

# Dynamical Behavior of Fuel Cost Component in Total Electricity Cost of Nuclear Power Plants with WWER-type Power Units

A.V. Kryanev<sup>1,2</sup>, N.I. Geraskin<sup>2</sup>, V.V. Haritonov<sup>2</sup>, S.G. Klimanov<sup>2</sup>, V.I. Savander<sup>2</sup>

<sup>1</sup>*Laboratory of Information Technologies, JINR*

<sup>2</sup>*Moscow Engineering Physical Institute (State University)*

## Abstract

The paper describes a technical and economical analysis of those changes in the fuel component of prime electrical energy cost, which are caused by implementing various versions of nuclear fuel design and nuclear fuel cycle (NFC) schemes on example of WWER-440 power reactors.

## 1 Introduction

At present time, thirty-one nuclear power units are under operation in the Russian Federation, including fifteen power units of WWER-type (six WWER-440 power units and nine WWER-1000 power units). In addition, thirty-nine Russian nuclear power units were built-up abroad (twenty WWER-440 power units and nineteen WWER-1000 power units). The Federal Purposeful Program “Development of Russian Nuclear Power Industrial System in 2007-2010 and, in perspective, up to 2015” was adopted by the Russian Government on October 6, 2006, and the Program set a task for the accelerated deployment of nuclear power plants and upgraded efficiency of electricity generation at nuclear power plants (NPP) through reducing specific expenses, for instance, by reducing fuel cost component in total cost of electricity generated by NPP (The Federal Purposeful Program, 2006; Strategy for development of Russian nuclear power in the first half of the XXI century, 2001).

In order to improve efficiency of fuel utilization and increase its competitiveness in the last few years in Russia some new design versions of fuel assemblies and advanced fuel cycles have been developed and implemented into Russian NPP and some Russian-design NPP abroad. Transition to new types of nuclear fuel with increased uranium enrichment and new fuel cycles with increased multiplicity of refuelings pursues the 0, fuel and investment components (Shevelev, Klimenko, 1996; Economics of nuclear power industry, 2004; Gordeev, 2001; Sinev, 1986; Kononov *et al.*, 2002). When implementing a new fuel type or an advanced scheme of refueling, we decrease the fuel component in prime cost of electrical energy. Under constant cost of the delivered electrical energy, full economy in the fuel component may be used for increasing the investment component, and this can give an additional impetus to further development of nuclear power industry in Russia.

The paper presents the following studies:

1. Technical and economical analysis of those changes in the fuel component of prime electrical energy cost, which are caused by implementing various versions of nuclear fuel design and NCF schemes on example of WWER-440 power reactors.
2. Sensitivity assessment of the fuel component to the predicted price variations.
3. Determination of risk to lose economical efficiency.

## 2 Static model

A variant of WWER-440 design with well-profiled fuel distribution in fuel assemblies (average uranium enrichment - 3.82 % <sup>235</sup>U) was adopted as a basic case for further comparative analysis of fuel utilization schemes in power reactors of WWER-440 type. Similar fuel is being used

now in 4-year fuel campaigns of NPP “Dukovany” (EDU3), NPP “Mohovce” (EMO1) and NPP “Bogunice” (EBO4). Currently, the second-generation fuel assemblies loaded with uranium-gadolinium fuel (average uranium enrichment - 4.25% <sup>235</sup>U) have been developed, and they are being implemented now into fuel cycles of WWER-440. These fuel assemblies are planned for using in 5-year fuel campaigns of Cola NPP and NPP “Dukovany”.

The fuel component in prime cost of electrical energy for various fuel types was calculated for once-through fuel cycle of WWER-440. It means that spent fuel assemblies are transported for long-term storage and reprocessing without any recycle of residual uranium and accumulated plutonium. The following expenses were taken into account:

1. expenses for natural uranium needed for fabrication of the feeding fuel;
2. expenses for conversion of natural uranium;
3. expenses for uranium isotope enrichment;
4. expenses for fabrication of different fuel assemblies for simultaneous loading into the reactor core;
5. expenses for SNF management (interim storage and reprocessing).

The fuel component in prime cost of electrical energy  $Y$  (US dollars per MW·day) is defined as a ratio of the feeding fuel cost  $3$  (US dollars), including all the expenses listed above, to full amount of thermal energy produced for the reactor operation time between two consecutive refuelings  $W$  (MW·days):

$$Y = \frac{3}{W}. \quad (1)$$

It was assumed that thermal efficiency factor for all versions of WWER-440 under consideration here was of identical value.

Specific consumption of natural uranium  $M_i(x)$  for fabrication of one fuel assembly of  $i$ -th type with uranium mass  $m_i$  and uranium enrichment  $x$  may be calculated from the following equation (Gordeev, 2001):

$$\begin{aligned} M_i(x) &= f(x, y, c) \cdot m_i \\ f(x, y, c) &= \frac{x-y}{c-y}, \end{aligned} \quad (2)$$

where  $c, y$  - fraction of <sup>235</sup>U (“uranium enrichment”) in natural uranium and in uranium waste, respectively;  $f(x, y, c)$ - consumption factor.

The expenses for uranium isotope enrichment are defined by the number of the Separative Work Units (SWU) per production of one kilogram of uranium enriched up to  $x$ . The number of the SWU depends on uranium enrichment in product and in waste, as it follows from the following equation (Gordeev, 2001):

$$\begin{aligned} ERR(x, y) &= (2 \cdot x - 1) \cdot \ln \left( \frac{x}{1-x} \right) + (2 \cdot y - 1) \cdot \frac{x-c}{c-y} \ln \left( \frac{y}{1-y} \right) \\ &- (2 \cdot c - 1) \cdot \frac{x-y}{c-y} \ln \left( \frac{c}{1-c} \right). \end{aligned} \quad (3)$$

So, total cost of enriched uranium for fabrication of the feeding fuel may be calculated by using the formula:

$$3_U = (C_e + C_k) \cdot \sum_i n_i \cdot M_i + C_R \cdot \sum_i n_i \cdot m_i \cdot ERR_i, \quad (4)$$

where  $C_e$  – cost of natural uranium (USD/kg U),  $C_k$  – cost of uranium conversion (USD/kg U),  $C_R$  – cost of one Separative Work Unit (USD/SWU),  $n_i$  – the number of fuel assemblies of  $i$ -th type.

The expenses related with fabrication of fuel assemblies and SNF management are proportional to uranium mass in fuel assemblies of any type. So, these expenses may be calculated by using the following formula:

$$3_{FA} = \sum_i C_i^{izg} \cdot n_i \cdot m_i + C_X \cdot \sum_i n_i \cdot m_i, \quad (5)$$

where  $C_i^{izg}$  - cost for fabrication of fuel assemblies of  $i$ -th type;  $C_X$ - cost for storage of spent fuel assemblies per one kilogram of fuel.

The main factor that makes it possible to increase fuel burn-up is related with higher uranium enrichment in the feeding fuel. Another factors, such as the increased multiplicity of refuelings, the lower neutron absorption in structural materials (by using thinner wrappers of fuel assemblies, for instance), proper axial distribution of fuel, can lead to the higher fuel also, but to the less degree. By using the adopted methodology, the fuel components in prime cost of NPP-generated electrical energy were calculated for all the ways towards upgrading the fuel utilization efficiency in power reactors of WWER-440 type. Uranium enrichment in the feeding fuel was varied within the range from 3.82% to 5.0%. Multiplicity of refuelings was varied from 4 to 6, including mixed refuelings. Two versions were considered for increasing fuel load in pellet: removal of central void cavity from the pellet, elongation of fuel column in fuel rod on 60 mm. Slight reducing the number of fuel rods in fuel assembly (from 126 to 120) resulted in some larger pitch of fuel lattice. Fuel loading was profiled by using the lower-enriched uranium in axial blankets (100-mm long).

The following prices at different NFC stages were used in numerical analysis of the variants listed above:

- price of natural uranium -  $C_e=46.0$  USD/kg U;
- price of SWU -  $C_R=88,0$  USD/SWU;
- price of uranium conversion -  $C_K=7.5$  USD/kg U;
- price of fuel fabrication for all types of fuel assemblies -  $C_i^{izg}=310$  USD/kg U;
- price of SNF long-term storage and reprocessing -  $C_X=650$  USD/kg U.

The results obtained in the calculations are presented in Fig. 1 in form of dots on the plane, where average values of fuel burn-up in discharged fuel assemblies are laid on axis of abscissas and the fuel components in prime cost of electrical energy are laid on axis of ordinates for all the variants. As is seen, the dependence has a non-monotonous nature though general tendency is traced as a linear recession of the fuel component with growth of fuel burn-up. Therefore, these data were treated with the least square method and presented in Fig. 1 in form of linear function. The following unambiguous conclusion can be derived from these results: major factor, which is able to decrease the fuel component in prime cost of electrical energy, is related with the utmost possible growth of fuel burn-up, regardless the way we used to succeed it. Indeed, the higher fuel burn-up, the larger proportionally expenses for natural uranium and uranium enrichment, but expenses for fabrication of fresh fuel assemblies and expenses for SNF management reduce proportionally to increasing fuel burn-up because cost of SNF management, according to our assumptions, is proportional to SNF mass.

Comparison of two variants with maximal difference between the values of fuel burn-up may be used here as an illustration to the conclusion. In the variant with maximal value of fuel burn-up, contribution of the expenses for natural uranium and its isotope enrichment into the fuel component in prime cost of electrical energy is equal to about 54%. If fuel burn-up increases, the fuel component drops down, and this decrease may be decomposed onto contributions of individual NFC stages. It turned out that the less expenses for natural uranium and its isotope enrichment contribute only 23% into total economy of the fuel component. The less expenses for SNF management gave a main contribution into reduction of the fuel component.

### 3 Dynamic model

Further, we consider dynamic behavior of the fuel component in prime cost of electrical energy under uncertain conditions of time-dependent variations in price characteristics of different NFC stages. Dynamic analysis of the fuel component under uncertain price variations requires making

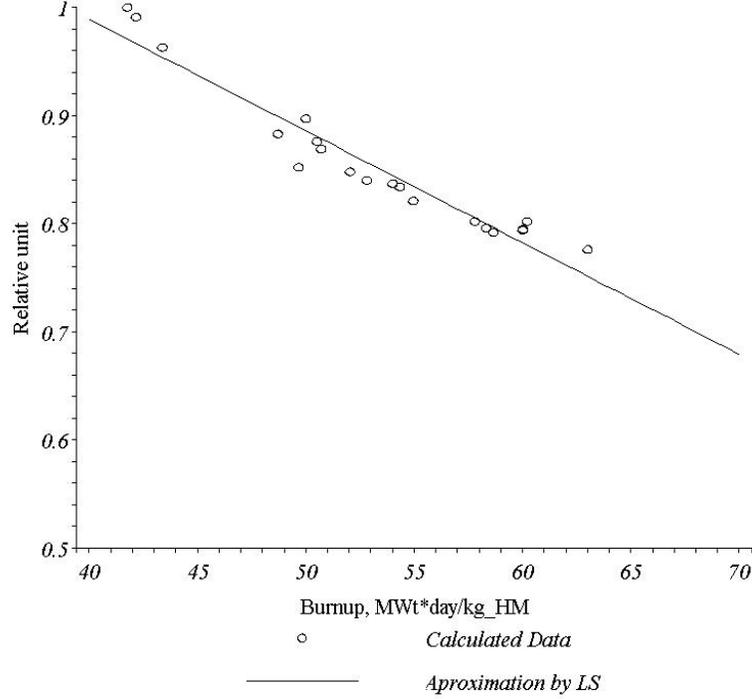


Fig. 1: Dependence of the fuel components in prime cost of electrical energy on fuel burn-up in spent fuel assemblies

a prognosis on time-dependence of the following parameters for some given period of NPP operation: the normalized expenses for fuel fabrication and storage at all NFC stages; tariff on electrical energy and rate of discount.

All the calculations were carried out under the following assumption: time  $t$  takes only discrete values, i.e.  $t = 0$  means a start-up date of the reactor operation;  $t = 1$  means the end of the first year of the reactor operation and so on. Full period of the reactor operation is equal to  $N$  years (we used  $N = 20$  in our calculations).

Time-dependent uncertainties of price characteristics are expressed here in the following forms:

$$C_j(t) = C_j^{PRED}(t) \cdot [1 + \varepsilon_j(t)], \quad (6)$$

where  $C_j^{PRED}(t)$  - the predicted price value of  $j$ -th price component at time moment  $t$ ;  $\varepsilon_j(t)$  - random fluctuation of appropriate price component in the vicinity of its predicted value. The variable  $j$  corresponds to individual price components, namely  $C_e$  - price of natural uranium;  $C_R$  - price of separate works;  $C_k$  - price of uranium conversion;  $C_i^{izg}$  - price of fuel fabrication for all types of fuel assemblies;  $C_x$  - price of long-term storage per 1 kg of spent fuel.

The discounted cost of electrical energy produced for some time period from  $t=0$  to  $t=\tau$  is calculated by the following formula:

$$W(\tau) = W_0 \cdot \sum_{t=1}^{\tau} \frac{LF(t) \cdot C_T(t)}{(1 + r(t))^t}, \quad \tau = 1, \dots, N, \quad (7)$$

where  $W_0$  - annual production of electrical energy for NPP operation at constant level of installed power,  $LF(t)$  - load factor of installed power in year  $t$ ;  $C_T(t)$  - average tariff of electrical energy in year  $t$ ,  $r(t)$  - rate of discount.

The values presented above were taken as initial costs at different NFC stages. Initial tariff of electrical energy was taken as  $C_T(0) = 0.041\$/(\text{kwt} \cdot \text{h})$ .

Numerical algorithm for evaluating the dynamic variations of prices and tariffs foresees a possibility to take into account the correlations between vector components of the random fluctuations in prices and tariffs. The random fluctuations are defined by the covariance matrix  $K_\varepsilon$ , elements of which are equal to the dispersions in vector components of the random fluctuation dispersions (diagonal elements) and co-variations between couples of vector components (non-diagonal elements) (Kryanev and Lukin, 2006).

Acquisition of sufficient statistical information about distributions of specific expenses at different NFC stages, which were calculated by formulae (6-7), made it possible to determine risk for specific expenses of the fuel component by the following formula:

$$p(Z(\tau) \geq Z^*) = p_{risk}, \quad (8)$$

where  $p(Z(\tau) \geq Z^*(\tau))$  - probability for element  $Z(\tau)$  of the fuel component to be larger than the utmost possible value  $Z^*$ ,  $p_{risk}$  - the given risk probability, which was used in calculations, if the random price fluctuations took place (usually, standard value of the risk probability  $p_{risk} = 0.05$  is taken in the calculations).

It is assumed in the calculations that time is counted out from the date when all fuel assemblies of the given type are loaded into the reactor core, i.e.  $t = 0$ . The number of fuel assemblies  $n_{ieff}$ , necessary for refueling in every calendar year, was calculated by the formula:  $n_{ieff} = 365n_i/T_{eff}$ , where  $T_{eff}$  - average effective time (in calendar days) between two consecutive refuelings.

The growing linear and piecewise-linear functions are used in the forecasting models of price dynamics:

$$C_J^{PRED}(t) = C_J \cdot (1 + k_J \cdot t) \quad , \quad (9)$$

where  $C_J$  - initial price at  $j$ -th stage of nuclear fuel cycle,  $k_J$  - coefficients of linear or piecewise-linear growth of appropriate prices.

Time-dependencies were calculated for main constituents of the fuel component for various values of initial parameters. Results of the calculations are presented in Figs. 2 and 3. The ordinates are the values of the discounted expenses  $Y^*$  for appropriate constituents of the fuel component. These values were obtained from the following inequality  $P(Z(t) \geq Z^*) = P_{risk}$ , where  $P(Z(t) \geq Z^*)$  - probability for the specific discounted expenses be larger than  $Z^*$ ,  $p_{risk}$  - the given risk value (in the calculations it was adopted that  $p_{risk} = 0.05$ ). Standard deviation of chaotic component in relative units was taken as  $\sigma = \sigma(0) = 0.1$ , and it grew with time as the following function:  $\sigma(t) = \sigma(0) \cdot t^{0.5}$ .

Several scenarios of price variations were considered for time period of 10-15 years. The first scenario, which may be called "neutral", foresees identical growth rate for all the prices, including tariffs. It may be anticipated that, under identical growth rate of all the prices, the fuel component does not change with time. Since main contribution into reduction of the fuel component is related with the expenses needed for SNF management, two other scenarios consider different growth rate of the expenses for SNF management in comparison with the growth rates at other NFC stages. In the second scenario the growth rate of the expenses for SNF management is lower on 50% than the growth rates at other NFC stages. The third scenario is a direct alternative to the second one, i.e. the growth rate of the expenses for SNF management is higher on 50% than the growth rates at other NFC stages. In addition, one separate scenario was considered, in which the growth rate of natural uranium price was substantially higher than the growth rates at other NFC stages. Results of the calculations are presented in Figs. 2 and 3.

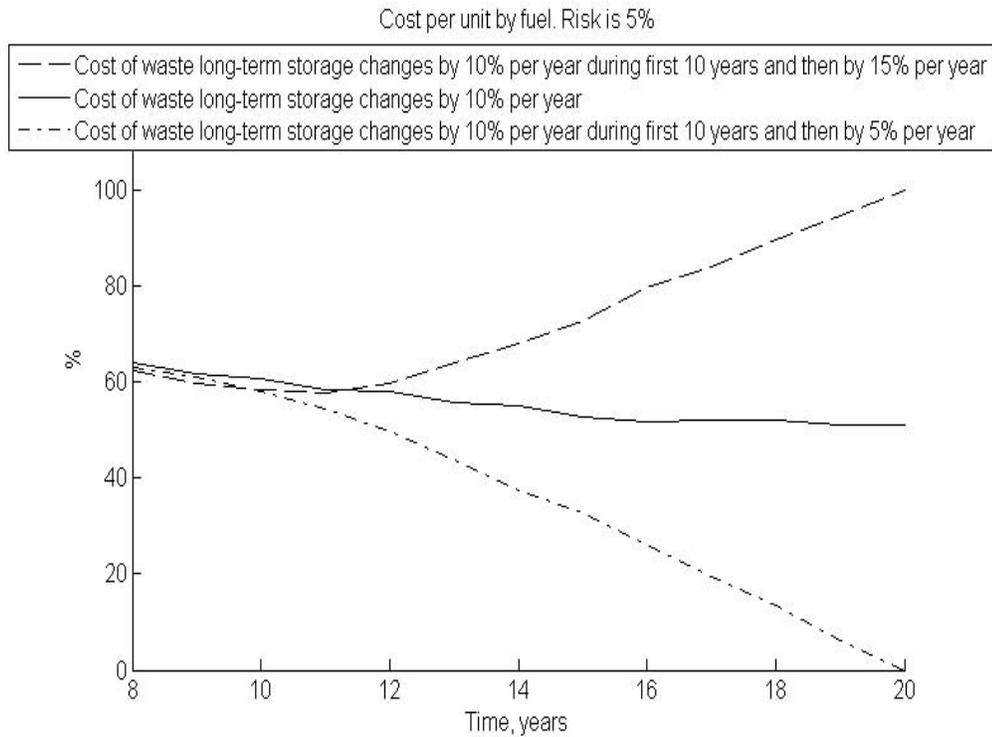


Fig. 2: Variations of specific expenses caused by price variations at different NFC stages. 1 – all the prices increase on 10% per year. 2 – price of SNF management increases on 5% per year; prices at the remaining NFC stages increase on 10% per year. 3 – price of SNF management increases on 15% per year; prices at the remaining NFC stages increase on 10% per year

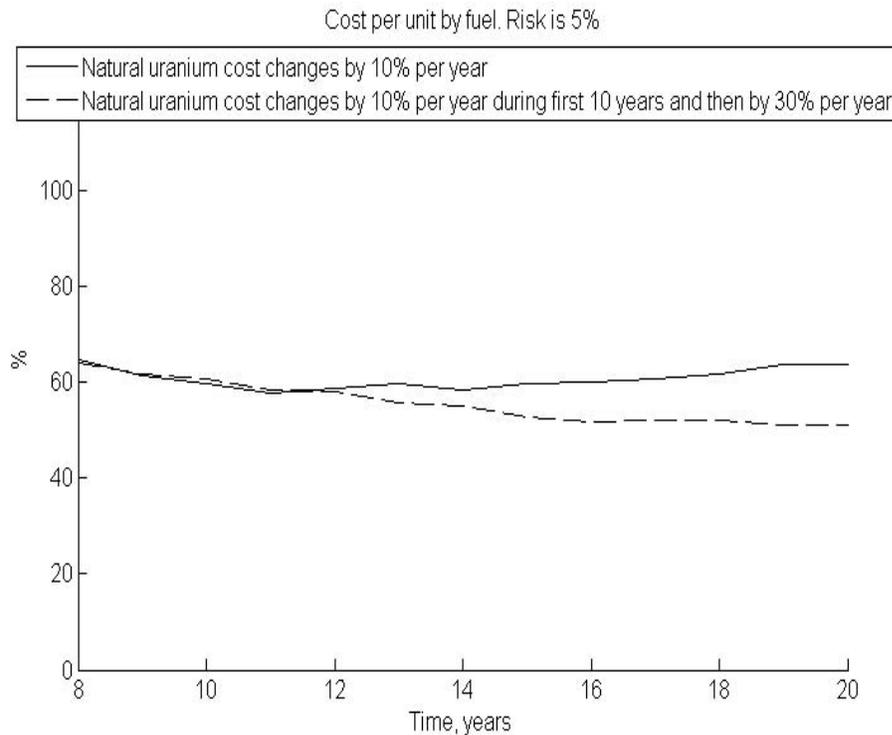


Fig. 3: Variations of specific expenses caused by price variations of natural uranium. 1 – all the prices increase on 10% per year. 2 – the outstripping growth of natural uranium price (10% per year in the first ten years and 30% per year in subsequent years)

## 4 Conclusion

The numerical analysis demonstrates that, under current price conditions at different NFC stages, increase of fuel burn-up is an effectual way to reducing the fuel component in prime cost of NPP-produced electrical energy.

Increase of initial uranium enrichment leads to proportional growth of fuel burn-up. However, main contribution into reducing the fuel component is given by economy of the expenses for fabrication of fresh fuel assemblies and for spent fuel management.

The methodology, which was used in the study for determination of the fuel component in prime cost of electrical energy produced by WWER-type power reactors, can analyze various forecasting options for dynamic price variations at different NFC stages, calculate the values for all the constituents of the fuel component and evaluate risks and uncertainties of these values. The calculations demonstrated that, in neutral scenario (identical growth rate for all the prices, including tariffs), the fuel component, normalized to the tariff rate, remains constant with time, despite significant variations of partial constituents occurred. Under the prevailing growth of the expenses for SNF management in comparison with another NFC stages, the fuel component sharply increases. Under relatively slow growth of the expenses for SNF management, the fuel component sharply drops down.

In scenario with the prevailing growth of natural uranium cost, time variations of the normalized fuel component become significantly lower. This means that variations of natural uranium cost, within the range under consideration here, give practically no effects on the values of the fuel component.

### Acknowledgement

We would like to thank Associate Professor at MEPhI Department of Theoretical and Experimental Nuclear Reactor Physics Vladimir Apse for his work on translating this paper.

## References

- [1] The Federal Purposeful Program (2006) ‘Development of Russian Nuclear Power Industrial System in 2007-2010 and, in perspective, up to 2015’. *Decree No. 605, dated October 6, 2006, was issued by the Government of the Russian Federation.*
- [2] Strategy for development of Russian nuclear power in the first half of the XXI century (2001). Moscow, Cniiatominform.
- [3] Shevelev Ya.V., Klimenko A.V. (1996). Effective economics of nuclear power and nuclear fuel system. Moscow, Russian State Humanitarian University.
- [4] Economics of nuclear power industry (the lecture course) (2004). *The training manual. Edited by Professor Haritonov V.V.* Moscow, MEPhI.
- [5] Gordeev B.K. (2001). Introduction to economics of nuclear fuel cycle. Moscow, Cniiatominform.
- [6] Sinev N.M. (1986). Economics of nuclear power industry. Moscow, Energoatomizdat.
- [7] Konovalov V.F., Vorobiev A.I., Glushkov A.N., Kozhin V.M. (2002). Corporative management of Russian nuclear power system. Publishing House “Graal”.
- [8] Kryanev A.V., Lukin G.V. (2006). Mathematical methods for processing of uncertain data. Moscow, Nauka.