000. According to safety regulations a core under normal operating conditions can contain no more than 500 FE claddings having a gas leaking, while a direct fuel-coolant contact is allowed for 50 claddings only [5].

– Core sensors (CS) are used in the automated system controlling fuel properties for measuring coolant temperature and neutron flux values which are necessary for the simulation model.

– Marshalling cabinets (MC) are used for transformation of values of physical parameters obtained from core sensors into electric signals being sent to the low-level and high-level equipment of the in-core instrumentation system.

– Low-level and high-level equipment of the in-core instrumentation system (ISE) is intended for processing information obtained from MC and sending it to the main control room for using it by reactor operators. ISE includes information-measuring equipment and special-purpose software.

– Simulation model for fuel performance optimization (SM) includes the CET-model for cladding damage parameter calculation based on the synergic CET-method as well as a criterion model taking into account safety and economic requirements simultaneously. Optimization calculations are made using specialized software (“Reactor Simulator”, “Femaxi”, etc.).

– Data comparator (DC) is intended for periodical analysis of current cladding damage parameter values $\omega(\tau)$ and comparing them to corresponding pre-determined limit values $\omega^{lim}(\tau)$. If current $\omega(\tau)$ is too close to $\omega^{lim}(\tau)$, then a reactor loading optimization procedure starts.

– Reactor loading optimization block (RLO) is a block calculating the objective function for reactor loading optimization so that cladding damage parameter values could not exceed their limit values. The reactor power is changed by inserting boric acid into the active core. The boric acid volume required for a reactor power change is calculated in RLO also.

– Main control room (MCR) is a place where operators ensure normal exploitation of a reactor unit based on current information on technological parameters.

– Executive device (ED) used for reactor power change is a solenoid-controlled valve.

– Fuel rearrangement optimization block (FRO) is a block calculating the objective function for FA rearrangement optimization so that cladding damage parameter values could not exceed their limit values.

– Fueling machine operation optimization block (FMO) is a block calculating the fueling machine operation algorithm.

– Fueling machine control panel (FMP) is intended for delivering information on FA rearrangement and fueling machine operation algorithms to the fueling machine.

– Fueling machine (FM) makes rearrangements of fuel assemblies in the core.

Conclusions. The procedure of VVER-1000 fuel performance optimization using an objective function ensuring the fuel operation safety-efficiency balance has been explained. The automated system for control of reactor fuel properties considering fuel cladding damage parameter, fuel burnup and axial offset has been proposed. The composition and structure of this prospective automated system

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minimizing the radioactive leakage into the reactor circuit under normal conditions, based on minimizing the cladding damage parameter and using the synergic CET-method, have been discussed.

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