COMPARATIVE ANALYSIS OF ELECTRICITY GENERATION FUEL COST COMPONENT AT NPPs WITH VVER AND BN-TYPE REACTOR FACILITIES

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Abstract. The fuel cost component (FCC) of electricity generation is defined as a specific indicator - the cost of 1 kWh of electricity produced. This value is obtained as the levelized (discounted) nuclear fuel cost value, generally beginning with natural uranium procurement and ending with spent fuel handling, normalized to the total electric energy generated over the nuclear power plant lifetime. I.e. the result is the FCC average value over the entire lifetime.

The methodology of levelized FCC calculation is based on the concept of taking into account the disparity in the value of money, referring to different moments of time, and thus, the possibility of technical and economic comparison of projects with significant lifecycle. The nuclear fuel life cycle is known to normally cover a period of 50-100 years.

The paper describes the basic essential methodological and factual materials for the fuel component calculation for NPPs with fast and thermal reactors. However, these reactors are expected to be in the NE system, together with the nuclear fuel cycle facilities. In such a case, as is well known, plutonium is a link between thermal and fast reactors. The calculations were performed for the fast reactor BN-1200 in version with MOX-fuel, as well as for the VVER-TOI thermal reactor. The calculations have shown that at constant prices for natural uranium the values of levelized FCC with BN and VVER reactors are sufficiently close to each other. With regard to the escalation of prices for natural uranium, the levelized FCC for the entire life cycle of nuclear power plants with a natural uranium fuel thermal reactor significantly increases depending on the MOX fuel fraction in the core inventory, whereas for fast reactor NPPs it remains constant and much lower. The calculations have shown that for the fast reactor the fuel fabrication cost makes the main contribution to FCC, and for the thermal reactor – it is the cost of natural uranium and its enrichment**..**

Key Words: Fuel cost, Levelized nuclear fuel cost, BN-1200.

1. Introduction

Any expected growth in the operational capacity up to 40 — 60 GWe in Russia by 2030 can be achieved by using VVER-type reactors and open fuel cycle. With such a level of NP development, a real inherent problem for nuclear industry will lie in a deferred decision on the accumulated spent fuel from these reactors. In this connection, the paper considers a solution to the problem of spent nuclear fuel in modern NP, based on the use of core technologies developed for BN reactors, MOX fuel and hydrometallurgic reproccesing of spent fuel, and introduced in Russia. However, acceptability of such technologies depends a lot on the cost of electricity generation.

The present paper looks at the key economic indicators of the closed fuel cycle such as specific costs of new fuel fabrication, spent fuel reprocessing and final RADW management. The analysis makes it possible to obtain values (or a range of values) of the studied parameters, when the cost of electricity generation at NPPs with BN-1200 will be comparable to that at commercial NPPs with thermal reactors.

The LUFC of electricity generation is defined as a specific indicator - the cost of 1 kWh of produced electricity. This value is the levelized (discounted) cost of nuclear fuel normalized to the total electric energy generated over the nuclear power plant lifetime. It comprises a number of economic costs, generally beginning with procurement of natural uranium and ending with spent fuel handling, and the end result being the average LUFC value over the entire lifetime.

The paper proposes comparison of performance indicators for NPPs with BN-1200 reactors with the similar ones for NPPs with VVER-TOI thermal reactors operating in the open fuel cycle. However, as part of proposals concerning two-component nuclear energy system to be developed in Russia [1], BN-1200 and VVER-TOI reactors are the main elements of the same nuclear energy system and cannot compete against each other. Together, by solving different tasks, they are to ensure competitiveness of NP on the Russian market of power-suppliers.

Calculations of specific levelized costs made for the research are based on the methods stated in OECD and IAEA documents [2, 3, 4] and adapted to Russian conditions [5]. Subject to the condition, the FCCBNN and ECOSYS calculation codes were developed to calculate the levelized values of the FCC and the overall cost of electricity generation.

The aims and tasks of the research – to analyse the effect of the BN-1200 reactor performance and its closed fuel cycle on the cost of produced electricity.

1. Analysis and preparation of initial data on NFC

A high-power BN-1200-type reactor is considered. It is a fast-neutron reactor with MOX fuel and bottom axial and radial blankets [1,6], nuclear fresh fuel fabrication and reprocessing being centralized. Specific costs concerning NFS are used as basic data for calculating the LUFC of the specific electricity generation cost in accordance with the calculation method.

LUFC calculations are mainly based on specific cost data obtained by analysing data from national and international handbooks [1]. Use was also made of some data presented in the paper [7].

In order to take into account the scale factor of NE development, the research is done for a small series of the BN-1200 reactors (9 power units). When assessing fuel fabrication costs, it was taken that the plant production is 120 tonnes/year for heavy metal and 230 tonnes/year for treatment of the spent nuclear fuel, which is consistent with the indicated small series.

Calculations were performed with the discount rates of r=0% and r=5%.

Table I contains the key parameters of the BN-1200 and VVER-TOI type reactors and their fuel cycles.

TABLE I: KEY PARAMETERS OF THE BN-1200 AND VVER-TOI TYPE REACTORS AND THEIR FUEL CYCLES.

Parameter	**Value**	
	BN-1200	**VVER-TOI**
Type of the reactor	Sodium cooled fast reactor	Pressurized water reactor
Thermal capacity	2800 MW	3312MW
Electrical capacity	1220 MW	1250MW
Reloading factor	0.9034	0,94
Year of commissioning	2025	2025
Operating life	60 years	60 years
Average burnup	9,2% (104 MW·days/kg) – the initial stage; 13,3%(152 MW·days/kg) – the main stage of operation	48,6 MW·days/kg

Table II presents specific costs concerning NFS conversions, which have been used in the paper. Table III presents adopted initial data on the fuel cycles of the VVER-TOI and BN-1200 reactors, which is necessary for calculating the levelized FCC. The data specified match those on the fuel cycle considered in the paper [1].

TABLE II: ADOPTED COSTS CONCERNING NFC.

Production	**BN-1200**	**VVER-TOI**
Purchase of natural uranium	-	100$/kg
Escalation in the price of natural uranium	-	0-4%⁄год
Conversion	-	10$/kg
Isotopic enrichment	-	110$/SWU
Procurement of waste uranium	0	-
Procurement of plutonium	0	-

Fabrication of core FAs, including axial blanket (BN)	3500$/kg	350$/kg
Fabrication of radial blanket FAs (BN)	300$/kg	-
Transportation of fresh FAs	100$/kg	50$/kg
Transportation of spent FAs, including those from RB (BN)	100$/kg	50$/kg
Interim storage of spent FAs	14$/kg	14$/kg
Treatment of the spent fuel	770$/kg	600$/kg
Final waste handling	860$/kg	850$/kg

TABLE III: DATA ON THE FUEL CYCLE OF THE BN-1200, VVER-TOI REACTORS.

Parameter	**Value**	
	BN-1200	**VVER-TOI**
The number of reloadings per design life	59	59
Time before fuel irradiation in the reactor (till the date of the reactor loading) for: – procurement of natural uranium – procurement of depleted uranium – conversion – isotopic enrichment – fabrication of FAs	 - - - - 6 months	 2 years 1 year 18 months 1 year 6 months
Another 6 months are added to each of the stages for the first fuel loading	-	-
Delay time (after the date of the fuel unloading): – transportation of spent FAs (including two-year on-site cooling)	2 years	5 years
– interim storage of spent fuel on the reprocessing facility	2 years	1 year
– reprocessing of spent fuel	3 years	6 years
– final waste handling	55 years	56 years
Accepted losses when FA fabricating of: – uranium – plutonium Other operations losses	 1,0% 1,0% 0%	 1% - 0%
Reference date for prices	2015	2015
Reference date (the date of the reactor	2025	2025

Parameter	Value	
	BN-1200	VVER-TOI
commissioning)		
Discount rate, annual	varying	
Annual escalation in prices for natural uranium	-	0%, 4%

Initial data on the fuel characteristics, which are necessary for LUFC calculations of the reactor facility with BN-1200 and VVER-TOI, are brought together in Tables IV and V.

TABLE IV: BASIC DATA ON LOADING THE MOX FUEL FOR THE BN-1200 REACTOR.

Loading / Parameter	Initial	Annual
1 Loading of depleted uranium (U-238), total, tonnes hm	98,8	15,0
core, tonnes hm	34,2	6,3
bottom radial blanket, tonnes hm	20,2	3,7
radial blanket, tonnes hm	44,4	5,0
2 Loading of plutonium, total, tonnes hm core, tonnes hm	7,4 7,4	1,4 1,4

TABLE V: DATA ON THE FUEL LOADING FOR THE VVER-TOI REACTOR.

Initial loading		**Annual loading**	
Enrichment, %	Mass, kg hm	Enrichment, %	Mass, kg hm
3,9	77000	4,74	23400

2. LUFC calculation results concerning NPPs with BN-1200 and VVER-TOI

Table VI presents the LUFC calculation results.

It can be seen from the data given below that the main contribution to the LUFC value for BN-1200 is due to fabrication of FAs for the core. This contribution is not less than 50% in all the considered cases and it increases to 80% if the discount rate of discounting increases to r=5%. Therefore, in order to reduce LUFC it is necessary in the first place to reduce the fuel costs. Consequently, if the price of plutonium and waste uranium is taken to be zero the cost of FA fabrication should be decreased. In addition to improvement in manufacturing solutions, reduction in the FA fabrication cost is greatly affected by the scale factor. *FIG. 1.* [8] shows dependence of the fuel fabrication cost on the specific plant production. It is evident that increase in the plant production can reduce the cost concerned by several fold.

TABLE VI: LEVELIZED LUFC FOR THE CONSIDERED MODIFICATIONS OF THE BN-1200 REACTOR AND ITS FUEL CYCLE, MILLS/KILOWATT-HOUR.

NFC conversions	**BN-1200 with MOX fuel**	
	r=0 %	**r=5 %**
Initial stage of the fuel cycle		
Core FAs fabrication	4,46	5,23
Radial blanket FAs fabrication	0,18	0,22
Fresh core FAs transportation to NPP	0,13	0,15
Fresh radial blanket FAs transportation to NPP	0,06	0,07
Total for initial stage	4,83	5,67
Final stage of the fuel cycle		
Spent core FAs transportation to reprocessing facility	0,13	0,09
Spent radial blanket FAs transportation to reprocessing facility	0,06	0,04
Interim storage of spent core FAs	0,02	0,01
Interim storage of spent radial blanket FAs	0,01	0,01
Core spent FAs reprocessing	0,97	0,65
Radial blanket of spent fuel's reprocessing	0,45	0,29
Final waste handling	1,59	0,09
Total for final stage	3,22	1,18
Total cost	**8,05**	**6,85**

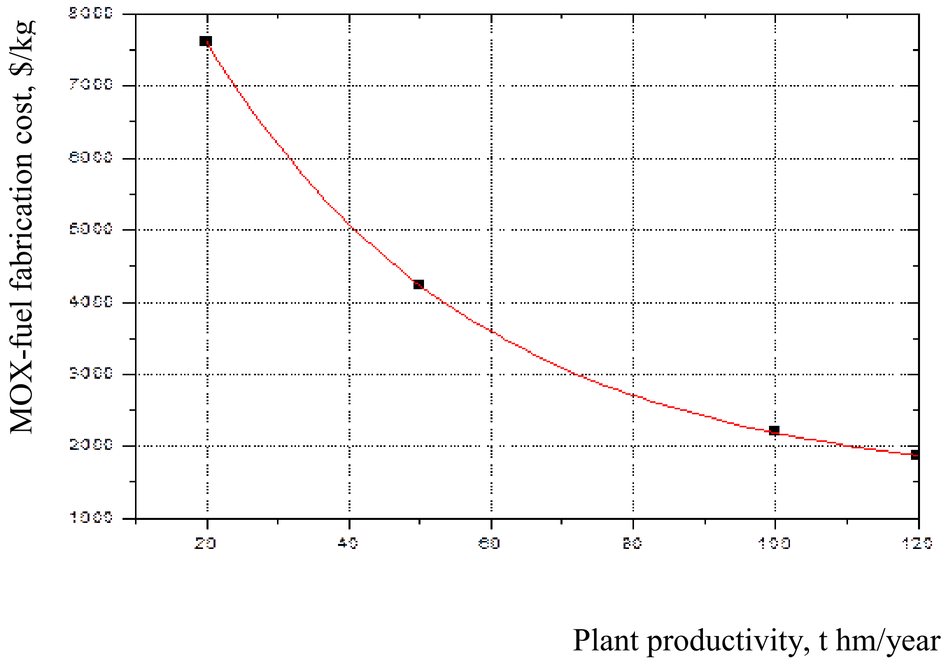

FIG. 1. MOX-fuel fabrication cost as the plant production function.

The discount rate introduces a distinct though not a fundamental difference to the LUFC value. At the initial stage transition from the zero discount rate leads to some increase in the corresponding costs, which is related to the need for the payment of the first fuel loading before power revenues are collected. However, costs at the final stage of the fuel cycle decrease since they are covered after the sale of electric energy. In general, transition from the zero to 5% rate of discounting leads to decrease in LUFC.

For comparison results of calculating LUFC for NPPs with the fast BN-1200 reactor and the thermal VVER-TOI reactor with uranium fuel are given in Table VII and *FIG. 2.* below.

Calculations were performed with natural uranium priced at US$100/kg, which was the price in 2015.

A possible change in the price of natural uranium was taken into account during the entire life time of the NPP when its annual escalation was specified for the calculation. The range of annual escalation from 0 % to 4 % was considered, given that the prices of the other fuel cycle conversions remained unchangeable. Such an approach is consistent with the inevitability of the rise in the price for the required and non-renewable natural resource. Like in the case of the BN-1200 reactor, LUFC calculations for the thermal reactor were performed at the zero and 5 % rate of discounting.

Dependence of LUFC on the escalation of uranium price is significant – transition from zero to 4 % escalation practically doubles LUFC. It should be noted that the maximum considered escalation in the uranium price that is 4 % per year, corresponds to the increase in the average uranium price over the NPP life time (60 years) from the taken initial price of 100 US$/kg to values of the order of 300 US$/kg.

As one can see from the data, LUFC for BN-1200 is less than that for VVER-TOI in terms of all the examined parameters. LUFC for VVER-TOI is practically twice as large as that for BN-1200 even with a 3 % increase in the price of uranium (which corresponds to the average price of 250 US$/kg for uranium over the power unit life cycle).

TABLE VII: COMPARISON OF LUFC VALUES FOR BN-1200 AND VVER TOI AT THE ZERO AND 5 % RATE OF DISCOUNTING, MILLS/KWH.

Escalation in the price of uranium, %		**0**	**1**	**2**	**3**	**4**
BN-1200	**r=0%**	8,05	8,05	8,05	8,05	8,05
	r=5%	6,85	6,85	6,85	6,85	6,85
VVER-TOI	**r=0%**	9,13	10,3	12,4	15,6	19,6
	r=5%	7,38	8,25	9,4	11,4	14.4

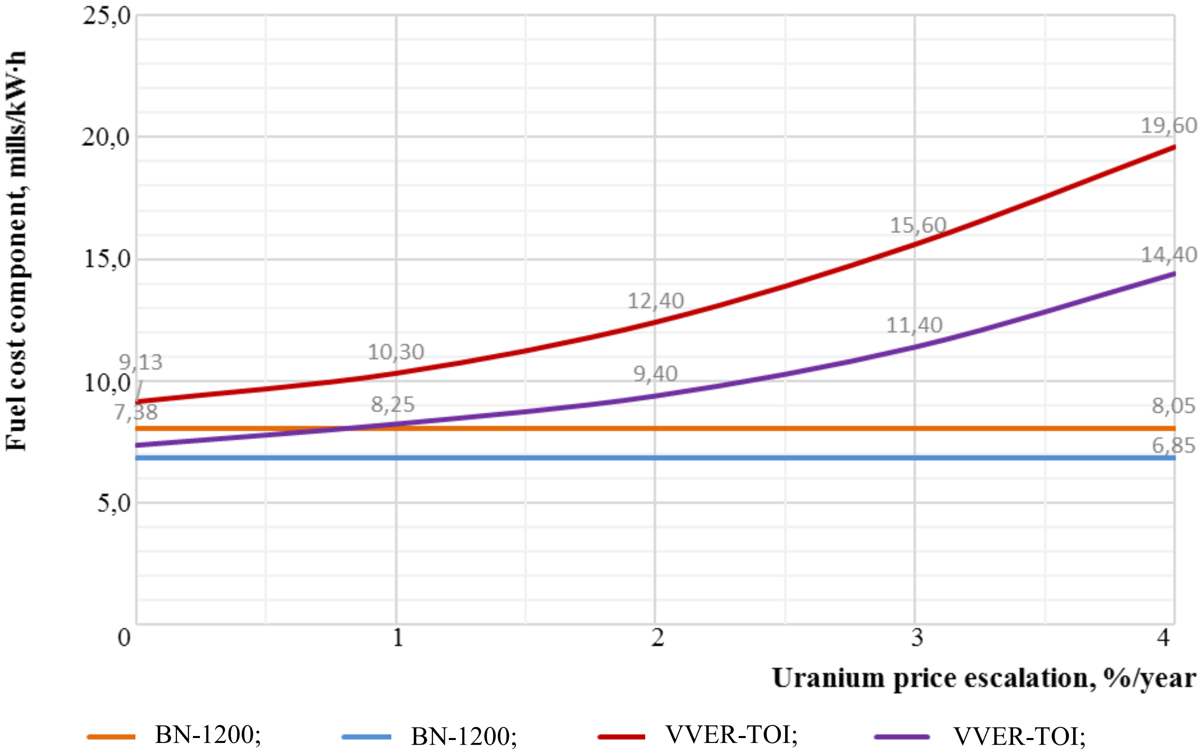

FIG. 2. Comparison of LUFC values for BN-1200 and VVER TOI at the zero and 5 % discount rate

CONCLUSION

Analysis of the Levelized unit fuel cost (LFFC) of power generation at an NPP with the BN-1200 reactor with MOX fuel showed that the main contribution to the LUFC value for BN-1200 is due to fabrication of FAs for the core. This contribution to the total LUFC is 80% if the rate of discounting is r=5%. Therefore, to in order to reduce LUFC it is necessary in the first place to reduce the costs associated with FA fabrication. In addition to improvement in manufacturing solutions, reduction in the FA fabrication costs is greatly affected by the scale factor, i.e. specific production of the plant fabricating MOX fuel, and, thereby, by the scale factor of fast neutron NP development.

The LUFC value for the considered modification of BN-1200 turned out to be 6,8 mills/kWh, with fuel fabrication price at US$3500/kg, plutonium priced at zero and the rate of discounting being 5%.

LUFC for an NPP with VVER-TOI with uranium fuel is 7,4 mills/kWh if the escalation in the price of natural uranium is zero, which is close to that of BN-1200 with MOX fuel. The research shows that LUFC for VVER-TOI reaches the value of 11,4 mills/kWh even with a 3 % increase in the price of uranium (which corresponds to the average price of 250 US$/kg for uranium over the power unit life cycle). This value is almost twice as large as LUFC for BN-1200 with MOX fuel.

Since many of the considered power units parameters and those of the closed NFC in particular are currently known to be with certain error, the results presented are sort of preliminary assessment and to be clarified in the future. However, since many of the characteristics are of a relative nature, it appears that the results obtained may indicate quite clearly further lines of research into enhancement of the BN-1200 reactor performance and its fuel cycle.

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