ENERGETICS. HEAT ENGINEERING.
ELECTRICAL ENGINEERING

ENERGETика. ТЕПЛОТЕХНИКА.
ЕЛЕКТРОТЕХНИКА

UDC 621.039.548

S. Pelykh1, DSc, Prof.,
M. Frolov1
A. Nalyvayko1,
Huiyu Zhou2

1 Odessa National Polytechnic University, 1 Shevchenko Ave., Odessa, Ukraine, 65044; e-mail: 1@pelykh.net
2 Northwestern Polytechnical University, 127 Youyi W Rd, 710065 Xi‘an, China; e-mail: huiyu.zhou2@gmail.com

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

S. Pelykh, M. Frolov, A. Nalyvayko, Huiyu Zhou. Автоматизована система керування властивостями ядерного палива ВВЕР-1000 з урахуванням параметра пошкодження оболонок твілів. Запропоновано автоматизовану систему керування властивостями ядерного палива (ЯП) реактора ВВЕР-1000 з урахуванням параметра деформаційного пошкодження оболонок твілів, глибини ви-горання ЯП і аксіального офсету. Використовуючи синергетичний метод управління властивостями ядерного палива (ЕВТП-метод), показана можливість оптимізації режимів навантаження і перестановок ТВЗ реактора ВВЕР-1000, що забезпечує баланс між безпекою та економічністю експлуатації ЯП.

Keywords: automated control system, VVER-1000 reactor, 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 synergistic 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

DOI: 10.15276/opu.1.54.2018.06

© 2018 The Authors. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
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 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 $o(t)$, 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 $o(t)$ 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 $o(t)$ using the normative SC4 criterion [5].

Step 1. The list of controlled parameters $\{c_i\}$ as well as the adjusted factors $\{d_i\}$ 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 ($o$), 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) $\{c_1 = o, c_2 = B, c_3 = AO\}$ and (2) $\{c_1 = o, c_2 = B\}$.

As FE maximum linear heat rate $q_{\text{max}}$ 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 $q_{\text{max}}$, that is $d = q_{\text{max}}$.

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:

$$c_i^{lim} \leq c_i \leq c_i^{opt} \text{ or } c_i^{opt} \leq c_i \leq c_i^{lim}.$$  \hspace{1cm} (1)

For instance, according to SC4 criterion for cladding damage parameter $c_i^{lim} = o_{i, lim}^{lim} = 0.1$ [5].

Having rewritten $c_i, c_i^{lim}$ and $c_i^{opt}$ in a dimensionless form:
The objective function $ Eff $ for control of reactor fuel properties is written in the form [6]:

$$
Eff = 1 - \frac{L}{L_{\text{lim}}},
$$

where

$$
L = \sqrt{\sum_{i=1}^{n_c} (1 - c_i^*)^2}; \quad L_{\text{lim}} = \sqrt{\sum_{i=1}^{n_c} (1 - c_{\text{lim}*})^2},
$$

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

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

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

$$
\{ c_i = c_{\text{opt}}^* \text{ for any } i, \text{ that is } \omega = \omega_{\text{opt}}, B = B_{\text{opt}} \text{ and } AO = AO_{\text{opt}} \},
$$

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

$$
\{ c_i^* = c_{\text{opt}*}^* = 1 \text{ for any } i, \text{ that is } \omega^* = \omega_{\text{opt}*}^* = 1, B^* = B_{\text{opt}*}^* = 1 \text{ and } AO^* = AO_{\text{opt}*}^* = 1 \},
$$

$$
Eff = Eff_{\text{max}} = 1.
$$

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

- if for a controlled parameter $ c_i $ the condition $ c_i < c_{\text{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_{\text{ch}} = \text{const} $ (method I);
- steam pressure at the second circuit inlet is fixed: $ p_2 = \text{const} $ (method II);
- coolant temperature at the core inlet is fixed: $ t_{\text{ch},0} = \text{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 $ AO_{\text{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 $ \omega^* $) 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 = \text{const} $ for 10 months.
Algorithm 2. $ N $ var for 3 months, $ N = \text{const} $ for 9 months.
Algorithm 3. $ N $ var for 4 months, $ N = \text{const} $ for 8 months.
Algorithm 4. $ N $ var for 5 months, $ N = \text{const} $ for 7 months.
Algorithm 5. $ N $ var for 6 months, $ N = \text{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.
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 $\omega(\tau)^{\text{lim}}$. If current $\omega(\tau)$ is too close to $\omega(\tau)^{\text{lim}}$, 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
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.

Література

1. Review of fuel failures in water cooled reactors. IAEA Nuclear Energy Series No. NF-T-2.1.Vienna: International Atomic Energy Agency, 2010. 191 p.
2. Zhou H., Pelykh S.N., Odrekhovska I.O., Maksymova O.B. Optimization of power control program switching for a WWER–1000 under transient operating conditions. Problems of Atomic Science and Technology. Ser. Vacuum, Pure Mate-rials and Super-conductors. 2018. Iss. 1(113), P. 218–222.
3. Соснин О.В., Горев Б.В., Никитенко А.Ф. Энергетический вариант теории ползучести Новосибирск: СО АН СССР, 1986. 95 c.
4. Kim J.H. Deformation behavior of Zircaloy-4 cladding under cyclic pressurization. Journal of Nuclear Science and Technology. 2007. Vol. 44. P. 1275–1280.
5. Правила ядерной безопасности реакторных установок атомных станций НП-082-07. Москва: Федеральная служба по экологическому, технологическому и атомному надзору, 2008. 21 c.
6. Pelykh S.N., Maksimov M.V., Nikolsky M.V. A method for minimization of cladding failure parameter accumulation probability in VVER fuel elements. Problems of Atomic Science and Technology. Ser. Physics of Radiation Effect and Radiation Materials Science. 2014. Iss. 4. P. 108–116.
7. Филимонов П. Е., Мамичев В. В., Аверьянова С. П. Программа "Имитатор реактора" для моделирования маневренных режимов работы ВВЭР–1000. Атомная энергия. 1998. Т. 84, № 6. С. 560–563.
8. Сузуки М. Моделирование поведения тзвла легководного реактора в различных режимах нагрузки. Одесса: Астропринт, 2010. 248 c.

References

1. Review of fuel failures in water cooled reactors. (2010) IAEA Nuclear Energy Series No. NF-T-2.1.– Vienna: International Atomic Energy Agency.
2. Zhou H., Pelykh S.N., Odrekhovska I.O., & Maksymova O.B. (2018). Optimization of power control program switching for a WWER-1000 under transient operating conditions. Problems of Atomic Science and Technology. Ser. Vacuum, Pure Materials and Super-conductors, 1(113), 218–222.
3. Sosnin O.V., Gorev B.V., & Nikitenko A.F. (1986). The Energy Variant of the Theory of Creep. Novosibirsk: The Siberian Branch of the USSR Academy of Sciences.
4. Kim J.H. (2007). Deformation behavior of Zircaloy-4 cladding under cyclic pressurization. Journal of Nuclear Science and Technology, 44, 1275–1280.
5. Nuclear safety regulations for NPP reactor plants NP-082-07. (2008). Moscow: The Federal Service for Ecological, Technological and Nuclear Supervision.
6. Pelykh S.N., Maksimov M.V., & Nikolsky M.V. (2014). A method for minimization of cladding failure parameter accumulation probability in VVER fuel elements. Problems of Atomic Science and Technology. Ser. Physics of Radiation Effect and Radiation Materials Science, 4, 108–116.
7. Filimonov P.E., Mamichev V.V., & Averyanova S.P. (1998). The "reactor simulator" code for modeling of maneuvering WWER–1000 regimes. Atomnaya Energiya, 6, 560–563.
8. Suzuki M. (2010). Modelling of light-water reactor fuel element behaviour in different loading regimes. Odessa: Astroprint.

Nelyy Sergiy Mykolayovyych; Pelykh Sergey, ORCID: https://orcid.org/0000-0003-1608-8089
Frolov Maxim Oleksandrivych; Frolov Maksym, ORCID: https://orcid.org/0000-0002-4406-2970
Nalyvayko Artem Volodymyrovych; Nalyvayko Artem, ORCID: https://orcid.org/0000-0003-3220-925X
Zhou Huiyu; Zhou Huiyu, ORCID: https://orcid.org/0000-0003-2878-628X

Received January 21, 2018
Accepted March 01, 2018