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EFFECTS OF ACCIDENT-TOLERANT NUCLEAR FUEL ON NPP ECONOMIC PARAMETERS

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One of the relevant factors when increasing the competitiveness of water-cooled reactors is the introduction of accident-tolerant fuel to significantly reduce economic risks during NPP operation. The present study aims to develop a methodology for assessing the impact of this fuel on NPP competitiveness criteria. The main attention is paid to the assessment of the maximum permissible increase in production costs – the manufacture of fuel assemblies, ensuring the preservation or reduction of the fuel component in the cost of NPP electricity. A new condition for the competitiveness of accident-tolerant fuel, indicating the possibility of increasing the costs of its production by a half compared to the conventional fuel, was formulated.

Due to increased competition for energy sources, exhaustion of conventional hydrocarbon resources, and preferential investments in renewable energy, the question of nuclear power competitiveness becomes more acute. When aiming to increase the competitiveness of the most commonly used water-cooled reactors, a major factor is the development of accident-tolerant fuel, which is based on the elimination of the vapor–zirconium reaction to achieve a significant reduction in economic risks during the operation of a nuclear power plant (NPP) [1–4]. It is possible to eliminate the vapor–zirconium reaction by applying protective coatings on the zirconium fuel rod cladding or using new fuel rod cladding and fuel matrix materials having a higher density and thermal conductivity. Leading nuclear fuel manufacturers play a key role in this research process (Table 1). In Russia, the second cycle of operation with accident-tolerant fuel rods, previously tested in the MIR research reactor of the Research Institute of Atomic Reactors (SSC RIAR), commenced at the Power Unit 2 of the Rostov NPP [1–5].

The introduction of accident-tolerant fuel into light-water reactors is associated with a change in the technology of fuel rods, FAs, and core, as well as the physics of the reactor, which will entail a change in economic indicators and the competitiveness of nuclear power plants [4].

The present study is aimed at the creation of an analytical methodology for assessing the effect of accident-tolerant fuel on the competitiveness of NPPs. Here, the main focus is on an assessment of the maximum permissible increase in fuel production costs to preserve or reduce the current contribution of the fuel component in the cost of electricity produced by NPPs.

Economic effects of accident-tolerant fuel. The cost impacts of using such fuels at operating NPPs can be divided into direct and indirect, as well as current and prospective, effects. Direct effects are associated with the costs of changing the production technology, extending the fuel campaign by increasing the density and/or enrichment of uranium above 5%, which increases burnup. An increase in enrichment of more than 5%, which is possible for conventional uranium dioxide fuel with zirconium claddings, leads to additional costs in obtaining the necessary permissions from the national regulatory organization, updating the licenses of enrichment, production, and transport companies to work with an increased level of the product enrichment, etc. Since the cost of producing FAs with increased enrichment can increase the cost of conventional fuel, the transition to the enrichment of more than 5% is economically feasible, when an integral economic effect is achieved by a fuel that is additionally tolerant to accidents.

The indirect (prospective) economic effects of the fuel include:

– reduced costs of individual stationary equipment – engineering safety barriers, e.g., hydrogen removal system, molten core catcher, emergency diesel generators, etc.;

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TABLE 1. Areas of Research on Accident-Tolerant Fuel and Key Participating Organizations

Research areas	Program guidance	Organizations engaged in the certain R&D areas	Reactor studies
New materials of fuel rod claddings			
New coatings of zirconium fuel rod claddings	TVEL (Russia), Westinghouse Electric (USA), Atomic Energy Commission, Framatome, Electricité de France (France), KEPCO, KAERI (South Korea)	VNIINM (Russia), BNL, University of Wisconsin (USA), Karlsruhe Institute of Technology (Germany)	SSC RIAR (Russia), INL, ORNL, MIT (USA), Halden Project (Norway)
Iron–chromium–aluminum alloy (FeCrAl)	GE/GNF (USA), MEXT (Japan), KEPCO, KAERI (South Korea)	GNF, ORNL, BNL (USA)	ORNL, University of Michigan (USA), Halden Project (Norway)
Ceramic fuel rod claddings (SiC)	TVEL (Russia), Westinghouse Electric (USA), Framatome (France), Toshiba (Japan), KEPCO, KAERI (South Korea)	Karlsruhe Institute of Technology (Germany), Paul Scherrer Institute (Switzerland), General Atomik, PNNL, United Technologies Research Center (USA)	–
42KhNM alloy	TVEL (Russia)	VNIINM (Russia)	SSC RIAR (Russia)
New composition of nuclear fuel			
Doped uranium oxide	Westinghouse Electric (USA), Atomic Energy Commission, Framatome, Electricité de France (France), KEPCO, KAERI (South Korea)	ORNL, University of Florida (USA)	INL, ORNL (USA), Halden Project (Norway)
Uranium–molybdenum	TVEL (Russia)	VNIINM (Russia)	SSC RIAR (Russia)
Uranium silicide	TVEL (Russia), Westinghouse Electric (USA)	VNIINM (Russia), LANL, NNL, BNL (USA)	SSC RIAR (Russia), INL, MIT (USA)
Uranium nitride	Westinghouse Electric (USA), Atomic Energy Commission, Framatome, Electricité de France (France)	–	INL (USA)

– reduced insurance deductions due to the reduced risks of emergency situations in connection with the exclusion of a vapor–zirconium reaction;

– change in the market positions of fuel companies in connection with the advance (delay) of entering the FA world market, etc.

Thus, for new NPP projects with accident-tolerant fuel, economic benefits are possible due to a design that takes new safety parameters into account. Up to 40% of contemporary NPP capital expenditures are spent on safety systems. Therefore, a simplification of their design can have a significant economic effect, which will result in a reduced unit capital costs and the cost of electricity, as well as in an increase in the competitiveness of NPPs over other energy sources [6]. A direct effect of introducing this fuel on the economic indicators of the fuel cycle will be manifested at the first stages.

Criteria for the competitiveness of energy technologies and nuclear fuel. One of the most common criteria for the competitiveness of power generating plants is the levelized cost of electricity (LCOE), typically measured in RUB/(MWh) [7]. The LCOE expression, arising mathematically from the definition of the main investment efficiency criterion – net present value (NPV), integrated for the convenience of NPP project variable assessments, has the form [8, 9]

$$\mathrm{LCOE} = (AK + Y)/E, \quad (1)$$

where A – effective depreciation rate of capital expenditures, which depends on the discount rate of cash flows, 1/yr or %/yr; K – total capital costs for the NPP design and construction, RUB; Y – average annual total operating costs, RUB/yr; E – average annual amount of sold electricity, MWh/yr.

Expression (1) typically refers to the steady-state mode of the reactor operation with a constant level of electricity production E and operating costs Y. Ratio Y/E represents the operational component of the electricity cost. Operating costs consist of the fuel component Y_F, including the costs of the nuclear fuel cycle (NFC): FA production and spent nuclear fuel management:

$$Y_F = (C_{FA} + C_{SNF})P = C_{NFC}P, \quad (2)$$

where $C_{NFC} = C_{FA} + C_{SNF}$ – cost of the NFC (open or closed) per 1 kg of uranium or heavy metals in the fuel, RUB/kg of heavy metals, including the cost of the spent fuel management C_{SNF} and the FA cost $C_{FA} = C_x + C_\Phi$; C_x, C_Φ – cost of enriched uranium and the FA production; P – average annual reactor fuel requirement, kg/yr, determined by the ratio of the average annual thermal power of the reactor Q·ICUF (MW) to the average depth of the fuel burnup B (MWd/kg):

$$P = 365Q\cdot\text{ICUF}/B = E/(24\eta B). \quad (3)$$

Here, ICUF – reactor installed capacity utilization factor (usually ICUF ≤ 92%); $E = W\Delta t$ICUF – average annual amount of the sold electricity, MWh; W – installed electric power of the power unit, MW; Δt = 8760 h/yr; $Q = W/\eta$ – installed thermal power of the reactor at a gross efficiency η.

In Eq. (3), the numerical coefficients 365 and 24 take into account the number of days in the year and hours in the day in accordance with the generally accepted dimension of initial values. Thus, for contemporary PWR reactors with typical parameters W = 1200 MW, η = 34%, V = 55 MWd/kg, ICUF = 0.85, the fuel requirement is P ~ 20 t/yr.

The production of the fuel with the mass P and enrichment x requires the mass of natural uranium F and the work for separating uranium isotopes R (SWU/yr), determined by expressions [10, 11]

$$F = P(x - y)/(c - y); \quad R = P\Phi(x) + D\Phi(y) - F\Phi(c);$$

$$\Phi(z) = (1 - 2z)\ln[(1 - z)/z]; \quad z = x, y, c,$$

where $D = F - P$ – mass of waste uranium with ^{235}U enrichment of y; c = 0.711 wt% – concentration of ^{235}U in natural uranium; $\Phi(z)$ – separation potential.

As a result, for the FA cost per 1 kg of heavy metals, including the cost of purchasing natural U_3O_8 and its conversion into uranium hexafluoride, uranium isotope separation, disposal of the wastes, and manufacture of fuel assemblies, we obtain the expression

$$C_{FA} = \frac{x-y}{c-y}C_F + \left[\Phi(x) + \frac{x-c}{c-y}\Phi(y) - \frac{x-y}{c-y}\Phi(c)\right]C_R + \frac{x-c}{c-y}C_D + C_\Phi, \quad (4)$$

where $C_F = C_{U_3O_8} + C_{UF_6}$ – cost of natural uranium hexafluoride; $C_{U_3O_8}$, C_{UF_6}, C_D – price of natural uranium in the form of U_3O_8, conversion of U_3O_8 into hexafluoride, and utilization of depleted uranium hexafluoride (dump) per 1 kg of metallic uranium, RUB/kg; C_R – price of the separation work, RUB/SWU.

According to Eq. (4), at a given fuel enrichment of x and certain prices, the FA net cost depends only on the depth of the separation dump y. Moreover, the FA net cost is minimal at an optimal depth of the dump y_0. The value of y_0 depends only on the price ratio $(C_F + C_D)/C_R$ [10, 11]. At $(C_F + C_D)/C_R = 1$, we have y_0 = 0.228%, while at $(C_F + C_D)/C_R > 1$, it is advantageous to reduce the amount of used natural uranium; therefore, y_0 < 0.228%. Since at $(C_F + C_D)/C_R < 1$, it is advantageous to reduce the amount of the separation work, y_0 > 0.228%. Thus, according to [12], over the past 5 years, market quotations for natural uranium in the form of hexafluoride are approximately twice as high as quotations for the separation work, reducing the optimal dump depth to y_0 = 0.16–0.19%.

Along with the LCOE, the competitiveness criteria include the internal rate of return, which limits the discount rate and the discounted payback period, not considered here [8, 11].

Price characteristics of uranium fuel. Market prices for natural uranium, as well as conversion and enrichment services, are significantly dependent on market conditions and the overall situation on the global energy market. According to [12], in 2011, the market prices for uranium and its enrichment were at their historical peaks: $C_{U_3O_8}$ = 148 a.u./kg, C_R = = 149 a.u./SWU (Table 2). After the accident at the Fukushima NPP (Japan), there was a long-term decline in market prices, which reached a minimum in 2017–2018: $C_{U_3O_8}$ = 57 a.u./kg, C_R = 36 a.u./SWU (see Table 2, Fig. 1). The transition of French and American enrichment plants in 2011–2013 from gaseous diffusion to gas centrifuge uranium enrichment technology significantly reduced the costs and market price of the separation work.

TABLE 2. Market Prices for Natural Uranium, Uranium Conversion and Enrichment Services, and Estimated Economic Parameters of the Fuel Cycle [12]

Parameter	2011	2013	2015	2017	2018	2019	2020	2021
Price, a.u./kg:								
uranium	148	99	94	57	65	68	75	91
conversion	11	10	7.6	5.5	10	18	21	19
hexafluoride uranium	159	109	102	63	75	86	96	110
separation work, a.u./SWU	149	109	70	43	36	45	49	55
Optimal dump depth, %	0.22	0.229	0.189	0.189	0.155	0.163	0.16	0.158
Net cost of enriched uranium, a.u./kg*	2772	1955	1552	958	1002	1182	1317	1496
FA manufacturing price, a.u./kg**	350	350	350	350	350	350	350	350
Net cost of FA, a.u./kg	3122	2305	1902	1308	1352	1532	1667	1846
Price of the spent fuel management, a.u./kg of heavy metals**	800	800	800	800	800	800	800	800
Net cost of NFC, a.u./kg of heavy metals	3922	3105	2702	2108	2152	2332	2467	2646
NPP average annual fuel costs, million a.u./yr**	78	62	54	42	43	47	49	53
Fuel component of the electricity cost $LCOE_F$, a.u./MWh***	8.8	7	6.1	4.7	4.8	5.2	5.5	5.9

* At the enrichment $x = 4.95\%$ and the optimum dump depth. ** $C_Ф = 350$ a.u./kg, $C_{SNF} = 800$ a.u./kg of heavy metals are taken unchanged due to the lack of market quotations and the data scattering. *** For an 1200 MW power unit with an average annual electricity production of 8.9 TWh/yr and an average annual fuel requirement of 20 tons/yr with $x = 4.95\%$ enrichment.

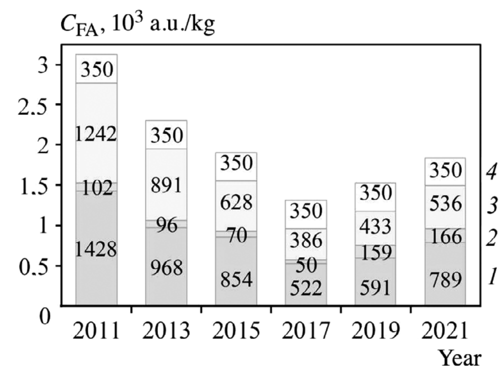

Fig. 1. Contribution of natural uranium (*1*), services for the conversion (*2*) and enrichment (*3*) of uranium, and FA manufacture (*4*) to the cost of 1 kg of nuclear fuel [12].

The cost of FA manufacture, spent fuel management, and disposal of uranium hexafluoride, which is less determined by market conditions due to the lack of a unified market-forming product, can vary in the range of $C_Ф = 250–400$ a.u./kg, $C_{SNF} = 600–2000$ a.u./kg of heavy metals, $C_D = 7–10$ a.u./kg, depending on the manufacturer.

As follows from Table 2 and Fig. 1, the FA net cost per 1 kg of uranium in fuel, which is calculated according to Eq. (4), at the enrichment of the conventional fuel of $x = 4.95\%$ varied similar to its components several times in the period of 2011–2021 due an initial decrease and subsequent increase in market prices for natural uranium, as well as conversion and enrichment services. However, at a time when market prices for natural uranium and separation work were minimal, the cost proportion of FA manufacture increased from 11% in 2011 to 27% in 2017. Nevertheless, the contribution of the uranium FA manufacture cost to the annual fuel costs of NPPs does not exceed 13% at the cost of the spent fuel management not less than 800 a.u./kg of heavy metals. If assuming a doubling of the accident-resistant fuel manufacture cost as compared to the conventional fuel at unchanged prices in 2021, then the increase in the FA net cost and the fuel costs of NPPs will be less than 19 and

13%, respectively. Let us note that the cost of the spent fuel management C_{SNF} = 800 a.u./kg of heavy metals is used in calculations as a variable parameter for approximating the costs of transportation, temporary storage, and processing at a radiochemical enterprise. An assessment of the costs of the spent accident-tolerant fuel management requires an additional study.

Effects of accident-tolerant fuel on the fuel component of the electricity cost. Let us consider the contribution of each parameter to expression (1) for estimating the NPP levelized cost of electricity. Almost every engineering and economic parameter of the power unit with this fuel Z_F may differ from the similar parameters of the power unit with conventional fuel Z by ΔZ: $Z_F = Z + \Delta Z$. When using the accident-tolerant fuel, the relative variation in the parameter Z will be further denoted by $\delta_Z = \Delta Z/Z$. The variation in any parameter ΔZ can be either positive – $\Delta Z > 0$ or negative – $\Delta Z < 0$. Thus, at a given installed capacity, the variation in the power unit's requirement for accident-tolerant fuel ΔP according to expression (3) is associated with a variation in the electricity production ΔE due to a variation in ICUF and burnup ΔB:

$$P_F = P + \Delta P = (E + \Delta E)/[24\eta(B + \Delta B)]; \quad \delta_P = \Delta P/P = (\delta_E - \delta_B)/(1 + \delta_B).$$

If a relative increase in the burnup ($\delta_B > 0$) due to the growth of the ICUF exceeds the relative increase in the amount of the sold electricity δ_E when replacing the conventional fuel with an accident-tolerant equivalent, then the reactor fuel requirement decreases $\delta_P < 0$. For example, an increase in the burnup from 55 to 70 MWd/kg (δ_B = 27%) and ICUF from 0.85 to 0.9 (δ_E = 5.9%) results in a 17% reduction in the accident-tolerant fuel requirement as compared to the conventional fuel.

Similarly, Eqs. (1), (2) can be used to estimate the relative change in the fuel component of the electricity cost:

$$\delta_{LCOE} = \Delta(LCOE_F)/LCOE_F = (\delta_{NFC} - \delta_B)/(1 + \delta_B), \tag{5}$$

where $\delta_{NFC} = (\Delta C_x + \Delta C_\Phi + \Delta C_{SNF})/C_{NFC}$.

When using accident-tolerant fuel, the relative change in the cost of the fuel cycle δ_{NFC} according to Eq. (5) should not exceed the relative increase in the fuel burnup provided that the fuel component of the electricity cost does not exceed that for the conventional fuel ($\delta_{LCOE} \le 0$). In other words, the condition $\delta_{NFC} \le \delta_B$, which can be referred to as a condition for the competitiveness of accident-tolerant fuel, must be met. Hence the conclusion: if the burnup of the accident-tolerant fuel remains constant in comparison with the conventional one ($\delta_B = 0$), then it is unlikely to provide the condition $\delta_{NFC} \le 0$, i.e., to reduce costs for all NFC stages. In particular, if the production of the considered fuel only applies protective coatings on FA zirconium claddings to prevent a vapor–zirconium reaction and the remaining FA parameters are constant, then $\Delta B = 0$ and $\Delta C_x = \Delta C_{SNF} = 0$. In this case, $\delta_{LCOE} = \Delta C_\Phi/C_{NFC} > 0$, i.e., the fuel component of the electricity cost will increase due to the increase in the cost of FA manufacturing. According to [13], the cost of manufacturing uranium FAs by 50% consists of the cost of materials and the manufacture of FA claddings. The doubling of the FA cladding manufacturing cost due to the application of protective coatings will lead to a relative increase in the fuel component of the electricity cost by no more than $0.5C_\Phi/C_{NFC}$ ~7% (in 2021 prices), which is significantly less than the variations due to fluctuations in market prices for natural uranium, conversion, and separation work (see Table 2, Fig. 1).

If other materials of the fuel matrix and cladding are used in the production of accident-tolerant fuel instead of conventional uranium and zirconium dioxide, then all variations in the parameters of Eq. (5) are non-zero. In this case, it is more convenient to present the competitiveness condition of accident-tolerant fuel $\delta_{NFC} \le \delta_B$ in the form

$$\Delta C_\Phi \le (\Delta B/B)C_{NFC} - \Delta C_x - \Delta C_{SNF}, \tag{6}$$

where C_{NFC} and B are the characteristics of the conventional NFC, with which the considered cycle with accident-tolerant fuel is compared.

The right part of expression (6) represents the upper limit of the variations in the cost of the fuel manufacturing, at which the fuel component of the electricity cost is the same when using the conventional fuel. If the right part of expression (6) is negative, then an FA made of accident-tolerant fuel should be cheaper than a conventional FA, which is unlikely. In order to make the right part of (6) positive, which permitsBatt an increase in the cost of manufacturing FAs with accident-tolerant fuel, it is necessary to achieve an increase in the first term of the right part of (6), i.e., an increase in the fuel burnup ($\Delta B > 0$), which is typically achieved by increasing the enrichment of the fuel and the cost of enriched uranium ($\Delta C_x > 0$).

Since, for the most common open NFC of thermal reactors, the spent nuclear fuel management costs of both conventional and the considered fuel appear to be negligible, $\Delta C_{SNF} = 0$ can be taken as a first approximation. If we consider the

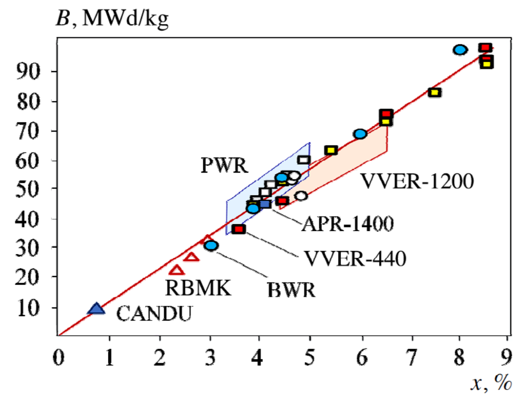

Fig. 2. Relationship between the enrichment and the average burnup of uranium fuel in thermal reactors – a direct approximation in the form of $B = 11.6x$.

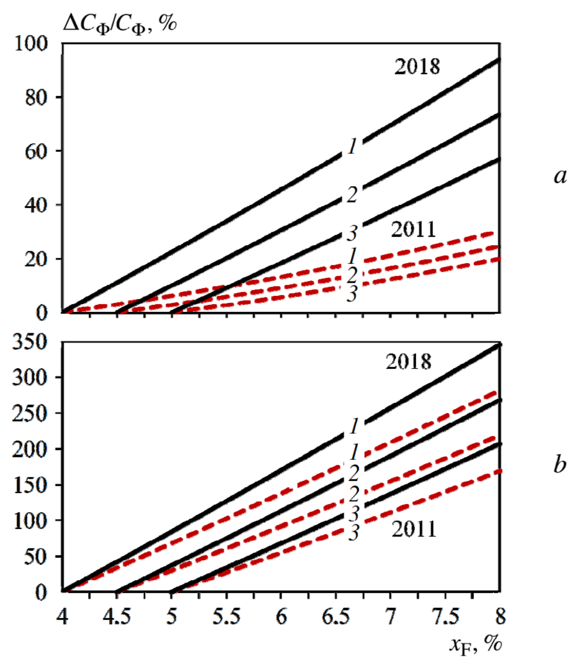

Fig. 3. Effect of the accident-tolerant fuel enrichment (x_F = 4–8.5%) on the permissible increase in the relative cost of the FA manufacture ($\Delta C_\Phi/C_\Phi$, %) at a constant fuel component of the electricity cost for the maximum (2011) and minimum (2018) market prices for natural uranium, as well as its conversion and separation work, calculated according to formula (6) under the following parameters of the initial conventional fuel: burnup B = 55 MWd/kg; enrichment x = 4 (*1*), 4.5 (*2*), 5% (*3*); FA manufacture cost C_Φ = 350 a.u./kg; spent fuel management cost C_{SNF} = 0 (*a*) и 800 a.u./kg of heavy metals (*b*) according to Table 2.

popular balanced, closed NFC type, which provides for the reprocessing of the spent fuel for the production of a mixed fuel based on regenerated uranium or mixed uranium-plutonium fuel, then $\Delta C_{SNF} \neq 0$ is possible, since the unconventional composition of the fuel may require a significant modernization of the spent fuel reprocessing technology [12, 14, 15].

Maximum permissible cost of manufacturing accident-tolerant fuel. As follows from the above data, in order to quantify the fulfillment of the competitiveness condition (6) and thereby the possibility of reducing the fuel component of the electricity cost for the NPP, operating with accident-tolerant fuel, it is necessary to determine the relationship between its burnup and enrichment. This relationship depends on many parameters, including the fuel campaign, the number of reloaded FAs, etc. [16–18].

For the assessing the competitiveness, the results, shown in Fig. 2, can be used, according to which the relationship between the fuel enrichment and its burnup is described by the approximating linear function $B \sim 11.6x$ in the burnup range of

0–80 MWd/kg and more. In this case, the relative variation in the burnup is equal to the relative variation in the fuel enrichment ($\Delta B/B = \Delta x/x$).

The permissible increase in the cost of manufacturing accident-tolerant fuel is shown in Fig. 3 for two options – with the cost of the spent fuel management equal to zero and 800 a.u./kg of heavy metals. In both cases, $\Delta C_{SNF} = 0$. The cost of enriched uranium was determined for high market prices, observed in 2011, and for low prices in 2018, at an optimal dump depth of 0.22 and 0.155%, respectively.

If the NFC cost includes high costs for the spent nuclear fuel management, it becomes permissible to increase the cost of the fuel manufacture by 1.5–2.5 times without changing the fuel component of the electricity cost (see Fig. 3*b*). This is due to a decrease in the contribution of the enriched uranium incremental cost ΔC_x, which increases at the growing NFC cost C_{NFC}. From Fig. 3 it also follows that an increase in the enrichment of accident-tolerant fuel above the conventional 4–5% makes it possible to compensate for a part of the FA manufacture cost by increasing the burnup and, correspondingly, reducing the average annual requirement for it.

An increase in market prices for uranium and separation work, along with an increase in the cost of enrichment, leads to an increase in the cost of enriched uranium and a decrease in the permissible margin in the cost of manufacturing fuel assemblies. Therefore, the greater the difference between the enrichment of accident-tolerant fuel and conventional fuel, the higher the permissible margin for the cost of the FA production (see Fig. 3).

Conclusion. The presented assessment of the competitiveness criteria for NPPs with accident-tolerant fuel forms a basis for determining the maximum permissible increase in the cost of its production without increasing the fuel component of the NPP electricity cost as compared to the conventional NFC. The formulated new condition of competitiveness $\delta_{NFC} \leq \delta_B$ means that, in order to maintain the constant fuel component of the NPP electricity cost, it is necessary to increase the fuel burnup as compared to the conventional one. Moreover, the relative increase in fuel cycle costs, including the spent fuel management, should not exceed the relative increase in the burnup of accident-tolerant fuel.

Based on the typical maximum and minimum market prices for natural uranium for 2011–2021 and associated conversion and enrichment costs, savings in consumption will increase the cost of manufacturing fuel assemblies by up to 2 times at an increase in the enrichment of accident-tolerant fuel to 7% and consequent burnup to 65–75 MWd/kg without a negative effect for NPP operators depending on the cost of the spent fuel management. This means that the costs of the fuel development can be offset by a mark-up on manufacturing services, which will be painlessly accepted by the market. In other words, the development of accident-tolerant fuel is beneficial to all participants in the processes of the nuclear fuel production and consumption:

NPP operators have opportunities to improve operational safety along with direct and indirect positive economic effects;

– fuel producers can modernize production and obtain a more significant market share by offering innovative products;

– uranium enrichment companies acquire an additional demand for their services; uranium production and conversion companies acquire a deferred demand due to the effect of accident-tolerant fuel on the safe and stable development of nuclear energy.

REFERENCES

1. *Increased Accident Tolerance of Fuels for Light Water Reactors*, Workshop Proc. OECD/NEA, France, (2013).
2. *State-of-the-Art Report on Light Water Reactor AccidentTolerant Fuels*, OECD/NEA, (2018).
3. Zh. Bin, G. Pengcheng, X. Tao, et al., "Performance evaluation of accident tolerant fuel under station blackout accident in PWR nuclear power plant by improved ISAA code," *Nucl. Engng Technol.*, **54**, No. 7, 2475–2490 (2022).
4. A. V. Kuryndin, A. M. Kirkin, A. Z. Karimov, and S. V. Makovskii, "On the approaches to regulating the safety of using the accident-tolerant nuclear fuel," *Yad. Rad. Bezopasn.*, No. 4(102), 14–23 (2021).
5. *Development of Light Water Reactor Fuels with Enhanced Accident Tolerance: Rep. to Congress*, United States Department of Energy, June 2015 [electronic resource].
6. A. A. Makarov, T. A. Mitrova, and V. A. Kulagin (eds.), *Forecast for the Development of Energy in the World and Russia 2019*, Energy Center of the Moscow School of Management Skolkovo, INEI RAN, Moscow (2019).

7. *Projected Costs of Generating Electricity. 2020 Ed.*, Paris, IEA, OECD-NEA (2020).
8. V. V. Kharitonov, N. V. Kosolapova, and Yu. A. Ul'yanin, "Forecasting the efficiency of investments in multi-unit power plants," *Vest. NIYaU MIFI*, **7**, No. 6, 545–562 (2018).
9. E. V. Semenov and V. V. Kharitonov, "Microeconomics of NPP safety improvement based on the accident-tolerant fuel," *Mikroeconomika*, No. 5(100), 49–62 (2021).
10. N. M. Sinev, *Economics of Nuclear Energy. Fundamentals of Technology and Economics of the Nuclear Fuel Production. NPP Economics: Textbook*, Energoatomizdat, Moscow (1987).
11. V. V. Kharitonov, *Dynamics of Nuclear Energy Development. Economic and Analytical Models*, NIYaU MIPhI, Moscow (2014).
12. *Annual Reports of the Rosatom State Corporation for 2018–2021* [electronic resource], https://report.rosatom.ru/53, acc. Feb. 20, 2023.
13. *Nuclear Fuel: from Ore to Disposal*, Scientific and Business Portal "Atomic Energy 2.0" [electronic resource], http://www.atomic-energy.ru/SMI/2017/03/15/73650, acc. Feb. 20, 2023.
14. *Balanced NFC*, Electronic Periodical ATOMINFO [electronic resource], http://www.atominfo.ru/newsz05/a0501.htm, acc. Feb. 20, 2023.
15. Yu. A. Ul'yanin and V. V. Kharitonov, "Economics of a balanced nuclear fuel cycle with innovative remix fuel," *Mikroeconomika*, No. 2, 55–63 (2021).
16. A. K. Gorokhov, Yu. G. Dragunov, G. L. Lunin, et al., *Justification of the Neutron-Physical And Radiation Sections of VVER Projects: Monograph*, IKTs Akademkniga, Moscow (2004).
17. *High Burnup Fuel: Implications and Operational Experience: Proc. Techn. Meeting*, Buenos Aires, Nov. 26–29, 2013, IAEA, Vienna (2016).
18. *Very High Burnups in Light Water Reactors*, Nucl. Sci. Publ. OECD-NEA (2006).