The European Proceedings of
Social & Behavioural Sciences
EpSBS

Future Academy ISSN: 2357-1330

https://dx.doi.org/10.15405/epsbs.2019.04.77

CIEDR 2018
International Scientific and Practical Conference
"Contemporary Issues of Economic Development of Russia: Challenges and Opportunities"

NEW CHALLENGES IN THE WORLD MARKET FOR NUCLEAR POWER TECHNOLOGIES

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Abstract

Mine production constrained including shutdowns and mine depletion in combination with expanded demand for natural uranium following an increase in nuclear power capacity worldwide push the price for natural uranium up and form new challenges for market players by making it very important to measure a contribution of modern reactor types to the minimization of fuel component in the total cost of energy produced by NPP. The study carries out a comparison analysis between Generation IV Nuclear Reactors using a step-by-step algorithm for calculation of fuel component in the total cost of nuclear energy produced by NPP to show which reactor design the policy makers should choose if they want to minimize the expenses for nuclear fuel. Research shows that one of the apparent advantages of Russian reactor design VVER1200 in comparison with EPR, APR1600 and AP1000 reactor types is low expenses on the nuclear fuel. It will allow NPP equipped with VVER1200 to receive the leverage in competing in the world market for nuclear power technologies. The results of the study can be used by countries which already have, develop or have intention to develop nuclear power in order to make the decision which reactor design to employ for the national nuclear power industry.

Keywords: Closed nuclear fuel cycle, fuel component in the total cost of energy, fuel recycling, Generation IV Nuclear Reactors, REMIX-fuel.

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eISSN: 2357-1330

1. Introduction

1.1. The situation in the market for natural uranium. Demand side

As we can see from Figure 01 below, the demand for natural uranium in 2017 amounted to 65 014 tons, or 76 671 tons of U_3O_8, – a 2.5% improvement in comparison with previous year (World Nuclear Power Reactors & Uranium Requirements, 2018).

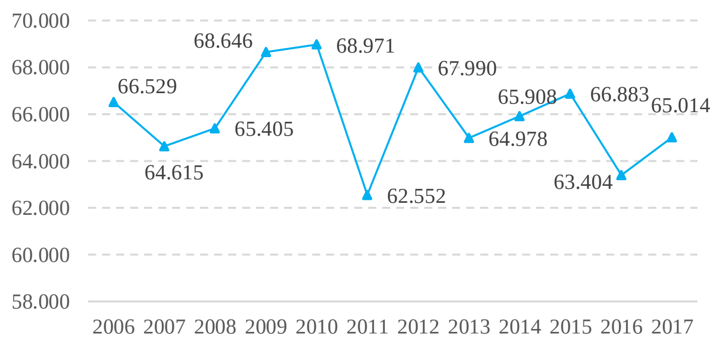

Figure 01. World demand for natural uranium, tons

According to Ux Consulting Company, LLC (UxC) estimates, in 2030 annual demand for natural uranium (including inventory build) will skyrocket by more than 50% from 2017 level. Such an optimistic forecast is drawn from countries' data on reactors in operation, under construction and planned or proposed published by World Nuclear Association (WNA). WNA reports 453 reactors in operation and 55 new ones under construction worldwide including 15 reactors being built in China, nine – in Russia and seven - in India as of date September 2018 (Why the uranium prices must go up, 2018). China's National Development and Reform Commission intends to raise the percentage of electricity produced by nuclear power to 6% by 2020 from the current 2% as part of an effort to reduce air pollution from coal-fired plants. Ultimately, uranium demand will triple inside six years. In India, the government is expected to spend nearly $150 B to develop nuclear power over the next 10-15 years. India now has nuclear energy agreements with about a dozen countries and imports primarily from France, Russia and Kazakhstan. Japan has currently nine reactors back into operation after their shutdown for the safety checks due to the accident at Fukushima Daiichi plant in 2011. In addition to car producers' plans to invest more than 140 billion dollars in electric vehicles (EV's) industry it means that demand for uranium will continue to grow in order to meet the expected capacity for nuclear power.

1.2. The situation in the market for natural uranium. Supply side

Figure 02 shows that there are several leaders in the world market for natural uranium in 2017: JSC KazAtomProm (Kazakhstan, about 25% of world production), Cameco Corp. (Canada, 18%), ROSATOM State Corp. (Russia, 16%), Orano Group (USA, 16%), CNN&CGN (China, 7.8%), Rio Tinto (Australia-Great Britain, 5%), BHP Billiton (Australia - Great Britain, 4.7%), Mining and Metallurgical Company Novoi (Uzbekistan, 4.8%), Paladin Energy (Australia, Canada, Namibia, 1.9%) (Market share of the world's largest uranium producing companies in 2017, 2018).

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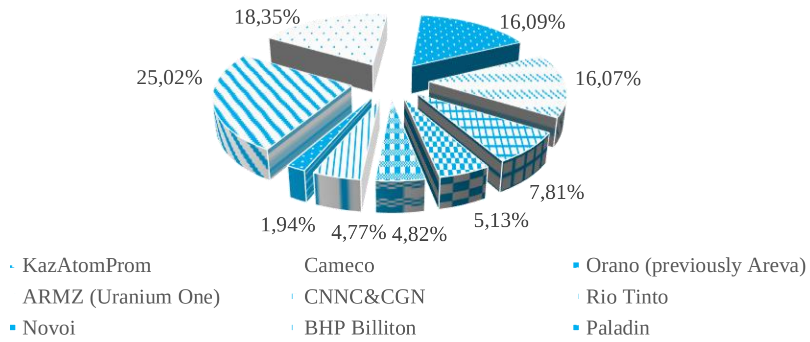

Figure 02. Leading uranium mining companies worldwide by production output in 2017, metric tons

The leader in the market for natural uranium - state-owned company KazAtomProm - has recently announced it will cut 20% of its production over next three years. Cameco Corp. closed its Rabbit Lake mine in 2016 and put on hold operations at McAthur River and Key River mines in 2017. Paladin Energy closed its Langer Heinrich mine due to its depletion. For the same reason Rio Tinto has plans to shut down Ranger mine in 2026. As a result, the mine production has been declining since 2016. Last year UxC claims a 5.5% decrease in the world production of natural uranium in comparison with 2016. The main reason for constrained mine production is low price for natural uranium in the world market which is below the production costs. For the producers is more profitable to buy uranium in the spot market to fulfill their obligations for the long-term contracts with utilities than to mine uranium. This year expected production level will decline by further 12.5% and fall far behind demand driving up the price for natural uranium in the world market as soon as spot market runs out of its supply (Why the uranium prices must go up, 2018).

2. Problem Statement

In the light of growing prices for natural uranium in the world market the transfer to fuel recycling is getting appealing for national nuclear power industry in many countries. The choice between direct disposal and reprocessing of spent fuel – so-called open and closed nuclear fuel cycle – is predetermined by spent fuel management policy in a certain country. The most advanced direct disposal technologies of spent fuel are used in the USA, Canada, Sweden and Finland. Partially closed nuclear fuel cycle is operated in Russia, France, Japan, England, and China. In France, in particular, the MOX fuel (oxide mixture of reprocessed uranium, plutonium, and depleted uranium) is used in recycling process. The alternative approach which is based on the fuel fabrication using a REMIX-fuel (regenerating mixture of uranium and plutonium oxides) for reuse in the same thermal reactors which generate the spent nuclear fuel has been developed in Russia. Using of REMIX fuel in the nuclear fuel cycle of thermal reactors makes possible multiple recycling of plutonium and uranium total amount regenerated from spent nuclear fuel; reduction in the accumulated spent nuclear fuel amount as well as in the amount of consumed natural uranium (Fedorov et al., 2013).

Generation IV nuclear power reactors are designed for use in both nuclear fuel cycles. Most of them are light water reactors (LWR) which are still at the early stages of development, but they play an

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essential role in the nuclear power perspective due to its improved safety features and increased efficiency. The data on reactors used in the study are shown in the Table 01. The Advanced Passive PWR -AP1000 – is currently under construction in the USA and China. The Evolutionary Power Reactors – EPR – are currently being built in Finland, France and China. Advanced Power Reactor 1400 – APR1400 – is under construction for Shin Kori 3&4 in South Korea and Barakah in UAE. VVER1200 – is under construction at Leningrad and Novovoronezh plants in Russia (Lewis, Onder, Nihan, & Prudil, 2017).

Table 01. Advanced reactor types under construction

Reactor	**Design org/Country**	**Cooling/ Moderator**	**Thermal capacity, [MWth]/Electrical capacity, [MWe]**	**Discharge burnup [GWd/t]/Capacity factor**
AP1000	Westinghouse/ USA	Light water/Light water	3400/1200	60/93%
EPR	AREVA (&EdF)/France	Light water/Light water	4590/1770	60/92%
APR1400	KEPCO/KHNP/Rep of Korea	Light water/Light water	3983/1455	44.6/90%
VVER1200	Gidropress/ Russia	Light water/Light water	3200/1170	60/92%

High prices for natural uranium in the world market make it very important to measure a contribution of modern reactors' types to the minimization of fuel component in the total cost of energy produced by NPP. It is becoming a benchmark for making decision about their application in the open and closed nuclear fuel cycle.

3. Research Questions

Which reactor design the decision makers should choose if they want to minimize the expenses for nuclear fuel and fully utilize the safety and efficiency features of Generation IV reactors.

4. Purpose of the Study

Many countries have plans to develop nuclear power and pay a close attention to the economics of nuclear power cycle as well as safety features of Generation IV reactors. In order to identify the reactor which will allow to minimize the expenses for natural uranium the comparison analysis of several Generation IV reactors is carried out.

The results of the study can be used by countries which already have, develop or have intention to develop nuclear power in order to make the decision which reactor design to employ for the national nuclear power industry.

5. Research Methods

For the research purpose, the author used data for Generation IV Nuclear Reactors according to WNA classification on four reactor designs under construction to identify pros and cons of each type in terms of electricity production cost (US$/kg), and more specifically – fuel component in the production cost of energy (¢/kWth).

In order to make assessment of the fuel component in the total cost of energy produced by each type of reactors under consideration the author employed a step-by-step algorithm described in (Osetskaya, Ukraintsev, & Galkovskaya, 2017; Galkovskaya, 2018) for fuel component calculation and current world prices for nuclear fuel cycle stages published by UxC which are provided in the Table 02 (UxC nuclear fuel price indicators, 2018).

Table 02. Prices for main repartitions of front end and back end of NFC in the world in $\frac{doll.}{kg\ h.m.}$ ($\frac{doll.}{kg\ SWU}$)

Name	Price in the world market as of 30.07.2018
Front end of NFC	
Mining	56.66
Conversion	9.50
Enrichment	34
Fuel production:	
thermal reactors	92
fast reactors	no data available
Back end of NFC	
Direct disposal	
Transportation and intermediate storage	230
Encapsulation and direct disposal	610
SF retreatment	
Transportation and intermediate storage	60
Spent nuclear fuel retreatment	820
Vitrification and disposal of nuclear waste	100

6. Findings

The summary of the results is presented in the Table 03. Table 03 shows calculation results for the fuel component in the total cost of energy for the case of direct disposal and SF retreatment.

Table 03. Fuel production costs for the different type of reactors without SF recycling

Name	AP1000	EPR	APR1400	VVER1200
Front end of NFC				
Mining	12 904 405.86	19 243 163.47	16 967 721.49	12 015 369.61
Conversion	2 163 640.23	3 226 439.34	2 844 923.30	2 014 578.38
Enrichment	4 831 070.16	7 247 492.04	6 014 383.07	4 481 564.07
Fuel production	1 892 690.91	2 761 700.61	2 987 702.81	1 785 845.45
Total costs – Front end of NFC	21 791 807.16	32 478 795.45	28 814 730.67	20 297 357.51
Back end of NFC				
Direct disposal				
Transportation and intermediate storage	4 731 727.27	6 904 251.52	7 469 257.03	4 464 613.64
Encapsulation and direct disposal	12 549 363.64	18 311 275.76	19 809 768.65	11 840 931.82

Total costs - Direct disposal	17 281 090.91	25 215 527.27	27 279 025.68	16 305 545.45
SF retreatment				
Transportation and intermediate storage	1 234 363.64	1 801 109.09	1 948 501.83	1 164 681.82
Spent nuclear fuel retreatment	16 869 636.36	24 615 157.58	26 629 525.07	15 917 318.18
Vitrification and disposal of nuclear waste	2 057 272.73	3 001 848.48	3 247 503.06	1 941 136.36
Total costs - SF retreatment	20 161 272.73	29 418 115.15	31 825 529.96	19 023 136.36
Fuel production costs without SF retreatment, US$/kg	1 899.26	1 921.96	1 727.29	1 885.64
Fuel production costs with SF retreatment costs, US$/kg	2 039.26	2 061.96	1 867.29	2 025.64
Fuel component in the cost of energy (direct disposal) ¢/kWth	**0.39967531**	**0.40445283**	**0.48899556**	**0.39681041**
Fuel component in the cost of energy (SF retreatment) ¢/kWth	**0.42913659**	**0.43391411**	**0.52862957**	**0.42627169**

As we can see from the table above the lowest fuel component in the total cost of energy we have for VVER1200 design. In case of direct disposal, it is 18.9%, 1.9% and 0.7% lower than similar indicator for APR1400, EPR and AP1000 accordingly. In case of SF retreatment, the numbers mirror previous results with 19.4%, 1.8% and 0.7% respectively.

7. Conclusion

Nuclear power industry is a dynamic industry driven by new challenges in the market for nuclear power technologies which all market players must undertake. Despite the industry complexity one of the apparent advantages of Russian reactor design VVER1200 is low expenses on the nuclear fuel. The situation with growing prices for natural uranium makes this advantage crucial for the policy makers responsible for choosing the reactor designs for national nuclear power.

Study results show that in case of direct disposal fuel component of 1 kWth of energy cost produced by APR1400 reactor type exceeds fuel component of 1 kWth of energy costs produced by VVER1200 by 0.09 ¢, for EPR and AP1000 it is 0.007 ¢ and 0.003 ¢ respectively. In case of spent fuel reprocessing the fuel component of 1 kWth of energy cost produced by APR1400 reactor type exceeds fuel component of 1 kWth of energy costs produced by VVER1200 by 0.10 ¢, for EPR and AP1000 it is 0.008 ¢ and 0.003 ¢ respectively.

Acknowledgments

I would like to thank my academic advisor Maria Osetskaya (Project Leader, Rosatom Technical Academy) for her valuable comments and ideas for the research.

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