ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

UDC 629.031

V. Skalozubov, DSc., Prof.,
Iu. Katsarskyi,
Iu. Komarov, DSc.,
Ye. Mazur,
V. Kochnieva
Odessa Polytechnic National University, Shevchenko Ave. 1, Odesa, Ukraine, 65044, e-mail: valer_nov13@ukr.net

QUALIFICATION OF NUCLEAR REACTOR NOMINAL POWER UPGRADES

В. Скалозубов, Ю. Кацарський, Ю. Комаров, Є. Мазур, В. Кочнєва. **Кваліфікація модернізацій номінальної потужності ядерних реакторів.** В екстремальних умовах воєнного часу внаслідок пошкодження/руйнування/ окупації цілого ряду енергогенеруючих об'єктів та безперервних пошкоджень/руйнувань критичної інфраструктури енергетики України пріоритетна і актуальна задача експлуатуючої організації атомних електричних станцій (Державне підприємство «Національна атомна енергогенеруюча компанія Енергоатом») – підвищення ефективності безпечної експлуатації діючих атомних енергоблоків на основі кваліфікації та впровадження стратегій підвищеної номінальної потужності та тривалості паливної кампанії ядерних реакторів. Представлено аналіз відомих підходів обґрунтування (кваліфікації) стратегій експлуатації ядерних реакторів типу ВВЕР/PWR на підвищеній номінальній потужності. Встановлено, що основні недоліки відомих підходів кваліфікації модернізацій активної зони ядерного реактора полягають у залежності результатів кваліфікації від способів реалізації стратегії експлуатації ядерних енергоустановок у режимах підвищеної номінальної потужності, а також від ефектів різниці детерміністських кодів та/або користувачів кодами, що зрештою ускладнює об'єктивну інтерпретацію результатів кваліфікації. Розроблено критеріальний метод кваліфікації стратегії експлуатації ядерних реакторів на підвищеній номінальній потужності на основі модернізації теплофізичних властивостей ядерного палива та конструкційно-технічних параметрів елементів твелів, який виключає вплив ефектів різниці детерміністських кодів та/або користувачів кодами та враховує умови забезпечення безпеки щодо гранично допустимих температур оболонок твелів і ядерного палива.
Ключові слова: кваліфікація, підвищення номінальній потужності, ядерний реактор

V. Skalozubov, Iu. Katsarskyi, Iu. Komarov, Ye. Mazur, V. Kochnieva. **Qualification of nuclear reactor nominal power upgrades.** In extreme wartime conditions due to damage/destruction/occupation of a number of power generating facilities and continuous damage/destruction of the critical energy infrastructure of Ukraine, the priority and urgent task of the operating organization of nuclear power plants (State Enterprise "National Nuclear Energy Generating Company “Energoatom”) is to increase the efficiency of safe operation of operating nuclear power units based on qualification and implementation of strategies for increased nominal power and duration of the fuel campaign of nuclear reactors. An analysis of known approaches to substantiating (qualifying) strategies for operating nuclear reactors of the VVER/PWR type at increased nominal power is presented. It is recognized that the main shortcomings of known approaches to qualifying nuclear reactor core modernizations lie in the dependence of the qualification results on the methods of implementing the strategy for operating nuclear power plants in increased nominal power modes, as well as on the effects of the difference in deterministic codes and/or code users, that ultimately complicates the objective interpretation of the qualification results. A criterion-based method for qualifying the strategy for operating nuclear reactors at increased nominal power based on the modernization of the thermophysical properties of nuclear fuel and the structural and technical parameters of fuel elements has been developed, which eliminates the influence of the effects of the difference in deterministic codes and/or code users and takes into account the conditions for ensuring safety regarding the maximum permissible temperatures of fuel and nuclear fuel claddings.
Keywords: qualification, increased nominal power, nuclear reactor

Introduction

The installed capacity utilization factor of the installed capacity is the most significant indicator of nuclear power plant efficiency. It is determined by the ratio of the actual thermal power N for the duration of the operating modes of the reactor t_R to the design-established rated power N_D for the period of operation t_0:

$$\mathrm{ICUF} = N_D^{-1} t_0^{-1} \int_0^{t_R} N(t)dt\ .$$

Thus, the perspective direction of increasing the utilization factor of the installed power (and, accordingly, the efficiency of NPP operation) can be a relative increase in the nominal power of the reactor in operating modes N and the total duration of the operating modes of the reactor at the power t_R over the period of operation t_0.

The prospect of such a direction of increasing the utilization factor of the installed power of the

DOI: 10.15276/opu.2.70.2024.11

nuclear power plant determines the relevance of developing and substantiating (qualifying) safety strategies for operating at increased nominal power of the reactor in operating modes and / or increasing the total duration of the reactor operating modes at power (increasing the duration of “fuel campaigns”).

The need for qualification of strategies for increasing the nominal capacity to ensure nuclear safety conditions is determined by the general regulatory requirements established for the modernization of **systems important to the safety of nuclear power plants (SIS NPP)**.

Traditionally, the design qualification of SIS NPP upgrades is based on the results of design modelling by deterministic codes (DC) of emergency modes.

The main disadvantage of this approach of qualification of modernization of SIS NPP is that the results of the design modelling of the DC of emergency modes can significantly depend on the difference between different DC and/or different users of the same DC. In this case, there may be a negative impact on the results of qualification of modernization of the effects of the DC difference and/or DC users, which ultimately complicates the objective interpretation of the results of qualification of modernization of SIS NPP.

Thus, alternative methods of qualification of strategies of the NWP to ensure the necessary conditions of nuclear safety are the actual development. This determines the goals and objectives of the presented work.

Analysis of literature data on known results of qualification of NPP core upgrades and problem statement

In the works [1, 2], the results of qualification of modernization of the nuclear power plant core with VVER were analyzed by diversification of fuel assemblies (FA) of Westinghouse, based on the design simulation of DC of postulated accidents. The analysis found a significant impact on the qualification results of the negative effects of the difference between DC/DC users. In particular, separate deterministic codes RELAP calculations established the impracticability of safety conditions when diversifying Westinghouse FAs.

The works [1, 2] also developed an alternative method for qualification of VVER core modernization by diversification of Westinghouse FA, which does not depend on the effect of DC/DC users difference effects on qualification results. The qualification results developed in [1, 2] by an alternative method established the fulfilment of nuclear safety conditions during the maximum design basis accident (rupture of the main circulation pipeline), taking into account the design and technical differences between the design FA A and FA Westinghouse.

In works [3, 4] the analysis of modernization of thermophysical properties of nuclear fuel is carried out. As a result:

1) preventive decrease in thermal conductivity of nuclear fuel leads to a relative increase in the operating temperature of the fuel (other things being equal) and the corresponding increased nominal power of the reactor;

2) however, a significant increase in the temperature of nuclear fuel can lead to degradation of fuel matrices and their subsequent destruction, which is confirmed by numerous results of experimental qualification of modernization of the thermophysical properties of nuclear fuel;

3) a promising approach can be based on a two-layer fuel matrix of the fuel element: the central zone of the fuel matrix is modernized with chemical elements that reduce the thermal conductivity of nuclear fuel, and the surface layer (rim-zone) with chemical elements that increase the thermal conductivity of nuclear fuel.

However, regarding the prospects of a two-layer fuel matrix model of the fuel element, it is possible to give the following comments:

1) it is necessary to assess the maximum permissible increase in the temperature of nuclear fuel in the central zone of the fuel matrix, in which in case of accidents there may be a violation of safety conditions leading to a nuclear (severe) accident;

2) in order to ensure nuclear safety conditions during accidents, it is also necessary to determine the optimal ratio of thermophysical properties and dimensions of the central and rim zones of the fuel element fuel matrix.

In works [5, 6] the analysis of known approaches of substantiation (qualification) of NPP operation strategies with increase of reactor rated power based on iterative results of design modelling of DC of design accidents is presented. In general, the qualifications of such strategies are as follows.

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

1. First, a priori, the level of nominal power increase is set within the design margin before boiling (heat exchange) crisis in the reactor operating mode.

2. Under initial conditions, in accordance with the adopted a priori nominal power increase of the reactor, in the operating mode, the design simulation of accident monitoring and analysis of the feasibility of safety conditions during such accidents are carried out.

3. In order to establish the maximum permissible nominal power of the reactor with provision of the required margin for boiling crisis in operating modes and safety conditions in emergency modes at the next stages of qualification, iterations of the initial conditions for the nominal power increase of the reactor are carried out with repeated design modelling of accidents.

The main drawbacks / limitations of the above approach of qualification of modernization of reactor nominal power increase strategies are as follows.

1. In general, the implementation of the reactor's nominal power increase is possible by the following methods: modernization of neutron-physical properties / parameters of nuclear fuel and/or thermophysical properties of nuclear fuel and/or structural and technical parameters of core elements. The choice of the method of implementing the nominal power increase of the reactor not only affects the maximum temperature of the nuclear fuel (and, accordingly, the heat flux density on the fuel element surface), but can also affect other parameters that determine the thermal power of the fuel element. In particular, in case of reactor nominal power increase by the method of highly enriched nuclear fuel / MOX fuel (modernization of neutron-physical properties of nuclear fuel), the results of qualification of the reactor nominal power increase strategy may be affected by corresponding changes in the thermophysical properties of highly enriched nuclear fuel/MOX fuel.

Thus, when qualifying the strategies of the nominal power increase reactor, it is necessary to take into account the method of increasing the rated power.

2. A necessary condition for the boiling (heat exchange) crisis on the fuel element surface is a stable surface steam zone.

A necessary condition for the occurrence of thermoacoustic instability of the coolant is the intense surface ("underheated") boiling of the bubble structure (for example, [7 – 10], etc.). The consequences thermoacoustic instability of the coolant in the core can be high-frequency and high-amplitude dynamic loads on the fuel element, which can lead to a violation of the tightness of the fuel element shell (protective safety barrier) [7, 8].

Thus, the required conditions of thermoacoustic stability of the coolant are carried out at lower thermal loads in the core than the required conditions of boiling crisis (heat exchange). Therefore, the maximum permissible thermal power of the fuel element in the operating modes of the reactor is determined not by the conditions ("reserve") of the boiling crisis, but by the conditions of the beginning of intensification of surface ("underheated") boiling in the core.

3. Negative consequences of repeated deterministic modelling of accidents may be the effects of the DC/DC user difference, which complicate the objective interpretation of qualification results [5, 6].

Thus, on the basis of the analysis of known approaches to qualification of reactor core modernization, the relevance of developing alternative methods for qualification of reactor nominal power increase strategies in operating modes of NPP operation was determined.

The purpose of the study is to develop an alternative method of qualification of nominal power increase to determine the maximum permissible rated thermal power of the reactor and the temperature of nuclear fuel in operating modes that provide the necessary conditions for nuclear safety in the postulated process of maximum design basis accident (MDA).

The main tasks

Analysis of known approaches and methods for qualification of core modernization strategies.

Development of a criterion method for qualification of the nominal power increase strategy of the reactor in operating modes, which does not depend on the effects of the DC/DC user difference.

Analysis of the results and practical recommendations

Criterion method of qualification of the strategy of increased nominal reactor power.

General provisions and assumptions.

1. In general, the qualification (justification) of the nominal power increase reactor strategy is based on the following provisions:

– nominal power increase of reactor can be realized by modernization of neutron-physical and / or thermophysical properties of nuclear fuel and / or structural and technical parameters of fuel element;

– due to the nominal power increase of the reactor (other things being equal), there may be a relative increase in the maximum temperature of the nuclear fuel, and accordingly an increase in the depth of combustion of the nuclear fuel.

2. Qualification criteria are set:

– limiting power of the fuel element of the beginning of intense surface vaporization ("underheated" boiling) in the operating mode of the N_b reactor;

– maximum permissible temperature of fuel claddings of the beginning of intensification of the steam-zirconium reaction during MDA $\max T_W$;

– maximum permissible temperature of the beginning of melting / destruction of the fuel matrix during the MDA $\max T_F$.

3. Conditions of fuel element modernization qualification in operating and emergency modes:

$$\max N \le N_b, \tag{1}$$

$$T_F < \max T_F,\ T_W < \max T_W, \tag{2}$$

where N – thermal power of fuel element;

T_F, T_W – nuclear fuel and fuel cladding temperature.

4. Parameters of modernization of the reactor nominal power increase strategies are defined as follows:

– thermophysical properties of nuclear fuel and fuel cladding;

– structural and technical parameters of fuel elements.

Influence of these parameters on qualification conditions (1) and (2) is taken into account by thermal resistance of fuel element R_T:

$$R_T = \frac{\delta_F}{\lambda_F} + \frac{\delta_g}{\lambda_g} + \frac{\delta_W}{\lambda_W}, \tag{3}$$

where δ_F, δ_g, δ_W – thickness of fuel matrix, fuel element gas gap and fuel element shell wall;

λ_F, λ_g, λ_W – indicators of thermal conductivity of nuclear fuel, fuel element gas gap and fuel element cladding.

Linear approximation R_T is justified for fuel element diameters d, which are much lower than fuel element height H [6]:

$$d \ll H. \tag{4}$$

5. The required qualification conditions (2) are determined on the basis of criteria of thermodynamic similarity of non-stationary processes of the initial stage of MDA of the modernized and successfully qualified design modes of reactor operation.

The results of design modelling of the design mode with the maximum fuel cladding temperature during MDA are conservatively taken into account.

Taking into account the accepted assumptions, the heat balance equation of the fuel element in the operating stationary mode of the reactor [6]:

$$N = G\Delta i = \alpha F_W (T_W - T_{\text{in}}) = R_T^{-1} F_W (T_F - T_{\text{W}}), \tag{5}$$

where N – thermal power of fuel element;

G – mass flow of coolant, reduced by one fuel element;

Δi – difference in specific enthalpy of the coolant at the outlet and inlet of the core;

α – heat transfer parameter on fuel element surface;

F_W – fuel element surface area;

T_{in} – coolant temperature at the core inlet.

After the transformations of equation (5), we obtain the dependence of maximum temperatures of nuclear fuel and fuel cladding on the maximum permissible power (1) in the upgraded operating mode and at the initial moment of the accident:

$$T_{F0m} = T_{Fm}(t=0) = \frac{G\Delta i_b}{F_W}(R_t + \alpha^{-1}) + T_{\text{in}m}, \tag{6}$$

$$T_{W0m} = T_W(t=0) = \frac{G\Delta i_b}{F_W} + T_{\text{in}m}, \tag{7}$$

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

where Δi_b – difference in specific enthalpy of the coolant under conditions of the beginning of intensification of surface boiling at the outlet of the core.

Heat balance equation for fuel matrix and fuel element cladding at the initial stage of MDA until connection of hydraulic accumulators of emergency core cooling system t_g:

$$C_F M_F \frac{dT_F}{dt} = N - R_T^{-1} F_W (T_F - T_W), \tag{8}$$

$$C_W M_W \frac{dT_W}{dt} = R_T^{-1} F_W (T_F - T_W) - \alpha_{cr} F_W (T_F - T_{\text{in}}), \tag{9}$$

where C_F, C_W – specific heat of nuclear fuel and fuel cladding;

M_F, M_W – weight of nuclear fuel and fuel cladding;

α_{cr} – heat transfer parameter for heat exchange crises.

In the criterion (dimensionless) format of equation (6) – (9):

$$\frac{d\mathbf{T}_F}{d\mathbf{t}} = \mathbf{K}_1 - \mathbf{K}_2,\ \mathbf{T}_F(\mathbf{t}=0) = \mathbf{K}_F = 1, \tag{10}$$

$$\frac{d\mathbf{T}_W}{d\mathbf{t}} = \mathbf{K}_3 - \mathbf{K}_4,\ \mathbf{T}_W(\mathbf{t}=0) = \mathbf{K}_W = 1, \tag{11}$$

where $\mathbf{T}_F = \frac{T_F}{T_{F0}}$, $\mathbf{T}_W = \frac{T_W}{T_{W0}}$, $\mathbf{t} = \frac{t}{t_g}$;

$$\mathbf{K}_1 = \frac{N t_g}{C_F M_F T_{F0}},\ \ \mathbf{K}_2 = \frac{F_W (T_F - T_W) t_g}{C_F M_F T_{F0}}; \tag{12}$$

$$\mathbf{K}_3 = \frac{F_W (T_F - T_W) t_g}{C_W M_W T_{W0}},\ \ \mathbf{K}_4 = \frac{\alpha_{cr} F_W (T_W - T_{\text{in}}) t_g}{C_W M_W T_{W0}}; \tag{13}$$

$$\mathbf{K}_F = \frac{N}{F_W T_{F0}} (R_T + \alpha^{-1}) + \frac{T_{\text{in}}}{T_{F0}}; \tag{14}$$

$$\mathbf{K}_W = \frac{N}{\alpha F_W T_{W0}} + \frac{T_{\text{in}}}{T_{W0}}. \tag{15}$$

Process identity conditions at the initial stage of MDA for design D and upgraded m reactor modes:

$$\mathbf{K}_{1m} = \mathbf{K}_{1D},\ \mathbf{K}_{2m} = \mathbf{K}_{2D},\ \mathbf{K}_{Fm} = \mathbf{K}_{FD}; \tag{16}$$

$$\mathbf{K}_{3m} = \mathbf{K}_{3D},\ \mathbf{K}_{4m} = \mathbf{K}_{4D},\ \mathbf{K}_{Wm} = \mathbf{K}_{WD}. \tag{17}$$

Then, after transformations (16) and (17), conditions of qualification of the reactor operation strategy on nominal power increase:

$$\frac{G \Delta i_b}{C_{Fm} M_{Fm} T_{F0m}} = \frac{N_D}{C_{FD} M_{FD} T_{F0D}}; \tag{18}$$

$$\frac{T_{F0m} - T_{W0m}}{C_{Fm} M_{Fm} T_{F0m} R_{Tm}} = \frac{T_{F0D} - T_{W0D}}{C_{FD} M_{FD} T_{F0D} R_{TD}}; \tag{19}$$

$$\frac{T_{F0m} - T_{W0m}}{C_{Wm} M_{Wm} T_{W0m} R_{Tm}} = \frac{T_{F0D} - T_{W0D}}{C_{WD} M_{WD} T_{W0D} R_{TD}}; \tag{20}$$

$$\frac{T_{W0m} - T_{\text{in}m}}{C_{Wm} M_{Wm} T_{W0m}} = \frac{T_{W0D} - T_{\text{in}D}}{C_{WD} M_{WD} T_{W0D}}; \tag{21}$$

$$\frac{G \Delta i_b}{F_W T_{F0m}} (R_{Tm} + \alpha^{-1}) + \frac{T_{\text{in}m}}{T_{F0m}} = \frac{N_D}{F_W T_{F0W}} (R_{TD} + \alpha^{-1}) + \frac{T_{\text{in}m}}{T_{F0m}}; \tag{22}$$

$$\frac{G \Delta i_b}{\alpha F_W T_{W0m}} + \frac{T_{\text{in}m}}{T_{W0m}} = \frac{N_D}{\alpha F_W T_{F0m}} + \frac{T_{\text{in}m}}{T_{W0m}}. \tag{23}$$

Analysis of qualification results

1. Based on the defined criteria of thermodynamic similarity (12) – (15) in the MDA process, the conditions for successful qualification of strategies nominal power increase (16) – (23) with the maximum permissible thermal power of the reactor, corresponding to the beginning of intensification of surface boiling of the coolant at the outlet of the core, are established for the modernized and qualified design conservative modes of reactor operation (the necessary conditions for the occurrence of thermoacoustic instability of the coolant).

Qualification conditions of strategies nominal power increase (16) – (23) can be provided by complex modernization:

– thermophysical properties of nuclear fuel and fuel cladding (parameters of thermal conductivity and heat capacity);

– structural and technical parameters of fuel elements (thermal resistance, dimensions and weight of fuel matrix and fuel element shells).

2. Unlike known approaches, the developed criterion method determines the comprehensive modernization of the thermophysical properties of nuclear fuel/fuel element cladding, structural and technical parameters of fuel elements to ensure the maximum permissible safety conditions of the reactor nominal power increase and the depth of nuclear fuel burnup, and does not require numerous repeated calculation simulations of the DC for qualification, the results of which may significantly depend on the negative effects of the difference between the DC/DC users.

Conclusions

1. The analysis of known approaches to substantiation (qualification) of strategies for operation of VVER/PWR nuclear reactors at increased nominal power is presented. It has been determined that the main disadvantages of the known approaches of qualification of modernization of the core of a nuclear reactor are the dependence of qualification results on the methods of implementation of the strategy of operation of nuclear power plants in modes of increased nominal power, as well as on the effects of difference of deterministic codes and/or user codes, which ultimately complicates the objective interpretation of qualification results.

2. A criteria method of qualification of the strategy of operation of nuclear reactors at increased nominal power has been developed on the basis of modernization of thermophysical properties of nuclear fuel and structural and technical parameters of fuel elements, which excludes the effect of effects of difference in deterministic codes and/or user codes and takes into account the conditions for ensuring safety for maximum permissible temperatures of fuel elements and nuclear fuel shells.

Література

1. Вєрінов О. Стратегії випробувань систем, важливих для безпеки ЯЕУ. LAP LAMBERT Academic Publishing, 2024. 47 с. ISBN 978-620-7-63924-3.
2. Підвищення безпеки ядерної енергетики з урахуванням уроків важких аварій / Кондратюк В. А., та ін. *Ядерна та радіаційна безпека*. 2022. № 3. С. 76–81. DOI: https://doi.org/10.32918/nrs.2022.3(95).08.
3. Analysis and generalization of the experimental data on heat transfer in the staggered bundles of the flat-oval pipes / Kondratiuk V., Terekh A., Rogachov V., Baranyuk A., Rudenko A. *International Journal of Energy for a Clean Environment*. 2017. Vol. 3 (18). P. 189–202. DOI: 10.1615/InterJEnerCleanEnv.2017021912.
4. Вєрінов О., Канівець А., Вербило І. Оптимізація періодичності планових ремонтів активних систем безпеки ядерних енергоустановок.*IX Int. Scientific and Practical Conf. «Promising Ways of Information Technology Development»*, Bilbao, Spain. 2023. P. 360–364. ISBN 9-789-46485-378-0.
5. Vierinov O., Kanivets A., Hayo H. Optimization of metal control frequency of safety related systems of nuclear power plants.*VII Int. Scientific and Practical Conf. «Problematic Questions of Science and Problems of Development»*, Berlin, Germany. 2023. P. 315–319. ISBN 9-789-46485-372-8.
6. Вєрінов О. М. Планування технічного обслуговування систем атомних електростанцій. LAP LAMBERT Academic Publishing, 2022. 200 с. ISBN 978-620-4-74932-7.
7. Qualification method for active safety system modernizations to prevent hydrodynamic instability/ Vierinov O., Kondratiuk V., Kosenko S., Alali M., Algerby R.K.A. *XXXI Int. Scientific and Practical Conf. «Modern innovations and promising ways of development of culture and science»*, Boston, USA. 2022. P. 242–243. DOI: 10.46299/ISG.2022.1.31.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

8. Вєрінов О., Канівець А., Вербило І. Оптимізація планових ремонтів обладнання ядерних енергоустановок. *VIIIInt. Scientific and Practical Conf. «Modern Technologies of Human Development»*,Bordeaux, France.2023. P. 308–314. ISBN 9-789-46485-377-3.
9. Filonova Y., Dubyk Y., Filonov V., Kondratjuk V. Improved computational fluid dynamics framework for reactor core baffle swelling assessment. *Journal of Nuclear Engineering and Radiation Science*. 2021. Vol. 1(7). DOI: https://doi.org/10.1115/1.4047495.
10. Kondratyk V., Komarov Ju., Kosenko S., Fedorov D. Prevention of hydrodynamic instability conditions in safety systems with pumps of nuclear power plants. *Proceeding of Odessa Polytechnic University*. 2022. Vol. 1(65). P. 70–75. DOI: 10.15276/opu.1.65.2022.08.

References

1. Vierinov, O. (2024). *Strategies for testing safety-related systems of nuclear power facilities*. LAP LAMBERT Academic Publishing, 47 p. ISBN 978-620-7-63924-3.
2. Kondratyuk, V., Pysmennyy, Y., Verinov, O., Filatov, V., & Ostapenko, I. (2022). Improvement of nuclear safety taking into account the lessons learned from severe accidents. *Nuclear and Radiation Safety*, 3, 76–81. DOI: 10.32918/nrs.2022.3(95).08.
3. Kondratiuk, V., Terekh, A., Rogachov, V., Baranyuk, A., & Rudenko, A. (2017). Analysis and generalization of the experimental data on heat transfer in the staggered bundles of the flat-oval pipes. *International Journal of Energy for a Clean Environment*, 3(18), 189–202. DOI: 10.1615/InterJEnerCleanEnv.2017021912.
4. Vierinov, O., Kanivets, A., & Verbylo, I. (2023). Optimization of the frequency of scheduled repairs of active safety systems of nuclear power facilities. *IX Int. Scientific and Practical Conf. «Promising Ways of Information Technology Development»*, Bilbao, Spain, 360–364. ISBN 9-789-46485-378-0.
5. Vierinov, O., Kanivets, A., & Hayo, H. (2023). Optimization of metal control frequency of safety related systems of nuclear power plants. *VII Int. Scientific and Practical Conf. «Problematic Questions of Science and Problems of Development»*, Berlin, Germany, 315–319. ISBN 9-789-46485-372-8.
6. Vierinov, O. (2022). *Nuclear power plant systems maintenance scheduling*. LAP LAMBERT Academic Publishing, 200 p. ISBN 978-620-4-74932-7.
7. Vierinov, O., Kondratiuk, V., Kosenko, S., Alali, M., & Algerby, R.K.A. (2022). Qualification method for active safety system modernizations to prevent hydrodynamic instability. *XXXI Int. Scientific and Practical Conf. «Modern innovations and promising ways of development of culture and science»*, Boston, USA, 242–243. DOI: 10.46299/ISG.2022.1.31.
8. Vierinov, O., Kanivets, A., & Verbylo, I. (2023). Optimization of scheduled repairs of nuclear power facility equipment. *VIII Int. Scientific and Practical Conf. «Modern Technologies of Human Development»*, Bordeaux, France, 308–314. ISBN 9-789-46485-377-3.
9. Filonova, Y., Dubyk, Y., Filonov, V., & Kondratjuk, V.(2021). Improved computational fluid dynamics framework for reactor core baffle swelling assessment. *Journal of Nuclear Engineering and Radiation Science*, 1(7), 3–7. DOI: https://doi.org/10.1115/1.4047495.
10. Kondratyk, V., Komarov, Ju., Kosenko, S., & Fedorov, D. (2022). Prevention of hydrodynamic instability conditions in safety systems with pumps of nuclear power plants. *Proceeding of Odessa Polytechnic University*, 1(65), 70–75. DOI: 10.15276/opu.1.65.2022.08.

Скалозубов Володимир Іванович; Volodymyr Skalozubov, ORCID: https://orcid.org/0000-0003-2361-223X
Кацарський Юрій Сергійович; Iurii Katsarskyi, ORCID: https://orcid.org/0009-0001-9932-2880
Комаров Юрій Олексійович; Iurii Komarov, ORCID: https://orcid.org/0000-0002-4696-6551
Мазур Євгеній Олександрович; Yevhenii Mazur, ORCID: https://orcid.org/0009-0005-0936-4411
Кочнєва Валерія Юріївна; Valeriia Kochnieva, ORCID: https://orcid.org/0000-0001-7397-3573

Received November 01, 2024

Accepted December 15, 2024