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Research Article

Analytical dependence of burnup on enrichment of prospective fuel and parameters of reactors fuel campaign*

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Abstract

The paper is devoted to the definition of an analytical expression for estimating the burnup depth of nuclear fuel depending on its enrichment level, the periodicity of refueling, thermal stressthermal stress and the duration of the time period between refueling (reactor campaign) in a wide range of changes in key parameters for different types of thermal neutron reactors. The analytical expressions obtained in the work for the burnup depth are compared with numerous neutron physics calculations and experimental data from different authors for uranium fuel enrichment up to 9%. Calculations of the fuel share of the cost of electricity of nuclear power plants with PWR type reactors were performed and its sensitivity to changes in burnup depth and enrichment of fuel, the refueling periodicity, as well as to market prices for natural uranium, conversion, enrichment, fabrication of fuel assemblies and SNF handling were determined.

Keywords

NPP, nuclear fuel burnup, enrichment, refueling periodicity, reactor campaign, fuel share in electricity cost

Introduction

An important energy and economic characteristic of nuclear fuel is the so-called fuel ***burnup*** (or ***specific energy yield***) that influences the NPP economic performance (Gorokhov et al. 2004; OECD/NEA 2006; ORNL 2012; NF-T-3.8 2011; Jatuff 2016). A higher burnup leads to a smaller reactor demand for fuel, less spent fuel and a smaller volume of its transportation operations, and a longer reactor refueling periodicity (that is, the so-called reactor campaign) (Future of Nuclear Power 2003; Xu 2003; Gorokhov et al. 2004; OECD/NEA 2006; Nuclear Fuels 2009; NF-T-3.8 2011; Semchenkov et al. 2011; ORNL 2012; Jatuff 2016; Burns et al. 2020). Current light-water reactors of the VVER, PWR and BWR types are normally designed for the uranium fuel burnup of about 50 to 60 MW·day/kgU with the existing enrichment limit of 5%. In recent decades, there has been an increasing trend in fuel burnup in light-water reactors with the fuel enrichment simultaneously increased to more than 5% and the reactor refueling periodicity extended to 24 months (Future of Nuclear Power 2003; Xu 2003; Gorokhov et al. 2004; OECD/NEA 2006; Nuclear Fuels 2009; NF-T-3.8 2011; Semchenkov et al. 2011; ORNL 2012; Jatuff 2016; Burns et al. 2020). Newly developed accident tolerant fuel due to avoiding the steam-zirconium reaction suggest an increase in the fuel burnup and a change in the fuel enrichment (as compared with UO_2 two-oxide fuel) due to using

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other fuel matrix and cladding materials (Younker and Fratoni 2015; OECD/NEA 2018; Kuryndin et al. 2021; Semenov and Kharitonov 2021; Zhang et al. 2022). The relationship between fuel burnup and fuel enrichment, refueling periodicity, fuel mass in fuel assembly (FA) and in fuel rods, as well as other reactor core and FA parameters, is found based on neutron-physical calculations (Future of Nuclear Power 2003; Xu 2003; Gorokhov et al. 2004; OECD/NEA 2006; Nuclear Fuels 2009; Semchenkov et al. 2011; Jatuff 2016; Burns et al. 2020). In Jatuff 2016, Semchenkov et al. 2011, Nuclear Fuels 2009, Xu 2003 the results of calculations are presented in the form of grid diagrams reflecting the above-mentioned interrelations. In Xu 2003, Future of Nuclear Power 2003, a quadratic dependence of fuel enrichment on its burnup and refueling multiplicity is given on the basis of approximation of numerical calculations. However, curiously enough, in the literature it was not possible to find analytical expressions for the construction of grid diagrams of the above-mentioned interrelations, which is necessary, for example, for variant calculations of economic characteristics of tolerant nuclear fuel and the fuel component of the cost of electricity production at NPP. Therefore, the purpose of this paper is to obtain, based on physical principles, the analytical expression for estimating the nuclear fuel burnup as a function of fuel enrichment, thermal stressthermal stress, refueling periodicity and refueling multiplicity, as well as for determining the sensitivity of the NPP electricity cost's fuel component to the above parameters.

Analytical relationships of fuel burnup and npp fuel cycle parameters

To identify analytical possibilities for selecting economically feasible parameters of the fuel cycle of NPPs with an extended reactor campaign, we consider three approaches to the evaluation of nuclear fuel burnup.

Firstly, the uranium fuel burnup, B, (MW·day/kgU) is connected with the reactor operating time, T, (days) with thermal power Q to the replacement of N fuel assemblies (FA) via a known expression (Gorokhov et al. 2004):

$$B = (Q\times T)/(N\times M_{FA}) = q\cdot n\times T, \quad (1)$$

where M_{FA} is the mass of uranium in each FA (kgU); $n = N_{CORE}/N$ is the refueling ratio; and N_{CORE} is the number of FA in the reactor core. Quantity $q = Q/M_{CORE}$, where $M_{CORE} = N_{CORE}\times M_{FA}$ is the mass of fuel in the reactor core, is referred to as specific thermal stressthermal stress of fuel (about 40 kW/kgU for UO_2), and relation $NM_{FA}/T = Q/B = P$ represents the reactor fuel demand (kg/day or kg/year depending on the dimensionality used for B). As it follows from Fig. 1, which presents the results of calculating $N(T, B)$ using formula (1), 30 to 50 FAs are extracted during refueling (depending on the specified burnup) when the reactor campaign is 12 months ($T \approx 330$ days), and more than 70 FA are extracted when the reactor campaign is 24 months ($T \approx 680$ days).

Secondly, back in the 1950s, the concept of an ideal fuel reloading regime was introduced, in which the reactor is fed with fresh fuel in microdoses with mixing throughout the entire core volume (Future of Nuclear Power 2003; Gorokhov et al. 2004; Nuclear Fuels 2009). With the refueling multiplicity being n, the achieved burnup, B, is less than the ideal burnup, $B\infty$, according to the expression below (Future of Nuclear Power 2003; Gorokhov et al. 2004; Nuclear Fuels 2009)

$$B(n) = B\infty\, n/(n + 1) \quad (2)$$

Normally, $n = 3–5$, so the burnup is 75 to 83% of the ideal burnup.

By excluding n from formulas (1) and (2), we find the dependence of burnup on the fuel thermal stressthermal stress and the reactor campaign as the remainder in the following

$$B=B_{\infty} - qT \quad (3)$$

Thirdly, burnup can be expressed in terms of the mass of the nuclides burnt during the reactor campaign. Since the thermal energy generated for the reactor campaign, $Q = \Delta M_f(E_f/m_f)$, is directly proportional to the mass of the nuclides burnt, ΔM_f, which is nearly equal to the fission product mass, expression (1) for the fuel burnup can be reduced then as follows

$$B = (\Delta M_f/M_5)(M_5/M_F)(E_f/m_f) = (E_f/m_f)\,(\Delta M_f/M_5)x. \quad (4)$$

In the obtained expression (4), $M_F = N\cdot M_{FA}$ is the mass of the fuel extracted during refueling; M_5 is the mass of uranium-235 in the fresh fuel loaded into the reactor instead of the spent fuel during reactor campaign; $x = M_5/M_F$ is the fresh fuel enrichment; $E_f/m_f = 970$ MW·day/kgU is the average caloric value of fissionable nuclides (uranium and plutonium) with an error of ± 1% (with the uranium and plutonium caloric values being in accordance with data in Glushkov et al. 1985.

Using enrichment in %, as generally accepted, expression (4) can be written as

$$B(\text{MW}\times\text{day/kgU}) = 9.7x(\%)\Delta M_f/M_5 \quad (5)$$

As can be seen, nuclear fuel burnup is directly proportional to the product of only two variable parameters: initial enrichment (x, %) and ratio of the burnt fuel mass (approximately equal to the mass of fission products) to the initial mass of fissionable nuclides (that is, in the loaded fresh fuel), $\Delta M_f/M_5$. By comparing expressions (5) and (2), we obtain an important relation

$$(\Delta M_f/M_5)(n + 1)/n = B\infty\,(m_f/E_f)/x \quad (6)$$

By definition, the right-hand part in the above expression does not depend on the refueling multiplicity.

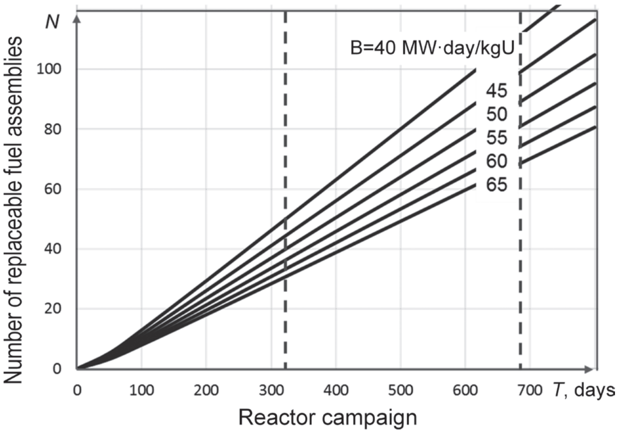

Figure 1. Number of replaceable FAs (N) as a function of reactor campaign (T, days) and fuel burnup (B, MW·day/kgU) with the installed reactor thermal power (Q = 3200 MW), mass of fuel in each FA (M_{FA} = 470 kgU), number of FAs in core (N_{CORE} = 163), and maximum theoretical ICUF ($T/(T + \Delta T)$), where ΔT = 32 days is the time of the reactor outage for refueling and repair. Calculation based on formula (1). Vertical dashed lines are the boundaries of the actual reactor operating times to refueling in 12- and 24-month cycles.

Therefore, the left-hand part is not expected to depend as well on n, that is, the relative mass of fission products in extracted fuel during refueling depends only on the refuel in result unknown before. Meanwhile, as shown in Fig. 2, which presents the fuel burnup neutron-physical calculation results for PWR- and VVER-type reactors in a broad range of enrichments (3 to 10%) and refueling ratios (1–8) (see Future of Nuclear Power 2003; Xu 2003; Nuclear Fuels 2009; Semchenkov et al. 2011; Jatuff 2016; Burns et al. 2020), processed using formulas (5) and (6), the left-hand part in expression (6) can be considered to be a constant value of 1.53 which does not practically depend on fuel enrichment, and either on fuel burnup or refueling multiplicity, that is, can be taken roughly

$$\Delta M_f/M_5 = 1.53n/(n + 1) \quad (7)$$

As it follows from Fig. 2, the largest deviations from dependence (7) are +8.5% and -4%. The dataset scatter about dependence (7), which does not exceed 8.5%, can be explained by the neutron-physical calculation errors from averaging the fuel burnup and enrichment values, since in-core fuel burnup is not uniform under actual conditions, and FAs are used with different enrichments and even with the enrichment distribution by fuel elements within one FA, so FAs with different burnups are extracted during refueling which requires special consideration.

Finally, it follows from expression (7) with typical values of n=3–5 that $\Delta M_f/M_5$=1.1–1.3, that is the mass of fissionable nuclides (mass of fission products) burnt exceeds by 10 to 30% the initial mass of uranium-235 in fresh fuel due to the generated plutonium burnup which is confirmed by experimental data OECD/NEA 2006 (Table 1).

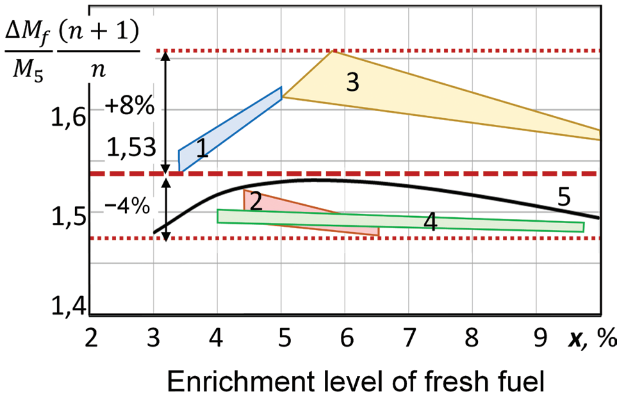

Figure 2. Dependence of the product of the relative mass of fission products (burnt-up nuclides, $\Delta M_f/M_5$) by the function of refueling ratio, $(n+1)/n$ with $n = N_{CORE}/N$, on enrichment of replaced FAs. *Source*: plotted by authors based on grid diagram data in Nuclear Fuels 2009, Xu 2003, Future of Nuclear Power 2003, Burns et al. 2020 for PWR and VVER reactors: 1 – Jatuff 2016, 2 – Semchenkov et al. 2011, 3 – Nuclear Fuels 2009, 4 – Xu 2003, 5 – approximation Xu 2003, Future of Nuclear Power 2003. Dash line: calculation based on formula (7). The polygons reflect the boundaries of the grid diagrams obtained as the result of neutron-physical calculations in Jatuff 2016, Semchenkov et al. 2011, Nuclear Fuels 2009, Xu 2003 for PWR and VVER reactors.

Table 1. Influence of uranium fuel enrichment and burnup on the mass of fission products in the PWR reactor SNF with one fourth of the reactor core refueled. *Source*: authors' calculation of the $\Delta M_f/M_5$ values using formula (4) and of the $(\Delta M_f/M_5)(n + 1)/n$ value using formula (7) based on data in NF-T-3.8 2011

Average uranium-235 enrichment of replaced fuel x, %	Average burnup of replaced fuel B,MW·day/kgU	Relative mass of fission products in replaced fuel, $\Delta M_f/M_T$, kg/t h.m.	Ratio of fission product mass in SNF to U-235 mass in fresh fuel $\Delta M_f/M5$	Parameter $(\Delta M_f/M_5)(n + 1)/n$
3.8	44.9	47	1.23	1.54
4.5	54.3	57	1.27	1.59
5.4	64.1	67	1.24	1.55
6.5	73.8	78	1.2	1.50
7.5	84.0	89	1.19	1.49
8.5	93.7	99	1.16	1.45

Analytical expressions for construction grid diagrams of uranium fuel high burnup

Substituting the obtained relation (7) into expression (5), taking into account (1) and (2), leads to the sought-after analytical relationship of fuel burnup with fuel enrichment, refueling ratio, thermal stress and reactor campaign in the following form

$$B(\text{MW}\times\text{day/kgU}) = 14.8x(\%)n/(n + 1);\ B\infty = 14.8x(\%). \quad (8)$$

$$B(\text{MW}\times\text{day/kgU}) = 14.8x(\%) - q\ (\text{kW/kgU})\times T(\text{day})/1000. \quad (9)$$

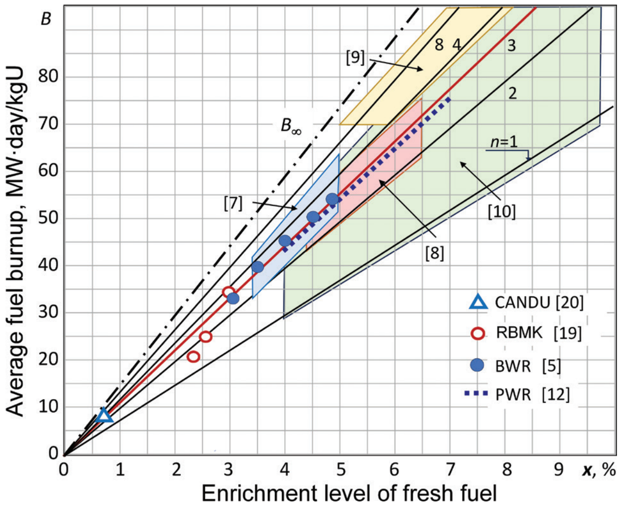

Figure 3. Relationship between average burnup (B, MW·day/kgU), enrichment (x, %) and refueling multiplicity ($n \geq 1$) for uranium fuel for different thermal neutron reactors. *Source*: plotted by authors based on experimental and calculated data in OECD/NEA 2006, ORNL 2012, NF-T-3.8 2011, Jatuff 2016, Semchenkov et al. 2011, Nuclear Fuels 2009, Xu 2003, RBMK Channel Nuclear Reactor 2006, Lee et al. 2007. The straight lines are the calculation using formula (8) for different n=1–8. The polygons reflect the boundaries of the grid diagrams obtained as the result of neutronic calculations in Jatuff 2016, Semchenkov et al. 2011, Nuclear Fuels 2009, Xu 2003 for PWR and VVER reactors.

Burnup calculations using formulas (8) and (9) describe satisfactorily the grid diagrams contained in Jatuff 2016, Semchenkov et al. 2011, Nuclear Fuels 2009, Xu 2003, Future of Nuclear Power 2003. Fig. 3 shows that the linear dependence of burnup on fuel enrichment (8) in a first approximation generalizes data in a satisfactory way practically for all types of thermal reactors, including CANDU, RBMK, VVER, PWR and BWR reactors (with UO_2 fuel), that is, in a broad range of the fuel cycle parameters: enrichment of 0.711 to 10% and refueling multiplicity of n=1 to 8 independently of the fuel thermal stress. The dash-and-dot line representing the ideal burnup (the second one of formulas (8)), is above all calculated and experimental data exactly as one could expect.

As it follows from expression (9) and Fig. 4, with the preset values of the fresh fuel enrichment (x) and reactor campaign (T), the burnup decreases as the fuel thermal stress grows. The grid diagrams for fuel burnup are constructed by way of combining Figs 3 and 4.

Therefore, analytical expressions (7)–(9), obtained for the first time in the paper, allow estimating analytically the dependence of nuclear fuel burnup on fuel enrichment, refueling multiplicity(or number of discharged FAs), reactor campaign(refueling interval) and fuel thermal stress, which is required for plotting grid diagrams as a convenient tool for selection of the fuel cycle parameters.

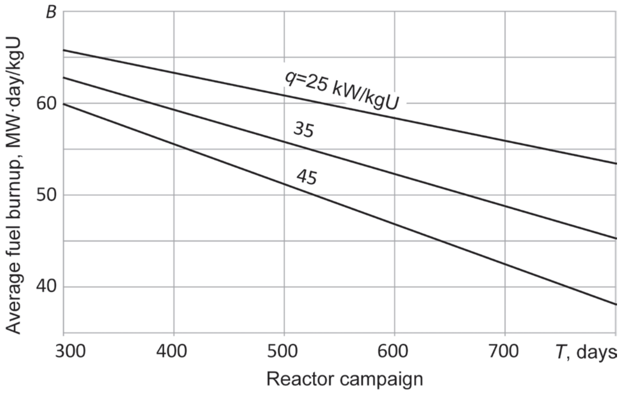

Figure 4. Average fuel burnup (B, MW·day/kgU) as a function of PWR-type reactor campaign (T, days) and fuel thermal stress (q=25–45 kW/kgU) with an enrichment of x=4.95%. Calculation based on formula (9).

Influence of burnup on the fuel share of the levelized cost of the NPP electricity

The fuel component, Y_F, (Rub/kW·h) in the NPP operating costs includes the FA fabrication and spent nuclear fuel (SNF) handling cost and is proportional to the reactor fuel demand, P (kg/year)

$$Y_T = P(C_{FA} + C_{SNF}) = PC_{NFC}. \tag{10}$$

Quantity $C_{NFC} = C_{FA} + C_{SNF}$ can be called as the cost of the nuclear fuel cycle (open or closed) in terms of 1 kg of uranium (or heavy metals) in fuel (Rub/kg h.m.), including the FA cost, $C_{FA} = C_X + C_{FAB}$, and the SNF handling cost, C_{SNF}. Quantities C_X and C_{FAB} are the costs of enriched uranium and FA fabrication; P is the annual average reactor fuel demand (kg/year) defined by the ratio of the annual average thermal power of the reactor, Q (MW), to the average fuel burnup, B, (MW·day/kg) according to (1):

$$P = 365 \times Q/B = E/(24\eta B), \tag{11}$$

where $E = W \cdot \Delta t \cdot ICUF$ is the annual average amount of the electricity sold (MW·h/year); W is the installed electric power of the NPP unit, MW; Δt is the number of hours per year (8760 h/year); and $Q = W \cdot ICUF/\eta$ is the reactor thermal power with gross efficiency η. In expressions (11), numerical coefficients 365 and 24 take into account the number of days per year and the number of hours per day in accordance with the commonly accepted dimensionalities of the initial quantities. Thus, for current PWR-type reactors with typical parameters such as W = 1200 MW, η = 34%, B = 55 MW·day/kgU, and $ICUF$ = 0.85, the annual fuel demand is $P \approx 20$ t/year.

The ratio of fuel costs to the electricity sold, Y_F/E, represents the fuel component of the electricity cost (Levelized Cost of Electricity or $LCOE$) (Kharitonov et al. 2018):

$$LC_F = Y_f/E = P(C_{FA} + C_{SNF})/E = (C_{FA} + C_{SNF})/(24\eta B). \quad (12)$$

If burnup is measured in MW·day/kgU, then LC_F is expressed in Rub/MW·h.

To estimate the cost of manufacturing the FAs replaced with fuel mass P (kg/year) and enrichment x is necessary to know the consumed mass of natural uranium, F (kg/year) and uranium isotope separation work, R (SWU/year), found by standard expressions (Kharitonov et al. 2018)

$$F = P(x - y)/(c - y); R = P\Phi(x) + D\Phi(y) - F\Phi(c); \quad (13)$$

$$\Phi(z) = (1 - 2z)\ln(1/z - 1); z = x, y, c, \quad (14)$$

where $D = (F - P)$ is the mass of depleted uranium with the mass concentration of uranium-235, y; $c = 0.711\%$ is the mass concentration of uranium-235 in natural uranium; and $\Phi(z)$ is the separation potential. As a result, for the production cost of fuel assemblies (per 1 kg of h.m.), including the costs of purchasing natural uranium and its conversion into uranium hexafluoride, uranium isotope separation, waste disposal and fuel assembly fabrication, we obtain the expression

$$C_{FA} = C_F(x - y)/(c - y) + C_R[\Phi(x) + \Phi(y)(x - c)/(c - y) - \Phi(c)(x - y)/(c - y)] + C_D(x - c)/(c - y) + C_{FAB}, \quad (15)$$

in which $C_F = C_{U3O8} + C_{UF6}$ is the price of natural uranium hexafluoride; C_{U3O8}, C_{UF6}, C_D are prices of natural uranium (in the form of oxide concentrate), oxide concentrate conversion to uranium hexafluoride, and recycling of depleted uranium hexafluoride (waste) per 1 kg of uranium metal (Rub/kg); and C_R is the separation work price (Rub/SWU). It follows from expression (15) that the FA cost with the preset fuel enrichment level, x, and determined prices (C_F, C_R, C_D, C_{FAB}) depends only on the separation waste dump depth (tails assay), y, while there is an optimal tails assay, y_0, with which the FA cost is as small as possible. Quantity y_0 depends only on the ratio of prices $(C_F + C_D)/C_R$ (Kharitonov et al. 2018). Since $(C_F + C_D)/C_R = 1$, we have that $y_0 = 0.228\%$; with $(C_F + C_D)/C_R > 1$, it is advantageous to save on natural uranium, so $y_0 < 0.228\%$; and with $(C_F + C_D)/C_R < 1$, it is advantageous to save on separation work, so $y_0 > 0.228\%$. According to data from JSC Atomenergoprom (Annual Reports 2021), the market quoted prices for natural uranium (in the hexafluoride form) in the past five years are twice higher than the separation work prices, which leads to an optimal tails assay of $y_0 = 0.16–0.19\%$. In 2011, the market prices for uranium and enrichment reached their historical peaks: $C_{U3O8} = 148$ \$/kg, $C_R = 149$ \$/SWU (Annual Reports 2021) (Table 2). After the Fukushima Daiichi accident, nuclear power worldwide found itself under severe pressure which led to a long-term decrease in market prices which reached the bottom in 2017–2018: $C_{U3O8} = 57$ \$/kg, $C_R = 36$ \$/SWU (Table 2). It follows from expression (15) that the cost of enriched uranium increases nearly linearly with the fuel enrichment growth and, thus, with the fuel burnup growth.

Table 2. Historical dynamics of market prices for natural uranium and uranium conversion/enrichment services, and of estimated cost of enriched uranium ($x = 4.95\%$). *Source*: compiled by authors based on data in Annual Reports 2021

Parameter	2011	2018	2021
Uranium oxide concentrate price, C_{U3O8}, \$/kgU	148	65	91
C_{UF6}conversion price, \$/kgU	11	10	19
Uranium hexafluoride price, C_F, \$/kgU	159	75	110
Separation work price, C_R, \$/SWU	149	36	55
Optimal tails assay, y_0, %	0.220	0.155	0.158
Enriched uranium cost, C_x, \$/kgU	2772	1002	1496

Table 3. Influence of uranium fuel burnup on the NFC cost characteristics. *Source*: compiled by authors based on data in OECD/NEA 2006 for high and low market prices for natural uranium and separation work based on data in Table 2

Burnup depth, B, MW·day/kgU		45	55	65	75	85	95
FA fabrication cost, C_{FAB}, \$/kgU		300	330	360	390	420	450
SNF transportation cost, $C_{TR,}$ \$/kgU		230	280	330	380	430	480
SNF encapsulation and disposal cost, C_{DIS}, \$/kgU		610	745	880	1015	1150	1290
SNF handling cost, $C_{SNF}=C_{TR}+C_{DIS}$, \$/kgU		840	1025	1210	1395	1580	1770
Fuel enrichment*,x, %		3.9	4.6	5.6	6.5	7.3	8.2
Enriched uranium cost**, C_x, \$/kgU	2011	2090	2545	3200	3800	4330	4940
	2018	760	920	1150	1360	1540	1750
FA cost, $C_{FA}=C_x+C_{FAB}$, \$/kgU	2011	2390	2875	3560	4190	4750	5390
	2018	1060	1250	1510	1750	1960	2200
Fuel component of NPP electricity cost***, LC_F, \$/MWт·h	2011	8.8	8.7	9.0	9.1	9.1	9.2
	2018	5.2	5.1	5.1	5.1	5.1	5.1

* Calculation based on formula (8) with $n = 3.63$;
** Calculation based on formula (16) with $C_D = 7$ \$/kgU;
*** Calculation based on formula (13) with the NPP efficiency of $\eta = 34\%$.

The costs of fuel assembly fabrication and SNF management are to a lesser extent determined by market quotations, but may depend on the depth of fuel burnup (enrichment). Since according to data in OECD/NEA 2006 (see Table 3), the increase in the PWR fuel burnup from 45 to 95 MW·day/kgU leads to the FA fabrication cost, C_{FAB}, growing from 300 to 450 \$/kgU, and the SNF handling cost, C_{SNF}, growing from 840 to 1770 \$/kgU, which is practically proportional to the burnup. Such regularity is explained by the growth in the FA fabrication costs due to the increase in the enriched uranium radioactivity level and the SNF handling costs with an increased content of fission products in highly burnt-up SNF. With these data accepted, the fuel component of the NPP electricity costs, as shown by the above formulas (Table 3), changes slightly in a range of 8.7 to 9.2 \$/MW·h with high market prices for natural uranium and separation work (2011) and in a range of 5.1 to 5.2 \$/MW·h with low market prices (2018). A weakly pronounced minimum in the vicinity of the 55 MW-day/kgU burnup is observed. Such pattern is defined by a practically linear dependence of the numerator in formula (12) on fuel burnup (see Table 3).

It is important to note that, according to the presented results, the market prices for natural uranium and separation work have major effect on the fuel component of the electricity cost as compared with effects from fuel burnup and, accordingly, fuel enrichment.

Conclusions

The paper presents newly obtained analytical expressions (8), (9) for estimating the burnup of nuclear fuel depending on fuel enrichment, refueling periodicity, reactor campaign and specific thermal stress of fuel in a wide range of these parameters (without taking into account the constraints from the physicochemical processes in conditions of high burnups) as applied to thermal reactors. It has been shown that nuclear fuel burnup is directly proportional to the multiplication of only two parameters: enrichment of the fuel loaded during refueling, and ratio of the burnt fuel mass (≈ fission product mass) to the mass of fissionable nuclides in the loaded fuel according to expression (4). The latter ratio ($\Delta M_f/M_5$) depends practically only on the refueling multiplicity and changes in a range of 1.0 to 1.5. The obtained analytical expressions for the burnup estimation are convenient as applied to variable-based economic, thermal-physical, strength and other calculations for reactor fuel batches with different cycle durations (12 to 24 months) and fuel enrichments (up to 10%), including the accident tolerant fuel under development.

It has been shown that fuel burnup increases practically linearly with the enrichment growth in the considered range of 0.7 to 10% with the preset refueling multiplicity, as shown by expression (8), and decreases linearly with the reactor campaign(refueling interval) increase with the preset fuel enrichment according to (9).

It has also been shown that the fuel component of the PWR NPP electricity cost is not so particularly sensitive to the fuel burnup change but is much more sensitive to the volatility of market prices for natural uranium, conversion and separation work or to changes of enriched uranium cost.

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