

Influence of the composition and burnup of accident-tolerant fuel on the fuel component of NPP electricity cost

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Abstract

This study evaluates the impact of accident-tolerant fuel compositions on the nuclear power plant (NPP) electricity cost associated with the fuel component across a broad spectrum of fuel cycle parameters. The cost of electricity is influenced by changes in burnup, fuel enrichment, thermal stress, reactor campaign, as well as market prices for natural uranium, its conversion, enrichment, fabrication of fuel assemblies, and the cost of spent fuel treatment. From derived analytical expressions that depict the relation between fuel burnup and various reactor operation parameters, grid diagrams were developed. By adhering to specified limitations on burnup and the fuel-related component of NPP electricity cost, these diagrams facilitate the selection of the fuel cycle.

Introduction

In addition to the new composition of a fuel pellet or fuel cladding, the development of accident-tolerant nuclear fuel involves variations in its enrichment, as well as an increase in the burnup and campaign of more than 60 MWd/kg and up to 24 months, respectively. A significant variation in the parameters of the fuel cycle requires the analysis of the economic consequences of its implementation. The present study aims to develop an analytical procedure for evaluating the effect of the accident-tolerant fuel composition on the fuel component of the electricity cost for VVER NPPs across a wide range of fuel cycle parameters, including burnup, enrichment, thermal stress, refueling frequency, reactor campaigns, as well as market prices for natural uranium, its conversion and enrichment, fabrication of fuel assemblies (FAs), and the cost of handling of spent fuel.

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Fuel component of the levelized NPP electricity cost

The methodology for calculating the fuel component of the NPP electricity cost [1–3] reflects the costs for the fabrication of FAs and spent nuclear fuel handling per unit of electricity sold, including discounting. According to the definition of the levelized cost of electricity [1, 3], the fuel component is estimated by the formula

$$\text{LCOE}_F = \frac{C_{\text{FA}} + C_{\text{SNF}}}{24\eta B}, \quad (1)$$

where $C_{\text{FA}} = C_x + C_{\text{FB}}$ —FA cost, including the cost of enriched uranium C_x and FA fabrication C_{FB} , rub./kg; C_{SNF} —cost of spent fuel handling, rub. per 1 kg of fresh uranium or per 1 kg HM of spent fuel; η —NPP net power efficiency factor; B —average fuel burnup, MWd/kg HM. The coefficient 24 takes into account the number of hours in a day in accordance with the generally accepted burnup dimension of MWd/kg.

The cost of enriched uranium includes the cost of purchasing U_3O_8 , its conversion to uranium hexafluoride, uranium enrichment and disposal of uranium tails:

$$C_x = C_F \frac{x-y}{c-y} + C_R \left[V(x) + V(y) \frac{x-c}{c-y} - V(c) \frac{x-y}{c-y} \right] + C_D \frac{x-c}{c-y}, \quad (2)$$

where C_F —price for natural uranium hexafluoride, rub./kg; C_R —price for the separation work, rub./SWU; C_D —price of utilizing depleted uranium hexafluoride (tails), rub./kg; $V(z) = (1-2z)\ln(1/z-1)$ —separation potential; $z = x, y, c$ —concentration of ^{235}U in the fuel (fuel enrichment), tails and natural uranium, respectively.

According to expression (2), the cost of enriched uranium depends only on the tails assay y at a given fuel enrichment and known prices. Moreover, the cost of enriched uranium is minimal at an tails assay y_0 . The value of y_0 depends only on the price ratio $(C_F + C_D) / C_R$ [10, 11]. At $(C_F + C_D) / C_R = 1$, $y_0 = 0.228\%$. Since at $(C_F + C_D) / C_R > 1$ it is advantageous to save natural uranium, $y_0 < 0.228\%$. However, at $(C_F + C_D) / C_R < 1$, it is advantageous to reduce the amount of the separation work; therefore, $y_0 > 0.228\%$. Prices in formulas (1) and (2), which are discounted due to the diversity of costs for all stages of the fuel cycle, take into account production losses [1].

The main problem of applying formulas (1) and (2) consists in the need to determine the relationship between enrichment, burnup, and the number of refuelings for various fuel compositions.

Relationship of the fuel composition and thermal stress

One of the critical core parameters with respect to its safety is the density of the thermal flux from the surface of fuel elements to the coolant q_F . In VVER reactors, surface-water boiling is allowed in the most thermally-stressed FAs while limiting the vapor content to 11%. The density of the thermal flux is limited by the reserve before the water boiling crisis in the most thermally-stressed FAs. Therefore, regardless of the fuel composition in the fuel elements, the density of the heat flux from the surface of fuel elements should remain constant to also maintain the surface temperature of the fuel cladding. The thermal stress of the fuel q , which is equal to the average thermal power of the fuel element per unit mass of fuel pellets in the fuel element, can be used in the calculations along with the surface density of the thermal flux, its linear q_l and volumetric q_v density,

Table 1 Properties of the accident-tolerant alternative to uranium dioxide fuel

Fuel	Density, g/cm ³		Melting point, °C	Thermal conductivity, W/(m · K)	Thermal stress*, kW/kg	
	Fuel	Uranium			Fuel	Uranium
U ₃ Si ₂	12.2	11.31	1665	16.3	29.8	32.2
U ₃ Si	15.4	14.8	985	20	23.6	24.6
UN	14.3	13.5	2850	20.9	25.4	27
UC	13.6	12.9	2507	20	26.7	28.2
UMo	17.4	16.7	1150	25	21	21.8
UO ₂	10.9	9.61	2840	4.6	33.5	37.9

*For a PWR reactor at $q_l = 165 \text{ W/cm}$, $q_F = 0.577 \text{ MW/m}^2$, $q_V = 0.254 \text{ GW/m}^3$, $d = 9.1 \text{ mm}$, $d_F = 7.6 \text{ mm}$

which are equal to the average thermal power of the fuel element per unit length and volume (typically per unit volume of the core), respectively. The listed values are interrelated by the following ratios:

$$q_l = q_F \pi d; q = \frac{q_F}{\rho} \frac{4d}{d_p^2} = \frac{q_V}{\rho} \left(\frac{d}{d_p} \right)^2, \tag{3}$$

where d , d_p —outer diameter of the fuel cladding and the fuel pellet, respectively, m; ρ —density of the fuel pellet material, kg/m³. For example, in VVER-1200 at an average fuel thermal stress of ~40 kW/kg, the maximum and average linear thermal flux is 420 and 165–187 W/cm, respectively.

As follows from the last relation (3), at a given geometry of fuel elements and the density of the thermal flux from their surface, a variation in the composition of the fuel pellet affects the thermal stress due to a variation in its density: the higher the density of the pellet material, the lower its thermal stress. In accordance with Table 1, the thermal stress of accident-tolerant fuel materials, alternative to uranium dioxide, ranges from 22 to 38 kW/kg at the same dimensions of fuel elements and the surface density of the thermal flux.

The greatest thermal stress is characteristic of the traditional uranium dioxide fuel, while the lowest figure pertains to an UMo metal alloy, for example, OM9AO with 9–10 wt% of molybdenum and a content of aluminum and tin equal to 0.1–0.15 wt%, and uranium monosilicide U₃Si. The alternative fuel has a thermal conductivity 3–5 times higher than uranium dioxide, which reduces the temperature drop in the fuel pellet by 3–5 times—and, accordingly, the heat stored in the fuel, which is important for improving the reactor safety [4–7].

Interrelation of thermal stress, composition, burnup, enrichment, and the number of refuelings

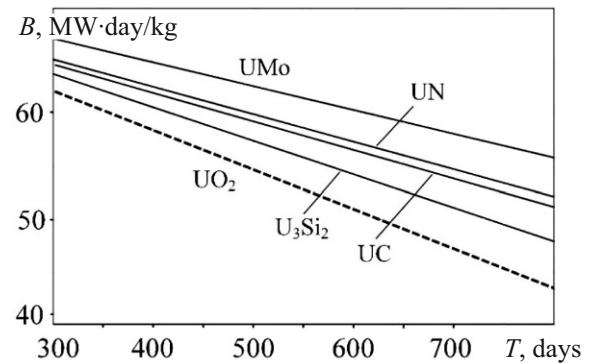
Fuel burnup is an important energy and economic characteristic, which affects the fuel demand, reactor campaign duration, spent fuel accumulation, FA fabrication cost, spent fuel management, and, ultimately, the fuel component of the LCOE [8, 9]. The relationship of the fuel burnup with its enrichment, thermal stress, campaign, the number of reloaded FAs, and other parameters of the core is determined on the basis of three-dimensional neutronic calculations for a particular reactor [10–16]. Alternative engineering and economic calculations of various fuel types require analytical relations and grid diagrams that are consistent with neutron-physical calculations at an acceptable accuracy. Let us present the derivation of such relations.

From the definition of the burnup as the amount of thermal energy released during the combustion of a unit mass fuel in the reactor [13, 17]

$$B = nqT, \tag{4}$$

where $n = N_c/N$ —number of refuelings; N_c —number of FAs in the core; N —number of reloaded FAs.

Fig. 1 Burnup of the fuel, alternative to uranium dioxide, on the reactor campaign at an enrichment of 4.95% and the thermal stress from Table 1 according to formula (11)



Light water reactors are typically designed for a uranium fuel burnup of 50–60 MWd/kg at an enrichment of up to 5% and thermal stress of uranium dioxide fuel of about 40kW/kg. In this case, according to expression (4), 30–50 FAs are extracted during refueling during the 12-month reactor campaign ($T \sim 330$ days); during the 24 months campaign ($T \sim 680$ days), more than 70 FAs are extracted (at $N_c = 163$).

The best refueling mode is the continuous makeup of the reactor using fresh fuel with the rearrangement of FAs over the entire volume of the core [13, 17]. At a number of refuelings n , the achieved burnup $B(n)$ is less than the best mode B_∞ according to the expression

$$B(n) = B_\infty n / (n + 1). \quad (5)$$

Typically, $n = 3-5$, so the burnup equals 75–83% of the optimal figure. Excluding n from formulas (4), (5), we obtain the dependence of the burnup on the thermal stress of the fuel and the duration of the campaign as a difference

$$B = B_\infty - qT. \quad (6)$$

The fuel burnup is associated with the mass of burnt (fissioned) nuclides (uranium and plutonium) in the unloaded fuel ΔM_f :

$$B = \frac{\Delta M_f E_f}{M_F m_f} = x \frac{\Delta M_f E_f}{M_5 m_f} = 9.7x \frac{\Delta M_f}{M_5}, \quad (7)$$

where $E_f/m_f \sim 970$ MWd/kg—average ratio of fission energy to the mass of fissile nuclei; M_T —mass of the unloaded (loaded) fuel; M_5 —mass of ^{235}U in the fresh fuel; $x = M_5/M_T$ —enrichment of the fresh fuel, loaded during refueling.

Comparing expressions (5), (7), we obtain a dimensionless ratio

$$\frac{\Delta M_f}{M_5} \frac{n + 1}{n} = \frac{B_\infty}{9.7x}, \quad (8)$$

which can be called the relative consumption of fissile nuclides (uranium and plutonium). The right part of expression (8), which by definition does not depend on the number of refuelings. As shown by the comparison of formulas (5) and (8), with the experimental and calculated burnup and enrichment of the PWR, BWR, and

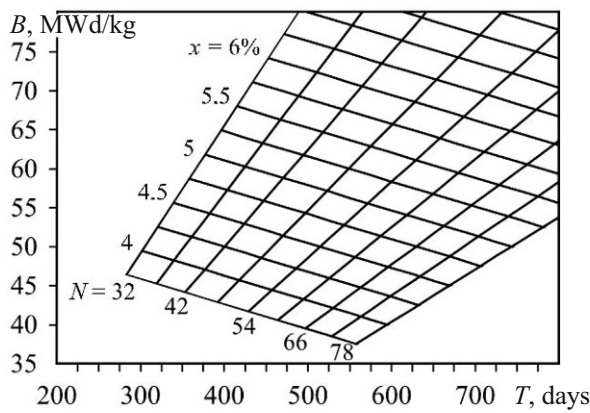


Fig. 2 U₃Si₂ fuel burnup at a thermal stress of 32 kW/kg and 163 FAs in the core

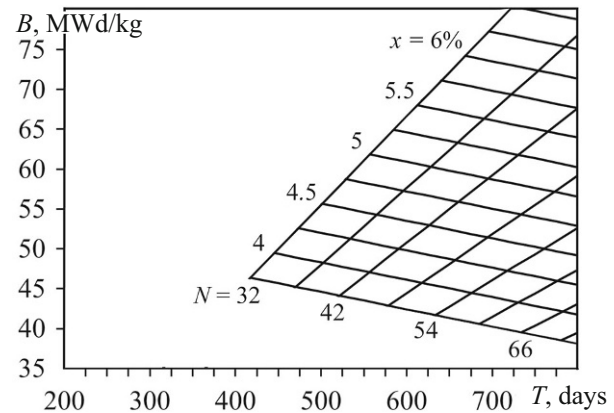


Fig. 3 UMo fuel burnup at a thermal intensity of 22 kW/kg and 163 FAs in the core

VVER uranium fuel [10–16], it is independent of the fuel enrichment, i.e., the relative consumption of fissile nuclides is almost constant in a wide range of parameters $x = 0.711\text{--}10\%$, $B = 8\text{--}100$ MWd/kg, $n = 1\text{--}8$:

$$\frac{\Delta M_f}{M_5} \frac{n + 1}{n} \sim 1.53. \tag{9}$$

The maximum deviation of the most detailed neutron-physical grid calculations for PWR and VVER reactors presented in [12–16] from the dependence (9) is +8.5% and –4%, respectively.

The substitution of the ratio (9) into the definition of the burnup (7), taking into account the expression (6), allows obtaining the desired analytical relationships of the fuel burnup with its enrichment, thermal stress, number of refuelings, and the reactor campaign in the form

$$B = B_\infty \frac{n}{n + 1}; B_\infty = 14.8x; \tag{10}$$

$$B = B_\infty - qT; B = nqT. \tag{11}$$

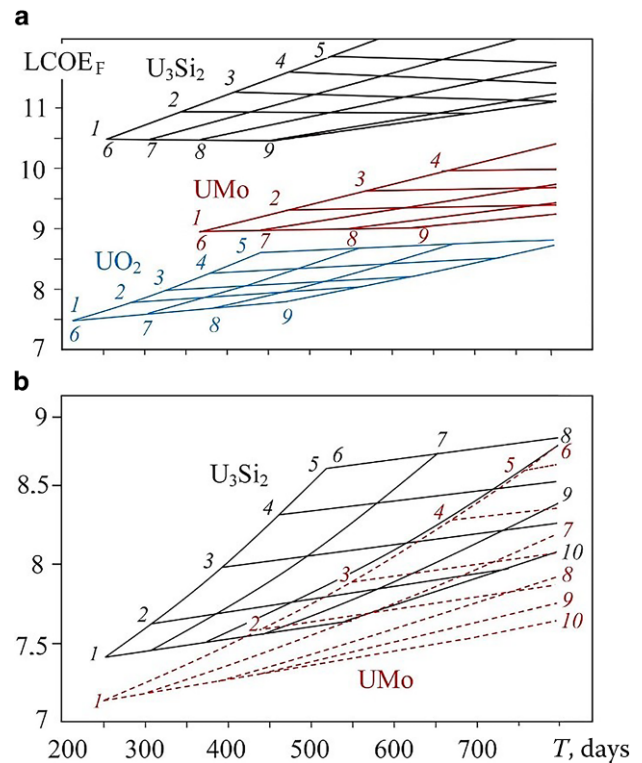
In the above expressions, the burnup is measured in MWd/kg; the thermal stress of the fuel q —in MW/kg; the reactor campaign—in days; enrichment—in %. According to expressions (10), the burnup of thermal reactors depends only on the enrichment and the number of refuelings in a wide range of fuel cycle parameters. This is evidenced by the comparison of experimental and calculated data [10–17]. According to the first formula (11), where the number of refuelings is replaced by the duration of the reactor campaign, the burnup of the alternative to uranium dioxide fuel increases linearly at increasing enrichment, determining the value B_∞ , and decreasing linearly with increasing thermal stress and the campaign (Fig. 1).

Thus, expressions (10) and (11) obtained in this work can be used to analytically assess the dependence of the fuel burnup on the enrichment, number of refuelings or unloaded FAs, reactor campaign, and the thermal stress of the fuel.

Fuel burnup grid diagrams

Dependencies (10), (11) are typically depicted in the form of grid diagrams. Figures 2 and 3 show that for metal fuel, due to its low thermal stress, the region of the implemented fuel cycle parameters shifts to the region of longer reactor campaigns at a lower enrichment, fuel burnup, and number of reloaded FAs compared Atomic Energy

Fig. 4 Dependence of the LCOE fuel component for different (a) and the same costs of fabricating FAs and handling spent fuel (b) on the reactor campaign, number of reloaded FAs, equal to 30 (1), 42 (2), 54 (3), 66 (4), and 78 (5), and fuel enrichment of 3.5 (6), 4.5 (7), 5.5 (8), 6.5 (9), and 7.5% (10) for 163 FAs in the core



to the U_3Si_2 fuel. According to the grid diagram for uranium dioxide [12], a 24-month fuel cycle ($T \sim 680$ days) can be implemented at an enrichment of more than 6.1%, burnup of more than 60 MW·day/kg, and number of reloaded FAs less than 78. A similar cycle with the U_3Si_2 fuel can be implemented at $x > 4.6\%$, $B > 46$ MWd/kg, and $N < 78$; with UMo fuel—at $x > 3.5\%$, $B > 42$ MWd/kg, and $N < 60$. In other words, a longer alternative fuel campaign is achieved at significantly lower enrichment and burnup values.

Grid diagrams for the fuel component of the LCOE

Having the analytical relationships of fuel cycle parameters in the form of (10) and (11), it is possible to construct grid diagrams for the fuel component of the LCOE using formulas (1) and (2). The market prices included in formula (2) are considered as initial parameters. It should be noted that market prices for natural uranium, as well as its conversion and separation work, are characterized by strong volatility under the influence of demand growth expectations or volatility in prices for oil, gas, and other energy sources. Market prices for natural uranium, conversion, and separation have increased since 2017, when a multi-year minimum was recorded (by 2–5 times in 2022) [18]. As a result, the cost of enriched uranium increased to 2130 USD/kg or by 2.3 times as compared to 2017 prices. Since as compared to the cash flow discounting the variation in the cost of enriched uranium and FAs is more dependent on market prices for natural uranium, conversion, separation work, and spent fuel treatment, the above estimates are obtained in the approximation of a zero-discount rate [1].

Although the cost of fabrication FAs and handling spent nuclear fuel is determined by the market quotation to a lesser extent, it depends on the composition and burnup of the fuel. Thus, according to [10], at an increase in the burnup of the traditional PWR fuel from 35 to 95 MWd/kg, the cost of manufacturing FAs increases from 300 to 450 USD/kg, while the cost of handling spent fuel is almost proportional to the burnup—from 840 to 1770 USD/kg HM. This pattern is explained by the increase in personnel protection costs for the fabrication of

FAs with increased enrichment and for handling spent fuel with a high content of fission products. Data of [10] can be approximated by linear functions

$$C_{FB} = 165 + 3B; C_{SNF} = 18.6B. \tag{12}$$

Thus, at a burnup of 70MWd/kg, the cost of manufacturing fuel and handling spent fuel is 375USD/kg and 1302USD/kg HM, respectively. It was impossible to find dependencies similar to (12) for the composition of the fuel alternative to uranium dioxide. Therefore, two options of grid diagrams are provided for the fuel component of the LCOE: at the same cost of fabrication and handling spent fuel (12) for all fuel types and at different costs. In the latter case, the cost of manufacturing fuel and handling spent UMo and U₃Si₂ fuel is assumed to be 1.5 and 2 times more expensive, respectively, as compared to UO₂ fuel:

$$C_{FB}(\text{UMo}) = 247 + 4.5B; C_{SNF}(\text{UMo}) = 28B; \tag{13}$$

$$C_{FB}(\text{U}_3\text{Si}_2) = 330 + 6B; C_{SNF}(\text{U}_3\text{Si}_2) = 37B. \tag{14}$$

By substituting expressions (10)–(14) into formulas (1) and (2), it is possible to obtain the desired dependence, which is convenient for presentation in the form of grid diagrams. Figure 4 shows that the fuel component of the LCOE decreases at an increasing fuel enrichment in all cases despite the increase in the cost of enriched uranium. This is due to the fact that, according to the denominator of expression (1), the burnup increases significantly at an increasing enrichment as compared to the fuel cost. Since the burnup is inversely proportional to the number of reloaded FAs according to expression (4), the fuel component of the LCOE increases at an increase in the number of reloaded FAs. In other words, at a constant reactor power and increase in the burnup, the fuel demand decreases. This is reflected in a decrease in LCOE_F at a decrease in the number of reloaded FAs and an increase in the enrichment.

Variations in fuel parameters over a wide range do not lead to an equally significant variation in the LCOE_F. Thus, for the traditional uranium dioxide fuel, the range of LCOE_F variations is 7.5–8.8 USD/(MWh) (see Fig. 4a). At the same cost of fabricating FAs and handling spent nuclear fuel composed of various materials, the range of LCOE_F variations is also small (see Fig. 4b): 7.2–8.7USD/(MWh). An increase in the cost of fabricating FAs and handling spent accident-tolerant fuel by 1.5 (UMo) and 2 (U₃Si₂) times leads to a noticeable stratification of the fuel component contribution to the LCOE for various fuel types (see Fig. 4a). Thus, for U₃Si₂ fuel at *N*=78, the fuel component of the LCOE increases from 8.7 to 11.7USD/(MWh).

Conclusions

The new analytical expressions obtained in the study for calculating the burnup of the accident-tolerant fuel depending on its composition, enrichment, refueling frequency, and reactor campaign, can be used to build grid diagrams for the fuel component of the LCOE at minimum expenses, acceptable accuracy, and without resorting to time-consuming neutron-physical calculations.

It is shown that wide-ranging variations of enrichment (3.5–7.5%), number of reloaded FAs (30–78), and reactor campaigns (250–800 days) for a given composition of accident-tolerant fuel do not lead to a significant variation in the fuel component of the LCOE, which varies up to 15–18%. The greatest differences in LCOE_F are characteristic of 24-month fuel cycles.

At an increase in prices for the fabrication of FAs with accident-tolerant fuel by 1.5–2 times compared to the traditional UO₂ fuel, the LCOE_F will increase by 23 and 40%, respectively.

The accuracy of economic estimates for the fuel component of the LCOE with both accident-tolerant and traditional fuel depends to the greatest extent on the accuracy of the prices used in the calculations for key technological processes of the nuclear fuel cycle.

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